# Performance of a Novel Downward Plug-Flow Anaerobic Digester for Methane Production from Chopped Straw

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In China, there is an urgent need for an efficient anaerobic digester to sustainably treat rice straw. In this study, a downward plug-flow anaerobic digester (DPAD) was designed in which the total working core is separated into three sections: an upper liquid zone, a lower liquid zone, and a solid-state bed (SSB) in the middle. A solid/liquid separation mechanism was designed to recirculate liquor and the discharged solid residue after complete digestion. The 70-L DPAD was run indoors for 100 d, time in which chopped rice straw (30 to 50 mm in length) was fed every 20 d. The digestion performance and biogas production were analysed to assess the feasibility for practice application. The results showed that the DPAD can control scum formation and offers a methane yield of 162.60 L/kg volatile solids, 21.1% higher than that of the control test. It was also found that straw was continuously and efficiently digested by the DPAD in 3 experimental stages. Methane production rates increased by 76.30%, 57.37%, and 13.33% on the second day compared to the first day, respectively, and then, all decreased as the substrate was gradually exhausted. Based on the results, it is clear that the DPAD is a promising solution for chopped straw digestion.

*Keywords: Downward plug-flow digester; Methane; Anaerobic digestion; Rice straw; Solid/liquid; Separation*

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## INTRODUCTION

Approximately 211 million tons of rice straw, a by-product of the most important food in China, are produced annually. Most of the rice straw is tilled back into the soil or disposed of by open-field burning, causing widespread environmental concerns (Mussoline *et al.* 2013). Rice straw is a rich source of fermentable sugars in the form of both soft carbohydrates and lignocellulose (Park *et al.* 2011). It can be converted into renewable energy sources such as ethanol, butanol, and methane (Svensson *et al.* 2006; Amiri *et al.* 2014). Anaerobic digestion is considered one of the most environmentally friendly processes for converting straw into methane, requiring much less energy than comparable thermochemical processes. Further, anaerobic digestion can accommodate either wet or dry feedstock economically and across a range of scales (Chynoweth *et al.* 2001).

Considering the above advantages, significant effort is aimed at developing full-scale biogas plants utilizing rice straw in China. Unfortunately, an efficient method for wide application has not yet been developed due to the low biogas yield, high energy input, and blockages in the reactor. This is mostly because rice straw has relatively high lignin content (10 to 15% of its dry weight) and the ligno-carbohydrate complexes are strongly bonded together and less prone to degradation. This makes dissolution difficult, decreases flowability, and causes straw accumulation (Shen *et al.* 2011; Mussoline *et al.* 2013). Furthermore, the characteristic floating of rice straw accelerates scum formation during the entire anaerobic digestion process. The floating layer of straw on the liquid surface cannot be completely digested, and the scum inhibits methane release (Jagadabhi *et al.* 2008). Currently, two methods are considered potential solutions to the above problems: one is to use rice straw after reducing its size *via* mechanical action to adapt to existing digesters, and the other is to develop a novel digester to improve the efficiency of anaerobic digestion and solve the mentioned operational problems.

Although milling, crushing, and extrusion can rupture the cell wall and make the organic matter of straw more susceptible to microorganism decomposition, a large amount of energy is required (Hideno *et al.* 2009; Chen *et al.* 2014). It is not a practical or cost-effective technology for farm-scale commercial application in China, considering the limited investment capabilities of farmers and the poor economic benefit it would provide them with (Browne *et al.* 2013). Fortunately, China will have mechanized most of its rice production by 2020, at which time straw can be directly cut into pieces 30 to 50 mm in length. Under such circumstances, the direct digestion of chopped straw would dramatically improve the economic benefits of anaerobic digestion. Recently, a few new digesters have been designed to digest chopped straw. Lehtomaeki *et al.* (2008) designed a batch leach bed reactor. However, it is not a mature solid-state reactor due to huge fluctuations in biogas production and methane content. Mumme *et al.* (2010) designed an upflow anaerobic solid-state reactor system, composed of three reactors, for chopped rice straw digestion. Some of the weaknesses in their design include difficult organic loading, impossible natural withdrawal of the solid residue, and complexity that seriously restricts its application on a large scale. Developing a new digester that can efficiently digest chopped rice straw and continuously produce methane will help China to achieve efficient conversion of rice straw to biogas (Silvestre *et al.* 2013).

