**RESEARCH ARTICLE**

# Ecological analysis of a typical farm-scale biogas plant in China

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**Abstract** The aim of this work was to present the common anaerobic digestion technologies in a typical farm-scale biogas plant in China. The comprehensive benefits of most biogas plants in China have not been fully assessed in past decades due to the limited information of the anaerobic digestion processes in biogas plants. This paper analyzed four key aspects (i.e., operational performance, nonrenewable energy (NE) savings, $CO_2$ emission reduction (CER) and economic benefits (EBs)) of a typical farm-scale biogas plant, where beef cattle manure was used as feedstock. Owing to the monitoring system, stable operation was achieved with a hydraulic retention time of 18–22 days and a production of 876,000 $m^3$ of biogas and 37,960 t of digestate fertilizer annually. This could substantially substitute for the nonrenewable energy and chemical fertilizer. The total amount of NE savings and CER derived from biogas and digestate fertilizer was $2.10 \times 10^7$ MJ (equivalent to 749.7 tce) and $9.71 \times 10^5$ kg, respectively. The EBs of the biogas plant was $6.84 \times 10^5$ CNY·yr$^{-1}$ with an outputs-to-inputs ratio of 2.37. As a result, the monitoring system was proved to contribute significantly to the sound management and quantitative assessment of the biogas plant. Biogas plants could produce biogas which could be used to substitute fossil fuels and reduce the emissions of greenhouse gases, and digestate fertilizer is also an important bio-product.

**Keywords** biogas plant, monitoring system, ecological benefits, NE savings, $CO_2$ emission reduction, economic benefits

## 1 Introduction

Consumption of fossil fuels has resulted in serious environment pollution and greenhouse gases (GHGs) emissions (Chen and Zhang, 2010; Chen and Chen, 2011a; Li et al., 2013; Li and Chen, 2013). A lot of efforts have been made to alleviate the environmental crisis associated with the waste management and global warming. Biogas technology is renewable, economical, and environmentally-friendly, it has been widely applied in energy production in many countries, particularly in rural areas (Limmeechokchai and Chawana, 2007; Zeng et al., 2007; Gautam et al., 2009), because it not only produce clean energy (i.e., biogas), but also transfer the agricultural wastes into organic fertilizers with high-nutrients. In China, the biogas plant has been put into practice since the 1970s (Zheng et al., 2010). In 2007, 26.5 million biogas plants were operated in China with an annual biogas output of 10.5 billion $m^3$ (100 million tons of coal equivalent) (Chen et al., 2010). By 2015, the total number of rural households using biogas will amount to 60 million in China with an annual biogas production of approximately 23.3 billion $m^3$, and the number of large-scale farm biogas plants will amount to 8,000 with an annual biogas production of 670 million $m^3$ (Zhang and Sun, 2008). Compared with household biogas digesters, biogas plants can bring more benefits due to their standardized and advanced technologies and equipment (Jiang et al., 2011).

Anaerobic digestion (AD), the core of biogas technology, is a complicated, sensitive, multi-step bioprocess involved with many kinds of microorganisms (Karellas et al., 2010). Previous studies found that AD is particularly adapted to diverse biomass feedstock and operating conditions (Genovesi et al., 1999; Bruni et al., 2010; Tock et al., 2010). Whereas the main objective of biogas plants may be different, such as maximization of biogas production, minimization of the chemical oxygen demand

of the effluent during the waste treatment process, and achieving the required standards or advanced treatment when integrated with aerobic treatment processes. It demonstrated that the well-structured processes are necessary. Nowadays, monitoring and control systems have become more and more important in maintaining stable operations of biogas plant and achieving high conversion rates during the treatment processes (Boe et al., 2010).

Computer technologies have been applied in the biogas industry since the early 1980s. In Europe, especially in Germany, which owns the most advanced biogas technology, computer technologies have been used for the monitoring and control systems of biogas plants. In comparison, manual controls have been proven to be an inefficient approach (Poeschl et al., 2010). On the other hand, choice of parameters reflecting the processes and further monitoring are also important (Jantsch and Mattiasson, 2004; Fdez-Güelfo et al., 2012; Ihunegbo et al., 2012). However, management of biogas plants mainly depended on experience in China, and few biogas plants have a monitoring system for operating parameters (i.e., temperature and loading rate). Due to the lack of available monitoring system, a biogas plant cannot be controlled precisely and effectively, and thus may have low efficiency and breakdown problems. Although significant research efforts have been made in this field in China (Wei and Li, 2010; Zhou et al., 2010), monitoring systems have not been widely applied, and therefore the comprehensive benefits of the biogas plant have not been assessed accurately.

