INTRODUCTION

Biogas is a promising renewable energy source, and can be produced from a wide range of organic waste. Biogas operating facilities provide large economic and environmental benefits (Song et al., 2014). In recent years, biogas technology has rapidly developed and has become popular in many countries (Deng et al., 2017; Poeschl et al., 2010; Xue et al., 2020). However, due to the increasing transportation cost, managing the liquid digestate (LD) generated by anaerobic digestion of livestock wastes is becoming a bottleneck, restricting the sustainable development of the biogas industry in China. The separation of livestock breeding and arable farming, caused by rapid intensive animal husbandry development, is the main reason for the LD problem. Researchers, government representatives, and biogas plant operators in China have invested significant research efforts to maximize biogas-linked agro-ecosystem balance, which is considered as an important solution to the LD problem. This article reviewed these studies and proposed several solutions from the following four aspects: breeding mode, waste treatment mode, LD transportation mode, and LD utilization mode. One proposal is to reduce the scale of newly built livestock farms and disperse them in farmland, by promoting the “company + agent” livestock breeding mode. In this approach, farm scale would be based on the size of available farmland, and would allow for the use of LD in the near farmland. The second approach involves the intense separation of the livestock slurry and further transportation of the LD produced by the thick slurry. The third one is to expand the possible distances for transferring LD, using a pipe network or vehicle supervised by a professional third party. Finally, the development of high value-added products and bringing them to market is the ultimate solution for the future.
some countries, including China (Dahlin et al., 2015; Monlau et al., 2015; Zhou et al., 2018).

Biogas facilities have been around for almost 100 years, since the development of the first hydraulic digester in China in the 1920s (Chen et al., 2010). In the past 40 years, China has constructed the largest number of household biogas digesters in the world (Chen et al., 2010). Although the number of household biogas digesters has declined in recent years, at the end of 2017, there were still 40.58 million digesters in China (MOA, 2017). The original purpose of biogas exploration in China was to address the rural energy shortage.

In China, the biogas industry currently includes household biogas digesters, agricultural waste biogas plants, and industrial waste biogas plants. The biogas produced from household biogas digesters and small-sized biogas plants is mainly used for domestic cooking, and biogas from large biogas plants is usually used for co-generation of heat and power. Figure 1 shows the changes in biogas production over the years in China. Owing to the changes in lifestyles and production methods, the construction of household biogas digesters in China has gradually stagnated, and the utilization rate of existing digesters has continued to decline. Moreover, the development of industrial waste biogas plants has also been relatively slow, and its percentage representation (about 2%) in the biogas industry in China has not changed much over the years.

However, the number of biogas plants for processing agricultural waste has been growing, accounting for 19% of biogas production in China by the end of 2017 (Figure 1). Biogas plants that address livestock waste, such as manure and wastewater (Wu et al., 2017), are playing an important role in China’s biogas industry. The sustainable development of China’s biogas industry is expected to be closely related to the development of livestock waste biogas plants.

The total volume of agricultural waste treated by biogas plants in China reached 20 million m$^3$ at the end of 2017 (MOA, 2017). In the context of full utilization, approximately 360 Mt of manure and wastewater can currently be treated using this approach, accounting for less than 10% of the national total (3800 Mt) (Ma, 2017). This clearly indicates that there still remains significant potential for the development of biogas plants to treat agricultural waste. However, the current utilization rate of biogas plants is not high in China. The biogas output from agricultural waste biogas plants was only 2.37 billion m$^3$ in 2017. This indicates that only 25% of current capacity filled at existing plants is being used in normal operations. A field study in Beijing confirms this low utilization rate (Ding et al., 2018). There were only 29 plants under actual operation in January 2018; however, there were 115 biogas plants in Beijing at the end of 2017 (Ding et al., 2018).

