Anaerobic Co-Digestion Scheme of Biogas Engineering Based on Feedstock and Temperature

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This article investigates the current status and distribution of the feedstock of biogas engineering in China, evaluates the temperature conditions for anaerobic co-digestion (AcoD), and assesses the biogas production potential of feedstock in AcoD, including six feedstocks, namely, maize straw (M), wheat straw (W), rice straw (R), pig manure (P), cow manure (C), and sheep manure (S). The total amount of M, W, and R was 3.89×10^8, 2.10×10^8, and 1.50×10^8 tons, respectively, and that of P, C, and S was 8.46×10^8, 1.31×10^9, and 4.95×10^8 tons, respectively. However, the spatial distributions and amount of those resources were found to be uneven in China. Heilongjiang has abundant maize straw, and Henan has abundant wheat resources. Sichuan is rich in cow manure, while Inner Mongolia is rich in sheep manure. The analysis of total biogas production (TBP) by mono-digestion and co-digestion (using two feedstocks at ratio of 1:9, 3:7, 5:5, 7:3 and 9:1) showed that co-digestion outperforms mono-digestion under 15 and 25 °C. Thus, it is necessary to study anaerobic co-digestion scheme (AcoDS), which will provide a reference for biogas engineering in different regions to promote the biogas yield based on their actual situation.

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Keywords: Anaerobic co-digestion scheme; Biogas engineering; Feedstocks; Temperature; Biogas yield

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INTRODUCTION

According to the requirement of ‘carbon neutral’, it is imperative to promote a revolution in energy production and consumption and to develop a green economy in China’s rural areas (Jiang *et al.* 2011; Zheng *et al.* 2020 Das *et al.* 2021; Zeng *et al.* 2022). As a promising clean energy source (Karve 2003), biogas energy is considered to be the most feasible form of renewable energy for rural areas (Morris and Jungjohann 2017; Zhang *et al.* 2022). This is because it makes rural energy consumption cheaper and more convenient, which is conducive to the improvement of rural ecological environment and the promotion of rural energy industry structure upgrading (Chen *et al.* 2010; Wang *et al.* 2018). China has a substantial focus on biogas for reducing energy consumption and carbon di-oxide (CO_2) emissions (Zhang *et al.* 2022). The national annual production capacity of biogas was 20.7 billion m^3, and carbon dioxide emission reduction reached 46.22 million tons in 2020. Therefore, rural biogas is a strategic choice for China’s sustainable development and response to global climate change. It is of great significance for the construction of ‘beautiful China’ and the rural revitalization strategy (Oslaj and Mursec 2009; Yadav 2012; Das *et al.* 2021; Mller *et al.* 2022).

In recent years, the Chinese government has been adjusting and optimizing the investment structure and support policies for rural biogas (Niu *et al.* 2021). The total investment in rural biogas was 50 billion RMB during the "13th Five-Year Plan", including 13.361 billion RMB for large-scale biogas projects, 9.1 billion RMB for medium-sized biogas projects, 5.9 billion RMB for small-scale biogas projects, 3.33 billion RMB for household biogas, and 189 million RMB for biogas science and technology innovation platforms (Ahmed *et al.* 2021). While with the large-scale development of planting-breeding and rapid urbanization, household biogas digesters are unsuitable for the new rural economic and social environment (Niu *et al.* 2021). Therefore, the scale biogas engineering (small: 5-150m^3/d, medium: 150-500 m^3/d, large: 500-5000 m^3/d, super large: ≥5000 m^3/d) will become the trend for Chinese rural biogas (Wang *et al.* 2020). However, its development also faces many challenges, such as large initial investment, the high cost of feedstock storage and transportation, questions about how to use agricultural organic waste more efficiently, and the need to improve biogas production, *etc*. (Wang *et al.* 2021).

Many kinds of feedstock can be used to AcoD in biogas engineering, such as livestock manure, crop straw, domestic sewage, and kitchen waste (Chen *et al.* 2013; Zhai *et al.* 2015; Munisamy *et al.* 2017; Mozhiarasi *et al.* 2019; Xing *et al.* 2020). As stated by the researchers, the feedstock with the characteristics of stable composition, easy collection, low cost, and sufficient quantity is more suitable for AcoD (Comparetti *et al.* 2012). Crop straw and livestock manure fit the requirements (Zeng *et al.* 2007; Wang *et al.* 2012a).

The substrate has to have the proper ratio of nutrients for the microorganisms for it to be biodegraded optimally. Therefore, substrate composition is very crucial for optimal biogas production of anaerobic digestion (Kunatsa *et al*. 2020). However, mono-digestion using only one straw or animal manure has many drawbacks. For instance, a high carbon to nitrogen ratio is one of the main hindrances in the anaerobic digestion of such agricultural waste as crop straw. Problems can include 'ammonium intoxication,' which is caused by too low or too high C/N ratio, digester instability, and low biogas yield (Li *et al.* 2018b; Zahan *et al.* 2018). Excess carbon results in accumulation of organic acids, which affects fermentation (Pagés Díaz *et al.* 2011). To overcome this issue, animal manure can be mixed with another suitable substrate rich in nitrogen content. Most of the researchers are focusing on co-digestion (Rajput *et al*. 2021). This is because multiple substrates digestion can improve biogas yield due to provision of additional nutrients and regulation of pH, thus enhancing the methanogenic efficiency. Several studies in the literature have shown enhancement in methane yield and optimization of AD process due to co-digestion (Zeshan *et al*. 2012). Co-digestion of chicken and dairy manure with wheat straw increased biogas production at C/N ratio of 25 to 30 (Wang *et al*. 2012). Apart from C/N ratio, co-digestion plays a vital role in improving the micro and macro nutrients, which improve methane yield (Zhang *et al*. 2014). Feedstock of co-digestion can better balance micro and macronutrient to support different bacterial and methanogenic pathways (Rajput *et al*., 2021; Haider *et al*. 2015; Supaphol *et al*. 2011). AcoD provides an opportunity to overcome the drawbacks of mono-digestion by simultaneously digesting two or more feedstocks (Karki *et al.* 2021). The major benefits of co-digestion include enhanced system stability by more diverse microbial community (Mata-Alvarez *et al.* 2014), increasing the bioavailability of nutrients in digestate (Bustamante *et al.* 2012), and relieving the pressure of excessive demand for one feedstock. Therefore, quality of substrate is very crucial in the anaerobic digestion process to produce biogas (Kunatsa *et al*. 2020).

Temperature is an important factor that affects AcoD (Niu *et al.* 2014). Biogas fermentation involves three temperature ranges for the optimal growth and reproduction of methanogens: low-temperature fermentation (10 to 30 °C), mid-temperature fermentation (30 to 40 °C), and high-temperature fermentation (50 to 60 °C) (Duran and Speece 1997;

Su *et al.* 2017; Yin *et al.* 2017). The TBP is linearly correlated with temperature in mid-temperature fermentation conditions (Chae *et al.* 2008). However, low temperature has a deleterious effect on methanogenesis and can cause decreased biogas yields and digester failure because microorganisms are unable to attach to substrates with lowered affinity (Singh *et al.* 1995; Rennuit and Sommer 2013; Mller *et al.* 2022).

This paper studied the biogas production potential of feedstock in AcoD with different proportions and temperature. Its purpose was to illustrate the importance of optimized AcoDS for biogas engineering and study how should different regions select best option to promote biogas yield and sustainable development of biogas engineering. It also provides a basis for rational planning for biogas engineering.