The main goal of the assessment is to examine the operational performance of the system and analyze its technical, economic and ecological potential. Numerous methods has been developed to assess the impacts of different energy and resources systems, such as ecological footprint (Chen et al., 2007; Nguyen and Yamamoto, 2007), life cycle assessment (LCA) (Pehnt, 2006; Gunamantha and Sarto, 2012; Cao and Pawłowski, 2013; Peng et al., 2013), material flow and balance analysis (Dai and Chen, 2010), emergy (Lefroy and Rydberg, 2003; Chen et al., 2006; Lu et al., 2006; Jiang et al., 2007; Xi and Qin, 2009; Ju and Chen, 2011), and exergy or extended exergy (Talens Peiró et al., 2010; Zhang and Chen, 2010; Dai and Chen, 2011; Koroneos et al., 2011; Simpson and Edwards, 2013). Also, hybrid methods, such as exergetic life cycle assessment (Ozbilen et al., 2012) and exergetic ecological footprint (Shao et al., 2013) have been used as well.

A biogas plant, an integrated system for producing renewable energy and recycling resources, is also an effective solution to waste management. It provides not only clean and cheap biogas for heating, illumination and powering machinery, but also liquid and solid digestate which could be used as a base fertilizer, top-dressings, and feed additives (Chen et al., 2012). Many studies have evaluated the performance of biogas plants in terms of their environmental impacts, ecological benefits, and economic benefits. The focus of these evaluations included biogas production using different types of feedstock (El-Mashad and Zhang, 2010; Xia et al., 2012), different biogas utilization pathways (Gebrezgabher et al., 2010; Patterson et al., 2011; Poeschl et al., 2012a), reduction of GHGs emissions (Yabe, 2013), digestate processing technologies (Rehl and Müller, 2011, 2013), and gas emissions from the biogas production processes (Poeschl et al., 2012b). Furthermore, the tradeoff between energy production and environmental impacts is also of great concern. The biogas plant has significant advantages over conventional ecological practices regarding its $CO_2$-neutrality. The production of biogas as renewable energy may substantially contribute to the mitigation of GHGs emissions by offsetting emissions from fossil resources and generated during the production and processing of the feedstock (Meyer-Aurich et al., 2012). The potentials of the extent in the decrease of $CO_2$ emissions depend on the size and the treatment processes of the biogas plant (Hoffmann et al., 2010). However, the comprehensive benefits of most biogas plants have not been fully assessed in past decades due to the lack of the real time information from the accurate monitoring system in biogas plants. Therefore, there is urgent need of an integrated assessment for the biogas plant based on accurate monitoring system used for biogas plant.

The aim of this study was to quantify a biogas plant under stable operating conditions in terms of its performance, NE savings, reduction of $CO_2$ emission and economic benefits. More specifically, the analysis of NE saving and $CO_2$ emission reduction mainly encompassed various biogas-to-energy conversion pathways and digestate utilization. Regarding the economic benefits, the income of carbon credits and operation cost (i.e., depreciation cost, maintain cost, power consumption cost, water consumption cost, human labor cost, and feedstock cost) are taken into consideration as well.

## 2    Method

### 2.1    The farm-scale biogas plant

The farm-scale biogas plant is located near the city of Sanhe in Hebei Province. The plant was built for the treatment of 20,075 t manure from 4,600 head beef cattle annually in 2009. The biogas plant was built in a beef cattle farm, where feedstock is substantial and convenient. The investment of the equipment and structures was 2.49 and 1.38 million CNY (Chinese Yuan), respectively. The biogas plant consists of five units, which include a monitoring system (e.g., monitoring computer), manure

pretreatment (sinking sand pool, regulating & heating pool, and heating device), AD (liquid-gas integrated anaerobic digester), biogas purification and utilization (purifying equipment, biogas generator equipment) and digestate utilization (storage tank of biogas residues and slurry). The schematic of the sub-systems and processes of the farm-scale biogas plant is shown in Fig. 1. The fresh manure and wastewater were firstly collected in the farm, treated by the manure pretreatment system, and then pumped into the digester for further treatment. The digester was a continuously stirred liquid-gas integrated anaerobic digester, with a total volume of 3,000 m$^3$ and a working volume of 2,700 m$^3$. Samples were collected periodically at three sampling points in the digester. Temperature sensors, pressure sensors, liquid level sensors, gas sensors ($CH_4$, $CO_2$, and $H_2S$), alarm sensors and flow meters were used. A heating device was installed and operated for the preheating of the fermentation material and maintaining the stable fermentation temperature in the digester during the cold seasons. Additionally, a monitoring system was used to monitor the performance of the biogas plant and stabilize its operation.

The biogas produced was mainly for three terminals. One is as cooking fuel for the local 435 households, the other is to generate electricity for lighting and powering machines in the beef cattle farm and biogas plant. The left biogas was used for the biogas plant's normal working (i.e., heating digester). The digestate was separated into solid and liquid by the solid-liquid separator. The biogas

residues were supplied for the production of organic fertilizer, while biogas slurry was processed as refluxing liquid or liquid fertilizer.

## 2.2 Functions of the monitoring system

The monitoring system consisted of a monitoring computer (PC), a data acquisition system, a relay execution system, a central control cabinet, an on-site control cabinet, on-site actuators (e.g., pump, valve), meters, sensors, a display screen and a power supply. The monitoring computer and central control cabinet were located in the central monitoring room. The main functions of the monitoring system have been listed as follows.