Noteworthy, the low utilization rate of biogas plants in China is due to technical factor, plant productive maintenance, and policy reasons, as well as the problems of managing LD. In particular, the LD problem is becoming a major factor limiting the development of large-scale biogas plants. Usually, the LD from livestock waste biogas plants contains high concentrations of organic matter (OM) and nutrients, which results in high cost of standard treatment. Therefore, land application has been the main approach for managing LD in China (Chang et al., 2014). Some successful biogas-linked agro-ecosystems have been constructed since the emergence of the household biogas era (Chen, 1997; Chen & Chen, 2012; Dai et al., 2015; Zhang & Qiu, 2018). In general, a household biogas-linked agro-ecosystem facilitates a balance based on nutrients utilization between livestock breeding and arable farming, because only a small amount of LD is produced. However, the intensive development of livestock farming has increasingly led to larger livestock farm-based biogas plants, resulting in the production of more LD in one place. The nutrients balance between livestock breeding and arable farming will be broken.

**FIGURE 1** Changes in China’s biogas production over time (MOA, 2017)
Liquid digestate has high water content, which results in high storage requirements and high transportation costs. As such, there is too much LD being generated for the existing farmland capacity at increasingly larger biogas plants. The cost of both in situ standard treatment prior to discharge and off-site transportation of LD for fertilizer use is high. Therefore, maximized biogas-linked agro-ecosystem balance is needed to address the LD problem. Researchers, government representatives, and biogas plants operators in China have devoted great efforts in exploring this problem. However, previous reviews focused more on the development of biogas technology in China and paid less attention to LD issues (Chen & Liu, 2017; Chen & Chen, 2012; Deng et al., 2017). Therefore, this article reviewed the exploration of root causes of the LD problem and its solutions. The main objective is to help solve the LD problem for the sustainable development of biogas industry in China and other countries.

2 | INTENSIVE LIVESTOCK BREEDING AND BIOGAS PLANT CONSTRUCTION

Intensive development of China’s livestock industry is a growing trend (Hu et al., 2017; Jiang, Sommer, et al., 2011). From 1961 to 2010, the livestock density in China increased by approximately 10 times, which was about twice the growth in the yield of cereals per hectare of agriculture land (Ma et al., 2018). Figure 2 shows the changes in the number of annually slaughtered fattened hogs and the number of pig farms with different slaughtered fattened hogs in China. From 2007 to 2017, the number of annual slaughtered fattened hogs in China generally increased, with small fluctuations. The number of nonscale farms (annual slaughter capacity <500 pigs) decreased by more than a half. The total count of livestock at farms with an annual slaughter capacity of less than 50 pigs decreased from 80 to 36 million. However, the number of large-scale farms increased annually, in particular, the farms with an annual slaughter capacity of more than 50,000 pigs. The number of these farms increased seven times over 11 years.

The biogas system in rural China is also in the process of upgrading from dispersion to concentration (Chen & Liu, 2017). The number of biogas plants in China has rapidly increased since 2006 (Figure 3a); moreover, there has also been an increase in the average volume of biogas plants, from 108 m³ in 2006 to 182 m³ in 2017 (Figure 3b). The growth rates in the number of plants and the total volume of small- and medium-sized biogas plants has slowed down and even started to drop. However, there has been a rapid increase in the number and volume of the large-sized biogas plants (Figure 3c,d).

Increasing number of large livestock farms and their associated biogas plants leads to the concentration of large amounts of digestate in one place, resulting in an imbalance between crop and animal production. Thus, the lack of farmland that can be used to accept LD is a major problem facing livestock farm biogas plants.

3 | FEATURES/PROPERTIES OF LIQUID DIGESTATE FROM LIVESTOCK FARMS

3.1 | Nutrients in liquid digestate from livestock farms

In China, the main reason to build a biogas plant in a livestock farm is to treat manure and wastewater for reduction of OM. Therefore, to reduce the load of the biogas plant and...
subsequent processing, and increase profits, a solid–liquid separation can be performed before the wastewater enters the biogas digesters. This results in lower concentration of wastewater entering the biogas plant and lower concentration of nutrients in the LD.

