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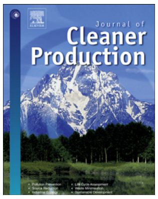

# Anaerobic mono-digestion of pig manure in a leach bed coupled with a methanogenic reactor: Effects of the filter media

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ABSTRACT

This work pioneered the efficient coupling of a leach bed reactor (using a filter medium and no anaerobic sludge) and a continuous stirred-tank reactor (LBR-CSTR) to perform the anaerobic mono-digestion of pig manure. The leachate residue of the pig manure (LR-PM) was dried by a biodrying process. The results revealed that the LBR-CSTR (with ceramsite (C) as the filter medium) showed the best performance (the biogas production was 241.68 ml/g volatile solids (VS), which was 1.24 times higher than that of the control CSTR (CK)), the weight loss of pig manure was the highest (the reduction was 95.83%), and the organic degradation was 86.82% (which was 19.49% higher than that of the CK). The seed germination index (GI) was higher than 50%, and the clogging of the leach bed was overcome. The energy and resource utilizations of pig manure were readily achieved.

## 1. Introduction

Generally, the water content in the excreta of livestock and poultry without bedding is higher than 80%, and the water content is still high after solid and liquid separation. It is essential to adjust the water content to approximately 65% with bulking agents (Bernet and Béline, 2009; Liedl et al., 2006) for compost. Unfortunately, Chinese bulking agents are limited and expensive because the material increases the cost.

Anaerobic digestion technology is regarded as one of the most sustainable technologies due to its low energy consumption, high efficiency and new energy production in the process of treating livestock and poultry wastes (Holm-Nielsen et al., 2009). Traditional wet digestion (total solid content: 12%) mainly results in a large biogas liquid volume and serious secondary pollution. The high nitrogen content, significant ammonia inhibition and blockage of the single-phase reactor cause low biogas production. Recently, more than 60% of new biogas projects in Europe have adopted the high concentration/solid anaerobic digestion technology (Tricase and Lombardi, 2009; Yang et al., 2015), but the difficulty in stirring the solid digestion matter and the difficult mass and heat transfer processes, in addition to the accumulation of acidification, negatively impact the biogas production efficiency.

Leach bed reactor (LBR) technology has overcome the above disadvantages of anaerobic digestion technology (Bayrakdar et al., 2018; Riggio et al., 2017b; Shewani et al., 2018). The leachate is returned to the leach bed to improve the utilization of raw materials through the effect of leachate infiltration on intensifying the heat and mass transfer processes, which is a new kind of anaerobic digestion process for livestock and poultry manure (Myint and Nirmalakhandan, 2009; Riggio et al., 2017a), straw (Lehtomäki, 2006; Tuesorn et al., 2013), and organic living waste (Chen et al., 2007) and other solid-state wastes (Riggio et al., 2017b). The latter suggests wide fields of application and suitable prospects. Degueurce et al. (2016) investigated the performance of batch-mode solid-state anaerobic digestion through several leachate recirculation strategies and achieved a suitable biogas production effect for cattle manure. Cysneiros et al. 2012a,b combined a flow anaerobic sludge bed reactor and an anaerobic biological filter tank, whereby a leach bed was used to investigate which combination of reactors could yield improved biogas and degradation rates. Bayrakdar et al. (2018) used a membrane-integrated LBR for the anaerobic digestion of chicken manure, which was a cost-efficient technology.

Previous studies have focused on the anaerobic co-digestion of

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corn straw with pig manure (Jin et al., 2018), and even though corn can be digested with pig manure to solve the clogging of an LBR, there are exceeding inconveniences in the actual collection and transportation processes (Viskovic et al., 2018). Because pig manure has a fine texture, it clogs the leach bed during mono-digestion. On the one hand, using an inorganic filter medium solves the clogging of the leach bed, and it can be reused at a low cost. On the other hand, the inorganic filter medium can absorb nitrogen, phosphorus and other pollutants. In this study, we chose three kinds of filtration medium materials for a pig manure leach bed to simplify the process without anaerobic sludge, and we directly used biogas slurry inoculation of the pig manure leach bed to promote acid production. Four litres of methane produced by the biogas slurry, which was used as the inoculation fermentation medium (Hussain et al., 2017), was returned to the leach bed, while the leachate flowed into a continuous stirred-tank reactor (CSTR) after 3 h, for 1 cycle per day; the leached pig manure residue was subjected to a biodrying process for further stabilization, and a total solids (TS) content of 4–5% was reached after mixed anaerobic digestion in contrast to that of the control CSTR (CK). The objective of this study was to improve the existing manure cleaning methods by water submersion and develop a new technology for the in situ remediation of pig manure waste with a small amount of biogas slurry to reduce pollution.

## 2. Materials and methods

### 2.1. Substrate and inoculum

Pig manure was collected from the Institute of Animal Husbandry (South China Agricultural University, Guangdong), and the initial properties of the pig manure are shown in Table 1.

The biogas slurry was the filtered supernatant of the anaerobic digestion of piggery wastewater residue, which was used as the inoculum. The pH was 7.22, the chemical oxygen demand (COD) content was 174.08 mg/L, the $NH_3$–N content was 224.68 mg/L, the total nitrogen (TN) content was 558.57 mg/L, and the total phosphorous (TP) content was 43.61 mg/L.

