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Batch and continuous biogas production arising from feed varying in rice straw volumes following pre-treatment with extrusion

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HIGHLIGHTS

- About 700 million tons of rice straw are produced in the world every year.
- Anaerobic digestion may offer a good alternative approach to appraise rice straw.
- Low rice straw content can equilibrate the C:N ratio of the diet for AD plants.
- Extrusion improved rice straw degradation, with a positive energy balance.
- High rice straw amount makes extrusion not energetically advantageous.

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ABSTRACT

This paper studies the synergistic effects on biogas production obtained when different feedstocks are co-digested with varying proportions of rice straw and explores their behavior at the laboratory scale in continuously stirred digesters. Evaluative measures included methane production, volatile solids degradation, ash accumulation, and extrusion effectiveness. The effect of extrusion on the production of energy was also investigated. Results indicated that continuous stirred digesters fed with substrates composed of 10% or 30% of ensiled rice straw (on total FM) produced 146.1 and 140.0 l_N CH_4 kg DM^{-1} day^{-1}, respectively. When extrusion was employed, organic matter degradation was promoted and methane production was significantly raised—by as much as 16%. For the feeds containing 10% rice straw, the increase in obtained energy was higher than the energy needed for the extrusion, but the energy balance was close to zero when the percentage of rice straw was the 30% of the feed.

1. Introduction

One potential solution to the food—feed—fuel debate is to use agricultural residues, as opposed to energy crops in anaerobic digestion plants. Among the various residue alternatives, rice straw is one of the most abundant and renewable energy sources in the world. Globally, 2012 production was about 720 million tons, of which 4 million was derived from Europe (Food and United Nations, 2014). Italy is the largest producer of rice in Europe and represents 40% of the continental crop production. Concentrated in northwestern Italy, more than 1.5 million tons of rice are harvested annually from a surface area of 246,500 ha (Food and United Nations, 2014). The dry weight ratio of rice straw to rice grains with chaff (between 0.8 and 1.2 (Zhang et al., 2012)) makes it possible to estimate that the rice crop of northwestern Italy alone produces 1.2–1.8 million tons of rice straw annually that require management.

Soil incorporation often fails as the optimal way to manage rice straw residue. Indeed, available research suggests that the practice can reduce crop yields by increasing foliar disease and degrading soil conditions (Zhang and Zhang, 1999). Moreover, not all soil conditions permit effective rice straw degradation, a process critical to preservation of ideal organic matter conversion for good soil fertility (Devèvre and Horwáth, 2000). In adverse pedo-climatic conditions in which organic matter degradation is slowed, some fermentative processes and toxic substance productions may compromise rice yields. For all these reasons, farmers often dispose of rice straw improperly, which can indirectly lead to widespread environmental concerns. Open-field burning is one such disposal method; however, the practice is now avoided in several Italian areas because of its polluting effects. Consequently, rice straw field

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removal often emerges as the best alternative (Bird et al., 2002; Hill et al., 2006).

One promising alternative to rice straw disposal problems in concentrated rice production regions is enhanced anaerobic digestion of the biomass. In fact, the energy content of rice straw (6533 kJ kg^{-1}) warrants consideration of this residue as a renewable resource for energy generation (Zhang and Zhang, 1999). Several rice straw compositional constraints must first be overcome to make its digestion feasible: low available structural carbohydrates (leads to an inadequate supply of net energy supply); silicified surface layer, lignin, and associated phenolics; intrinsic cell wall carbohydrate properties, such as crystallinity and esterified group substitution on a xylan backbone (Taherzadeh and Karimi, 2008). To mitigate the limited digestibility that each of these impediments presents in anaerobic digestion, the residue must be well managed with a pretreatment to reduce particle size and enhance degradability.

In general, rice straw is not considered a high methane-producing biomass due to its high ash content (15–20%) and the low digestibility of its fibers. Previous studies have measured rice straw methane production in a range between 110 and 180 l kg^{-1} of dry matter (Chen et al., 2014; Menardo et al., 2012); however, these analyses were limited to dry rice straw produced by the most common method of residue conservation. In fact, rice straw that is to be used as anaerobic digestion plant (ADP) feedstock is preferably ensiled to retain high moisture content while reducing biomass lignification (Ghasemi et al., 2013). Moreover, ensiled rice straw also limits ADP biogas outlet problems associated with crust formation from floating biomass. Finally, the high ash content and low digestibility of rice straw also causes the dry matter inside the digester to increase, which can consequently stress the mixing system and lead to higher energy consumption. To mitigate rice straw flotsam and ease digestate mixing—while simultaneously increasing rice straw digestibility and methane yield—pretreatment is necessary. Mechanical pre-treatments are not only practical at the individual farm scale, but they have demonstrated results at reducing particle size and improving methane production of ligno-cellulosic biomasses (Hjorth et al., 2011; Chen et al., 2014). Among the various mechanical options, extrusion pre-treatment works by shearing, heating, and disrupting the lignocellulose structure of the biomass to shorten and defibrillate the fibers (Kratky and Jirout, 2011).