Liquid digestate contains all nutrients required by crops. The most abundant nutrients in LD are nitrogen (N), phosphorous (P), and potassium (K). Figure 4a shows the NPK concentrations in LD from livestock farms in China. In general, N is the most abundant nutrient element in LD; its concentration can reach above 1000 mg L\(^{-1}\); however, mostly the concentrations lie between 200 and 900 mg L\(^{-1}\). The ammonium nitrogen (NH\(_4^+\)-N), which enables rapid growth of plants, is the major component of total nitrogen (TN) in LD (Monlau et al., 2015; Xia & Murphy, 2016). The concentrations of K are slightly lower than that of N, generally ranging from 200 to 600 mg L\(^{-1}\). The concentrations of P are generally below 100 mg L\(^{-1}\). The concentrations of these elements in LD are higher than those in municipal wastewater (Sun et al., 2016); thus, the treatment costs are higher. However, the NPK concentrations in LD are lower compared to those in liquid fertilizer (MOA, 2010), resulting in higher costs for long-distance transportation.

3.2 | Agricultural benefits of liquid digestate from livestock farms

Liquid digestate from livestock farms can be used as organic fertilizer, which helps in improving soil and crop quality (Nkoa, 2014; Walsh et al., 2012; Xu et al., 2019). LD is considered as a good source for soil improvement. The use of LD can increase soil OM content, as well as the nutrients content. LD from pig farms can increase surface soil OM to 3.0 kg hm\(^{-2}\), and increase total nitrogen content by 65% (Chen, Dong, et al., 2011; Chen, Li, et al., 2011). Shu et al. (2011) reported that with the application of LD, the effective microbial flora in the soil increased significantly, the soil OM
and nutrient content also increased significantly, and it also promoted soil urease and polyphenol oxidase activities. The pH of LD is generally neutral; therefore, the use of LD has a positive effect on the improvement of acid soil (He et al., 2012), as well as the coastal saline–alkali soil (Sun et al., 2018).

Liquid digestate is rich in amino acids, trace elements, humic acid, and other biologically active substances (Nkoa, 2014). It can stimulate crop growth and improve crop quality (Table 1). Moreover, the application of LD from livestock farms can reduce the nitrate content of vegetables (Wang et al., 2007), increase the vitamin C content of fruits and vegetables (Liu, Li, et al., 2009; Liu, Yang, et al., 2009; Wang et al., 2007), and increase the protein and mineral content in crops (Tang et al., 2010; Wu et al., 2014).

A few conflicting results pertaining to the effect of LD from livestock farms on crop yields have been reported in the literatures (Table 2). Application of 300 t hm\(^{-2}\) LD from a pig farm on a citrus field could increase yields by 8.59% compared to conventional chemical fertilizers (Wang et al., 2011). However, a study also showed that LD from pig farm did not increase wheat yield compared to chemical fertilizers at the same nitrogen application rate (Sun et al., 2012). Moreover, noteworthy, the applied amount of LD has a significant influence on crop yield. If the applied amount exceeds farmland capacity, a negative impact on crops and the environment is observed. Different types of crops require

### Table 1: Effect of liquid digestate (LD) on enhancement of crop quality

| Crop species   | Application effect                                                                 | References                               |
|----------------|------------------------------------------------------------------------------------|------------------------------------------|
| Chinese cabbage| Vitamin C increased by 45%, soluble sugar increased by 24%, and nitrate decreased by 52% (15 t hm\(^{-2}\) LD) | Wang et al. (2007)                       |
| Vegetables     | Enhanced contents of soluble sugar and protein; reduced nitrate content; increased vitamin C content | Liu, Li, et al. (2009), Liu, Yang, et al. (2009) |
| Rice           | Enhanced contents of protein and mineral elements of rice grains (18.75 t hm\(^{-2}\) LD) | Tang et al. (2010)                       |
| Maize          | Enhanced contents of Fe, Mn, Cu, Zn, Ca, and Mg in maize kernel (75–105 t hm\(^{-2}\) LD) | Wu et al. (2014)                         |