With emphasis on the weaknesses of current digesters and the availability of large amounts of chopped rice straw, the aim of the present study was to develop a novel downward plug-flow anaerobic digester (DPAD), which can convert chopped straw to methane with minimum mechanical pretreatment efficiently. Furthermore, the digestion characteristics of chopped rice straw digested in the DPAD, including the running performance, methane production yield, methane content, and utilization efficiency of the rice straw, were investigated thoroughly in order to evaluate the feasibility of the DPAD in rural areas of developing countries.

## EXPERIMENTAL

### Materials

*Feedstock and inoculum*

The inoculum used in this study was obtained from a mesophilic anaerobic digester near Chengdu, China. Rice straw with a size of 1 to 3 mm was used for digestion on days 1 to 20, and straw with a size of 30 to 50 mm was used for days 21 to 100. The main characteristics of the rice straw and the inoculum are shown in Table 1.

**Table 1.** Characteristics of Rice Straw and Inoculum

| Parameters | Rice straw | Inoculum |
|---|---|---|
| Total solids (%)* | 89.50 | 10.84 |
| Volatile solids (%)* | 65.66 | 52.34 |
| Total carbon (%)* | 37.91 | 2.31 |
| Total nitrogen (%)* | 0.88 | 0.81 |
| Carbon to nitrogen ratio (C/N)* | 43.08 | 2.85 |
| pH | ND | 6.85 |
| *Based on the wet weight; ND, not determined; Volatile solids is the VS% of the TS% | | |

The raw straw was pretreated in a composting aeration process for 10 d. During the composting period, the temperature rose and soluble compounds were extracted from the straw, thereby increasing the hydrolysis efficiency and digestibility (Dresboll and Magid 2006). Meanwhile, the bulk density of the 30 to 50 mm-sized straw following pretreatment was 88.43 kg/m$^3$, over twice than that of the raw straw (38.21 kg/m$^3$). Thus, the pretreatment process minimizes the digester volume required, as measured by the equivalent volatile solids (VS) input, and is beneficial to the entire application (Li *et al.* 2014).

## Methods

*DPAD design*

As Fig. 1 shows, the working zone of the DPAD is separated into three sections: a lower liquid zone, an upper liquid zone, and the solid-state bed (SSB) in the middle. The SSB is composed of two kinds of sieves. The upper sieve serves as a three-phase separator and keeps the SSB below the liquid surface. The lower sieve serves to separate solids and liquids in the digestate. The gravity-driver, which is made of steel, is used to prevent the new particle organic material (POM) from flowing out through the feed pipe, and to maintain the entire SSB below the liquid surface throughout the digestion. The connecting pipe, at the highest point above the liquid surface at all times, maintains a pressure difference between the lower liquid zone and the upper liquid zone to facilitate liquid permeation. Moreover, the connecting pipe also allows for the release of biogas produced in the lower part of the SSB and the lower liquid zone. The sludge outlet for solid residue is located at the lowest point of the lower sieve.

A plastic laboratory-scale DPAD made of transparent acrylic was constructed with a total working volume of 70 L and a gravity-driver with a total weight of 0.65 kg. The upper sieve was created by nesting 15 funnel-shaped rings to form a cone with 2-mm slots. The lower sieve was created by nesting 30 ellipses to form an inclined discharge plate with 2-mm slots. The upper liquid zone capacity is approximately 10 L; that of the SSB is 50 L and that of the lower liquid zone is 10 L.