This study had two main objectives:

- to investigate the effect of synergies on AD biogas production when different feedstocks are co-digested with varying proportions of rice straw in batch;
- to explore the behavior of increasing rice straw amounts at the laboratory scale in continuously stirred digesters (CSD), in terms of methane production, VS degradation, dry matter, ash accumulation, and the effect of feedstock extrusion.

2. Methods

2.1. Biomass sampling and feed composition

Four different feeds of increasing proportions of rice straw were analyzed for methane production in batch trials. Two of these feeds were selected in a follow-on step, according to their methane potential yield, and analyzed in a laboratory scale CSD.

The four initial feeds were composed of three different feedstocks: rice straw silage (RS), maize silage (MS), and triticale silage (TS). The analyzed feeds contained differing amounts of rice straw, 10% (RS10), 30% (RS30), 50% (RS50), and 70% (RS70). The remaining proportion of each feedstock was constituted of maize silage and triticale silage in a 2.5:1 ratio on a fresh weight basis (Table 1).

Table 1
Composition of the four different feedstocks analyzed for methane potential in batch. The percentage is expressed on wet weight.

Feeds	RS	MS	TS
	[%]		
RS10	10	64	26
RS30	30	50	20
RS50	50	36	14
RS70	70	21	9

Feedstock samples were collected at a farm sited in San Germano Vercellese in northwest Italy (45°27′N lat., 8°26′E long., 161 m a.s.l.). The biomasses were shredded into 1–2 cm particles and then ensiled in large plastic film silos. Core drilled samples of the feedstocks were retrieved three months after storage directly from the inner part of the silos, after which they were placed into vacuum-sealed bags and stored at −18 °C until trials began.

2.2. Extrusion pre-treatment

All three feedstock extrusions were performed at an ADP in San Germano Vercellese using a two counter-rotating screw extruder driven by a 74 kW motor, model MSZB-74E, produced by Lehmann Maschinenbaum GmbH, Pöhl, Germany. The expansion/wearing zone beyond the compression zone of the device consisted of double-spaced counter-twisting screw blades. At the outlet of the extruder, an adjustable plate controls the size of the opening, which can be varied in size to modify biomass compression. The plate was adjusted to 70% of its maximum for this experiment.

A total of 200 kg of each biomass (RS, MS, and TS) was fed into the extruder as a test. The first 100 kg were used to cleanse the extruder of the previous pretreated biomass, while the rest represented pure biomass and was sampled at the outlet. A total of 10 kg of each extruded biomass was collected in plastic (polyethylene) containers and stored at 18 °C until analysis.

2.3. Biochemical methane potential (BMP) test in batch

The BMP tests were conducted according to VDI 4630 (2006), in 2.0 l capacity batch digesters at 40 °C for 60 days with manual stirring at least once per day. The samples and inoculum were weighed in batches at a ratio of 1:2 (organic dry matter (VS) basis). The volume of produced biogas was monitored by means of a Ritter Drum-type Gas volume meter (TG05/5, Ritter Apparatebau GmbH & Co. KG, Bochum, Germany) every 1–2 day, depending on the biogas produced. Simultaneously, the biogas composition (CH_4, CO_2, H_2, O_2, H_2S concentrations) was determined by means of a gas analyzer with infrared sensors (model XAM 7000, Drägerwerk AG & Co. KgaA, Lübeck, Germany).

Each biomass/feed was digested in triplicate; the control sample was represented by inoculum alone. The inoculum used in the batch trials was the mechanically separated liquid fraction of the digestate produced by the biogas plant in San germane Vercellese (45°27′N lat., 8°26′E long.). The plant is usually fed with maize-, triticale-, or ryegrass-silage and ensiled rice straw, so the contained microbial population needed no adaptation for the tested feedstocks. Characteristics of the inoculum included 6.6% DM content, ash at 30.7% of DM, pH = 7.8, and NH_3-N of 0.23% (on fresh matter (FM)).

The biogas volume produced by the inoculum was measured and subtracted from the biogas yield obtained from each sample. The gas production was normalized to 0 °C and 101.3 kPa, and expressed as l_N per kg of VS. The batch headspace volumes allowed