EXPERIMENTAL

Feedstock

Pig, cow, and sheep manure were collected from farms in Cuixigou, Yangling, China. Manure from animals that were sick or recently used antibiotics was not collected. The manures were heaped for 7 days, stirring every 2 days. Wheat and maize straw were collected from the experimental fields of Circular Agriculture Engineering Technology Center in Shaanxi Provincial, while rice straw was purchased locally. The straws were air-dried and pulverized into 1 to 3 cm pieces. The inoculum was obtained from a biogas digester in Cuixigou, which is the model village of biogas utilization; more than 85% households installed biogas digesters. The biogas digester treats a mixture of live-stock manure, straws, and other food and agro-waste (fruit, vegetables, grass, *etc*.), operating under natural temperature and a retention time of some 60 days. To reduce error, inoculum was always obtained from the same biogas digester. The inoculum was mixed thoroughly and stored in plastic bottles at 4.0 °C (Wang *et al.* 2012b). The physicochemical properties of the feedstock were determined, as shown in Table 1.

Table 1. Basic Characters of Different Feedstock

Material	Carbon Content (%)	Nitrogen Content (%)	C/N	Total Solid (%)	Volatile Solid (%)
Inoculum	22.38	1.02	21.74	6.46	51.22
Maize straw	36.95	0.56	65.98	79.50	89.20
Wheat straw	27.18	0.48	56.62	78.31	86.87
Rice straw	35.04	0.47	74.55	83.50	80.95
Pig manure	34.39	1.07	32.14	20.18	86.92
Cow manure	34.06	1.13	30.14	15.16	83.47
Sheep manure	27.73	1.08	25.68	37.24	62.52

Test plan

AcoD refers to the fermentation using two kinds of feedstock at the ratio of 1:9, 3:7, 5:5, 7:3, and 9:1 (Table 2). As shown in Fig. 1, AcoD was carried out in triplicate at 15 ± 2 °C and 25 ± 2 °C with the total solid concentration of 8% for 50 days (Wang *et al.* 2012b). The 1 L glass reactor with 700 g of total liquid, including 140 g of inoculum, was conducted by a controlled and constant temperature device. The blank samples contained 140 g of inoculum and 560 g of distilled water. Daily biogas production was measured by the drainage collection method and three reactors were tested for TBP for each experimental condition. Samples were drawn periodically to measure volatile fatty acids, total ammonium nitrogen, total alkalinity, and pH.

Table 2. The Co-digestion Ratio of Six Feedstock at 15 °C and 25 °C

Temperature	Raw Materials	Maize Straw (M)	Wheat Straw (W)	Rice Straw (R)
15 °C and 25 °C	Pig manure(P)	1:9,3:7,5:5,7:3,9:1	1:9,3:7,5:5,7:3,9:1	1:9,3:7,5:5,7:3,9:1
	Cow manure(C)	1:9,3:7,5:5,7:3,9:1	1:9,3:7,5:5,7:3,9:1	1:9,3:7,5:5,7:3,9:1
	Sheep manure(S)	1:9,3:7,5:5,7:3,9:1	1:9,3:7,5:5,7:3,9:1	1:9,3:7,5:5,7:3,9:1

* The work contains the mono-digestion using one feedstock).

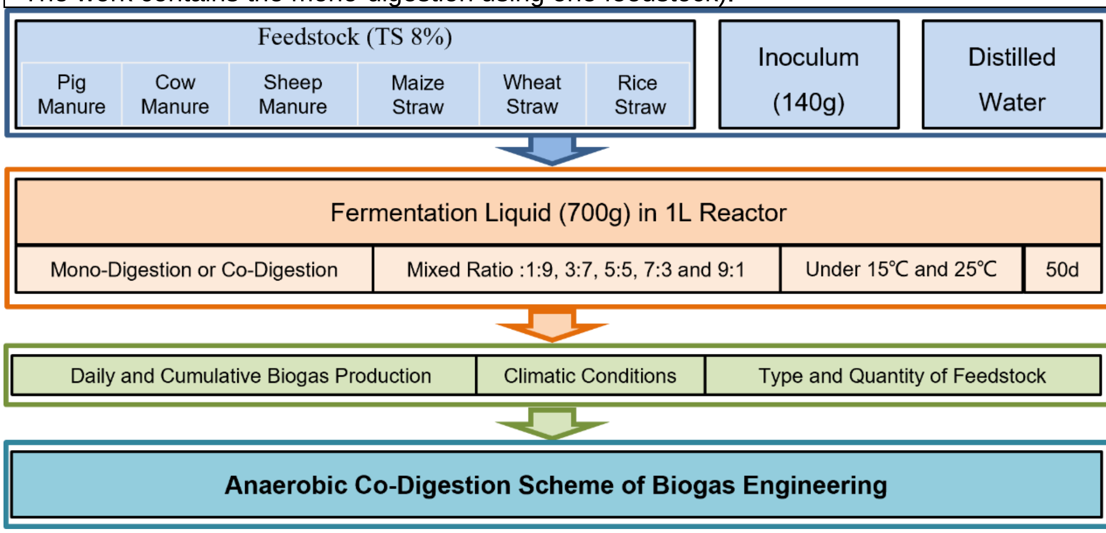


Fig. 1. The test plans

RESULTS AND DISCUSSION

Analyzing Feedstocks and Temperature Conditions

The data of crop yield, number of livestock and poultry breeding, and climate of different provinces were obtained from the China Statistical Yearbook published by the National Bureau of Statistics of the People's Republic of China (NCBC) in 2020 (NCBC,2020).

Straw

Total amount of straw resources

Straw, a common feedstock for AcoD, usually refers to the remainder of the harvested crops and is a multipurpose renewable biological resource (Yu *et al.* 2019; Zeng *et al.* 2007). Straw yield depends on the crops yield and the coefficient of straw (Wang *et al.* 2008; Zhong *et al.* 2003). Crops mainly include vegetable crops, cash crops, and food crops. Vegetable crops productions are mainly self-sufficient operations in rural areas (Cioabla *et al.* 2012). Their wastes are less and hard for long-term storage, so it is rarely used for AcoD of biogas engineering.

Figure 2 shows that the yields of the 12 types of major food crops were significantly different from those of economic crops in 2020. Grain crops provided the highest yield of 6.17×10^8 tons, that accounted for 54.8% of the total yield of food and economic crops.

Fruit yield ranked second at 2.87×10^8 tons. Various types of fruit crops are cultivated, but their wastes are difficult to collect. The storage period is short, so they are unsuitable as a stable source of fermentation raw materials. Crops with low yields, such as crude fiber crops (2.49×10^5 tons) or limited geographical distribution, such as cotton and tea, are also unsuitable as stable sources for fermentation materials. Feedstock in biogas engineering must be readily available at high amounts, widely distributed, and easily collected and stored (Li *et al.* 2001; Zhong *et al.* 2003). Given these characteristics, grain straw is a better choice.

