



Electrical energy production and operational strategies from a farm-scale anaerobic batch reactor loaded with rice straw and piggery wastewater



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ABSTRACT

A farm-scale biogas plant loaded with untreated rice straw and co-digested with raw pig wastewater was operated and monitored during a complete digestion cycle. One active anaerobic digester cell (6600 m³) containing 727 tons of rice straw, 285 tons of pig wastewater and approximately 1300 tons of water was operated for a total of 422 days. Cumulative energy production of 295 MWh and an estimated specific methane yield of 181 LCH₄/kgVS added was achieved. A direct correlation between daily power production and digester temperature was observed, with a maximum power production of 2.74 MWh/d. Mesophilic conditions were reached inside the digester during the summer months by recovering waste heat from the engine and recycling it through the leachate recirculation process.

A slow start-up period of approximately 200 days was observed, but increased leachate recirculation rates (from 0.04 to >0.14 m³/m³ straw-d) resulted in increased gas production that initiated the microbial growth phase in the digestion cycle. Although sufficient buffering capacity as well as macro- and micronutrients were supplied to the system by the pig wastewater, an overall straw (dry wt.) to wastewater ratio (wet wt.) of 1 to 1.4 is recommended to improve gas production and decrease the acclimation period. A raw economic assessment of the system shows an investment recovery time of 8.3 years. Improvements such as continuous leachate recirculation, a more efficient heat exchange system to maintain mesophilic conditions year round, and periodic addition of fresh wastewater and sludge acclimated to lignocellulosic material are recommended to achieve a more sustainable and profitable system.

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1. Introduction

Waste-to-energy projects are expanding beyond just landfill gas recovery and into agricultural wastes such as animal manure and cereals silage because of new legislation and governmental subsidies for renewable energy production. To the authors' knowledge, however, the farm-scale system discussed in this paper is the only facility in operation that uses the anaerobic digestion of rice straw for electricity production. In 2010, approximately 63% of the biogas produced in Europe (*i.e.* 7 million tons of oil equivalent) was from

sources other than landfill gas recovery including decentralized agricultural plants, household wastes and green waste methanation plants and centralized co-digestion facilities [1]. The Renewable Energy Directive (2009) by the European Union is aiming for 20% renewable energy share in energy consumption by 2020 [2], and the economic incentives are the driving force that can make these goals a reality. In Italy, for example, the government passed a law in July 2009 and agreed to pay €0.28/kWh for electricity generated by agricultural feedstock for farm-scale plants (*i.e.* <1 MW), which was the highest feed-in tariff in Europe [2].

In northern Italy, rice straw is an abundant source of biomass that has the potential to be harvested for renewable energy. Through the anaerobic digestion process, organic matter is microbially decomposed to produce biogas that can be incorporated directly into the natural gas grid (after purification) or used for the cogeneration of heat and electricity. Methane yields from untreated rice straw digested in optimum conditions in both

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lab and pilot-scale studies range from 190 to 280 LCH₄/kgVS added [3–6]. The ideal operational conditions for the anaerobic digestion of rice straw have been defined in numerous lab-scale studies [7] and two pilot-scale batch reactors (i.e. $\geq 1 \text{ m}^3$) [5,8].

One specific challenge associated with rice straw is that it is a complex, lignocellulosic material, resistant to anaerobic degradation because the lignin component acts as a shield and limits the hydrolysis process [9,10]. Pretreatment strategies have been effective in overcoming this challenge in laboratory-scale experiments [11–15]; however, these approaches are not practical for farm-scale applications because of design constraints, increased energy inputs, excess chemical and water requirements, and waste disposal issues associated with the digestate. From a farm-scale perspective, co-digestion of straw with animal manure is a practical way to improve gas production as it provides an appropriate balance of nutrients, buffering capacity, and a diverse microbial community to carry out the digestion process [5,16,17].

Implementing a farm-scale biogas plant using rice straw co-digested with piggery wastewater offers a sustainable alternative for managing the disposal of agricultural residues, and it reduces a significant portion of methane emissions. Rice paddy fields make up 10–13% of the global anthropogenic methane emissions [18], and removing the rice straw from the fields upon harvesting has been shown to reduce total greenhouse gas emissions (Mg CO₂ eq./ha) by 87% [19]. From an economic perspective, legislative incentives can offer a profit to the user and ultimately increase demand for and efficiency of methanisation units.