New POM is added manually through a vertical feed pipe ending at the top of the upper sieve, and effluent liquid and tap water from the buffer tank are added to the DPAD through the liquid inlet to keep the surface of the liquid in the digester above the highest point of the upper sieve. This is done to maintain anaerobic conditions. Solids are digested in the SSB, whereas liquids are digested in the upper and lower liquid zones. After anaerobic digestion, the digestate is separated by opening the liquid outlet valve, at which point effluent liquid is discharged into the buffer tank for temporary storage. When the lower liquid zone has emptied completely, sludge (solid residue) is discharged either automatically or manually by opening the solid outlet valve. After new POM is fed into the DPAD, the liquid in the buffer tank is transported to the upper zone by a recirculation pump. By the recirculating, the liquid (or leachate) transfers metabolites and anaerobic inoculum back to the top of the SSB (Lehtomaeki *et al.* 2008). Moreover, as the liquid permeates throughout the SSB, the acids content in the SSB is likely to decrease, and the acids can instead be converted to methane in the lower liquid zone.

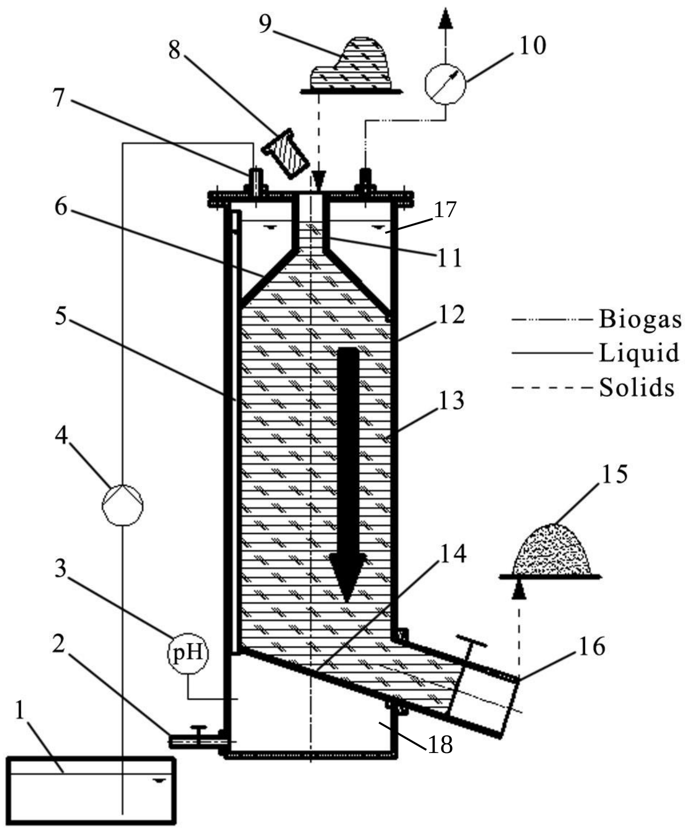


**Fig. 1.** Schematic diagram of the DPAD. 1: Buffer tank (temporary storage), 2: Liquid outlet, 3: pH sensor, 4: Recirculated pump (liquid recirculating and tap water adding), 5: Connecting pipe (facilitating liquid permeation and biogas releasing), 6: Upper sieve (three-phase separator), 7: Liquid inlet, 8: Gravity-driver (maintain the entire SSB below the liquid surface), 9: POM (new organic material), 10: Gas meter, 11: Feed pipe, 12: DPAD, 13: SSB (solid-state bed), 14: Lower sieve (solid/liquid separation), 15: Sludge (solid residue), 16: Sludge outlet, 17: Upper liquid zone, 18: Lower liquid zone

The DPAD system was operated continuously, indoors, for 100 d, in five consecutive stages. As most of the biogas plants in China are operated at ambient temperature without temperature raising measures, the DPAD was designed without a heating facility in order to investigate the adaptability of the process to temperature fluctuations. Stages I and II were used to investigate the biochemical methane potential (BMP). Stages III, IV, and V were used to investigate the biogas production inside the DPAD.