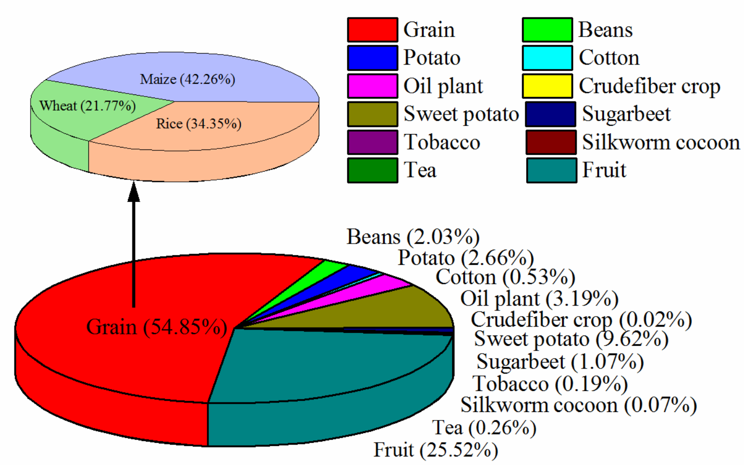


Fig. 2. The yields of the major food crops and economic crops in 2020

China has a high straw production as an agricultural country. Research shows that total annual straw production of approximately 1 billion tons in China. Rice, wheat, and maize are the three main sources of straw in China, accounting for approximately 83.51% (Xu *et al*. 2022). This is consistent with the finding that China has had a scale of straw yield about 800 million tons per year during the past decades (Bai *et al*. 2022; Ren *et al*. 2019; Sun *et al.* 2022). Figure 3 shows that the annual yields of maize, rice, and wheat were 2.61×10^8, 2.12×10^8, and 1.34×10^8 tons in 2020, respectively. The yields of these three crops account for 92.1% of the total food crop yield. Straw yield is associated with the straw coefficient. The straw coefficients of maize, rice, and wheat are 1.774, 1.014, and 1.163 respectively (Li *et al.* 2001; Zhong *et al.* 2003). According to Eq. 1, the total amount of maize, rice, and wheat straw in China in 2020 was 3.89×10^8, 2.10×10^8, and 1.50×10^8 tons, respectively. The total yield of three crop straw was 7.49×10^8 tons, which is close to the results of prior studies (Xu *et al*. 2022; Ren *et al*. 2019; Sun *et al*. 2022; Bai *et al*. 2022). Maize, rice and wheat provide massive straw yields, which can be used as feedstock for biogas engineering. Therefore, this paper focused on AcoD with maize straw, rice straw, and wheat straw.

$$CR = \sum_{i=1}^{n} Qc_i r_i \tag{1}$$

where CR is the straw yield, Qci is the crop yield, and ri is straw coefficient.

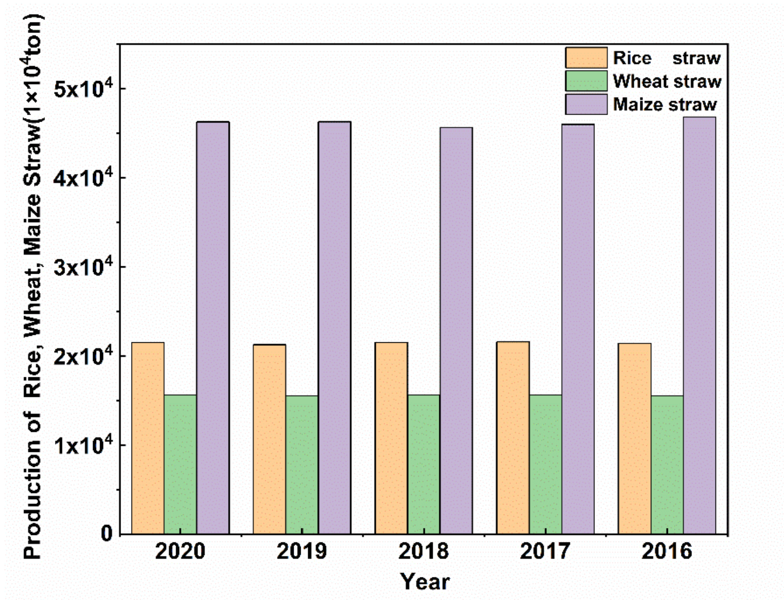


Fig. 3. The annual yields of maize straw, rice straw and wheat straw from 2016-2020

Distribution of straw resources

Figure 4 shows the mount of maize, wheat, and rice straw resources of each region in China in 2020. In east China, rice straw yield is higher than maize and wheat straw yield in Shanghai, Fujian, Zhejiang, Anhui, Jiangsu, and Jiangxi provinces, while maize and wheat straw yield in Shandong Province is higher than rice straw yield. North China is mainly rich in maize and wheat straw.

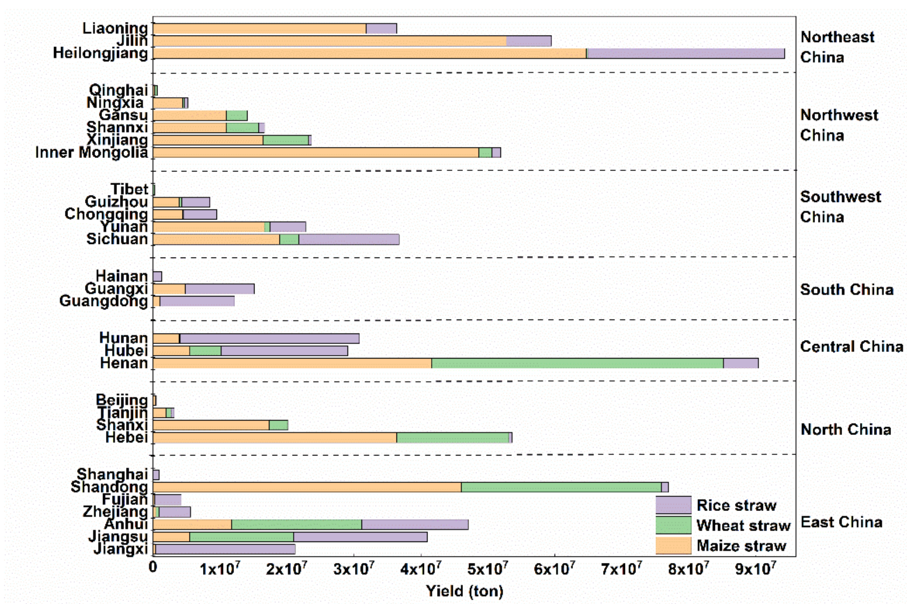


Fig. 4. The mount of maize, wheat, and rice straw of each region in China in 2020

Henan Province in central China has the highest wheat straw yield, reaching 4.36 $\times 10^7$ tons, followed by maize and rice straw. Hubei and Hunan have the highest yield of rice straw, followed by maize straw and wheat straw. Rice straw yield is the highest in

South China, followed by maize straw, and wheat straw yield is lower, especially in Hainan, where maize and wheat are hardly grown. In southwest, the yield of wheat straw Tibet is higher than that of maize straw, while rice straw yield is lower. The yields of maize straw in Sichuan and Yunnan are higher than that of rice straw and wheat straw. The yields of maize straw and rice straw in Chongqing and Guizhou are close, but the yields of wheat straw are low. In northwest China, the yield of wheat straw in Qinghai is higher than that of maize straw. Maize straw yield is higher than that of rice and wheat straw in Inner Mongolia and Ningxia. Maize straw in Xinjiang, Gansu and Shaanxi is more than wheat straw and rice straw. In northeast China, maize straw yield is higher than rice and wheat straw yield, and the output of maize and rice straw in Heilongjiang ranks first in China with production values of 6.47×10^7 and 2.94×10^7 tons, respectively.

Livestock Manure

Total amount of livestock manure

Animal manure as the most common C-rich feedstock co-digestion with straw can promote the stability and continuity of TBP in digester. It is the best choice as the raw co-substrate for biogas fermentation (Tatlidil *et al.* 2009; Pagés Díaz *et al.* 2011).

Amount of animal manure = (livestock amount or uncounted livestock amount) × daily excretion coefficient × feeding cycle (2)

Poultry, pigs, cows, sheep, horses, donkeys, mules, and camels are the major livestock animals reared in agricultural areas. The manures of horses, donkeys, mules, and camels are unsuitable for AcoD given the low populations and limited geographical distributions of these animals. The number of poultry breeding and slaughter in 2020 was 6.78 billion and 15.57 billion, respectively. Compared with pigs, cows, and sheep (Table 3), poultry have low manure production and short feeding cycle (2020).