The purpose of this research is to define and optimize operational parameters for a farm-scale anaerobic batch reactor loaded with rice straw and pig wastewater. From the existing literature, there are no other documented farm-scale or full-scale biogas plants currently using rice straw as the primary substrate. The specific objectives of this study are to monitor the operation of a farm-scale co-digestion plant, to recommend optimization strategies in regards to additional energy and wastewater inputs, and to determine if this system is sustainable on a long-term basis. The parameters that will be discussed include cumulative energy production, daily power production, biogas quality, specific methane yields, total solids concentration, straw to wastewater ratios, temperature, leachate recirculation strategies, and analytical monitoring of the leachate.

2. Material and methods

The biogas plant is located on a rice farm in the Pavia region of northern Italy and start-up was initiated in October 2010. An overall scheme of the plant including the digesters, gas collection system, biogas engine, and the leachate recirculation system are shown in Fig. 1. These components and the typical operational settings of the plant are described below.

2.1. Anaerobic digester cells

The farm-scale digester consists of two anaerobic cells with a total storage capacity of approximately 13,000 m³, which equates to approximately 1825 tons of rice straw. The digester cells are insulated with a 1-mm PVC-based liner on the top, a 3-mm polyethylene liner on the bottom, and an earthen berm and hydraulic seal around the perimeter. The footprint of each cell, including the earthen berm and hydraulic ditch, is 58.5 m long by 45.5 m wide. The surface area dedicated to the storage of rice straw is 46.5 m by 35.5 m for each cell, and the initial maximum height was 5 m for cell 1 and 4 m for cell 2.

The entire digester is designed as a batch reactor that is ideally loaded with rice straw once a year during the harvest season.

During the initial loading event, 3050 bales (1098 tons) of straw were added to cell 1 and 2020 bales (727 tons) of straw were added to cell 2. The rice straw had a TS concentration of 84.3% during the initial loading event. This quantity of rice straw was harvested during one season from a 365-ha (902-acre) rice farm in northern Italy. The digester was initially inoculated with a total of 285 tons (4.9%TS) of piggery wastewater, and approximately 1300 tons of water were added over time during the first year.

The first digestion cycle was initiated in October 2010 and completed in December 2011 and only cell 2 was active during this monitoring period. Therefore, the results and calculations reported herein are based only on the rice straw digested in the active cell over a 422-day digestion period. The overall weight ratio (in tons) of straw to wastewater in the active cell was 2.55 to 1, which equates to a straw (dry wt.) to wastewater (wet wt.) ratio of 2.15 to 1. The overall TS concentration of the entire cell after the addition of water and wastewater was 46%. However, the moisture content is stratified over the vertical profile of the digester, with the bottom third completely saturated and the top two-thirds only partially saturated. Assuming only 30% of the moisture is contained in the top two-thirds where the leachate flows through a repeated pathway, the estimated TS concentration of the bottom third of the digester is 23% and most of the gas production is presumably occurring in this zone.

2.2. Gas collection system

Biogas is transferred from the digester cells to the internal combustion engine by a gas collection system including eight 140-mm polyethylene lines (4 from each digester cell) and four 65-mm polyethylene lines (2 from each digester cell) situated on the west end of the digesters. The digesters are normally kept in negative pressure conditions. When enough biogas has accumulated inside the digester cells and the pressure reaches equilibrium (0 mm H₂O) or becomes slightly positive, the biogas is collected via a blower and used to power the engine for energy conversion. During the monitoring period, the negative pressure generally cycled between 0 and 300 mm H₂O in order to maximize the engine run time while being careful not to cause a breach in the hydraulic seal around the perimeter of the digesters. The primary blower has a variable speed setting with a maximum flow rate of 211.5 m³/h, and under normal operating conditions it is set at 50%. A secondary blower with a maximum flow rate of 171.6 m³/h is available as a precaution in case the primary blower fails. Upon collection, the biogas passes through an internal gas analyzer that displays the composition of the biogas (i.e. %CH₄, %CO₂, and %O₂), and depending on the quality it is either sent through the combustion process or released through the flare system.

2.3. Biogas engine

A 200-kWe IVECO internal combustion engine that has been modified to run solely on biogas (>37% CH₄) produces mechanical energy that in turn powers a generator for electricity production. According to manufacturer specifications, the electrical efficiency ranges from 28 to 36% depending on the energy setting. Energy is produced at a constant rate and the setting can be modified manually through the programmable logic control (PLC). The operational range is generally from 100 kWe (minimum) to 220 kWe (maximum). For optimum heat recovery, however, the minimum setting is used to extend the engine run time and maximize the heat transfer opportunity. The PLC records the cumulative electrical energy production (kWh) on a constant basis during the operation of the engine. Electricity is generated by a three-phase, 400-V Stamford generator and then transformed to

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