Filter media: 1) Perlite (P) was supplied by the Dow fertilizer factory and had a particle size of 3–5 mm; the main component was pumice pearlite, containing small amounts of transparent feldspar, quartz porphyritic, microcrystalline and various forms of crystallite and cryptocrystalline minerals, amphiboles and other circular arc cracks. There were uneven fractures, and a pearly lustre, weathered oily lustre, and white streaks were observed. After the medium was exposed to light, multi-functional new materials were formed. P was characterized by a low apparent density, low thermal conductivity, suitable chemical stability, wide-application temperature range, low hygroscopic capacity, non-toxicity and absence of taste.

2) Ceramsite (C) (supplied by the Xuanyi ceramic granule factory), with a particle size of 2–3 mm, was round, and the surface was a hard shell. The shell was made of ceramic material, which had the function of water insulation and air retention, providing C with a high strength and suitable chemical and thermal stabilities.

**Table 1**
Initial properties of the pig manure.

| | pH | TS % | VS % | TOC % | TN % | TP % | TK % |
|---|---|---|---|---|---|---|---|
| pig manure | 6.1 | 21.68–27.2 | 75.69–82.3 | 35.88 | 2.09 | 0.9 | 1.12 |

3) Rubber (R) granules (supplied by the WeiJi plastics factory), with a particle size of 2–4 mm, had a moderate elasticity and beautiful appearance, which was in line with national standards; the granules had moderate elasticity, anti-skid properties, suitable permeability, wear resistance, flame retardancy, non-toxicity, non-radioactivity, and anti-ageing properties, as well as a long life span.

Germination seeds: Seeds of cauliflower (49 kinds of oily green seeds) were supplied by the Guangzhou Changhe Seed Co., Ltd.); corn (no. 8 huamei tian) was provided by Guangzhou Huanongda Seed Industry Co., Ltd.; and Chinese cabbage (536 kinds of Chinese fast food) was provided by the Guangzhou Changhe Seed Co., Ltd.

### 2.2. LBR-CSTR equipment

Fig. 1A is a schematic diagram of the test device, while Fig. 1B shows the actual device. The leach bed reactor (using a filter medium and no anaerobic sludge) and a continuous stirred-tank reactor (LBR-CSTR) were made of stainless steel and contained a hot water interlayer to control the reaction temperature. The LBR had a volume of 15 L, and a 210 × 210 mm plate was situated to leave a volume of 1 L at the bottom of the reactor. The CSTR had a capacity of 40 L and an effective volume of 32 L, and the outlet was connected to a wet anticorrosive gas flowmeter (Changchun Alpha Meter Co., Ltd., model lmm-1). The other end of the flowmeter was connected to an aluminium foil gas sampling container (Dalian Haide Technology Co., Ltd., 30 L). The tests were started simultaneously with 3 sets of the same equipment.

Fig. 1C shows the biological drying device of the leachate residue of the pig manure (LR-PM). The air pump was controlled by a time control switch.

### 2.3. Anaerobic mono-digestion

The temperature of anaerobic digestion was 35 ± 1 °C. The experiments were performed via batch digestion.

Three groups of LBR-CSTR digestion devices were started simultaneously with P, C and R as the filter media. Three kinds of filter media, including 1 L P, Cand R, were placed on the filter plate of the percolation bed. Then, 2 L of pig manure (2.4 kg) was placed on the filter medium, and 4 L of biogas slurry was returned to the percolation bed, which was circulated once a day. After the biogas slurry remained in the leach bed for 3 h, the acidogenic leachate was pumped into the CSTR. The mixer was turned on before and after each effluent was returned to the CSTR, stirring occurred for 10 min, and the stirring speed was 60 r/min.

After completion of the batch biogas production, the LR-PM was stabilized with a biodrying device, which was controlled by a time-controlled switch, and air was supplied by intermittent ventilation with a frequency of 20 min/h at a ventilation rate of 12 L/min for 3 d.

### 2.4. Biogas production of the contrast experiment test

To obtain 2.45 kg of pig manure (TS = 27.2%, VS = 82.3%), 15 L of biogas slurry was added to the CSTR, which resulted in a mixture TS content of approximately 4–5%. The control experiment of fully mixed anaerobic fermentation was started, and stirring occurred regularly every day for 10 min, with a stirring speed of 60 r/min. The daily output of biogas was determined, and 5 ml of mixed liquid was collected for analysis.