Figure 5 indicates that in 2020, the livestock slaughter numbers of pigs, cows, and sheep were 527.04 million, 45.66 million, and 319.41 million, respectively, with breeding stock numbers of 406.5 million, 95.62 million, and 613.10 million, respectively.

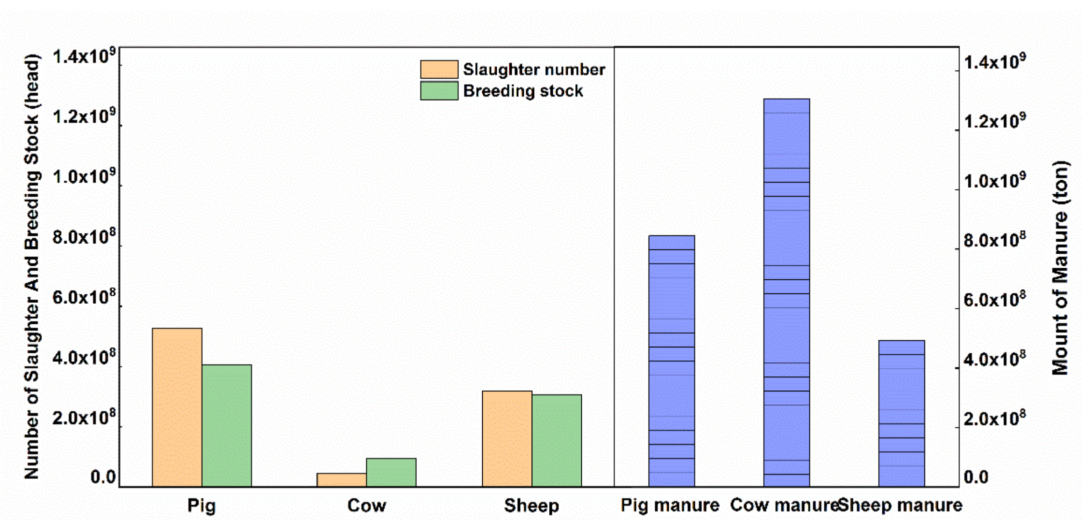


Fig. 5. Number of pigs, cow and sheep and the amount of their manure in China in 2020

According to Eq. 2 and the average excretion coefficients, the manure yields of pigs, cows, and sheep were calculated as 8.46×10^8, 1.31×10^9, and 4.95×10^8 tons, respectively. Pigs, cows, and sheep with high manure yields are ubiquitous and widely available. Combining these manures with straw as feedstock for AcoD provides great effects. Therefore, this work focuses on analyzing the AcoD of pig, cow, and sheep manures with maize, rice, and wheat straw.

Table 3. Pollutants and Discharging Coefficient (Liu *et al*. 2020; Niu and Ju 2017)

Category	Pig	Cow	Sheep	Poultry
Excretion coefficient of the manure for per unit animal (kg/d/head, FW) a	3.34	25.33	2.16	0.13
Feeding cycle period(d)	199	365	365	365 (egg chicken) 55 (Broiler chicken) 210 (Duck) 210 (Goose)

Distribution of livestock manure resource

The distribution of manure resources in various regions of China is shown in Fig. 6: pig manure > cow manure > sheep manure in eastern and central China; cow manure > sheep manure > pig manure in northwest China; and cow manure > pig manure > sheep manure in the north, south, southwest and northeast of China. Sichuan has the highest total output of pig manure (8.46×10^8 ton) and cow manure (8.13×10^8 ton), and Inner Mongolia has the highest total output of sheep manure (4.79×10^8 ton).

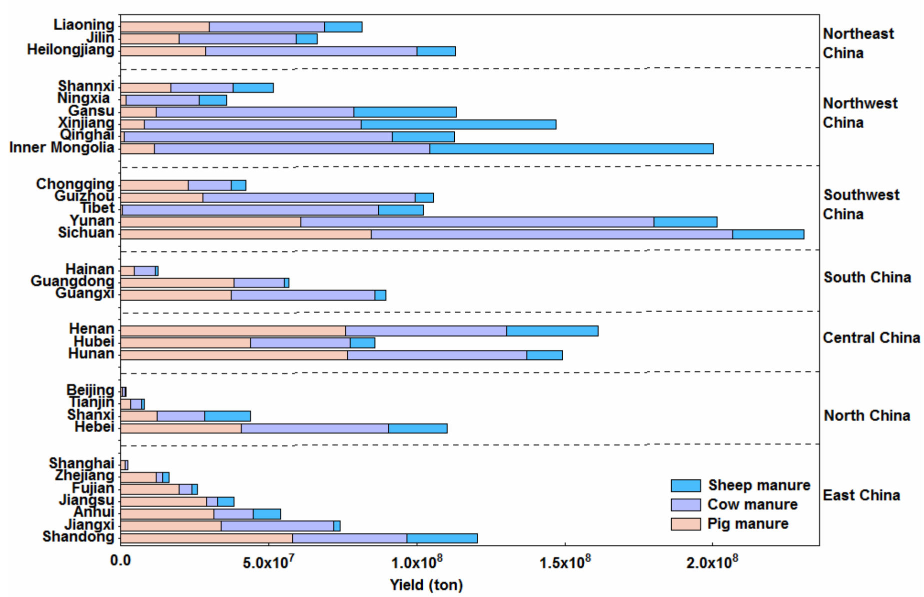


Fig. 6. The mount of pig, cow, and sheep manure of each region in China in 2020

Analyzing temperature condition

Figure 7 shows the monthly average temperature (MAT) of major cities of each province in China in 2020 (2020). Except for the MAT of Fuzhou and Guangzhou in July and MAT of Shanghai, Nanjing, Hangzhou, Fuzhou, Nanchang, and Haikou in August is over 30°C, the MAT of other regions is all below 30 °C in China. Thus, low temperature digestions would be the predominant way of fermentation under natural conditions in China. Low temperature leads to insufficient biogas supply, which further leads to poor experience of using biogas, and people's willingness to use biogas decreases (Dhungana *et* *al*. 2022; Yin *et al*. 2017). Increasing biogas production without the additional cost of biogas tank insulation and heating is a problem facing the development of rural biogas in China.