### Table 2: Effect of liquid digestate (LD) on enhancement of crop yields

| Crop species   | Application method and effect                                                                 | References                               |
|----------------|---------------------------------------------------------------------------------------------|------------------------------------------|
| Citrus         | 300 t hm\(^{-2}\) (1 year) LD from pig farm increased yields by 8.59% compared to conventional chemical fertilizers use | Wang et al. (2011)                       |
| Wheat          | 100% LD instead of chemical fertilizer did not reduce production                            | Sun et al. (2012)                        |
| Chinese cabbage| 15 t hm\(^{-2}\) LD increased yields by 8.32% compared to chemical fertilizers              | Wang et al. (2007)                       |
| Maize          | 90 t hm\(^{-2}\) LD increased yields by 0.62% compared to chemical fertilizers              | Wu et al. (2014)                         |
different amounts of LD. In general, crops such as forage grass, vegetables, and fruits have higher demand for LD than cereals. Figure 4b shows that grassland has the highest capacity to receive LD, up to 350 t hm\(^{-2}\). This is followed by fruits and vegetables, and by cereals, with a typical capacity within 50 t hm\(^{-2}\).

3.3 | The value of liquid digestate from livestock farms and its transport distance

Liquid digestate has a certain economic value due to its application as fertilizer. Even though, in China, the LD generated by most livestock farms is currently free for neighboring farmers, or costs only a small amount. According to the NPK levels shown in Figure 5a and the market prices described by Zhang et al. (2011), the average price of LD is only 4.6 yuan t\(^{-1}\). Owing to the low content of OM (the average value is only about 1%) in LD (Xu et al., 2019), even if the value of OM is considered, the price of LD still does not exceed 10 yuan t\(^{-1}\). The LD can completely or partially replace chemical fertilizers for many crops. The yield of tea with 82.5 t hm\(^{-2}\) of LD was equivalent to that with 0.45 t hm\(^{-2}\) of chemical fertilizers, indicating that the price of LD should be around 40 yuan t\(^{-1}\) (Fan et al., 2018).

Economic analysis shows that transportation cost and nitrogen content in LD are the main factors that determine the transportation radius of LD. A case study on a biogas project with a daily production of 1000 t of LD showed that the transportation cost of LD with 4.1 kg t\(^{-1}\) nitrogen was 7 yuan (km t\(^{-1}\)), revealing that the minimum LD transportation radius is just 3.18 km (Liu et al., 2021). This makes the long-distance utilization of LD uneconomical.

3.4 | Environmental risks of utilization of liquid digestate from livestock farms

Compared to the use of undigested manure, the anaerobic-digested livestock manure positively impacts the climate, the environment, and the farmer (Insam et al., 2015). A Nemerrow index-based assessment in the Suburban Areas of Yangtze Delta indicated that the pollution potential of LD irrigation was heavy metals risk-free (Zhou & Zhang, 2016). However, the unreasonable use of LD may still generate environmental risks. A study in Italy attributed the environmental risks of digestate from livestock farms to high levels of ammonium, salinity, COD, phosphate, and color (Tigini et al., 2016).

Ammonium is the main form of nitrogen in LD. The ammonia emission creates environmental risks to the atmosphere and to N-limited ecosystems. Reasonable fertilization methods, such as injection, could reduce this risk (Nkoa, 2014). As nutrients, ammonium and phosphate get transferred through water in soil, which poses potential pollution risks to surrounding surface water and groundwater. After the application of LD, nitrogen, phosphorus, and many other nutrients that are not absorbed by crops may accumulate in the soil or enter the surface water through surface runoff, resulting in soil salinization or water eutrophication. Therefore, control of the application amount of LD is highly desirable and strict nutrient management should be carried out. Studies have shown that ammonia nitrogen content increases in paddy water, but not in the soil where LD is applied for three consecutive years (the TN dosage is less than 540 kg hm\(^{-2}\)) (Jiang, Wang, et al., 2011).