### 2.2.1 Comparing the real-time status with former data

The monitoring system can collect and store real-time data continuously. By comparing the real-time data with those collected previously, the variations of those parameters (i.e., output of biogas, pH value, concentrations of $CH_4$, $CO_2$ and $H_2S$) could be detected. Then, correspondent actions could be taken as soon as possible to make the biogas plant to stay stable.

### 2.2.2 Real-time monitoring of sensitive parameters to maintain stable operations with visual images

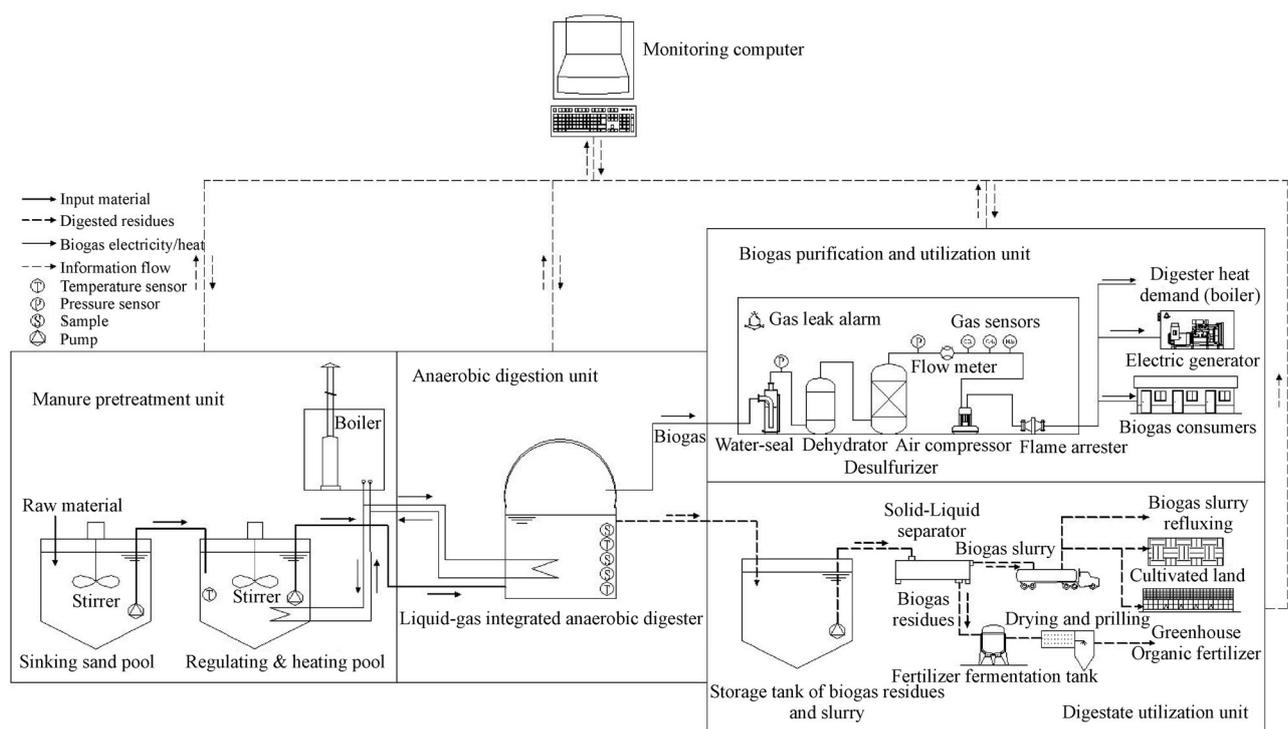Generally, status parameters which are capable of reflect-



**Fig. 1**   The schematic of the sub-systems and processes of the farm-scale biogas plant.

ing the AD processes and easy to handle were selected as monitoring parameters (Kuang et al., 2009; Boe et al., 2010). The microbial communities in each biogas plant were different from each other. Thus, the sensitive parameters also varied with each biogas plants. In this study, the following parameters were monitored, they are as follows: the input and output quantity, dry matter (*DM*), biogas quantity and quality ($CH_4$, $CO_2$ and $H_2S$ concentrations), fermentation temperature, and pH value of digestate liquid.

### 2.2.3 Mass balance and effectiveness analysis

This system also can be used to analyze the mass balance of the biogas plant including amounts of the material input, biogas output, digestate discharged, material conversion rates, and energy efficiency of the biogas plant. The long-term monitoring data can be used to crosscheck the analytical data and conduct comprehensive real-time assessment of the biogas plant.

