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Mass flow and energy balance plus economic analysis of a full-scale biogas plant in the rice–wine–pig system

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HIGHLIGHTS

- Wastewater and manure were digested in two CSTRs with different temperature.
- Mass flow and energy were balanced for the biogas plant.
- Output energy exceeded input energy at a surplus energy of 823, 221 kWh a^{-1}.
- The payback time for the biogas plant was 10.9 years.

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ABSTRACT

This paper presents mass flow and energy balance as well as an economic analysis for a biogas plant in a rice–wine–pig system at a practical rather than laboratory scale. Results showed feeding amount was 65.30 t d^{-1} (total solid matter (TSM) 1.3%) for the normal temperature continuous stirred tank reactor (CSTR), and 16.20 t d^{-1} (TSM 8.4%) for the mesophilic CSTR. The digestion produced 80.50 t d^{-1} of mass, with 76.41 t d^{-1} flowing into rice fields and 4.49 t d^{-1} into composting. Energy consumption of this plant fluctuated with seasons, and surplus energy was 823, 221 kWh/year. Thus, biogas plant was critical for material recycling and energy transformation of this agro-ecosystem. The economic analysis showed that the payback time of the plant was 10.9 years. It also revealed application of biogas as a conventional energy replacement would be attractive for a crop–wine–livestock ecosystem with anaerobic digestion of manure.

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1. Introduction

China is one of the largest agricultural countries, with pig rearing reaching 465 million heads in 2014 (Yu et al., 2015). This large number requires a huge amount of feed. In recent years, the world food shortages have resulted in increasingly tight supply of feed, thus causing many countries to find new feed resources (Pimentel et al., 2009). Distillers dried grains with solubles (DDGS), also termed distillery waste or byproduct of wine making, can be a good feed resource (Yang et al., 1991). In China, wine is made using sorghum, rice or wheat as the main raw material. Crude protein, fiber, minerals, organic acids and other organic matter that fail to ferment are left in the barrels. This waste is rich in nutriments, which cannot be matched by a general grain feed.

According to the National Bureau of Statistics of China, there was a wine production of 120 million tons in 2013 (Wang, 2015). Usually, producing 1 ton of wine leads to three tons of DDGS. An annual output of 3 million tons of wine can produce 9 million tons of DDGS for feed, equivalent to 30% savings in feed grain (Hu, 2010). Rational and effective use of DDGS for feed will undoubtedly make up for the lack of feed resources, so as to promote the development of animal husbandry in China. However, its disadvantages are obvious. First, DDGS, especially in the summer, can easily degrade and further ferment, prone to pests and mildew. Second, transportation and storage are extremely inconvenient, as DDGS is easy to spoilage. For large and centralized winery, it is more difficult to solve these problems (Xu, 2011).

On the other hand, due to the rapid growth in the global energy demand and to the growing concerns regarding pig manure disposal, more attention has been paid to the development of bioenergy, especially the one derived from anaerobic digestion of manure (Carrosio, 2013; Pucker et al., 2013; Qu et al., 2013; Szarka et al., 2013). Biogas technology can be an environmentally

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friendly solution that may contribute to a more efficient, economic, and safe recycling of manure to improve agricultural production, in addition to energy production.

Unlike traditional energy supply chains, the rapid development and wide application of biogas are influenced by local environment, the availability of raw materials for biogas production, transportation, storage, climate conditions, and supporting policies (Duan et al., 2013; Wang et al., 2012). Furthermore, the biogas usage in China related to rural energy development and corresponding economic growth, has led to complex interrelationships among society, economics, energy, and environment. This further gives rise to the objective of developing sustainable and integrated systems for energy-based agriculture and the rural economy. Faced with the problems in DDGS for feeding, pig manure disposal and bioenergy production mentioned before, a biogas-based bioenergy production system can undoubtedly play a role in solving these corresponding problems.

In fact, after a 40-year history of biogas in China, the purpose of developing biogas is not only to provide energy, but also to recycle biomass, such as the integrated pig–biogas–vegetable systems in northern China and the livestock–biogas–fruit systems in southern China (Wang et al., 2008). For this reason, modern biogas utilization has been popularized in combination with ecological agriculture for a better performance of harmonizing economic profits, environmentally friendly development, and resource consumption optimization.

In this paper, a full-scale biogas plant in a rice–wine–pig system was analyzed. In this system, rice DDGS was used to feed pig, avoiding the spoilage of DDGS, and anaerobic fermentation of pig manure was conducted at the Zhefang winery in Mang City, Yunnan province, China to provide bioenergy for the wine distillation. Digested material was then used to grow rice nearby, which formed a biogas-linked agricultural and industrial ecosystem. This study presented an assessment of the application of biogas fermentation in Zhefang winery, providing information about potential profitability and expenditures in terms of energy and economic impacts. For this purpose, the mass flow and energy balance in the biogas plant were investigated. The potential energy generated and consumed through biogas was analyzed. Furthermore, an economic analysis was performed to account for the introduction of the anaerobic digestion plant in the ecosystem.