Area	Province	City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Average
East China	Shang hai	Shanghai	7.3	8.6	12.3	15.2	22.3	25.3	26.6	30.5	24.3	19.2	15.3	7	**17.8**
	Jiang su	Nanjing	5.1	8.2	12.3	15.8	23	25.8	25.4	30.1	24.1	17.5	13.2	4.6	**17.1**
	Zhe jiang	Hangzhou	7.3	9.9	13.1	16.4	23.5	26.1	26.9	31	23.9	19.2	15	6.8	**18.3**
	An hui	Hefei	3.4	7.4	11.7	15.4	22.9	25.4	25.1	28.9	23.1	16.3	11.5	3.5	**16.2**
	Fujian	Fuzhou	13.4	13.6	15.7	17.8	24.7	28.8	30.7	30.1	26	22.3	20.5	13.9	**21.5**
	Jiangxi	Nanchang	7.3	11.1	14.2	17.8	24.9	27.6	28.8	30.7	23.7	19.6	15.8	7.7	**19.1**
	Shandong	Jinan	1.1	5.6	11.2	14.8	22.2	26.3	25.2	26.4	22.4	14.9	9.4	0.7	**15**
North China	Beijing	Beijing	-1.5	1	9.1	15.7	21.1	26.9	26.7	26.7	21.8	13.5	6.5	-2.2	**13.8**
	Tianjin	Tianjin	-1.1	1.9	9.3	15.3	20.7	26.4	27	26.3	21.4	13.4	6.9	-2.4	**13.8**
	Hebei	Shijiazhuang	-1	3.9	10.8	15.8	22	27.2	26	26.1	22.6	14.5	8.1		**14.7**
	Shanxi	Taiyuan	-3.4	0.6	8.3	12.1	20	23.6	23.2	22.4	18	10.2	4.3	-5.1	**11.2**
	Central Inner Mongolia	Huhehaote	-10.5	-4.1	2.3	9.3	16.5	21.8	21.7	20	14.9	6.1	-1.1	-12.9	**7**
Central China	Henan	Zhengzhou	2.7	6.3	12.8	16.2	24.7	27.1	26.6	27.5	24.6	15.6	10.9	2.9	**16.5**
	Hubei	Wuhan	4.1	8.6	13	16.8	23.1	26.5	26.5	30	23.1	16.7	12.5	4.8	**17.1**
	Hunan	Changsha	5.1	10	13.3	17	22.9	26.3	27.6	29.4	22	16.8	13.5	6.1	**17.5**
South China	Guangdong	Guangzhou	15.8	16.1	20	20	27.1	28.2	30.3	28.4	27	23.4	21.2	14.6	**22.7**
	Guangxi	Nanning	15.4	16.5	19	19.7	27.4	28.5	29.2	27.6	26.6	22.1	20.2	13.4	**22.1**
	Hainan	Haikou	20.4	20.8	24.8	24	29.6	30	30	28.4	28.4	25.3	23.4	18.6	**25.3**
Southwest China	Chongqing	Chongqing(Shapingba)	10	11.2	16	17.9	24.8	26.5	27.6	31.4	23.5	17.7	15.3	8.7	**19.2**
	Sichuan	Chengdu(Wenjiang)	7.1	9.7	13.5	16	22.6	24.8	25	24.8	21.2	15.9	13	5.6	**16.6**
	Guizhou	Guiyang	6.2	8.9	12.4	13.4	20.9	22.5	23.7	23.8	18.8	14.2	11.1	3.3	**14.9**
	Yunan	Kunming	9.9	11	16	16.1	20.6	22.5	20.6	20.8	19.4	16.5	13.5	10.7	**16.5**
	Tibet	Lhasa	-0.7	1.7	5.9	7.8	11.9	17.7	17.2	17.2	16.8	13.1	5	2.8	**9.7**
Northwest China	Shannxi	Xi'an(Jinghe)	2.4	6.2	12.6	16.4	23	24.9	25.7	25.4	21.8	13.6	9.4	1	**15.2**
	Gansu	Lanzhou(Gaolan)	-6.2	-3.2	4.5	9.9	15.7	20.4	21.6	19.8	14.8	7.9	0.5	-8.1	**8.1**
	Qinghai	Xining	-5.3	-2.4	2.8	6.6	11.7	14.8	16.8	16.1	12.4	6.2	0.7	-7.1	**6.1**
	Ningxia	Yinchuan	-4.2	0.2	7.2	12.8	18.8	23.7	25.1	22.5	17.3	8.8	2.7	-7	**10.7**
	Xinjiang	Urumqi	-9.3	-4.8	2.9	16.4	19.9	21.7	23.8	23.3	16.1	8	-1.3	-12.3	**8.7**
Northeast China	Liaoning	Shenyang	-9.9	-4.5	3.9	10.1	17	23.4	25.2	24.5	18	9.2	2.1	-8.4	**9.2**
	Jilin	Changchun	-12.5	-7.8	1.1	7.9	15.9	21.8	25	23.2	16.3	7.8	-1.4	-12.2	**7.1**
	Heilongjiang	Harbin	-16.9	-11.4	-1.1	7.5	15.6	19.9	24.4	21.7	16.3	7.2	-3.3	-15.2	**5.4**

＜10℃ 10-14.9℃ 15-19.9℃ 20-24.9℃ 25-29.9℃ ⩾30℃

Fig. 7. Monthly Average Temperature of Major cities in China in 2020 (°C)

The Character of Biogas Production by Different Feedstock under 15 °C

Figure 8 shows the TBP of mono-digestion and co-digestion at 15 ℃. The following TBP were: rice straw (350 mL) < pig manure (454 mL) < cow manure (610 mL) < wheat straw (1,054 mL) < maize straw (1,188 mL) < sheep manure (1,528 mL). The TBP of sheep manure was the highest, whereas that of rice straw was the lowest, and the former is 4.37 times that of the latter. The highest TBP of mixed fermentation of 3,754 mL was obtained at a sheep/rice 9:1, whereas the lowest production was of 950 mL was obtained at a pig/cow 7:3, which was 950 mL. Therefore, the minimum TBP of AcoD was still higher than that of mono-digestion with rice straw, pig manure, and cow manure alone.

Figure 8 shows that the TBP of the same feedstock at different proportions varied significantly ($P<0.01$) at 15 °C. AcoD of sheep manure and rice straw with the highest TBP as an example, the TBP of the five proportions is as follows: sheep/rice 3:7 < sheep/rice1:9 < sheep/rice5:5 < sheep/rice 7:3 < sheep/rice 9:1. The TBP at sheep/rice 9:1 was 3,754 mL, but that at a ratio of 3:7 was 1,166 mL, which was lower than the TBP of sheep manure alone (1,528 mL).

The TBP of AcoD with the same feedstock and proportion is remarkably different. Taking AcoD with two feedstocks (ratio of 9:1) as an example, the following volumes were obtained: pig/cow 9:1 (354 mL) <pig/sheep 9:1 (625 mL) <pig/maize 9:1 (946 mL) <pig/wheat 9:1 (1,092 mL) <pig/rice 9:1 (1,999 mL) <sheep/rice 9:1, (3,754 mL).

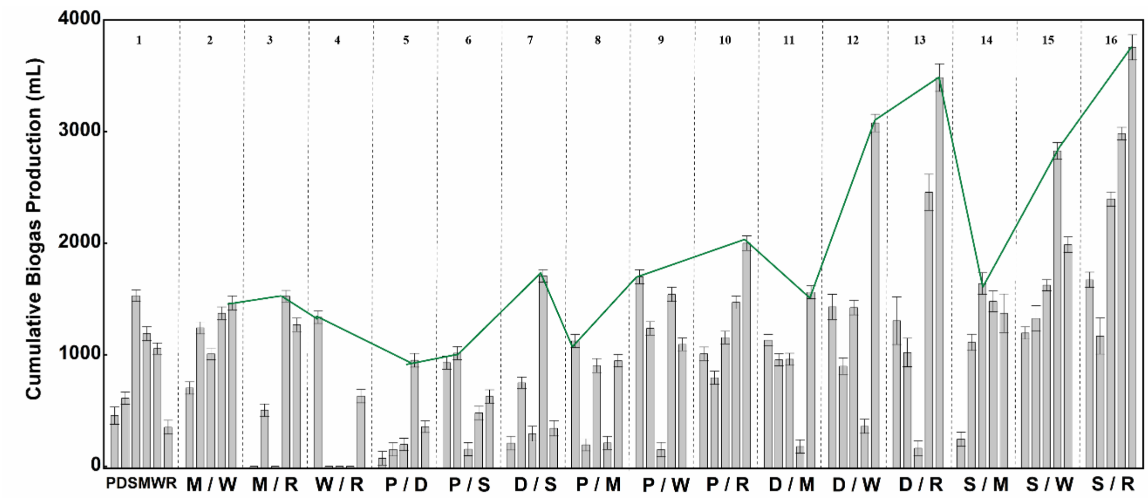


Fig. 8. The total biogas production by different feedstock under 15 °C. (M is maize straw. W is wheat straw. R is rice straw. P is pig manure. C is cow manure. S is sheep manure. M/W refers to the fermentation of maize straw and wheat straw in the following proportions: 1:9, 3:7, 5:5, 7:3 and 9:1. Others are same as above.)