### 2.3 NE savings

Anaerobic digestion can transform manure into biogas and fertilizers, where biogas is one type of renewable energy, and fertilizers can be used in agriculture. The NE savings are mainly calculated from the substitution of biogas and digestate fertilizer for nonrenewable energy and chemical fertilizers. The amount of biogas and each chemical fertilizer, as well as their related energy intensities are essential to quantify the amount of NE savings. Numerous studies have been conducted with respects to the analysis of NE savings (Ramírez and Worrell, 2006; Kahrl et al., 2010; Chen and Chen, 2011b). Yang and Chen (2012) had identified the energy intensities of different chemical fertilizers in China. The nonrenewable energy-intensity coefficients of potassium chloride, diammomium phosphate and urea are 13.78, 12.13 and 74.29 MJ·$kg^{-1}$, respectively (FAO, 1999; Li et al., 2012). There are mainly three terminals for biogas utilization — heating digester, cooking, and generating electricity, which are responsible for the substitution of biogas for nonrenewable energy (i.e., coal, electricity and diesel). Thus, the NE savings of biogas can be converted to standard coal. The mean calorific value of biogas is 20 MJ·$m^{-3}$ (Chen et al., 2012). The NE savings can be calculated by the following equation:

$$NE = \sum CF_i \times C_i, \quad (1)$$

where $CF_i$ stands for the amount of nonrenewable energy or chemical fertilizer $i$ (i.e., coal, potassium chloride, diammomium phosphate and urea) and $C_i$ is the corresponding nonrenewable energy-intensity coefficient of chemical fertilizer $i$.

### 2.4 CO$_2$ emission reduction (CER)

$CO_2$ emission reduction is identified from the amount of nonrenewable energy which can be further divided into two parts, one is from substitution of nonrenewable energy by biogas, and the other is based on the calculation of energy consumed for producing petro-chemical-based fertilizers. However, all the nonrenewable energy sources (e.g., coal, oil, natural gas) are main sources of $CO_2$ emissions (Yang and Chen, 2013). In general, 1 $m^3$ biogas equals 0.714 kgce. The mean $CO_2$ emission value of biogas combustion is 0.75 kg$CO_2$·$kg^{-1}$, which is equal to 2.28 kg$CO_2$·$kg^{-1}$ of total $CO_2$ emission combusted by coal (Bhattacharya et al., 2000; Zhang et al., 2000). Thus, while calculating the CER of biogas, its own $CO_2$ emission should be deducted. The $CO_2$ emission factors of potassium chloride, diammomium phosphate and urea are 0.44, 0.53 and 11.38 kg$CO_2$·$kg^{-1}$, respectively (Li et al., 2012; Yang and Chen, 2013). The equation used to calculate CER is

$$CER = CF_c \times EF_c - CF_b \times EF_b + \sum CF_i \times EF_i, \quad (2)$$

where $CF_c$, $CF_b$, $CF_i$ stand for the amount of coal, biogas and chemical fertilizer $i$; $EF_c$, $EF_b$, $EF_i$ are their corresponding $CO_2$ emission factors.

### 2.5 Economic benefits (EBs)

For a biogas plant, economic feasibility is an important factor. Generally, the total EBs consist of three parts: yields of biogas and digestate fertilizer, income of carbon credits and the operating cost of the biogas plant. The EBs can be calculated by the following equation:

$$EBs = Y + CC - C, \quad (3)$$

where $Y$ is the value of yield gained from biogas and biogas fertilizer; $CC$ represents the income of carbon credits; and $C$ is the operation cost of the biogas plant, which can be further calculated by Eq. (4):

$$C = DE + MA + PC + WC + HL + MC, \quad (4)$$

where $DE$, $MA$, $PC$, $WC$, $HL$ and $MC$ represent the depreciation cost, maintain cost, power consumption cost, water consumption cost, human labor cost, and material (manure) cost of the biogas plant, respectively. $DE$ stands for the sum of the depreciation cost of the structures and equipment, which is 20 years and 15 years over its lifetime for the structures and equipment, respectively, the residual value is 5% of the total cost of structures and equipment. $MA$ is the maintaining cost, accounting for 2% of the total investment in equipment and building structures. The total power and water consumed by the biogas plant in this study was 91,250 kW·h·$yr^{-1}$ and 11,315 t·$yr^{-1}$. There are

three workers in the biogas plant all the years. In accordance with the local prices of parameters mentioned above, the price of biogas, electricity, coal, water, human labor, manure, urea, diammonium phosphate and potassium chloride was $1.5 \, CNY \cdot m^{-3}$, $0.5 \, CNY \cdot kW^{-1} \cdot h^{-1}$, $1,000 \, CNY \cdot t^{-1}$, $4 \, CNY \cdot t^{-1}$, $36,000 \, CNY \cdot yr^{-1} \cdot person^{-1}$, $20 \, CNY \cdot t^{-1}$, $2,200 \, CNY \cdot t^{-1}$, $3,700 \, CNY \cdot t^{-1}$ and $2,900 \, CNY \cdot t^{-1}$, respectively.