In stage I (days 1 to 20), the DPAD was loaded with a mixture of rice straw and inoculum at a feedstock-to-inoculum ratio of 2:1 (based on TS) to obtain a TS content of 8% (70 L), which is in accordance with the privious researchs in authers' lab; the intial organic loading rate (OLR) was 2.45 g VS/(L·d). The inoculum and straw sized 1 to 3 mm yielded a C:N ratio of 29:1, suitable for anaerobic digestion. In the four following stages, 12.5 L of pretreated straw (size, 30 to 50 mm; pH, 5.51 to 5.96; and TS content, 8%); the OLR was 0.64 g VS /(L·d). The solid retention time for the experiment was 100 d. The volume of sluge taken out from the DPAD equaled to the volume of the feeding.

Lab batch digestion tests were used to contrast stages I and II (days 1 to 40) and were carried out in triplicate at 30 °C for 40 d in a water bath according to the method described by Wang *et al.* (2011). Each batch reactor had 1-L capacity and contained 500 mL of substrate. The same inoculum and rice straw with a size of 1 to 3 mm were used for batch tests. The feedstock-to-inoculum ratio was 2:1 (based on TS), and TS content was 8%.

*Analytical methods*

The feedstock and digestate were sampled for analysis during anaerobic digestion. The TS and VS were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA 1999). Liquid from the upper liquid zone was collected through the liquid inlet with a pipette. After each discharge, sludge and liquid from the lower liquid zone were collected to immediately measure TS.

The total carbon and total nitrogen contents were determined according to the method described by Wang *et al.* (2011). The caloric value was determined by measuring the heat output of 0.5 g of dried biomass using a C2000 analyser (IKA, Germany). Digested rice straw was also analyzed with a scanning electron microscope (JSM-7500F, JEOL; Japan) operating at an accelerating voltage of 5 kV.

During the DPAD digestion, biogas production was measured with an LML-1 multi-chamber rotor gas flow meter (Changchun, China), the daily ambient temperature was determined with an HR-7000 from Yadu (Shanghai, China) with a sensor placed on the DPAD surface every 2 h, and the pH was monitored near the liquid outlet with a PHS-3C+ pH meter (Fangzhou, China). During the batch digestion, biogas production was measured by the displacement of water. Standard mercury thermometers were used to measure the water temperature in the water bath (HH-SB, Kewei, Beijing, China). Both of the volumes of biogas were normalised to the standard conditions (15 °C, 101.325 K), and the methane ($CH_4$) contents in the biogas were analysed with a gas analyser (Gasboard-3200, Cubic, Wuhan, China).

## RESULTS AND DISCUSSION

### Running Performance

During the test, the characteristic ascent of the SSB was sustained without interruption from the first day of digestion. Because of the upper sieve and gravity-driver, no scum was observed on the top of the upper liquid zone. The TS contents of the upper liquid zone were 0.68%, 0.69%, 0.67%, and 0.68% before the feedings on days 20, 40, 60, and 80, respectively. No remarkable differences were observed among the TS content values, indicating that the upper sieve efficiently prevented the straw in the SSB from floating upwards. The DPAD controlled scum formation and maintained sufficient anaerobic conditions within the SSB (Jagadabhi *et al*. 2008).

Figure 2 is a photomicrograph of the rice straw sample. The image shows that the rough surface of the raw straw caused poor fluidity due to internal friction (Fig. 2a). As digestion continued, polysaccharides were attacked by microorganisms (Fig. 2b), and the structure of the straw became more loose (Fig. 2c), preventing the straw from agglomerating. As such, the digestate flowed more easily. This agrees with the assumption that sludge in the bottom part of the SSB was a non-Newtonian fluid with some flowability, which was beneficial to discharge; nevertheless, it was more difficult to discharge sludge with a higher dynamic viscosity (Spinosa and Lotito 2003).

