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The Effect of Feeding Frequency and Organic Loading Rate on the Anaerobic Digestion of Chinese Rice Straw

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Abstract

China produces over 200 tonnes of rice straw (RS) a year. This is an underutilized energy source that is often burned in the fields causing pollution and health problems for populations near and far. Anaerobic digestion (AD) can produce methane (CH_4) rich biogas (45-55%) from waste RS as an alternative to burning whilst being affordable.

Five 2L reactors were used to test the effect of feeding frequency (FF) and organic loading rates (OLR) on the anaerobic digestion of rice straw with input rates of between 5 feeds per week and one feed every 3 weeks. Two OLRs were used: 1gVS/L/d (OLR1) for 56 days and 2gVS/L/d (OLR2) for 83 days.

At the lower OLR1, the best average biogas yield was 300ml/L of reactor/d at 50% CH_4 and at OLR2 the best reactor achieved a mean biogas yield of 447ml/L/d at 52%CH_4. The best performing FF at OLR1 was 1/21 day whilst at OLR2 the 5/7 day FF produced the highest volume and quality of biogas.

Results confirm that biogas from rice straw anaerobic digestion could be used with combined heat and power (CHP) technology to potentially produce 0.5-0.8MWh of electricity per day per tonne of rice straw.

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Keywords: Rice Straw; Anaerobic Digestion; Frequency; OLR; China

Nomenclature

AD	Anaerobic Digestion	OLR	Organic Loading Rate (1gVS or 2gVS)
CHP	Combined Heat and Power	RS	Rice Straw
FF	Feeding Frequency	TS (VS)	Total Solids (Volatile Solids)
GHG	Greenhouse Gas	VFA	Volatile Fatty Acids

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1. Introduction

China is the world leader in rice production with ~195million tonnes with an average of 6.5 tonnes of rice hectare in China (closely followed by India with ~148million tonnes)[1]. Around 680 million tonnes of rice were produced in 2009, equating to around 920million tonnes of rice straw (RS) [2].

RS is a fibrous, lignocellulosic biomass with high volatile solids and low bulking density [2, 11] and represents around 62% of total crop residues in China. It tends to be produced in large quantities but as a crop is subject to growth and harvest cycles. It was traditionally used for foodstuff but as mechanization increased it is often burned *in situ*, taken for domestic fuel, or used as fertilizer [3, 4]. Open burning represents 13,359 tonnes of methane (CH_4) and 800 tonnes of nitrous oxide (N_2O) released to the atmosphere each year from India alone [5]. The exposure to soot and smoke causes respiratory issues amongst farmers and local people [6]. Incorporation of RS into the soil is difficult, due the relatively short time between harvest and seed, but can improve crop yield [4]. However, as RS decomposes in anoxic conditions the resultant CH_4 makes up 10-15% of world CH_4 emissions [2, 7, 8]. Developments in emissions targets and the energy value of waste products have increased the interest in harnessing energy from RS [9, 10]. Using RS in an anaerobic digestion (AD) system could be advantageous compared with other bioenergy crops as it does not divert land use from crop production.

Although RS is abundant and has high carbon, the process of digesting the complex lignocellulose structure – the world's most abundant biomass – is extremely difficult [12]. The recalcitrance of RS results in a lower CH_4 potential than other agricultural and bioenergy biomass i.e. CH_4 yield: RS 193-240L/kgTS compared with Rape: 300-350L/kg TS [13, 14]. AD of RS is not an optimized process and pre-treatments are often used to improve its biodegradability [15-17]. This causes a large input of RS to the waste cycle and conventional AD feeding frequency options (little and often) is difficult without a large storage capability. There have been few studies into the effect of extended starvation periods and bouts of plentiful feeding regimes of AD systems. The studies often focus on a narrow time margin such as Bombardiere, Espinosa-Solares [18] at 1-12 feeds/day. There are more studies focused on the OLR an AD system can tolerate but none using just RS as a substrate unless co-digested with something else, for example: RS and pig manure at 3-12kgVS/m^3d [19]. Infrequent FF inputs of RS into an AD system with increasing OLR was investigated for these reasons.

2. Methods

RS was obtained from China (Xiamen University) but no information regarding variety, harvesting or drying techniques was provided. The RS was provided as uncut lengths of straw that were homogenized to the desired size of 425µm. The anaerobic sludge inoculum was stock from within Newcastle University Environmental Engineering department and was acclimatized to RS in the reactors for two HRTs (100 days). The chemical characteristics of the RS and inoculum used are presented in Table 1.