## 3  Results and discussion

### 3.1  Operational performance

Anaerobic digestion can provide a higher biogas yield if running at optimum environmental conditions. Thus, it is necessary to install a monitoring system to make sure that the biogas plant is maintained under stable conditions. Previous studies found that a biogas plant without a

**Table 1**  The operational performance of the farm biogas plant

| Parameters | Values |
| --- | --- |
| pH value | 6.8–7.4 |
| Temperature/°C | 32–35 |
| Hydraulic retention time/d | 18–22 |
| DM/% | 6 |
| Average daily biogas yield/m$^3$ | 2,400 |
| Average biogas production/(m$^3 \cdot$t$^{-1} \cdot$DM$^{-1} \cdot$d$^{-1}$) | 242.4 |
| CH$_4$ content/% | 55–68 |
| Average volumetric biogas production/(m$^3 \cdot$m$^{-3} \cdot$d$^{-1}$) | 0.89 |
| Average daily digestate yield/t | 148.5 |
| Average daily recycled feeding quantity/t | 44.5 |
| Average daily discharging digestate quantity/t | 104.0 |

monitoring system, the temperature could fluctuate seasonally and caused lots of problems such as unstable biogas output, acidification, and low outputs-to-inputs ratio. In this study, because of the monitoring system, real-time feedback had been realized to assure efficient and stable operation of the biogas plant.

The operational performance of the biogas plant in 2011 was shown in Table 1. The pH value of anaerobic digestate was in the range of 6.8–7.4, which is suitable for anaerobic microbial activity. The temperature of the digestate is the dominant factor of anaerobic digestion, whereas it is easily influenced by outdoor temperature and feeding temperature. The fermentation temperature was kept at 32–35°C. Daily feeding quantity was regulated for a hydraulic retention time (HRT) of 18–22 days, with an average quantity of 55 t manure and 110 t wastewater per day. The *DM* is an important parameter which should be calculated to determine the mass of feedstock fed into the digester and to assess the biogas production rate. The *DM* was determined to be about 6% and the average biogas yield was $2,400 \, m^3 \cdot d^{-1}$, with a CH$_4$ content of 55%–68%. The average biogas production and the volumetric biogas production were $242.4 \, m^3 \cdot t^{-1} \cdot DM^{-1} \cdot d^{-1}$ and $0.89 \, m^3 \cdot m^{-3} \cdot d^{-1}$, respectively. The average digestate yield was about $148.5 \, t \cdot d^{-1}$, of which approximately 30% was used for recycled feeding and the rest was discharged for agricultural production.

The terminal products of the biogas plant can be divided into biogas and digestate fertilizer. Detailed information about annual yields, their relationships, and various utilization pathways are described in Fig. 2. The annual total biogas yield was 876,000 m$^3$, of which 21.75% biogas was used for cooking, 61.58% for electricity generation and 16.67% for the heating of the digester. Apart from 12,592.5 t of wastewater derived from the beef cattle farm and 16,242.5 t from refluxing liquid, an additional 11,315 t freshwater was added to the biogas plant per year.
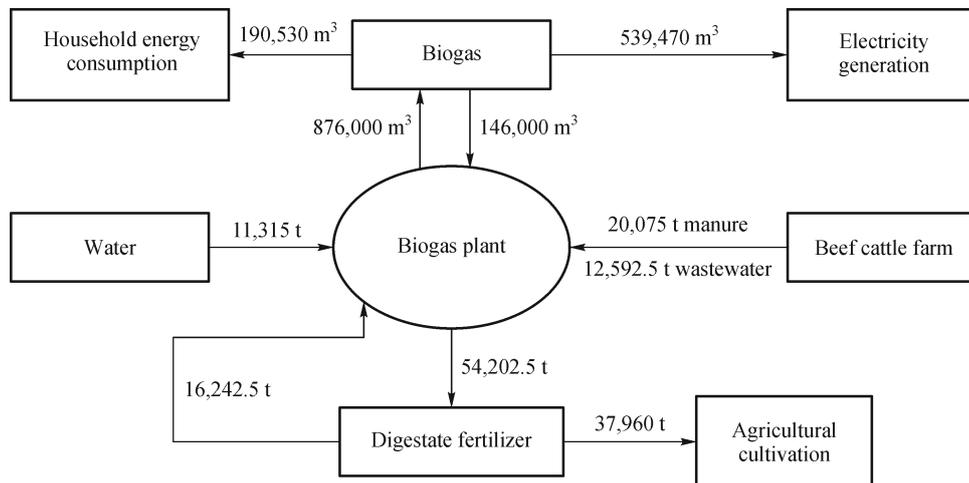


**Fig. 2**  Annual yields, their benefit relationships, and various utilization pathways of biogas and digestate.

**Table 2** Annual NE savings of digestate fertilizer

| Fertilizer source | | Quantity/% | | | Quantity/t | Quantity/t | | | Energy intensity/(MJ·kg$^{-1}$) | Energy/MJ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | NH$_3$-N | P$_2$O$_5$ | K$_2$O | | NH$_3$-N | P$_2$O$_5$ | K$_2$O | | |
| Digestate fertilizer | | 0.0563 | 0.0667 | 0.1130 | 37960 | 21.37 | 25.32 | 42.89 | — | — |
| Chemical fertilizers | Urea | 46 | — | — | 24.91 | 11.46 | — | — | 74.29 | 1.85×10$^6$ |
| | Diammonium phosphate | 18 | 46 | — | 55.04 | 9.91 | 25.32 | — | 12.13 | 0.67×10$^6$ |
| | Potassium chloride | — | — | 60 | 71.48 | — | — | 42.89 | 13.78 | 0.98×10$^6$ |
| Total | | — | — | — | — | — | — | — | — | 3.50×10$^6$ |