2. Methods

2.1. Plant description

Fig. 1 describes the process flowchart of the full-scale plant for manure biogas fermentation in rice–wine–pig system using continuous stirred tank reactor (CSTR). The plant consisted of collection tank, equalization tank, 500 m^3 normal temperature CSTR, 300 m^3 mesophilic CSTR, buffer tank, settling tank, solid–liquid separator, composting site for digested slurry, storage tank for digested effluent, 200 m^3 biogas holder, gas–water separator, desulfating tower, and flowmeter. Pig manure mixed with wastewater were used as raw materials and were diluted to a total solid matter (TSM) of about 8.4% for the mesophilic CSTR, and about 1.3% for the normal temperature CSTR. This process design was based on the research of Deng et al. (2012, 2014), which showed high gas production rate and fermentation stability by separation of swine slurry into different concentration fractions.

Approximately 75.00 t d^{-1} of wastewater and 6.50 t d^{-1} of manure passed through the fermentation system. From collection tank, wastewater was pumped directly by a submerged pump into normal temperature CSTR. The remaining liquid fraction was sent to equalization tank, where it was mixed with pig manure derived from the pig stables. Then the mixture was pumped into mesophilic CSTR with an overhead stirrer. This CSTR required a boiler to maintain the fermentation temperature at 35 °C, with a hot water recycle pump. The biogas produced within the anaerobic digesters was fed into a biogas holder and used for wine distillation or boiler

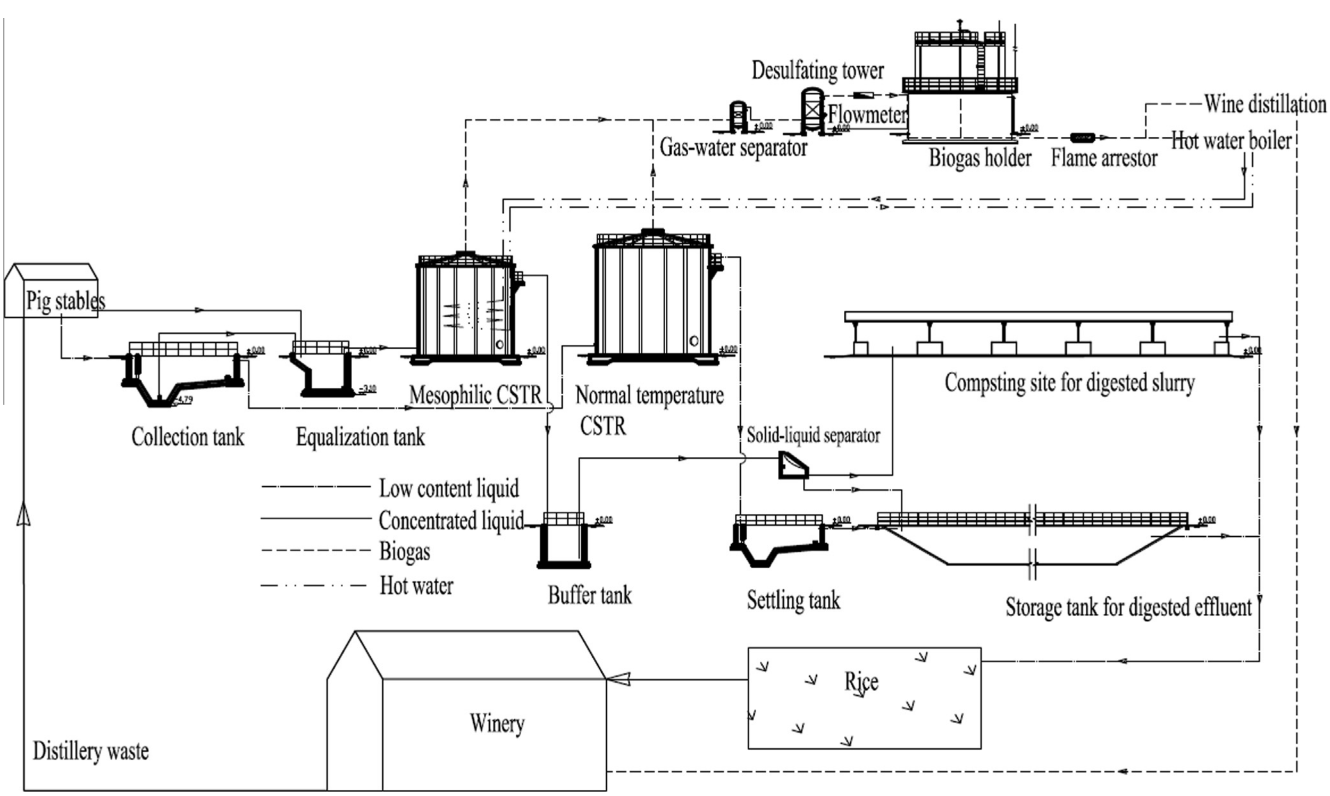

Fig. 1. The process flowchart of the biogas plant.

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