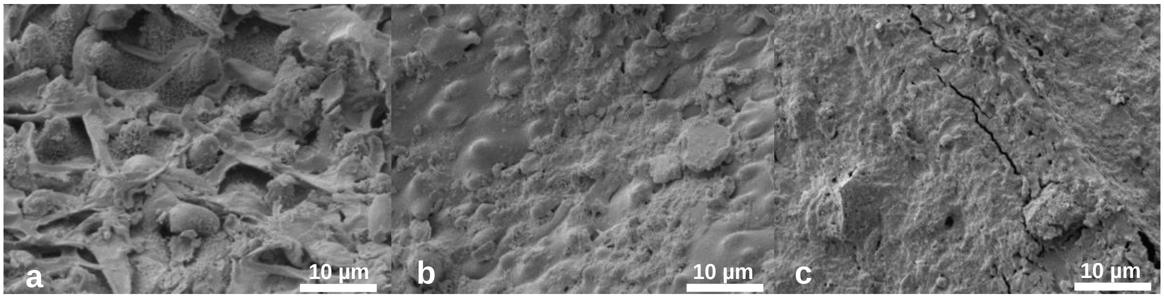


**Fig. 2.** Scanning electron microscopy of rice straw during the digestion in DPAD. (a) Raw straw, (b) fermentation for 20 d, and (c) fermentation for 100 d

As shown in Table 2, no remarkable differences were observed in the TS contents of the sludge at the bottom of the SSB at different discharges, and none were observed in the TS contents of the lower liquid zone. This indicates that the lower sieve efficiently separated the solid from the liquid. As a result, liquid could be discharged automatically. Furthermore, the liquid in the upper liquid zone and most of liquid in the SSB was also discharged out of the DPAD, due to the high permeate flux of the SSB. The solid deposited on the lower sieve on the force of gravity; therefore, the TS contents of the sludge in the bottom of the SSB were much higher. Thus, the dynamic viscosity was used as an indicator as to whether or not the sludge could be discharged automatically. Previous research by the author shows that sludge with a TS value below 9.52% has a relatively low dynamic viscosity, determining with a Model NDJ-1Rotational Viscometer (INESA, China). The dynamic viscosity increased rapidly with an increase in the TS concentration. It was difficult to automatically discharge sludge with a high TS concentration. This result is well-supported by the work of Bjerkholt *et al.* (2005). Manual intervention was needed to discharge the sludge at each discharge, such as artificial digging. As the automatic discharge method was not thoroughly considered in previous studies (Liang *et al.* 2011; Pohl *et al.* 2012), it is suggested that diluting the sludge could alleviate the need for manual discharge. Injection of effluent liquid into the sludge may be a feasible method of dilution.

**Table 2.** Total Solids Content of Digestate

| Parameter | Bottom of the SSB* (%) | Lower Liquid Zone* (%) |
|---|---|---|
| First discharge | 12.77 | 0.67 |
| Second discharge | 10.85 | 0.74 |
| Third discharge | 12.68 | 0.73 |
| Fourth discharge | 11.96 | 0.71 |
| *Based on the wet weight | | |

## Comparison of the Digestion in the Lab Batch Digester and the DPAD

As shown in Fig. 3, the increased methane conversion efficiency in the DPAD was reflected in the cumulative methane yields. Cumulative methane yields after 40 d of digestion were 162.60 (the new POM of stage II was only digested for 20 d) and 134.32 L/kg VS for the DPAD and lab batch digester, respectively. The methane yield from the DPAD was 21.1% higher than batch digestion, indicating its superior performance. Moreover, it was also higher than has been found in most studies with various pretreatment at the temperatures of 22 to 30 °C for 40 day's digestion (Ghosh and Bhattacharyya 1999; Lei *et al.* 2010; Li *et al.* 2010). That meant that the DPAD is an efficient digester.