## 3.2 Amount of NE savings

In this study, the nonrenewable energy inputs were not included; only the produced biogas and digeastate fertilizer were included in the calculations. The total biogas output was $8.76×10^5 \, \text{m}^3 \cdot \text{yr}^{-1}$, which equals to $1.75×10^7$ MJ. The content of ammonia nitrogen (NH$_3$-N), available phosphorus (P$_2$O$_5$) and available potassium (K$_2$O) in the digestate fertilizer was 0.0563%–0.1163%, 0.0667%–0.0847%, and 0.1130%–0.1450%, respectively (Duan et al., 2011). The minimum content was used to calculate the equivalent chemical fertilizers content in Table 2. Large amounts of fossil energy are consumed for producing chemical fertilizers (Vaneeckhaute et al., 2013), whereas, a remarkable NE savings could be done by the substitution of digeatate fertilizer for chemical fertilizer. The annual digeatate fertilizer yield in this study is 37,960 t, which can substitute 24.91 t urea, 55.04 t diammonium phosphate and 71.48 t potassium chloride. The total NE consumed to produce the above amounts of chemical fertilizer is $3.50×10^6 \, \text{MJ} \cdot \text{yr}^{-1}$. Among them, although the quantity of urea is the smallest, the NE saving from the substitution for urea ranks first because of its high nonrenewable energy-intensity coefficient, the number was amount to $1.85×10^6$ MJ, which account for about 52.86% of the total NE savings, The second is potassium chloride ($0.98×10^6$ MJ) and then diammonium phosphate ($0.67×10^6$ MJ). The substitution for nonrenewable energy and chemical fertilizer results in a total NE savings of $2.10×10^7$ MJ, where biogas accounts for 83.33% of the total NE savings. In this study, approximately 749.7 t standard coals can be saved by the substitution of the nonrenewable energy and chemical fertilizers for the renewable biogas and digestate fertilizer.

China is the largest energy consumers in the world at present, and the use of fossil fuels has resulted in serious environmental pollution and global warming. Therefore, how to reduce the use of fossil fuels and increase the share of renewable energy has always been of great concern to government (Kowalski et al., 2009; Xuan et al., 2009). Over the past few decades, many laws were issued by the Chinese government to encourage and support renewable energy development in China, such as "Renewable Energy Law", "Renewable Energy Prices and Cost-sharing Management Trial Procedures", "Regulations Related to Renewable Energy Power Generation", "Medium and Long-term Development Program for Renewable Energy". In the "China's 12$^{th}$ Five-Year Plan"(2011–2015), biogas plants are of high importance regarding its function for the development of biomass energy production, whereas supporting policies and raw materials sources should be considered, and then it could provide high-quality, clean and reliable energy. Additionally, World Bank and Asia Development Bank have also promulgated financial support programs for biogas plants and renewable energy productions in China. The common utilization of biogas include electricity generation, cooking and heating, the direction and scope of the biogas utilization are more flexible, such as the combination of heat and power generation, vehicle fuel, biogas liquefaction or compression. Numerous studies found that intensive utilization of chemical fertilizers could promote crop productivity, whereas this is not the case for soil ecosystem (i.e., metal pollution and biodiversity) in the long term (Ghosh, 2004). The digestate fertilizers from the biogas plant could guarantee the nutrients cycle of the agricultural ecosystem, where soil compatibility and soil health could also be improved.

## 3.3 Amount of CO$_2$ emission reduction

The annual CO$_2$ emission reduction due to using biogas and digestate fertilizer are shown in Table 3. Under stable operation conditions, there was $8.76×10^5 \, \text{m}^3$ biogas produced, which equals $6.25×10^5$ kgce. The density of

**Table 3** Annual CO$_2$ emission reduction through utilization of biogas and digestate fertilizer

| Item | Quantity/t | $EF_i$/(kgCO$_2$·kg$^{-1}$) | CER/kg |
|---|---|---|---|
| Biogas | 1.07×10$^3$ | −0.75 | −8.03×10$^5$ |
| Coal | 6.25×10$^2$ | 2.28 | 1.43×10$^6$ |
| Chemical fertilizers | | | |
| Urea | 24.91 | 11.38 | 2.83×10$^5$ |
| Diammonium phosphate | 55.04 | 0.53 | 2.92×10$^4$ |
| Potassium chloride | 71.48 | 0.44 | 3.15×10$^4$ |
| Total CER | — | — | 9.71×10$^5$ |