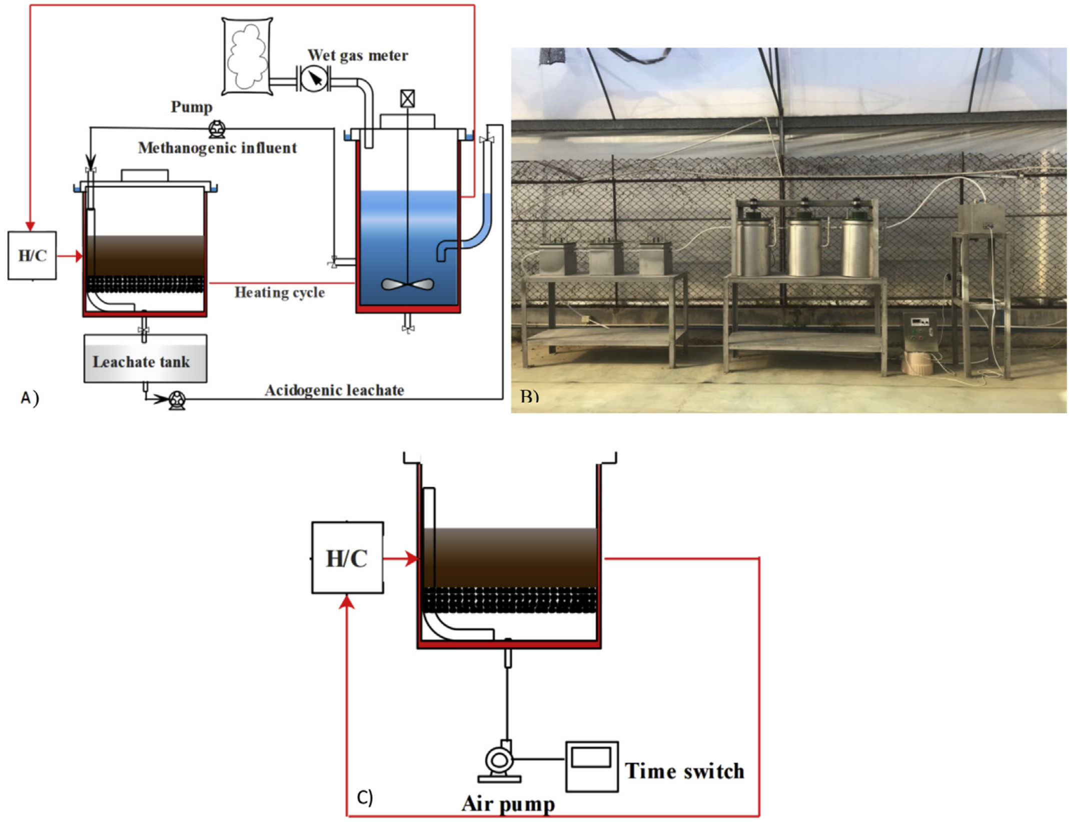

**Fig. 1.** Experimental Leach bed reactor and CSTR A), Experimental Leach bed reactor and CSTR B) and Experimental biodrying reactor C).

### 2.5. Analytical methods

At the start and end of the reaction, the pig manure was weighed by electronic scales, and the TS and VS contents were determined by the oven drying method. Fifteen millilitres of acidogenic leachate and methanogenic influent were collected every day to measure the indicators. A pHs-3c precision pH meter was used for the measurement of the pH. The COD, volatile fatty acid (VFA), $NH_3{-}N$, TN, and TP content measurements and other measurement methods were conducted according to the American Public Health Association (APHA) (2011). The biogas production during digestion was collected by a 30-L aluminium foil air collector, and the methane concentration was measured by a Gaetech Biogas 5000 methane composition analyser.

The product after the biodrying process was ground and screened, and the determination of the organic matter, N, P and K contents followed standard methods (NY 525–2012, Chinese). The pH value of the extract was measured in 100 g/L deionized water at room temperature after 1 h of 200 r/min oscillation leaching, and the electrical conductivity (EC) was measured with a dds-11a conductivity metre; 6 mL of filtered extract was collected, and the seed germination index (GI) was measured (Mediterrani and Marqués, 2002).

The removal rate of VS is calculated according to the following formulas:

$$W_{reduction} = \frac{W_{initial} - W_{final}}{W_{initial}} \cdot 100\%$$

$$TS_{initial} = \frac{TS_{initial} - TS_{final}}{TS_{initial}} \cdot 100\%$$

$$VS_{reduction} = \frac{VS_{initial} - VS_{final}}{VS_{initial}} \cdot 100\%$$

$$GI\,\% = \frac{Number\ of\ germinated\ seeds}{Number\ of\ seeds\ tested} \cdot 100\%$$

where $W_{reduction}$ is the weight reduction of the pig manure, $W_{initial}$ is the initial weight of the pig manure, $W_{final}$ is the final weight of the biologically dried product, $TS_{removal}$ is the removal efficiency of TS of the pig manure, $TS_{initial}$ is the initial TS content of the pig manure, $TS_{final}$ is the final TS content of the biologically dried product, $VS_{removal}$ is the removal efficiency of VS of the pig manure, $VS_{initial}$ is the initial VS content of the pig manure, and $VS_{final}$ is the final VS content of the biologically dried product.