To select feedstock with better biogas yield for rural biogas engineering according to the actual situation, this work analyses the TBP of mono-digestion and co-digestion (five proportions) at 15 °C. The result showed that the TBP of co-digestion using straw and manure was significantly higher than that of mono-digestion using one feedstock.

As shown in Fig. 9, for maize straw, the TBP of sheep/ maize 5:5 was the highest (1,637 mL), which is 1.4 times that of maize straw.

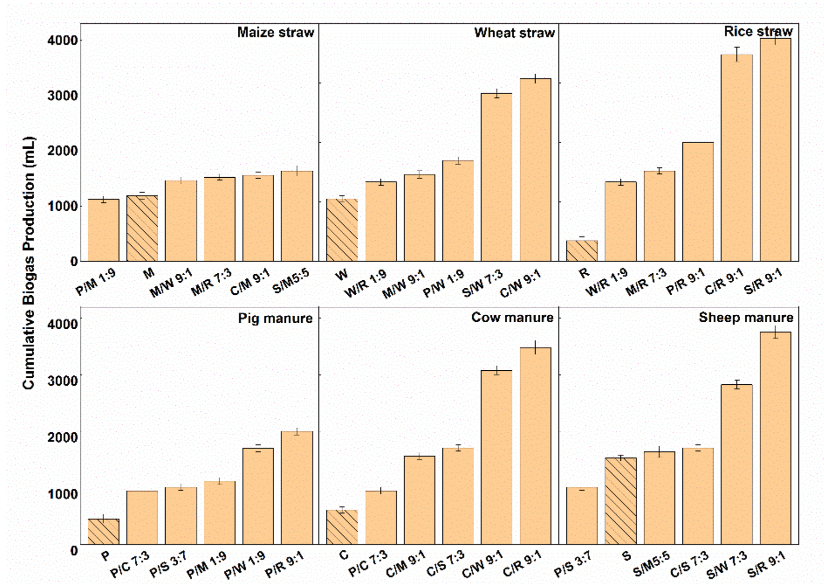


Fig. 9. Comparison the total biogas production of mono-digestion and co-digestion under 15 °C

However, not all the volume of TBP by co-digestion was higher than that of mono-digestion, in which the highest TBP of mixing pig manure and maize straw (1:9) was 1,122 mL, which slightly lower than that of maize straw alone (1,188 mL). For wheat straw, TBP of cow/wheat 9:1 reached 3,076 mL, which is 2.9 times that of wheat straw. For rice straw, the TBP of sheep/rice 9:1 was 3,754 mL, which is 10.7 times that of rice straw. For pig manure, the optimal proportion of co-digestion was pig/rice 9:1, resulting in a TBP of 1,999 mL, and this value is 4.4 times of that of pig manure alone. For cow manure, the highest TBP was obtained by cow/rice 9:1 resulted in a TBP of 3,482 mL, which is 5.7 times that of cow manure alone. For sheep manure, the TBP of sheep/rice 9:1 was the highest, reaching 3,754 mL, which is consistent with the optimal ratio obtained by rice straw.

Biogas Production by Different Feedstock under 25 °C

At 25 °C, the TBP of six feedstocks for mono-digestion was as follows (Fig. 10): wheat straw (542 mL) < rice straw (939 mL) < pig manure (5,639 mL) < sheep manure (6,188 mL) < maize straw (7,744 mL) < cow manure (8,614 mL). The TBP of cow manure was the highest, and the value was 15.9 times that of wheat straw. TBP of the most co-digestion was higher than that of mono-digestion, except that maize/wheat 1:9 (1,758 mL) was lower than that of maize straw alone (7,744 mL). As shown in Fig. 10, the TBP of AcoD by the same feedstock in five ratios was significantly different at 25 °C ($p<0.01$). Taking the AcoD by sheep manure with rice straw as an example, their TBP was the following: sheep/rice 1:9<sheep/rice 9:1<sheep/rice 7:3<sheep/rice 5:5<sheep/rice 3:7. The highest TBP was 15,287 mL obtained by sheep/rice 3:7, and this value was 24.5 times that of sheep/rice 1:9 (623 mL). Based on the AcoD of sheep manure and rice straw, the highest TBP at 25 °C (sheep/rice3:7; 15,287 mL) was 4.1 times that at 15 °C (sheep/rice 9:1, 3,754 mL).

The TBP of AcoD by the same feedstock in the same proportion also remarkably differed. For example, sheep/rice 9:1 (8,091 mL) < cow/rice 9:1 (9,723 mL) < pig/wheat 9:1 (12,694 mL); wheat/rice 1:9 (5,486 mL) < pig/cow 1:9 (7,842mL) < sheep/maize1:9, (10,654 mL). This may be due to the different C/N ratio of feedstock.

The following results of co-digestion with different feedstock and different ratios were more complex: maize/wheat3:7(1,648 mL) < pig/cow1:9(7,842 mL) < sheep/rice 9:1(8,091 mL) < pig /maize 5:5(13,964 mL) < cow /wheat7:3(16,199 mL). This provides more options for rural biogas engineering, that is, to adjust the AcoDS according to the type and quantity of feedstock, also to ensure the optimal biogas yield.

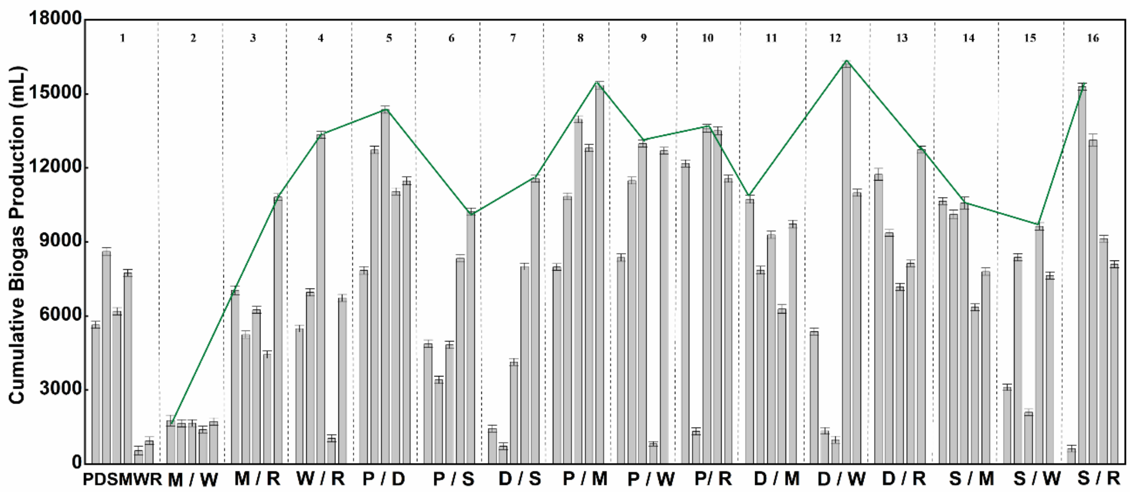


Fig. 10. The total biogas production by different feedstock under 25 °C

As shown in Fig. 11, for maize straw, the TBP of pig/ maize 9:1 was the highest (15,300 mL), and this value was 2.0 times that of mono-digestion only using maize straw and 24.0 times that of mono-digestion only using pig manure. However, the TBP of co-digestion with maize and wheat straw was 1,760 mL. This value is higher than that of mono-digestion using wheat straw (542 mL), but far lower than that of mono-digestion using maize straw (7,740 mL). For wheat straw, the TBP of cow/wheat 7:3 was the highest, reaching 16,200 mL, and this value is 30.0 times of that of mono-digestion only using wheat straw. The lowest TBP of pig/wheat 7:3 was 817 mL, which was still higher than that of mono-digestion with wheat straw alone (542 mL). For rice straw, the TBP of sheep/rice 3:7 (15,287 mL) was the highest, and this value is 16.3 times that of mono-digestion using rice straw. For pig manure, the TBP of mono-digestion using pig manure was 5,640 mL, while that of pig/maize 9:1 was the highest (15,300 mL), which was 2.72 times of the former. However, the TBP of the co-digestion by pig/sheep 1:9, 5:5, and 3:7, pig/rice 3:7, and pig/wheat 7:3 were lower than that of mono-digestion using pig manure.