biogas is about $1.22 \, \text{kg} \cdot \text{m}^{-3}$ (Liu et al., 2008), while the total amount of biogas is $1.07 \times 10^6 \, \text{kg}$. Compared with coal, $CO_2$ emission factor of biogas was lower. Thus, biogas seems more environmental friendly. The CER is $6.27 \times 10^5 \, \text{kg}$ and $3.44 \times 10^5 \, \text{kg}$ for biogas and digeatate fertilizer, respectively. The total amount of CER is $9.71 \times 10^5 \, \text{kg}$, where biogas accounted for 64.57% of the total amount. $CO_2$ emission factor was the highest in urea, Where $CO_2$ emission reduction was about 29.15% and 82.27% of the total CER and CER of digestate fertilizer, respectively. Because of a lower $CO_2$ emission factor, the substitution for diammonium phosphate and potassium chloride was only $2.92 \times 10^4 \, \text{kg}$ and $3.15 \times 10^4 \, \text{kg}$ CER. Therefore, the production and increased share of biogas and digeatate fertilizer are promising with respects to the reduction in $CO_2$ emission and improved performance in energy and environment benefits, especially for livestock farms. There is a rapid development of livestock farm in China, the amounts of manure and waste material (i.e., water and residues) are expected to increase in the future. The amounts of GHGs emissions from manure may increase and aggravates the environmental pollution of groundwater, soil and air at present. In this respect, manure and wastewater could be used for biogas plant, biogas produced could be energetically used and the digestate fertilizers could be recycled in agricultural ecosystem. In this way, the sustainable reduction in $CO_2$ emission is possible.

There are large amounts of biomass resources and a variety of models of biogas plants in China. Besides the manure mentioned in this work, industrial wastes, agricultural wastes, wastewater and kitchen wastes all can be used as substrate for the biogas production. Biogas energy is not only for rural areas, but also has great potential to meet energy needs in urban areas in the future.

3.4   Economic benefits analysis

Four scenarios have been taken into account for comprehensive analysis of the EBs of the biogas plant (Table 4). Scenario 1 is based on the current situation of the biogas plant, while the manure cost and the income from carbon credits is not included. Scenario 2 represents the future situation of the biogas plant. The income of carbon credits is an integral part of EBs. In scenario 3, the cost of the manure is considered as an important part of the operation cost. In the fourth scenario all above mentioned have been considered and calculated. The annual economic benefits of the four scenarios are shown in Table 4.

The annual biogas yield was about $8.76 \times 10^5 \, \text{m}^3$. In this study, biogas can be utilized as follows: 1) household cooking ($1.91 \times 10^5 \, \text{m}^3$); 2) heating the digester ($1.46 \times 10^5 \, \text{m}^3$); and 3) generating electricity ($5.39 \times 10^5 \, \text{m}^3$). Biogas used for heating the digester is classified as internal consumption, and so its economic benefit is not included. $1 \, \text{m}^3$ biogas produces $1.6 \, \text{kW} \cdot \text{h}$. The economic benefits from biogas sales of household energy and electricity generation are $2.87 \times 10^5$ and $4.31 \times 10^5 \, \text{CNY}$, The total income from biogas is $7.18 \times 10^5 \, \text{CNY}$. Owing to the application of digestate fertilizer, the EBs of increased yields of agricultural products are not considered in this study, and only the cost of substitution of chemical fertilizers for digeatate fertilizer is calculated that total income is $4.66 \times 10^5 \, \text{CNY}$. On the other hand, environmental benefits from CER have been considered in scenarios 2 and 4. The $CC$ value is $6.02 \times 10^4 \, \text{CNY}$ with the carbon price of $\$10 \cdot (\text{tCO}_2)^{-1}$ ($\$1 = \text{CNY} \, 6.20$) (Wei et al., 2011). The value of $DE$, $MA$, $PC$, $WC$, $HL$, and $MC$ is $2.23 \times 10^5$, $7.74 \times 10^4$, $4.56 \times 10^4$, $4.53 \times 10^4$, $1.08 \times 10^5$ and $4.02 \times 10^5 \, \text{CNY} \cdot \text{yr}^{-1}$, respectively. Consequently, the total running cost of the biogas plant is about $5.00 \times 10^5 \, \text{CNY} \cdot \text{yr}^{-1}$ in scenario 1 and 2, and the number had risen to $9.01 \times 10^5 \, \text{CNY} \cdot \text{yr}^{-1}$ in scenario 3 and 4. Annual inputs and outputs for economic analysis under four scenarios are shown in Table 5. The ratio of outputs/inputs (O/I) is used to evaluate the economic balance of the biogas plant.

