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# Reducing biogas emissions from village-scale plant with optimal floating-drum biogas storage tank and operation parameters

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## HIGHLIGHTS

- Performance of a village-scale plant with semi-continuous feeding was analyzed.
- Models, including biogas production rate and biogas consumption rates, were established.
- A biogas flow chart with key parameters was proposed.
- Optimal tank and appropriate operation could guarantee reduced biogas emissions.

## ARTICLE INFO

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## ABSTRACT

In this study, an approach to optimize the components and operation of biogas plant systems, which temporarily stores biogas in floating-drum biogas storage tank (BS) and feeds in a semi-continuous manner, was developed. First, the parameters of biogas production and consumption were characterized into mathematical models, and estimated with a 1-year operating data set of a village-scale biogas plant (fermentation volume, 80 $m^3$). Then, the established models, which included biogas production and consumption rates, were used to determine the optimal BS volume and operation parameters for improving biogas plant performance. In contrast to the biogas usage level achieved with the established BS (76.4%), that obtained with an optimal system could reach up to 85.7% and the feeding frequency for a 1-year operation could be decreased 6.5 times. Our proposed approach exhibited a number of attractive features, including accurate determination of parameters, reduced biogas emission, and cost efficiency, which may not only enhance biogas benefits, but also increase economic and environmental feedback on village-scale biogas plant operation.

## 1. Introduction

In recent years, village-scale biogas plant (fermentation volume: $300\,m^3 > V \geq 20\,m^3$), which can decentralize the supply of renewable energy, has been broadly applied, because of its suitability to relatively small-scale agriculture structures (village division, cultivated area, and livestock breeding) scattered throughout most of the regions of China [1,2]. This kind of biogas plants could be an ideal solution to treat distributed agricultural waste and produce both biogas and organic fertilizer conveniently and simultaneously, thus favoring long-term sustainable agriculture [3]. Besides, biogas plants could be a reliable renewable energy supply source in residential areas from the points of both technology and practice [4]. As a result, biogas can be delivered to nearby settlements, thus reducing the need for a large biogas pipe network, and fertilizer could be easily applied to the surrounding farmlands, without the need for transportation [5]. Based on these advantages, more than 103,000 village-scale biogas plants had been established in China by the end of 2015, and the number and volume of such plants are rapidly and continuously increasing. In addition, it is also very popular in developing regions, such as Vietnam and Africa [6].

Nevertheless, biogas emission in these plants may be overlooked under normal circumstances, because the relationship between biogas production and biogas consumption cannot be accurately managed. In commercial systems, most of the technical support personnel have recently tried to further improve high biogas production rate by some

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simple methods such as increasing feedstock input, with the sole aim of ensuring continuous biogas supply, rather than improvement in biogas usage level [7]. As a result, excess biogas may get released into the atmosphere and cause serious air pollution, thus compromising the environmental advantages of anaerobic digestion, because the global warming potential of methane is 25 folds higher than that of carbon dioxide [8]. Some studies have predicted that biogas emissions from digesters may reach as high as 12 Tg/year by 2020, accounting for more than 2% of global emissions and constituting a virtual climate bomb [9–11]. Therefore, there is an urgent need to limit biogas emissions from biogas plants to an acceptable range.

From a technical view point, a combination of multiple usages could be a feasible mechanism to completely utilize excess biogas, such as the combined generation of heat and power system [12]. However, real-world operation tends to span broad activities and requires consideration of multiple aspects, and an energy hub is necessary to dispatch energy flow for multiple energy system, which is still a flexible operation procedure [13,14]. Reinelt et al. found that this option is a significant biogas emission source on the operational state (unbalanced biogas production and utilization), even in large-scale agricultural biogas plants, because the biogas flare is always not necessarily activated owing to the manual dispatch system [15]. Meanwhile, based on lifecycle assessment (LCA) to analyze the economic and ecological performance of biogas project in China, Wang et al. reported that the conversion of biogas to electricity may result in a reduction in energy efficiency and sustainability of the system [16]. Furthermore, the number of village-scale plants accounted for approximately 83.96% of the total biogas plants for the treatment of agricultural waste, and the biogas is often only used for one purpose (e.g., cooking), without the installed electricity capacity or combustion furnace system [17,18]. Thus, it is obvious that multiple energy system is not currently suitable for village-scale biogas plant without accurate and automatic control systems.

Accordingly, production and supply of biogas without careful planning and accurate evaluation could cause poor operation performance owing to lack of defined operation parameters [19]. A mathematical modeling method is considered to be a feasible and effective way to optimize biogas flow chart and improve usage rate, and a dynamic optimal operation function should be formulated by considering biogas production and biogas demand.