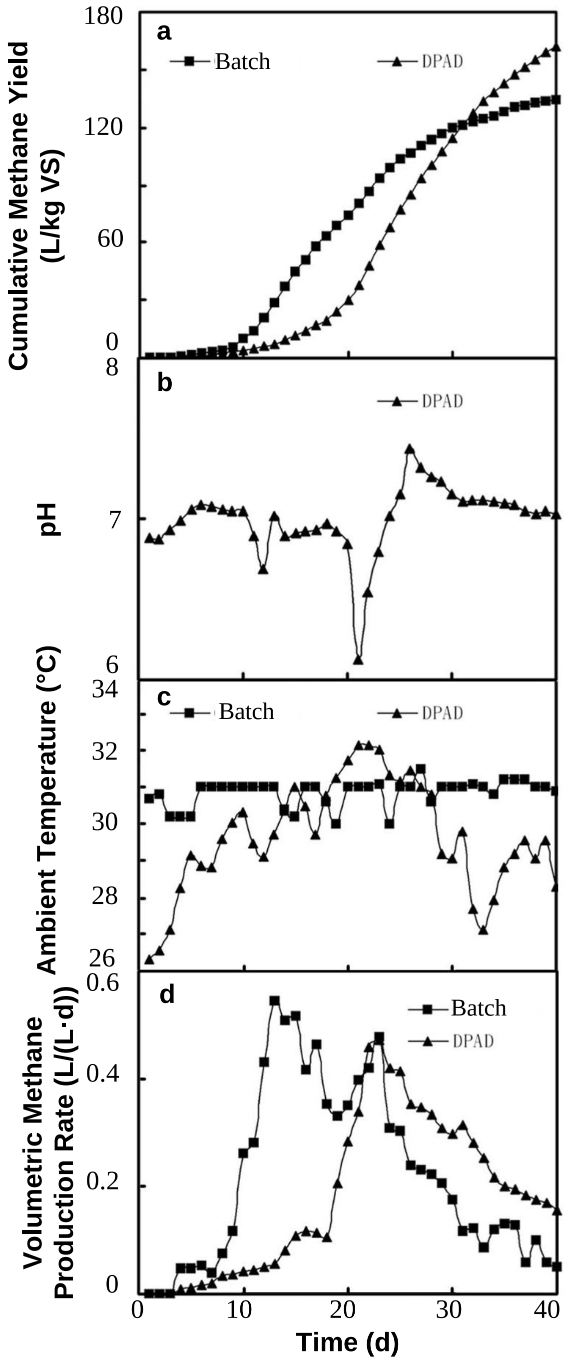


**Fig. 3.** Digestion characteristics of lab batch test and DAPD (stages I and II). (a) Cumulative methane yield, (b) pH, (c) ambient temperature, and (d) volumetric methane production rate

The main reasons for this are as follows: (1) the SSB was kept below the liquid surface with no scum floating; therefore, such a high-moisture environment made it convenient for the microbial community to adhere to and degrade the solid biomass at the top of the SSB; and (2) feeding and recirculation on day 20 improved the distribution of substrates and microorganisms and strengthened the buffering capacity. This was demonstrated by pH variation in the lower liquid zone. During days 1 to 20, the pH was within the neutral range. On day 21, the pH decreased to 6.13 following the second feeding. This probably was caused by the high OLR (at setup, 2.45 g VS/(L·d)), which could result in higher initial production of acids in the SSB during stage I in the process of substrate conversion. Consequently, acids were transferred to the lower liquid zone, and the pH immediately decreased. As digestion progressed, acids were consumed in the lower liquid zone, and the pH quickly rose to approximately 7.0 during stage II.

In stage I, the volumetric methane production rate in the DPAD was lower than that of lab batch digestion. After feeding and recirculation, the volumetric methane production rate in the DPAD increased to 0.47 L/(L·d) on day 23, higher than that of lab batch digestion. Since then, the DPAD was overwhelming in methane production, and the cumulative methane yield of the DPAD increased quickly and exceeded that of the batch test on day 31.

It was also noted that the DPAD was at an ambient temperature ranging from 26.34 to 32.14 °C, which was more varied than in lab batch tests (from 30.2 to 31.5 °C); the average temperature was also lower. It is known that high temperature variability and low temperatures can inhibit methane production. However, the DPAD can offer higher methane production yield under sub-optimal temperature conditions. The DPAD could also utilize feedstock more effectively, due to no scum floating and the good distribution of substrates and microorganisms (Madhukara *et al*. 1997; Mussoline *et al*. 2013).

## Biogas Production of the DAPD

As shown in Fig. 4, the average methane production rates were 13.57, 7.03, and 5.07 L/d for stages III (temperature between 22.72 and 29.50 °C), IV (between 20.10 and 24.74 °C), and V (between 19.38 and 23.23 °C), respectively.