For scenario 1, the value of $Y$, $CC$, and $C$ now is $1.18 \times 10^6$, 0, and $5.00 \times 10^5 \, \text{CNY} \cdot \text{yr}^{-1}$. Consequently, the total EBs of the biogas plant is $6.84 \times 10^5 \, \text{CNY} \cdot \text{yr}^{-1}$. Regarding the total outputs, biogas contributes to 60.65%, and share of the digeatate fertilizer was about 39.35%. The value of O/I is 2.37, which demonstrates that the biogas plant has a good performance in economic profitability and ecological sustainability. Compared with scenario 1, scenario 2 has a higher O/I value. The $CO_2$ emission in China now is the largest in the world, there is an urgent need to reduce the total $CO_2$ emission (Zhang et al., 2010), in this respects, renewable energy is a good choice. The application of biogas plant could not only reduce GHGs emissions, but also earn economic benefits (e.g., carbon

**Table 4**   Annual EBs of the farm biogas plant (unit: $\times 10^4 \, \text{CNY}$)

| Item | CC | Biogas | | Digestate fertilizer | | | C | | | | | | EBs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Household energy | Electricity | Urea | Diammonium phosphate | Potassium chloride | DE | MA | PC | WC | HL | MC | |
| Scenario 1 | — | 28.65 | 43.12 | 5.48 | 20.36 | 20.73 | 22.33 | 7.74 | 4.56 | 4.53 | 10.8 | — | 68.38 |
| Scenario 2 | 6.02 | 28.65 | 43.12 | 5.48 | 20.36 | 20.73 | 22.33 | 7.74 | 4.56 | 4.53 | 10.8 | — | 74.40 |
| Scenario 3 | — | 28.65 | 43.12 | 5.48 | 20.36 | 20.73 | 22.33 | 7.74 | 4.56 | 4.53 | 10.8 | 40.15 | 28.23 |
| Scenario 4 | 6.02 | 28.65 | 43.12 | 5.48 | 20.36 | 20.73 | 22.33 | 7.74 | 4.56 | 4.53 | 10.8 | 40.15 | 34.25 |

**Table 5** Annual inputs and outputs for economic analysis with four scenarios

| Item | Inputs/($\times 10^4$ CNY) | Outputs/($\times 10^4$ CNY) | O/I |
|------|------|------|------|
| Scenario 1 | 49.96 | 118.34 | 2.37 |
| Scenario 2 | 49.96 | 124.36 | 2.49 |
| Scenario 3 | 90.11 | 118.34 | 1.31 |
| Scenario 4 | 90.11 | 124.36 | 1.38 |

credits). As shown in scenario 3, feedstock is not only of great importance for the normal operation of biogas plants, but also for their economic benefits. The manure cost accounts for 44.56% of the total operation cost, and O/I value in scenario 3 is the lowest (1.31). Livestock farms with large amount of manure resources need suitable pretreatment technologies and biogas technologies that could optimize the production of biogas and digeatate fertilizer and reduce odors and pathogens. However, due to shortage of fermentation materials in some areas, co-digestion technology of suitable agricultural substrate and organic wastes is a good solution. Consequently, feedstock resources and its supplying capacity should be fully taken into consideration before the construction of the biogas plant. Scenario 4 gives us an integrated analysis of the three scenarios mentioned above.

The construction of biogas plant is subsidized in China, which could mitigate the economic pressure on conventional agricultural production and give the farmers an additional income. In this study, the O/I values of the four scenarios are all larger than 1, which means the biogas plant within the steady operation condition is feasible with respects to its economic benefits. In this work, the largest economic potential of a biogas plant is that biogas was used to generate electricity over the whole year round.

## 4　Conclusions

The aim of this study is to investigate the ecological benefits of a typical farm-scale biogas plant in China. Biogas technology is promising regarding its potential to provide renewable energy and mitigate environmental emissions. Because of the monitoring system, reliable and quantitatively evaluation of the ecological benefits of the biogas plant is possible, which could provide scientific foundation for further management and technology optimization. Our results suggested that a monitoring system is necessary component in the biogas plant in China.

Biogas and digestate fertilizer are of equal importance and both significantly contribute to the NE savings and $CO_2$ mitigation. The total amount of NE savings and CER of biogas and digestate fertilizer is $2.10 \times 10^7$ MJ (749.7 tce equivalent) and $9.71 \times 10^5$ kg. For the biogas plant, the digestate fertilizer yield is 37,960 t·yr$^{-1}$, which is equal to

24.91 t urea, 55.04 t diammonium phosphate and 71.48 t potassium chloride. Digestate fertilizer, as a valuable resource, should be probably managed; otherwise, it will lead to the environmental pollution. Thus, the rational utilization of biogas and digestate fertilizer is good for the economic benefits and environmental benefits, which could be improved by the optimized single or integrated technologies. Additionally, the utilization of digestate fertilizer helps achieve environmental-friendly positive recycling of nutrients.

The biogas plant, integrated with agricultural ecosystem, could have enormously economic, ecological and social benefits. In this study, the amount of EBs in a typical farm-scale biogas plant was $6.84 \times 10^5$ CNY·yr$^{-1}$, where EBs from electricity generation was $4.31 \times 10^5$ CNY·yr$^{-1}$, this indicates that power generation-oriented biogas plant may be popular in the future. The stable operation performance, substantial and safe raw materials, optimized utilization pathways of biogas and digestate fertilizer and national policy are the main components for the sustainable and environmental-friendly development of biogas plants in China.

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