For cow manure, the highest TBP obtained by cow/wheat 7:1 was 16,119 mL. For sheep manure, the TBP of sheep/rice 9:1 was the highest (15,300 mL), while that of co-digestion using sheep manure was 6,190 mL. Accordingly, AcoD has the advantage on TBP, but the co-digestion ratio must be selected reasonably. Otherwise, the TBP of AcoD may be lower than that of mono-digestion only using one feedstock.

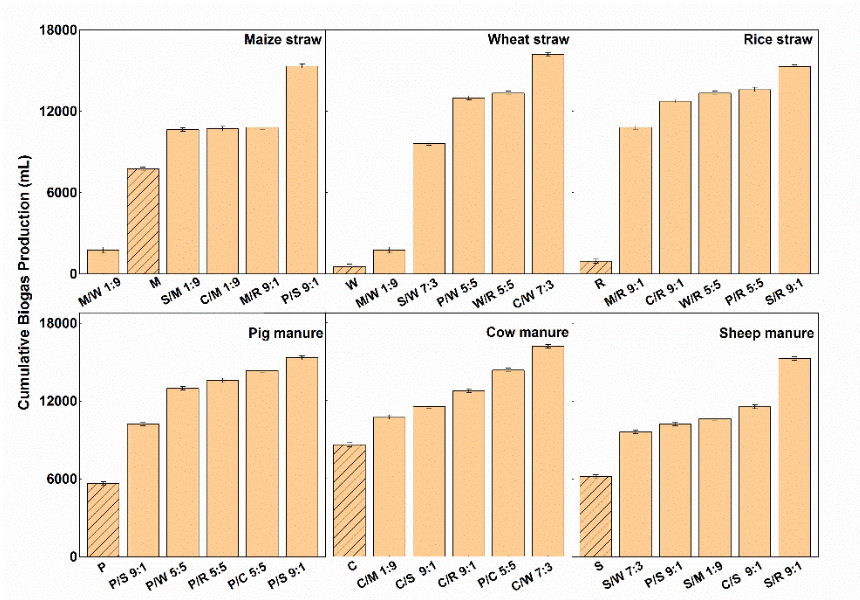


Fig. 11. Comparison the total biogas production of mono-digestion and co-digestion under 25 °C

The potential of biogas production of co-digestion is higher than that of mono-digestion under 15 and 25 ℃, which was caused by an appropriate C/N ratio provided by AcoD using straw and manure. C/N ratio is an important parameter influencing AcoD (Zhang *et al.* 2011; Li *et al.* 2018a; Xie *et al.* 2018; Ning *et al.* 2019). High C/N leads to the acidification and decreased buffer capacity of the reactor system, whereas low C/N results in a high concentration of total ammonia nitrogen, which inhibits biogas production (Ganesh *et al.* 2013). The low content of nitrogen inhibits mono-digestion, which leads to the inefficient TBP of straw, such that the TBP of wheat straw and maize straw under 15 ℃ was just 1054 mL and 1188 mL, respectively.

Anaerobic digestion of high nitrogen content waste such as animal manure will lead to high ammonia concentration, which is produced through the degradation of the nitrogenous matter in the feedstock, primarily in the form of proteins (Jiang *et al.* 2019). Ammonia, especially in the free molecular form (NH_3), is a potent inhibitor to methanogens responsible for the methanogenesis stage of the anaerobic digestion (Rajagopal *et al.* 2013; Jiang *et al.* 2019). Therefore, the TBP of pig, cow and sheep manure is not high either, because the nitrogen content of three types of manure is relatively high whether mono-digestion or co-digestion. For example, the TBP of pig manure and cow manure under 15 ℃ was 454 mL and 610 mL, respectively.

The main advantage of co-digestion using straw and manure is to adjust C/N ratio of substrate, thus further enhancing system stability and buffering capacity (Bolzonella *et al.* 2006; Mata-Alvarez *et al.* 2014), which facilitates biogas generation. The results of this study are consistent with the above studies. The TBP of sheep/rice 9:1 was 3754 mL, which was 8.3 times that of pig manure under 15 ℃. The TBP of cow/wheat 7:3 was 16199 mL, which was 29.9 times that of wheat straw under 25 ℃. Therefore, based on actual temperature conditions and characteristics of feedstock rural biogas engineering should select co-digestion using carbon-rich and nitrogen-rich feedstock to improve biogas production while promoting the efficient use of agricultural organic waste.

The Anaerobic Co-Digestion Scheme for Biogas Engineering

Based on feedstock and temperature, AcoDS is presented in Table 4. The histogram with diagonal lines in Table 4 shows that the highest TBP of feedstock with the most quantity was in a certain region. The AcoDS was more complicated under 25 °C. That was because the most abundant feedstock in this region may not get the highest TBP. Therefore, biogas engineering in each region should comprehensively consider the type, quantity, and convenience of obtaining feedstock according to the local actual situation. In combination with temperature conditions, a suitable AcoDS should be selected. When one or two feedstocks in the first best AcoDS is insufficient because of excessive consumption, another AcoDS could be selected as replacement to ensure the continuous of biogas yield.

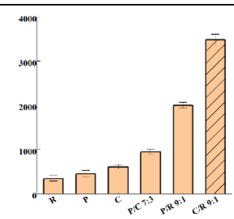
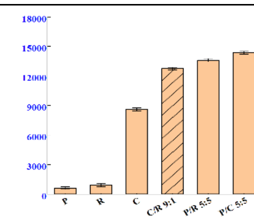
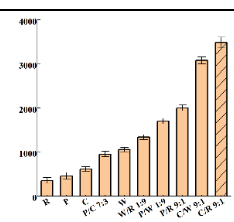
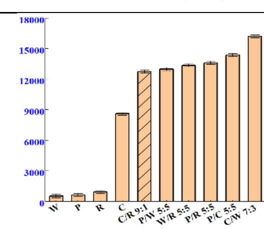
Table 4 showed the following findings:

●The feedstock in Shanghai, Zhejiang, Fujian, Jiangxi, Hubei, Hunan, and Hainan mainly includes rice straw, cow manure and pig manure; at 15 °C, the preferred AcoDS for above areas is co-digestion using cow/rice 9:1 or pig/rice 9:1; at 25 °C, the preferred AcoDS is pig/cow 5:5, pig/rice 5:5, and cow/rice 5:5.

●The feedstock in Jiangsu and Anhui are mainly rice straw, wheat straw, cow manure, and pig manure; at 15 °C, the preferred AcoDS for above regions is co-digestion using cow/rice 9:1 and cow/wheat 9:1; when cow manure is insufficient, pig/rice 9:1 or pig/wheat 1:9 can be selected; more schemes can be chosen at 25 °C. When sufficient feedstocks are available, cow/wheat 7:3 has the best TBP, and pig/cow, pig/rice 5:5, pig/wheat 5:5, or cow/rice 5:5 can also be selected.