The OM such as fatty acids is degraded during AD; however, the digestate still contains some difficult-to-degrade OM, such as humic acids and lignin, most of which are beneficial to crop growth and soil improvement. However, the
COD content of LD is still high, and some organic pollutants, such as antibiotics and resistant genes, still exist (Li et al., 2018; Zhang et al., 2020). Nonetheless, the research on the biochemical fractionation of digestate OM (Nkoa, 2014) has rarely been reported. Therefore, a lot of more systematic explorations are still demanded to pay attention to the risks of OM in LD.

Heavy metals such as copper (Cu) and zinc (Zn) in LD, which come from feeds and veterinary drugs, can pose a risk (Nkoa, 2014). Cu and Zn are trace elements required by plants; thus, most fertilizer standards do not regard these two elements as heavy metals. A survey of LD from 10 pig farms in Jiaxing, China, showed that the Cu concentrations ranged from 0.06 to 8.8 mg L\(^{-1}\) and the Zn concentrations ranged from 0.32 to 39.8 mg L\(^{-1}\) (Wei et al., 2014). Some field analysis indicated that application of LD did not significantly cause Cu and Zn accumulation in the soil (Wang et al., 2011; Xu et al., 2019); in fact, the accumulation was lower compared to the case when chemical fertilizer was applied in the same situation (Wang et al., 2016). Other studies also found that the reasonable use of LD did not lead to significant accumulation of Cu and Zn in crops (Chen, Li, et al., 2011; Chen, Dong, et al., 2011; Wang et al., 2011).

According to the literature, the concentration of Cd, Pb, Hg, and As in rice that was fertilized using LD from pig farms did not increase significantly (Jiang, Wang, et al., 2011). Long-term (up to 8 years) studies on soils fertilized using LD exhibited a slight increase in heavy metal levels, but they did not exceed the limit of China’s “Risk control standard for soil contamination of agricultural land (GB15618-2018)” (NS, 2018; Xu et al., 2019). In summary, the environmental risks of LD utilization from livestock farms can be controlled within the relevant standards through reasonable utilization and oversight.

### 4 | MANAGING LD FOR LIVESTOCK FARMS

Insufficient farmland around biogas plants and the high cost of transportation of LD are two key problems associated with LD. Figure 5 shows that it was not a problem in the household biogas era, because the farmland belonging to the biogas digester owner was enough to accept the LD (Chen et al., 2010). Nonetheless, for large-scale biogas plants, the livestock farm owners were also required to have enough farmland to absorb the manure when livestock farm and biogas plants were first constructed. However, the farmland in China is now subcontracted to households. The small farms may obtain farmland of the required size by leasing, while this is more difficult for large farms. A survey in Sichuan Province showed that only 30.8% of livestock farms have enough farmland to absorb manure (Xu et al., 2019). In general, the scale of a biogas plant is built according to the scale of the livestock farm. Therefore, livestock manure is the fundamental problem of LD. Solid manure and solid digestate can be made into organic fertilizers for long-distance transportation. Nevertheless, for the LD with low value, the transportation costs reduce the economic viability of a biogas plant (Delzeit & Kellner, 2013), thus limiting the development of the biogas industry.

The digestate produced by household biogas digesters is simultaneously used as a fertilizer by owners (Chen et al., 2010). In the early 1980s, China changed the agriculture system, which was transitioned from collective land ownership to individual household production (Jiang, Sommer, et al., 2011). Each household unit owned a certain area of farmland and some livestock; therefore, biogas technology bridged the gap that existed between crop and livestock production. In general, the farmland owned by farmers has been sufficient to absorb the manure generated by the livestock breeding, with chemical fertilizers being used as a supplement. In this situation, the LD could be used without long-distance transportation.