## 3. Results and discussion

### 3.1. Comparison of the filter speeds of the three filter media

When P, C and R were used as filter media in the percolation bed, after the biogas slurry had been soaked in the pig manure for 3 h, 4 L of the leached solution of the pig manure was used for 104 s, 98 s and 85 s. Fig. 2 shows the average filtration rates of the 4 L pig faecal leachates from the three filter media. The average filtration rate of R was higher, followed by C, and the average filtration rate of P was the lowest. The actual filtration test determined that the rubber particle filtration speed was the fastest because the rubber

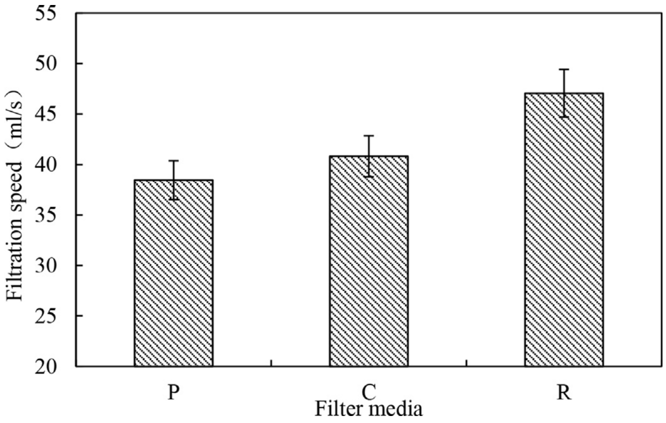

**Fig. 2.** The average filtration speed of three filter media.

material was an elastomer (Nguyen et al., 2014). In the water rinsing process, particles of different sizes on the filter layer would be redistributed, thus increasing the filtration speed and preventing plugging.

## 3.2. The performance in the LBR

### 3.2.1. Effect of the pH and VFA content on the LBR performance

As shown in Fig. 3A and B, the pH values of the methanogenic influent and acidogenic leachate in the three groups of pig manure batches in the LBR-CSTR were between 7.2 and 8.2 without acid accumulation and acid inhibition because the methanogenic influent neutralized the pH of the LBR. The pH values of the P (perlite-based leachate) and C (ceramsite-based leachate) leachates remained at approximately 7.4 from the beginning of the reaction to 8 d and gradually increased after 7 d, while the pH value remained stable at a value of approximately 7.8 after 11 d. These results indicated that after the start of the test, the materials in the LBR were mainly hydrolysed and acidified, and the organic acids that were generated neutralized the pH in a portion of the methanogenic influent. Meanwhile, the flow of acidogenic leachate that is returned to the CSTR from the LBR can adjust the pH of the CSTR. The optimal pH range for methane production is 6.5–7.5 (Chen et al., 2005; The Scientific World Journal, 2017). Therefore, Fig. 3A and B show that the weak alkaline environments of the methanogenic P and R influents may have led to decreased activities of the methanogens. The test results also confirmed that the biogas production volumes of the CSTR-P and CSTR-R were low. Therefore, it could be inferred that LBR-CSTR devices may show a decline in the daily biogas yield at approximately 7 d (Liu et al., 2012).

When the pH is approximately 5.5, propionic acid fermentation occurs (Blanc and Goma, 1987). In this study, the pH values in Fig. 3A and B were both higher than 7. In addition, Fig. 3C shows that the VFAs from the CSTR did not accumulate, so the problem of propionic acid accumulation was avoided in this study. Moreover, our other study data related to this topic have shown that the VFA content in the pig manure leachate in the new process of the LBR-CSTR is relatively high. Studies have shown that the accumulation of acetic acid is beneficial to the activity of methanogenic bacteria (Wang et al., 2009).