● In Guangdong, Guangxi, Chongqing, Guizhou, Yunnan, Sichuan, Liaoning, Jilin, and Heilongjiang, feedstock mainly include rice straw, maize straw, cow manure and pig manure; at 15 ℃, considering the large difference in TBP, the preferred AcoDS in these regions is cow/rice 9:1; when cow manure is insufficient, pig/rice 9:1 can be selected; at 25 °C, the optional AcoDS is pig/maize 9:1, pig/cow 5:5, pig/rice 5:5, or cow/rice 9:1.

Table 4. Anaerobic Co-digestion Scheme for Biogas Engineering

Province	Straws	Manures	15 °C	25 °C
Shanghai	Rice	Cow > Pig		
Zhejiang				
Fujian				
Jiangxi				
Hubei				
Hunan				
Hainan				
Jiangsu	Rice > Wheat	Cow > Pig		
Anhui				
Guangdong	Rice > Maize	Cow > Pig		
Guangxi				
Chongqing				
Guizhou				
Yunnan				
Sichuan				
Liaoning				
Jilin				

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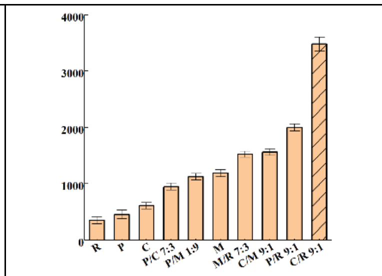
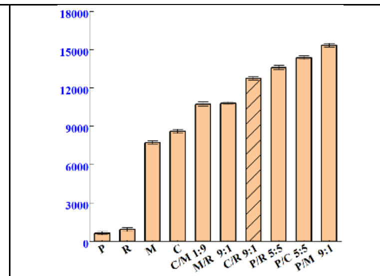
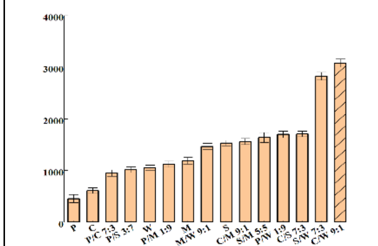
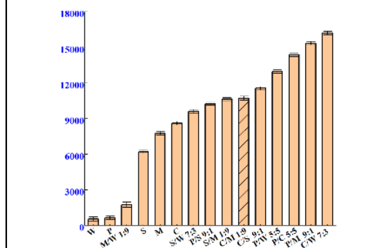
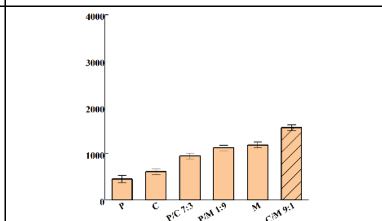
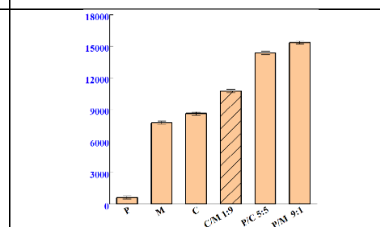
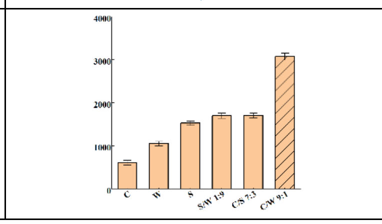
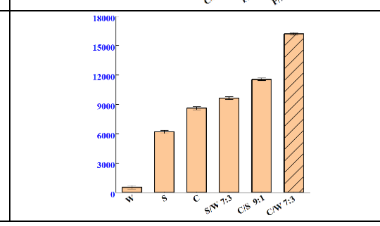
<tr><td>Heilongjiang</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Henan
Shandong
Hebei
Shanxi
Shannxi
Gansu
Qinghai
Ningxia
Xinjiang
Inner Mongolia</td><td>Maize > Wheat</td><td>Cow > Pig > Sheep</td><td></td><td></td></tr>
<tr><td>Beijing
Tianjin</td><td>Maize</td><td>Cow > Pig</td><td></td><td></td></tr>
<tr><td>Tibet</td><td>Wheat</td><td>Cow > Sheep</td><td></td><td></td></tr>
</table>

●The feedstock in Henan, Shandong, Hebei, Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Inner Mongolia mainly include maize straw, wheat straw, cow manure, pig manure, and sheep manure; at 15 °C, considering the large difference in TBP, the preferred AcoDS in these regions is cow/wheat 9:1 and sheep/wheat 7:3; at 25 °C, the preferred AcoDS is cow/wheat 7:3, followed by pig/maize 9:1, pig/cow 5:5, pig/wheat 5:5, or cow/maize 1:9.

●The feedstock in Beijing and Tianjin mainly includes maize straw, cow manure, and pig manure. At 15 °C, the preferred AcoDS is cow/maize 9:1, mono-digestion only using cow manure, or pig/maize 1:9. At 25 °C, the preferred AcoDS is pig/maize 9:1, pig/cow 5:5, or pig/maize 1:9.

●The feedstock in Tibet mainly includes wheat straw, cow manure, and sheep manure. The preferred AcoDS at 15 °C is pig/wheat 9:1, followed by cow/sheep 7:3 or sheep/wheat 1:9. The preferred AcoDS at 25 °C is pig/wheat 7:3, followed by cow/sheep 9:1 or sheep/wheat 7:3.

CONCLUSIONS

1. The total amount of maize, rice, and wheat straws in China in 2020 was 3.89×10^8, 2.10×10^8, and 1.50×10^8 tons. The manure yields of pigs, cows, and sheep was 8.46×10^8, 1.31×10^9, and 4.95×10^8 tons, respectively.
2. At 15 °C, the optimal fermentation scheme of maize straw, wheat straw, rice straw, pig manure, cow manure, and sheep manure is sheep/maize 5:5, cow/wheat 9:1, sheep/rice 9:1, pig/rice 9:1, cow/rice 9:1, and sheep/rice 9:1. At 25 °C, the optimal fermentation scheme of the six feedstocks is pig/maize 9:1, cow/wheat 7:3, sheep/rice 9:1, pig/maize 9:1, cow/wheat 7:3, and sheep/rice 9:1.
3. At 15 °C, the preferred AcoDS for areas with abundant rice straws and cow manure is co-digestion using cow/rice 9:1 or pig/rice 9:1; at 25 °C, the preferred AcoDS is pig/cow 5:5 or pig/rice 5:5.
4. At 15 °C, the preferred AcoDS in regions with abundant maize straws, wheat straws and cow manure is cow/wheat 9:1. At 25 °C, the preferred AcoDS is cow/wheat 7:3, followed by pig/maize 9:1 or pig/cow 5:5.
5. When one or two feedstocks in the first optimal schemes is insufficient due to excessive consumption, another scheme can be selected as a substitute to ensure the continuous and stable of biogas yield. The study provides a basis for rational planning and continuous running for biogas engineering.

ACKNOWLEDGMENTS

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Nomenclature:

Abbreviation	Meaning
anaerobic co-digestion	AcoD
anaerobic co-digestion scheme	AcoDS
TBP	total biogas production
M	maize straw
W	wheat straw
R	rice straw
P	pig manure
C	cow manure
S	sheep manure
M/W	The mixed fermentation by maize straw and wheat straw in the following proportions: 1:9, 3:7, 5:5, 7:3 and 9:1.
M/R, W/R, P/C, P/S, C/S, P/M, P/W, P/R, C/M, C/N, C/R, S/M, S/W, S/R	Same as above

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