Since the 1980s, several eco-agricultural models centered on household biogas digesters have been formed in rural China. Examples include “livestock-biogas-fruit” biogas systems in the south of China (Chen, 1997; Dai et al., 2015) and “4-in-1” biogas systems in the north of China (Qi et al., 2005). The essence of these models is to combine crop and livestock production through household biogas and to build biogas-linked agro-ecosystems. Each system includes a livestock subsystem, crop production subsystem, and biogas subsystem (Yang & Chen, 2014). Digestate use is the core that bridges the gap in these ecosystems.

The rapid progress of biogas-linked agro-ecosystem in rural China has promoted the development of not only the China’s biogas industry but also the livestock breeding. Livestock farms have expanded the biogas-linked agro-ecosystem. Noteworthy, expansion in the transportation distance of LD is the main way to expand the biogas-linked agro-ecosystem balance. For livestock farms of all sizes, strategies can be made in the following four sections: livestock breeding, wastes treatment, LD transportation, and LD utilization (Table 3).

### 4.1 | Balancing crop and livestock production—Practice of small biogas plants

According to China’s “Technical standard of preventing pollution for livestock and poultry breeding (HJ/T 81–2001)” (Environmental protection industry standards of the People’s Republic of China, 2001), livestock farm construction in China should adhere to the principle of combining crop planting and animal husbandry. This calls for a balance between
crop and livestock production. The scale of a livestock farm should be determined according to the land’s capacity to accept livestock manure and wastewater. For example, Sheng et al. analyzed the land area required to apply LD in two scenarios: (1) “AD after solid–liquid separation” and (2) “Direct AD of manure” (Sheng et al., 2015a, 2015b). The first scenario, “AD after solid–liquid separation,” requires relatively little land, 12.4–51.3 hm² farmland, for LD from a pig farm with just 10,000 pigs (Sheng et al., 2015a). In contrast, for the second scenario, 149.4–1248.8 hm² is required (Sheng et al., 2015b). The farmland is owned by the individual household in China; therefore, the livestock farm owner must use a lease to obtain the right to use the land around the farm. Small-scale farms are more likely to lease enough land.

The “company + agent” mode in pig husbandry supports a balance in crop and livestock production. Figure 6 shows that the “company” is responsible for breeding and selling pigs, while the “agent” is responsible for pig feeding (Xu et al., 2015). The “agent” is dispersed in the farmland, and the scale of the “agent” is determined based on the surrounding available farmland area. The minimum size of a typical “agent” is approximately 500 pigs. Under the scenario of “AD after solid–liquid separation,” less than 3 hm² of farmland is needed to absorb the LD.

### 4.2 Expanding the economic transport distance by improving the slurry management process

Solid–liquid separation of slurry is a common process in livestock farms in China. The solid parts can be transported to farther locations for use. However, most of the nutrients are still in the liquid part after mechanical separation (Hjorth et al., 2010; Yang et al., 2015), subsequently in the LD, which still require much farmland around the livestock farm for consumption. Therefore, a strategy for deep separation of livestock slurry after solid–liquid separation was proposed, which is also called the “thick-dilute separation” (Figure 7) (Deng et al., 2012, 2014; Yang et al., 2015). After precipitation, the slurry from solid–liquid separation was divided into 15% thick slurry containing the majority of the OM and phosphorus (more than 60%) for further anaerobic digestion, and 85% dilute liquid for AD or aerobic treatment (Yang et al., 2015). This strategy is conducive not only to improving biogas production efficiency but also to expanding the transportation distance of LD, thereby expanding the biogas-linked agro-ecosystem. Under the same economic conditions, the maximum transportation distance of thick slurry was about three times that