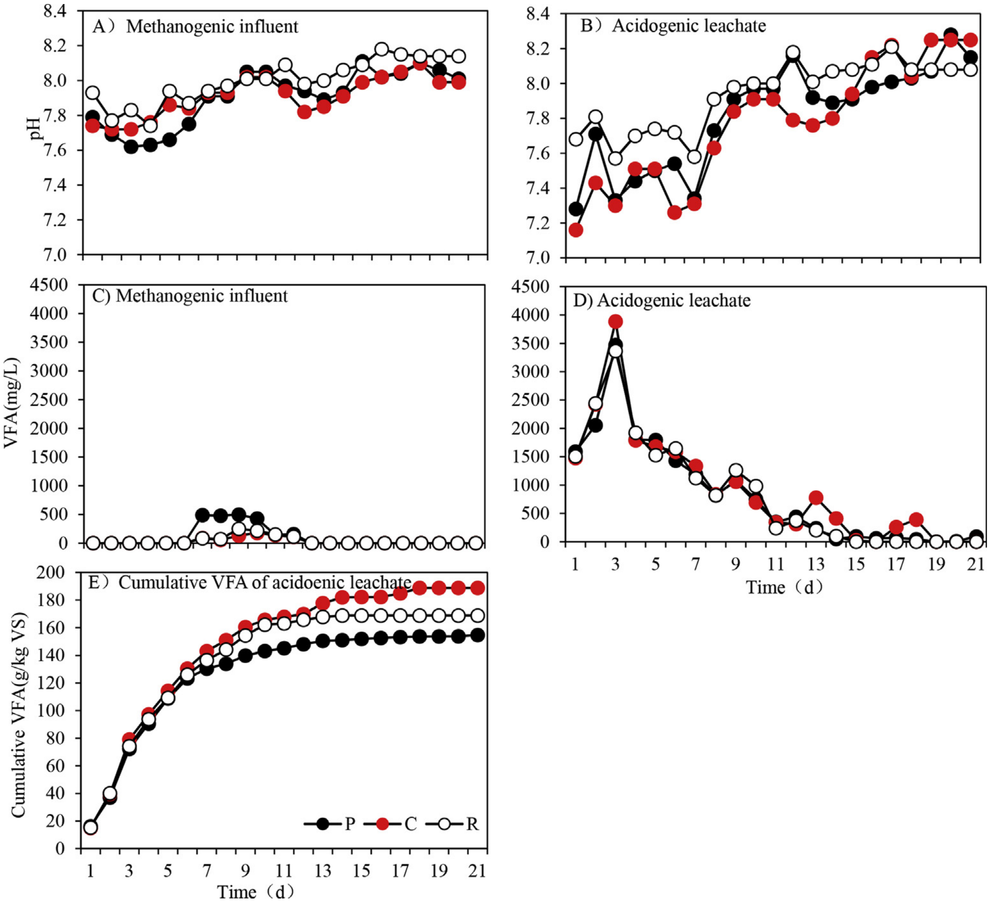

**Fig. 3.** PH variations of methanogenic influent A) and acidogenic leachate B), VFA of methanogenic Reflux C), acidogenic Leachate D) and cumulative acidoenic leachate E).

The pH has an important effect on VFA accumulation and fermentation inhibition. Many researchers believe that unionized VFAs inhibit microorganisms because they penetrate more deeply into the cells than ionic volatile acids, so the pH affects microorganisms by affecting the presence of VFAs (Trisakti et al., 2015; Yu et al., 2011). When the pH is acidic, unionized VFAs dominate. When the pH is neutral or slightly higher, VFAs occur mainly in the form of ions, which are relatively uninhibited. In this test, the pH is slightly higher, so the VFAs are mainly in ionic states. In the anaerobic fermentation process, when the pH is lower than 6.5, volatile acid inhibits the activity of anaerobic fermentation microorganisms (Parawira et al., 2004; Siegert and Banks, 2005), thus accelerating the rate of volatile acid accumulation and further inhibiting the anaerobic fermentation process. When the concentration of volatile acids does not exceed 100,000 mg/L for a long time, the pH of the fermentation broth can be reduced, and it then recovers to the range of pH 6.5–7.8 (Gujer and Zehnder, 1983), which is suitable for methanogens, and the methanogenic activity is not inhibited.

As shown in Fig. 3C, D and E, the concentration of VFAs in the methanogenic influent was almost zero within 6 d after the test. With the acidogenic leachate, the accumulation of low concentrations of acid occurred from the 7th day to the 12th day. The concentration of VFAs in the methanogenic C influent was low. The concentration of VFAs in the leachate reached its peak on the third day of the test, and the concentration of VFAs in the C leachate was higher. Then, the concentration gradually decreased, which was consistent with the change in the acetic acid concentration detected in the experiment. The utilization rates of the methanogenic bacteria for different organic acids were significantly different. The conversion rates of methanogens for the degradation of mixed organic acids in the reactor were ordered as acetic acid>ethyl acetate>butyric acid>propionic acid (Wang et al., 2009). Moreover, it can be observed from Fig. 3C that the VFA utilization rate in the leachate of the LBR by the CSTR was close to 100%, which should also indicate that the pH values of the three reflux groups in Fig. 3 were higher than 7.5.

### 3.2.2. Effect of the $NH_3$–N content on the LBR performance

As shown in Fig. 4, **A** is the change in the $NH_3$–N content in the reflux solution, and **B** is the change in the $NH_3$–N content in the leachate. Hansen et al. (1998) confirmed that the biogas yield rate of pig manure treated in a continuous stirred-tank mixer was significantly lower than the potential biogas yield rate of pig manure, suggesting that the ammonia inhibition effect was stronger. The concentration of $NH_3$–N in the leachate changed substantially, first increasing and then decreasing. The latter was because the protein content in the pig manure caused the ammonia nitrogen concentration to increase, and the ammonia nitrogen concentration tended to remain stable with the reaction and was far lower than the inhibitory ammonia concentration (Kayhanian, 1994; Sung and Liu, 2003). The concentration of $NH_3$–N in the methanogenic influent did not fluctuate significantly. The concentration of $NH_3$–N in the LBR-CSTR (C) was at the minimum level.