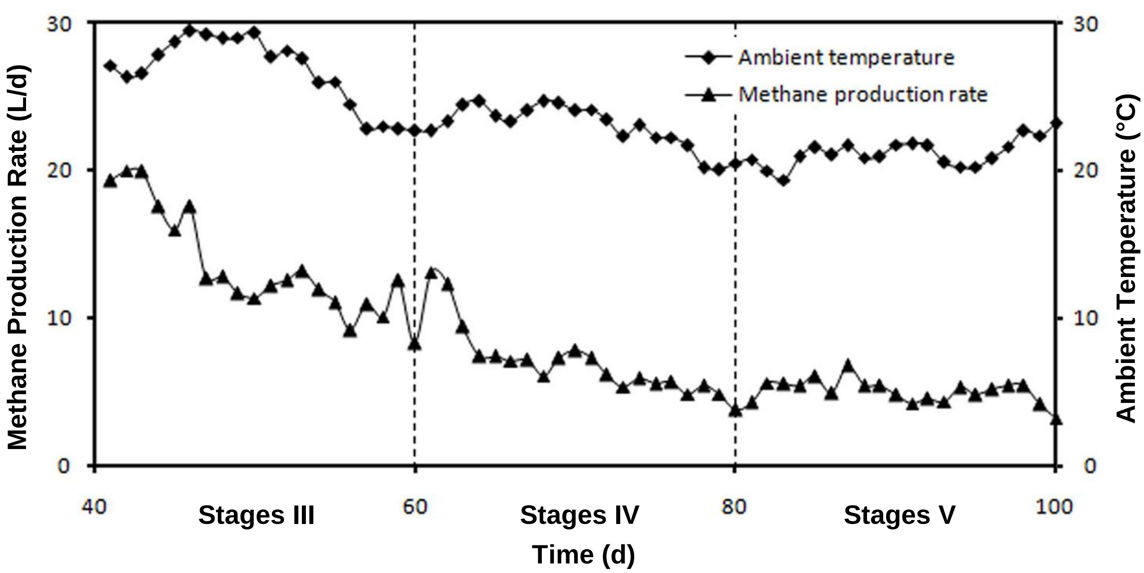


**Fig. 4.** Methane production rate and ambient temperature during stages III, IV, and V

The results in Fig. 4 indicate that the methane production rate was much higher at higher digestion temperatures. This finding is well-supported by previous research (Shi *et al*. 2013).

During each stage, the methane production rate decreased as the substrate was gradually exhausted. It can be assumed that the DPAD could provide stable methanogenic conditions. This is consistent with the pH of the lower liquid zone, as shown in Fig. 5, in which a neutral pH was maintained, indicating a high buffer capacity. Meanwhile, methane production rates were increased by 76.30%, 57.37%, and 13.33% on the second day after each feeding. These results illustrate that the DPAD could rapidly convert biomass into methane. These increases can be attributed to substrate feeding and the vertical movement of the SSB. New POM may have provided more organic matter for anaerobic digestion, and liquid recirculation may have transferred metabolites and anaerobic inoculum back to the upper zone, where they permeated into the POM; all of these are beneficial to methane production. On the other hand, feeding may mix the substrate and allow the release of methane. This is consistent with the conclusions of Shen *et al*. (2013). These observations suggest that the bacterial populations were well-established and that feeding had a significant effect on methane production, as reported by Zhang and Zhang (1999). It also means that the DPAD is more appropriate for continuous methane production than a batch digester (Lehtomaeki *et al*. 2008). However, the methane production rate still exhibited tiny fluctuations, which can be attributed to the degrading and reducing of the organic matter due to the long term feeding period for 20 days. It is suggested that a shorter feeding period would tend to increase the stability of the methane prodution rate. However, further research for the feeding process is still needed.

Figure 5 shows the methane content during stages III, IV, and V (days 41 to 100). The methane content remained between 50.4% and 60.4%. It is assumed that feeding does not obviously affect the methane content in the biogas, so the burning requirements for cooking can be met directly without a break-in period for substrate replacement.