### Table 3 Strategies for expanding biogas-linked agro-ecosystem balance

| Steps              | Strategies                                      | Digestate transportation methods | Maximum transport distance | Scope of application                      |
|--------------------|------------------------------------------------|----------------------------------|----------------------------|-------------------------------------------|
| Livestock Breeding | “company + agent” livestock breeding mode       | Pipe                             | 1–2 km                     | Large livestock enterprises               |
| Waste Treatment    | Solid–liquid separation + AD                   | Pipe                             | 5 km                       | Small and medium livestock farm, Family farm |
|                    | Solid–liquid separation + thick-dilute separation + AD | Pipe                             | 15 km                      |                                            |
| Liquid digestate transportation | Third-party service                              | Pipe network                      | 15–20 km                   | Livestock raising zone                    |
|                    |                                                  | Vehicles                          | 20–25 km                   | Countywide livestock farms                |
| Liquid digestate utilization | Concentrated fertilizer                           | Inside the farm                   | Depend on market             | Large and medium livestock farm          |
|                    | Cultivating high-value crops                   | Inside the farm                   | Depend on market            |                                            |

**FIGURE 6** The mode of “company + agent”
of raw slurry (Deng et al., 2012). The thick-dilute separation strategy has been implemented in some livestock farm biogas plants in China, and has also been promoted by the government of China.

### 4.3 Managing liquid digestate transportation in public areas to maximize biogas-linked agro-ecosystem balance

For large-scale livestock farms or districts, it is difficult to balance crop and livestock production. This puts forward the demand for transporting the LD to other places, in order to maximize biogas-linked agro-ecosystem balance. Managing this transportation in public areas between livestock farms and farmland is the key to solving the current LD-associated problem. Pipelines and vehicles are currently the two possible transport methods in China.

A case of pipeline transportation is in Hongya County, which has about 45,000 cows. Figure 8a shows that livestock farms and farmland owners are responsible for constructing and managing production and utilization facilities for LD, respectively. The county government mainly led the construction of the pipe network in the public area, building a 400 km long pipe network system centered on a large cow farm. The pipe network is managed by a third party, which operates by charging LD disposal fees from the livestock farm. It also receives some government subsidy. The LD is supplied to the crop farmer free of charge.

A case of truck transportation of digestate is in Qionglai City, which has 246 large-scale animal farms (Bluemling & Wang, 2018). Figure 8b shows that trucks are used to transport LD in public areas. The trucks were purchased by third-party cooperatives, and the government provided certain subsidies. The cooperatives charge transportation fees both from livestock farmer and crop farmer to maintain their operations. However, the transportation distance of the truck is limited, due to the low value of LD itself. Correspondingly high volume of LD impacts the economic situation of digestate marketing. Prohibitive transportation costs often preclude distribution over long distances (Huttunen et al., 2014).

According to Bluemling and Wang’s study, the distance between the location of a cooperative member and the manure receiver should not exceed 20–25 km (Bluemling & Wang, 2018).

The transportation of LD provided by pipelines and trucks essentially takes raw LD from the anaerobic storage tank and moves it to the required places. It is considered to be a by-product of biogas production, and the cost is mainly borne by livestock farmers and the government. For most users, there is no charge. However, because the LD contains the same nutrients as fertilizer, some crop farmers receiving LD also pay a fee to the third party responsible for transportation (Bluemling & Wang, 2018).
4.4 | High value-added utilization of LD to market

The development of a market for digestate product is a huge challenge for the biogas industry (Dahlin et al., 2015). High transportation costs make low-value LD difficult to be commercialized as a commodity. Concentration and development of high value-added products is an effective strategy (Tampio et al., 2016). There have been many studies in China on concentrating LD via techniques such as reverse osmosis (RO) and evaporation. These plants are already in operation and some products have been put into the market (Lu et al., 2017; Wu et al., 2019). In general, RO membrane can increase the nutrient concentrations in LD by four to five times, or as high as 10 times (Wu et al., 2019). However, other substances still need to be added to meet the standards of liquid fertilizer (Fan et al., 2015).