Table 1 RS and inoculum characteristics

Parameter	Unit	RS	Inoculum
TS	%DW	96.1	2.3
VS	%DW	87.3	71.2
Moisture Content	%DW	3.8	97.7
Ash	%DW	12.3	28.8
C	%DW	40.1	54.6
N	%DW	0.66	4.72
C:N	Ratio	60.4	11.6

Five Sartorius reactors of 2.5L capacity were used with 2L of working liquor. Each consisted of a heating jacket set to 37°C, gasbag and stirrer with airtight seal. The RS was mixed with 280ml distilled water and added after 280ml of reactor liquor had been removed (each week).

The daily biogas produced by each test was recorded daily using a 1L or 100ml gas tight syringe (SGE and Samco) The methane content of the biogas was analyzed using a Carlo Erber HRGC 5160 GC-FID fitted with a HP-PLOT Q column at 35°C with hydrogen as the carrier gas and Atlas software. TS, VS, MC, Ash, and VFAs were determined using the standard water and wastewater methods [20]. Total C, N and H were analyzed using Carlo Erba 1108 Elemental Analyser controlled with CE Eager 200 software and other C, N and S were analyzed using Elementar Vario Max CNS.

The first part of the experiment investigated the effect of feeding frequently (FF) using: One reactor fed every five days per week (5/7d), a second once a week (1/7d), and a third fed once every three weeks (1/21d). The reactors were fed the same load of 1gVS/L/d (OLR1) and ran for 56 days before (for the second part of the experiment) they were fed 2gVS/L/d (OLR2) for 83 days. Part 1 FF was maintained.

3. Results

At OLR1 the difference in biogas yield between the three feeding frequencies was insignificant with 5/7d the most at 300.9ml/gVS/d. The 1/21d FF produced a significantly higher methane percentage (50.3%) than the 5/7d FF at 40.2%CH_4 ($p=0.000$) but not versus 1/14d FF. The 1/21d FF also produced the highest mean volume of methane with 141.5mlCH_4/gVS/d with a $p=0.000$.

At OLR2 the 1/21d FF was immediately overwhelmed and the 1/14d FF approximately halfway through the experiment therefore the 5/7s FF produced a significantly higher mean biogas at 223.9ml/gVS/d. This was less than at OLR1 but at a higher methane percentage (52.1%) with less variation. This resulted in the 5/7d FF OLR2 yielding the highest methane at 125.4ml.gVS/d at $p=0.000$.

Comparing the biogas and methane yields as a function of OLR showed no significant difference except for where reactors failed i.e. 5/7d FF yields were almost the same at OLR1 and OLR2. The highest performing condition across the experiment was the 1/21d at OLR1 with 141.5mlCH_4/gVS as significantly higher than 5/7d at OLR1 or OLR2 (119.8mlCH_4/gVS and $p=0.005$; 125.4mlCH_4/gVS and $p=0.015$ respectively). Doubling the OLR does not result in a doubling of methane but could likely cause solids build up at a faster rate within the reactor.

However, when comparing the biogas and methane yields per litre of reactor there were significant differences. The 5/7d FF at OLR2 produced the highest biogas, methane percentage of all reactors with lower variation and a methane yield of 250.8mlCH_4/L/d, approximately 45% more than the next highest of 1/21d FF at OLR1 that produced 141.5mlCH_4/L/d. These methane yields and percentages were similar to others in the literature [15, 21, 22] and are shown with biogas in Table 2.

Table 2 Biogas and methane yields with methane percentage for each condition per litre of reactor

OLR	FF	mlBiogas/L/d	mlCH_4/gVS/d	mlCH_4/L/d	%CH_4
1gVS/L/d	5/7d	300.9 ±8.2	As right	119.8 ±4.6	40.2 ±1.3
	1/14d	294.9 ±10.0		133.8 ±6.0	45.4 ±1.4
	1/21d	284.9 ±12.2		141.5 ±6.0	50.3 ±1.2
2gVS/L/d	5/7d	477.9 ±10.1	125.4 ±4.4	250.8 ±8.7	52.1 ±1.4
	1/14d	278.8 ±20.1	63.5 ±5.5	126.9 ±11.0	38.7 ±2.3
	1/21d	84 ±16.7	7.9 ±1.2	15.4 ±2.4	21.7 ±1.4

The differences between methane percentage and yield performance at each OLR are compared in Figure 1 (OLR1 as red circles and OLR2 as blue squares) showing the superior methane production of 5/7d FF at OLR2 versus all other reactor conditions.