The anaerobic digestion process for biogas production is affected by several factors, such as temperature, organic loading rate (OLR), feeding method or interval, fermentation process, solid concentration [20–22]. If these factors—especially fermentation temperature and OLR—are well controlled during normal anaerobic digestion, the required biogas production rate could be achieved as scheduled in the given biogas plant [23]. However, in practice, the production rate could exceed the usage demand with a specific moderate digester owing to some convenient operation processes or absence of flexible usage model, which might consequently lead to an intrinsic biogas emission rate [24].

In common village-scale biogas plants, floating-drum biogas storage tanks (BS), functioning as a buffer tool and pressurizer simultaneously, are simple and good option with respect to the dynamic changes in biogas production and consumption [1]. However, if the biogas production is higher than the total consumption and buffering capacity, the excess biogas will be released into the atmosphere unavoidably [25,26]. Therefore, a method to accurately determine BS volume is needed to optimize the biogas flow chart, so that the excess biogas (generated at high production rates) could be effectively stored to suitably compensate the gap between production and consumption (created at low production rates) in the subsequent stage.

To achieve the above-mentioned objective, both the dynamic processes of biogas production and consumption should be quantitatively investigated. With regard to biogas production rate, a semi-continuous feeding is employed in most of the village-scale biogas plants owing to the low operation input, and the daily biogas production curve may present periodic changes from one feeding interval to another, which is usually designed to operate with both self-defined and constant parameters in successive days [21]. In other words, a steady daily biogas production rate cannot be sustained because a feeding interval of several days is employed, and it is impossible to maintain a constant daily OLR in the digester [27]. Although periodic variation in biogas production rates under semi-continuous feeding owing to several fermentation acclimation periods has been reported in previous studies, an efficient and effective mathematical model has not yet been developed to precisely analyze the change in biogas production rate [28,29]. Besides, it must be noted that biogas consumption is always driven by the residents' demand, which is affected by living habits, season, etc., and thus, the biogas demand may fluctuate, especially in small-scale biogas supply network [30]. Although some studies focusing on the average daily and seasonal variations in biogas consumption of centralized biogas supply project are found in the literature, those on the hourly changes in biogas consumption are rarely reported. Furthermore, there is also a lack of mathematical models focused on the changes in village biogas consumption with time, even though some models are available for natural biogas consumption at regional level [31].

Therefore, the main objective of this study was to find a reasonable method to optimize the operation performance of village-scale biogas plants by developing a mathematical procedure, which could be useful in analyzing biogas supply flow, and a simple and feasible way was presented to reduce the biogas emission by the optimal BS and corresponding operation scheme. First, biogas production and consumption of a village-scale biogas plant were experimentally investigated over a 1-year period. Subsequently, the production and consumption functions were formulated based on the analysis of experimental data, and a dynamic model, which includes production, consumption, and buffering, was established. Finally, optimal biogas storage volume (buffer volume) and operation parameters were achieved by using the dynamic model.

## 2. Materials and methods

### 2.1. Biogas plant system and analysis

#### 2.1.1. System description

A biogas plant, located in Deyang, Sichuan, southwest China, was established on 25 Feb. 2015, which formally supplied biogas on 6 Apr. 2015. The main experiment started when the digester was activated and ran normally. A schematic diagram of the biogas plant system is shown in Fig. 1. The digester was a continuous-stirred tank reactor with a fermentation volume of 80 $m^3$, and the effective volume of the BS was 30 $m^3$ [32]. The storage volume of the BS was in accordance with the common standard, i.e., more than 0.5 $m^3$ for each household. The biogas produced from the digester was supplied as domestic fuel to 52 households nearby. Redundant biogas could be released into the open air by the biogas storage tank discharging system. The leakage test was conducted before the establishment of the biogas plant system to confirm that the system's air tightness was excellent. Thus, the main emission from the system was the surplus biogas, which exceeded the total capacity of demand and storage.

The feed manure was obtained from a pig farm near the plant, and was mixed with ground water. The characteristics of the collected feedstock have been described elsewhere [1]. Semi-continuous feeding was employed and the feedstock was added into the digester with a total solids (TS) content of 8% (about 8 $m^3$) during each feeding.

#### 2.1.2. Biogas and temperature measurement

The daily biogas production was recorded at 09:00 h every day by using a fuel gas meter (G6.0, Shancheng, Chongqing, China). The biogas consumption of each household was measured using an IC prepaid gas meter (CG-L-4B, Kaidi, Tianjin, China). Ambient temperature