Another strategy is to use LD to cultivate high-value crops in situ and bring the crop products to the market. Microalgae is a promising option (Monlau et al., 2015; Xia & Murphy, 2016), which has great potential in biofuels, as well as pigment, feed, and food additive production (Hu et al., 2018; Mata et al., 2010). However, the high turbidity and presence of high levels of ammonia nitrogen in LD negatively influence the microalgae growth (Monlau et al., 2015; Xia & Murphy, 2016). Recently, our group has found that struvite precipitation and microalgal-bacterial consortium can help solve the above-mentioned problems (Jiang, Pu, et al., 2018; Jiang, Wang, et al., 2018). However, so far, the commercial application of microalgal cultivation in LD has not been extensively reported.

The LD is considered to be an effective nutrient source for high-quality vegetables under soilless cultivation (Liu, Li, et al., 2009; Liu, Yang, et al., 2009; Ronga et al., 2019). However, for better yield and quality of vegetables, some pretreatment techniques are required for LD. Dilution with clean water or commercial nutrient medium is a common method (Yang et al., 2017; Zhang et al., 2010; Zhou et al., 2013), which is capable of increasing the costs, thus limiting the commercialization of this technology.

5 | PROSPECTS

The development of China's biogas industry is closely related to the livestock and poultry breeding industry, and the intensive development of the livestock breeding industry is the root of the LD-associated problem. In the near future, the degree of intensification of China's livestock breeding industry will be further strengthened. Undoubtedly, the problem of LD will also become more prominent. Land application will still be the main method of LD disposal. In addition to using technical means to expand biogas-linked agro-ecosystems, it is also necessary to use economic methods to search for the best utilization mode.

Moreover, the use of ammonia stripping, activated sludge, and other methods to reduce the amount of nitrogen in the LD is also a way to solve the contradiction between the production of LD and the land absorption capacity. Nonetheless, this will cause more energy input and nitrogen waste, thus forwarding the need for economic analysis. However, the development of efficient LD utilization technologies, such as microalgae cultivation, is also required. Building an intensive planting that matches the level of intensification of livestock breeding is the fundamental solution to the problem of LD.

6 | CONCLUSIONS

Land application is currently China's primary disposal option for LD; as such, building balanced biogas-linked agro-ecosystems remains the main solution. The biogas-linked agro-ecosystems characterized by the combination of livestock breeding and arable farming originated from the era of household biogas in China. Livestock farm biogas plants account for an increasing proportion of China's biogas industry. LD disposal is becoming a key factor limiting the development of livestock farms biogas plants. This in turn affects the sustainable development of China's biogas industry. The rapid intensification of livestock breeding has separated livestock breeding and arable farming, leading to the LD problem.

The solutions to maximize biogas-linked agro-ecosystem balance proposed in this study were reviewed from the following four aspects: breeding mode, waste treatment mode, LD transportation mode, and LD utilization mode. The first one is to reduce the size of the livestock farms and disperse the livestock farms in the farmland, by promoting the "company + agent" livestock breeding mode. The size of each livestock farm should be determined based on the size of the available farmland. The second one involves the deep separation of the livestock waste and further transportation of the LD produced by the thick slurry. The third solution indicates the use of a pipe network or vehicle to transport the LD, thus expanding the range of the balanced biogas-linked agro-ecosystem. In this solution, a third party, independent of livestock breeding and crop planting, is responsible for managing the vehicle and pipe network. How to make crop farmers willing to pay for LD is still a problem to be solved. However, low value of the LD is the key root cause of the LD-related problem; as a result, the development of high value-added products and bringing them to market is proposed as the ultimate solution. LD concentration technologies, microalgae cultivation, and soilless cultivation are very promising. However, additional research is needed to develop economical pretreatment technologies for utilizing LD in the future.
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DATA AVAILABILITY STATEMENT
Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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