### 3.2.3. Effect of the COD content on the LBR performance

As shown in Fig. 5, the COD concentrations of the methanogenic influent and acidogenic leachate of the three groups both increased first and then decreased. As the soluble COD concentration in the LBR decreased with time, the differences between the last three groups of methanogenic influents and acidogenic leachates were not large. On the second day of the reaction, the COD concentration of the leachate in the three groups of LBRs peaked, indicating that the pig faeces began to acidify and that acidogenic bacteria had become more active. The cumulative amounts of COD were

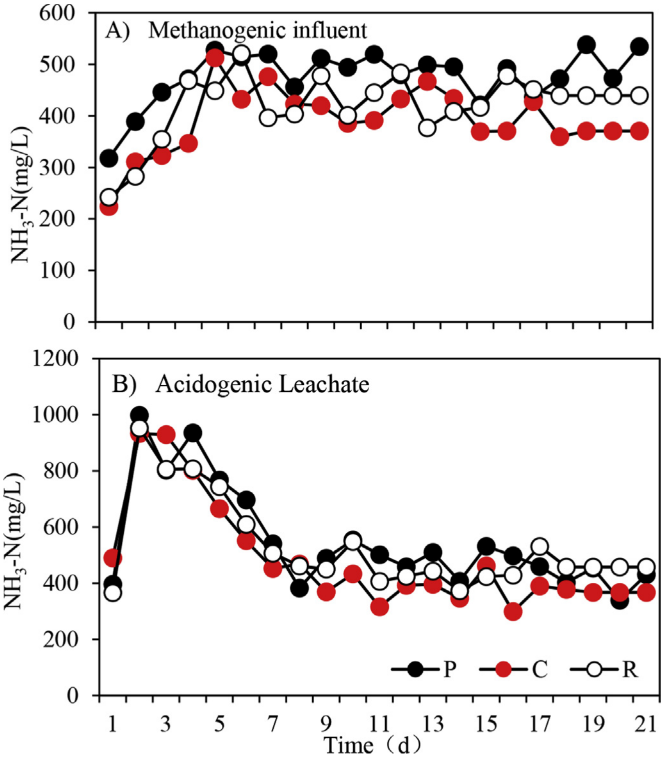

**Fig. 4.** $NH_3$–N variations of methanogenic influent A) and acidogenic leachate B).

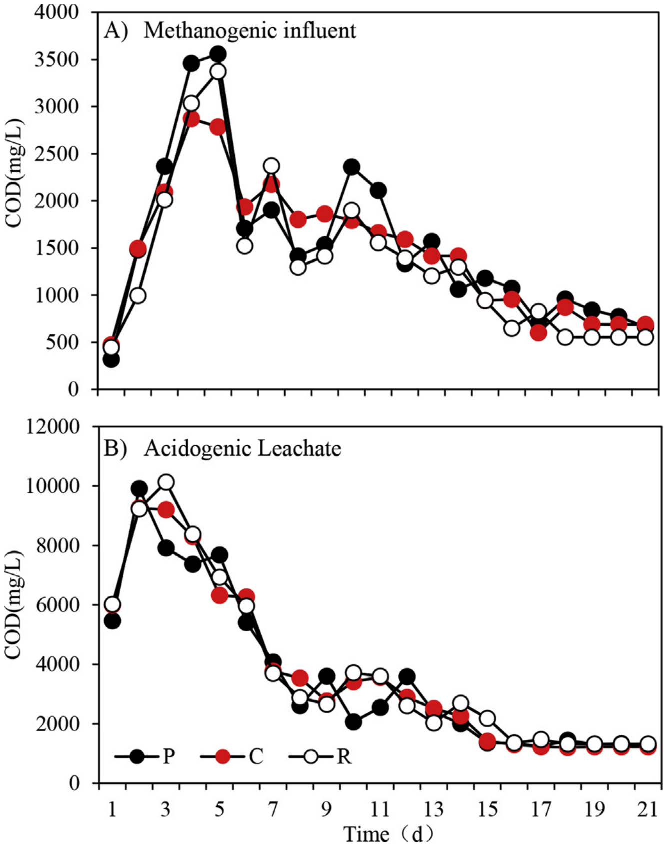

**Fig. 5.** $NH_3$–N variations of reflux and leachate
Fig.5. COD variations of methanogenic influent A) and acidogenic leachate B).

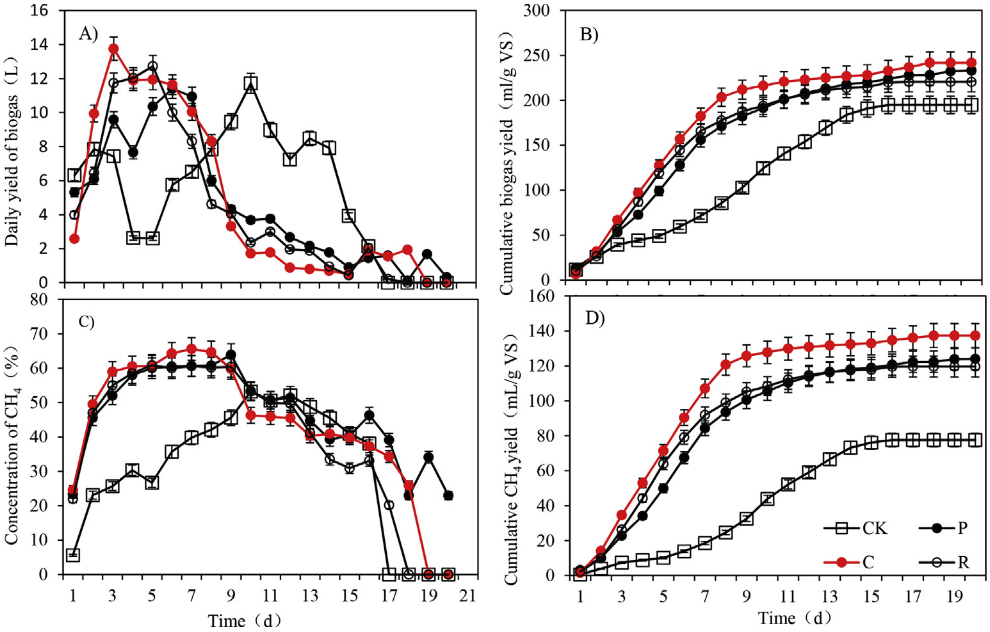

**Fig. 6.** Biogas production for daily yield A), cumulative yield B), concentration of $CH_4$ C) and cumulative $CH_4$ yield D).