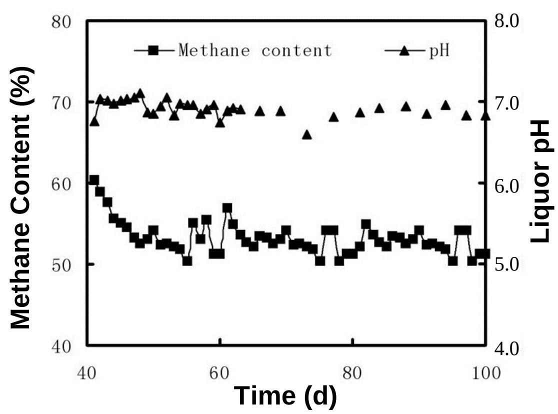


**Fig. 5.** Liquor pH and methane content during stages III, IV, and V

## Sludge Characteristics

After solid-liquid separation, the liquid was recirculated back to the DPAD and the solid disposed. The utilization efficiency of the straw was determined by the remaining methane generation potential of the sludge. Thus, both feeding and sludge were analysed for their VS and caloric values. As shown in Fig. 6, the VS and caloric values both decreased over time. During stage I, the VS reduction of day 1 to 20 was

56.7% of that of day 1 to 100, and the caloric value reduction of day 1 to 20 was 53.6% of that of day 1 to 100. These observations suggest that most of the soluble compounds in solid residuals are degraded during stage I. The degradation led to a slight pH drop during days 10 to 13 (Fig. 3b). After 100 d of digestion, the VS and caloric values of the solid residue, which can be degraded, were very low, indicating that the solid residue was hard to hydrolyse and that the remaining potential methane yield was small. Possible topics for future research include analysis of the efficiency and long term stability, the optimal operational parameters of the DPAD, such as OLR, SRT, and feeding intervals.

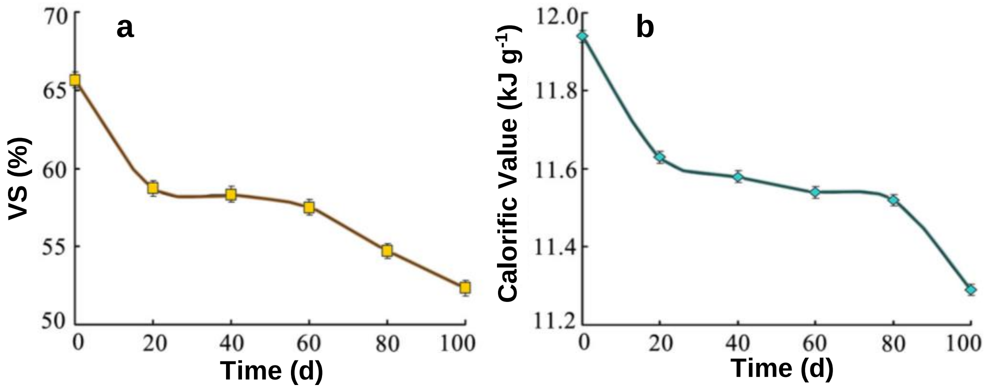


**Fig. 6.** (a) VS content and (b) caloric value of sludge during operation of the DPAD

## CONCLUSIONS

1. The experimental results presented in this study demonstrate that it is technologically feasible to use the developed DPAD system to digest chopped rice straw. The system can continuously and efficiently digest chopped straw (30 to 50 mm in size), and the SSB can be kept below the liquid surface with no scum floating.
2. Cumulative methane yields after 40 d of digestion were 162.60 L/kg VS at ambient temperatures ranging from 26.34 to 32.14 °C.
3. Methane production rates increased by 76.30%, 57.37%, and 13.33% on the second day following the stage III, IV, and V feedings, respectively. This illustrates that the DPAD could provide stable methanogenic conditions and convert rapidly new biomass into methane. The feeding and the vertical movement of the SSB are beneficial to methane production.
4. With proper design, a DPAD could be a low-energy input (no mechanical pretreatment or stirring) and smooth-running system.

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