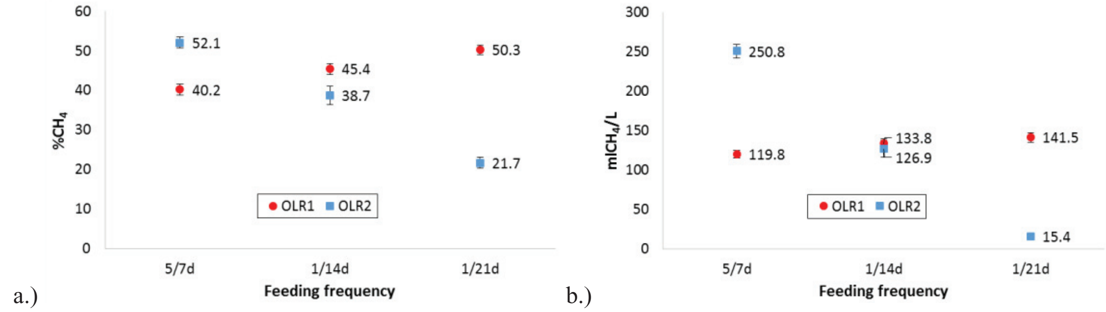

Figure 1 (a) Mean methane production and %CH_4 at 1gVS/L; (b) Mean methane production and %CH_4 at 2gVS/L

4. Energy potential

If a CHP plant were to be built and operated using just biogas from RSAD at the best feed frequency and OLR configurations from these two experiments the possible electricity returns are shown below based on a scale-up from 1-2gVS/L to 1 and 2 tonnes of VS per 1000m^3 AD reactor.

The 1/21d FF is used in this example as the higher percentage of methane provides a similar level of potential electricity to 5/7d but from a higher gas purity.

Average 284mlBiogas/LofReactor/d/1gVS added,

Scaled to m^3Biogas/1000$m^3$of reactor/1tRSVS at 50%CH_4 = 142m^3CH_4/1000m^3/d

1m^3CH_4 = 36MJ and 1kWh = 3.6MJ. So, 142m^3CH_4 = 1420kWh = 1.42MWh

Converted to electricity at an average of 35% = 0.5MWh/1000m^3/d

This 1/21d FF at OLR1 method could produce enough electricity to power 122 average Chinese households each day with just 1tRSVS/1000m^3/d (1.14t RS) (average household use is 1.5MWh/y according to [23]).

At OLR2 the 5/7d FF was the best performing condition so is used in the following potential electricity calculation.

Average ~450mlBiogas/ LofReactor/2gVS added,

Scaled to m^3Biogas/1000$m^3$of reactor/2tRSVS at 52%CH_4 = 234m^3CH_4/1000m^3/d

1m^3CH_4 = 36MJ and 1kWh = 3.6MJ. So, 234m^3CH_4 = 2340kWh = 2.34MWh

Converted to electricity at an average of 35% = 0.82MWh/1000m^3/d

This 5/7d FF at OLR2 method could produce enough electricity to power 200 average Chinese households each day with just 2tRSVS/1000m^3/d (2.28t RS) or 100 households with 1tRSVS/d.

If RSAD with CHP generation were rolled out and utilized even 10% of the ~920Mtonnes of RS produced each year there is potential to generate 75MWh of electricity per day.

5. Conclusion

The performance of the different feeding frequencies became a function of the OLR. Maintaining an OLR of 1gVS/L allowed the AD system to be fed infrequently at 1/21d and still produce the highest yield and the best quality biogas. Increasing the OLR to 2gVS/L reversed the trend with the 5/7d FF producing significantly more CH_4/L of reactor.

The higher OLR of 2gVS/L enabled a larger volume of waste RS to be digested and reduce the potential storage requirements whilst providing higher energy potential. It is presumed that the solid residuals in the reactor tanks would increase more quickly at this higher load but could be removed and used as a soil improver.

Results indicate that an AD reactor fed infrequently with large batches of feed could produce enough methane to generate useful amounts of electricity through CHP and a reactor at OLR2 will produce more than 50% more methane (of one at OLR1) but would require daily feeding. By utilizing just 10% of the RS produced in China there is significant electricity generation and biogas potential that could also be used at a smaller scale for lighting, cooking fuel and vehicles, requiring less infrastructure.

The data would suggest that there is an operator choice when anaerobically digesting rice straw. There is scope for infrequent feeding and low loading (1/21d feed at 1gVS/L/d) or frequent feeding at higher loading (5/7d feed at 2gVS/L/d). It also suggests that anaerobic digestion of rice straw is feasible without pre-treatment or co-digestion, though these may reduce reactor size and improve yield but would complicate operations. There is also enough rice straw produced in China to generate substantial amounts of electricity if this technology could be scaled up.

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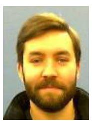

Biography

Andrew Zealand is a PhD student in the Environmental Engineering department at Newcastle University specialising in the anaerobic digestion of rice straw with a particular interest in developing a method that is reliable and requires minimum input from an operator.