43137.25 mg/L, 47533.50 mg/L and 49552.67 mg/L in the three groups of LBRs, and the final effluent COD concentrations of the CSTRs were reduced by 97.13%, 98.59% and 98.11%, respectively.

## 3.3. *Effect on the CSTR performance*

### 3.3.1. *CSTR biogas production*

As shown in Fig. 6, the methane peak value in the control test occurred 6 d later than that in the LBR-CSTR, and the total methane yield was 106.85 L. The daily methane concentration level was low, reaching 53.2%, and the methane yield was 77.58 ml/g VS. The performance of the wet anaerobic fully mixed fermentation reactor was notably poor, and the reaction rate was slow. The whole test cycle of the three-filter-media percolation bed lasted approximately 20 d, and the daily methane concentration of the LBR-CSTR in group 3 from the 2nd day to the 10th day was higher than 50%. The CSTR (R) was stopped after 17 d, and the accumulated biogas production was 86.81 L. The LBR-CSTR (C) reached its peak gas production on the third day of the reaction, and the cumulative biogas production on the 18th day was 95.18 L, which was the largest biogas production. In Fig. 6D, the cumulative methane production in the CSTR (C) was relatively large, reaching 137.39 ml/g VS. The latter was because the C particles were round, uniform, and rough on the surface, with well-developed pores and internal pores, and they had a large specific surface area, which was conducive to the attachment of biological bacteria and promoted the hydrolysis of the pig manure.

Table 2 compares the results with those of a previous study on the anaerobic digestion of animal manure. A previous study (Saritpongteeraka et al., 2014) reported the co-fermentation of pig manure and oil palm lignocellulosic residue for fatty acid production using cattle manure as the inoculum. Using biogas slurry as the inoculum could not only improve the biogas yield and production rate of the anaerobic digestion of livestock and poultry manure but also fully utilize the biogas slurry (Ye et al., 2013). The highest $CH_4$ content in this study was higher than that of the biogas slurry used as inoculum to digest deer manure. Pig manure and durian shells were co-digested with higher cumulative $CH_4$ yields than in our study; however, the transfer of durian shells is not convenient.

### 3.3.2. *COD, $NH_3$–N, TN, and TP contents of the CSTR effluent*

As shown in Table 3, the amounts of ammonia nitrogen and TN from the effluent of CSTR (C) were the lowest, thus indicating that C had a better adsorption of nitrogen, and because the largest volume of methane was produced, the COD was the lowest. The CSTR (R) showed the lowest TP concentration of the effluent, thus indicating that the R particles in the literature (Wang et al., 2013) had better phosphorous fixation properties.

**Table 2**
Compared with previous study of anaerobic digestion for animal manure.

| Substrate | inoculum | system | Biogas yield (ml/g VS) | $CH_4$ highest content (%) | $CH_4$ yield (ml/g VS) | reference |
|---|---|---|---|---|---|---|
| Deer manure | 30% Biogas slurry | Batch test | – | 55.79 | – | (Wang et al., 2013) |
| Pig manure and durian shell | Anaerobic sludge | Batch test | – | 48.3 | 224.8 | (Shewani et al., 2018) |
| Pig manure and oil palm lignocellulosic residue | Cow manure | LBR | – | – | – | Saritpongteeraka et al. (2014) |
| Pig manure | 100% Biogas slurry | LBR-CSTR | 241.68 | 65.60 | 137.39 | This study |
| Pig manure | 100% Biogas slurry | CSTR | 194.82 | 53.20 | 77.58 | This study |

**Table 3**
COD, $NH_3$–N, TN, TP concentration of effluent in LBR-CSTR.

| CSTR | COD (mg/L) | $NH_3$–N (mg/L) | TN (mg/L) | TP (mg/L) |
|---|---|---|---|---|
| P | 664.14 | 534.37 | 629.01 | 42.22 |
| C | 553.82 | 370.59 | 576.04 | 40.14 |
| R | 690.00 | 439.50 | 610.11 | 20.41 |

**Table 4**
Summary of organic removal efficiencies from pig manure.

| | CK | P | C | R |
|---|---|---|---|---|
| W initial(g) | 2450 | 2400 | 2400 | 2400 |
| W final(g) | 550 | 170 | 100 | 150 |
| Reduction(%) | 77.55 | 92.92 | 95.83 | 93.75 |
| TS initial(g) | 666.40 | 520.32 | 520.32 | 520.32 |
| TS final(g) | 215.03 | 146.45 | 86.02 | 129.36 |
| Removal efficiency(%) | 67.73 | 71.85 | 83.47 | 75.14 |
| VS initial(g) | 548.45 | 395.24 | 395.24 | 395.24 |
| VS final(g) | 179.19 | 78.25 | 52.07 | 73.10 |
| Removal efficiency(%) | 67.33 | 80.20 | 86.82 | 81.51 |

Municipal wastewater can be used for agricultural irrigation after suitable treatment (Axelrad and Feinerman, 2010); however, the farmer is the essential stakeholder (Zhang et al., 2012), and the use of industrial wastewater for irrigation cannot be ignored. Some farmers believe that irresponsible irrigation with new sources can affect the fertility of agricultural farmlands (Aljerf, 2018; Wassie and Pauline, 2018). This is based on rigorous analyses (Inthasaro and Wu, 2016), which can satisfy consumers (i.e. farmers). Aljerf (2018) surveyed 55 farmers about the use of industrial wastewater for irrigation, and the results showed that farmers generally approved the use of inexpensive industrial wastewater for irrigation under the premise of policy support; the wastewater not only provided nutrients for the land but also reduced agricultural expenditures. In addition, the recycling of industrial wastewater reduces the harm to the environment. Previous studies have shown that farmers are heterogeneous in their preferences for agricultural service providers (Aljerf, 2018; Laurenson et al., 2012), so the demand for clean water has increased to meet the needs of a sustainable rural society and to achieve a sustainability goal in the future.

Therefore, in this study, biogas slurry (no longer producing gas) from the CSTR can be considered for use in land irrigation after a certain purification treatment (Kouser et al., 2009) with the farmers' approval.

### *3.4. Pig manure reduction*

In controlled trials of renewal and pig residue measurement after the biodrying process for 3 d, as shown in Table 4, the pig weight reduction in the CK was 77.55%, and the three LBR-CSTR pig manure weights, which were initially 2400 g each, were measured as 170 g, 100 g, and 150 g. The moisture contents were 78.35 to 13.85%, 13.98%, and 13.76. Among the tested media, C was the fermentation filter medium system that obtained the largest pig manure weight reduction of 95.83%. In the LBR-CSTR (C), the degradation of the pig manure leached residue of the VS was 86.82%, which was 19.49% higher than that of the CK.

### *3.5. Characteristics of the pig manure leached residue*

As shown in Table 5, the pH of the product was neutral after biodrying the pig manure leached residue. As the pig manure leachate had been partially stabilized, further use of biodrying technology to rapidly reduce the moisture content of the pig manure leached residue would be beneficial for land use. The nutrients of the three kinds of leachate residues were similar, among which, the organic content of the pig manure leached residue in the LBR-CSTR (C) was the highest, with the seed GI higher than 50%, and the pig manure leached residue had decomposed. Moreover, the pig manure had a positive effect on the total mass of organic matter and the microbial biomass within the soil (Yagüe et al., 2012).

**Table 5**
Characteristics of biodrying products.

| | | P | C | R |
|---|---|---|---|---|
| pH | | 7.75 | 7.49 | 7.37 |
| EC(ms/cm) | | 1.23 | 1.47 | 2.01 |
| Organic materials(g/kg) | | 101.72 | 120.13 | 97.17 |
| Nutrient($N+P_2O_5+K_2O$,%) | | 0.88 | 0.89 | 0.99 |
| GI(%) | Cauliflower | 45.63 | 52.41 | 49.15 |
| | Corn | 53.61 | 55.54 | 54.71 |
| | Chinese cabbage | 50.12 | 59.52 | 54.78 |

## 4. Conclusions

The coupling of a leach bed reactor (using biogas slurry as the inoculum) and a continuous stirred-tank reactor (LBR-CSTR) to perform the anaerobic mono-digestion of pig manure was highly efficient. The LBR-CSTR with a ceramsite (C) filter medium had the best digestion performance (the biogas production was 24.05% higher than that of the control CSTR (CK)), and the cumulative VFA yield of the LBR (C) was the highest, which contributed to the methane production of the CSTR (C); the latter had a high methane yield (137.39 ml/g volatile solids (VS)). The concentrations of chemical oxygen demand (COD), $NH_3$–N and total nitrogen (TN) in the final CSTR effluent were minimal. The weight of the pig manure decreased 95.83% and 86.82% after degradation by the VS. After the pig manure leachate residue was biodried, it could be directly used as a base fertilizer.

Due to its high moisture content and long-term anaerobic conditions, traditional open pig manure composting will release odour. In an LBR, the soluble COD (SCOD) content in pig manure can be transferred into a biogas tank through water leaching to prevent the release of odour. The latter is also a pollution control method in clean production. The novelty of the LBR-CSTR for the treatment of pig manure is that the solid substances remain on the leachate bed, and the leachate enters the biogas tank, which effectively solves the operation problems of a traditional biogas tank. Moreover, the construction cost of the LBR-CSTR is very low. Only one pump and a series of water distribution pipes are needed during operation. The substances are pumped out of the sewage tank and sprayed on the bedding layer through the pipes.

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