

Performance of Food Waste Feeding Pilot Plant Biodigester Operated with Identified Potential Substrate Properties

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Abstract: Anaerobic digestion has been proven as sustainable process technology for organic waste conversion into renewable bio-energy. This study was conducted to evaluate the performance of mono-digestion process for different types of food waste substrates using pilot scale anaerobic bio-digester (1200 L) in terms of biogas production and the chemical oxygen demand (COD) removal efficiency. The biochemical methane potential (BMP) test of rice waste (R), vegetable waste (VW) and coconut meat residue (CMR) were tested at initial volatile solid (VS) loading of 0.1631, 1.1690, 1.0059 g VS/L, respectively at fixed inoculum/substrate (I/S) ratio of 0.5. Further study conducted by using rice waste (R) in pilot plant anaerobic bio-digester (1200L) for 43 days to investigate the reactor performance in term of COD removal efficiency. Interestingly, inoculum used for this study performs very well and able to digest food waste. Results demonstrate that the maximum specific biogas yield (SBY) was observed from rice waste (R) at 0.0587 L/kg VS compared to other substrates. Specific biogas yield (SBY) of rice waste (R) was 16.01% and 11.92% higher than substrate vegetable waste (VW) and coconut meat residue (CMR) respectively. High COD removal efficiency of pilot plant bio-digester (up to 93 %) using rice waste (R) as sole substrate indicates a good performance of reactor in treating food waste. Conversion of food waste to biogas in pilot plant bio-digester is highly potential as one of the sustainable waste treatment technology

Keywords: Anaerobic digestion, biomethane potential, biogas, food waste, inhibition effects, methane

1. Introduction

One of the highest wastes generated in Malaysia is food waste, which contributes to about 31% to 45 % of the total volume generated every day [1]. This waste commonly would be disposed of into landfills that could lead to the emission of greenhouse gas. Thus, to prevent this problem, an alternative method, such as anaerobic digestion, can be used since it is considered to be an economical and environmentally friendly technology [2].

In this study, the conversion of food waste to biogas was attempted in a pilot-scale anaerobic digester. Anaerobic digestion is a process where the organic materials are being digested by the microorganisms in the absence of oxygen to produce biogas. This biogas mainly consists of methane and carbon dioxide. Biogas can be directly used either for combustion or turned into electricity. Inside the digester, the food waste substrate will undergo the following stages:

hydrolysis, acidogenesis, acetogenesis, and methanogenesis. However, these processes are influenced by some physical and chemical parameters such as the total solids content (TS), the volatile solids content (VS), carbon and nitrogen ratio (C/N), particle size, temperature, pH, inoculum type, and co-digestion with other organic wastes (i.e., animal manure, sewage sludge, waste from the food industry) [3]. These all parameters are assessed in terms of biodegradability; the decomposition rate by the anaerobic processes.

One of the most relevant tests for assessing the biodegradability as it gives significant information about the biomethanation of specific substrates and provides experimental results essential to calibrate and validate mathematical models is biochemical methane potential analysis [4]. [5] stated that biodegradability assays are based on the measurement of either formation of one or more products involved in the biological reaction under investigation or measurement for substrate depletion. While for methods based on substrate depletion can be determined either as a lumped parameter (volatile solids (VS), chemical oxygen demand (COD), dissolved organic carbon (DOC), etc.) or directly analysis of the compound that is being used as a substrate [6]. As the biodegradability of substrate increases, the biomethanation rate also increases [4].

However, the inhibition factor may arise during the process. The inhibitors commonly present in anaerobic digesters include ammonia, sulfide, light metal ions, heavy metals, and organics [7]. Furthermore, the AD of food waste usually results in process inhibition due to the rapid accumulation of VFAs [8] and ammonia [9]. To maintain stable operation, the digesters are usually operated at a low organic loading rate (OLR) [10] or by mixing with sewage sludge, which has high C/N and low biodegradability [11].

Currently, the pilot-scale anaerobic digestion of different types of food waste has been studied extensively. [12] used 50 L digester for the anaerobic digestion of food waste (rice) at 35 °C with the mixing volume ratio of food waste to water was 1:1 in which resulted 95.3 and 123 liters of total cumulative biogas produced on the last day 20th for the non-inoculated and inoculated samples respectively. Meanwhile, the daily volume of biogas yield for anaerobic digestion of rice food waste was highest at day 18th with value of 10.2L and 12.3L for the non-inoculated and inoculated samples respectively. At the same time, a study from [13] used 70 L pilot-scale digester for anaerobic digestion of vegetable waste at 34 °C with a fixed hydraulic retention time of 25 days. The highest biogas production is 0.4 m³/kg VS (33.3 L/d) with suggested OLR of 1.4 kg VS/m³.d. Anaerobic digestion of food waste is achievable. However, different types of food waste result in varying degrees of methane yield. Thus, the effects of mixing various types of food waste and their proportions should be determined on a case by case basis [12].

This study was embarked to evaluate the performance of mono digestion for different types of food waste substrates in pilot-scale anaerobic biodigester (1200 L) in terms of biogas production and the chemical oxygen demand (COD) removal efficiency.

2. Materials and Methodology

2.1 Preparation of Substrates and Inoculum

The substrates that were used in this research are rice, vegetable waste, and coconut meat residue from a wet market in Kuala Terengganu, Terengganu. The inoculum is taken from the existing palm oil mill digester and stored in the refrigerator at 4°C. Each sample was blended with distilled water with a ratio of 1: 0.2, 1: 2, and 1: 1, respectively. The blended samples are used in biochemical methane potential (BMP) assay to determined their biodegradability potential and physicochemical analysis to determine the total solid (TS), volatile solids (VS), chemical oxygen demand (COD) and soluble chemical oxygen demand (sCOD) for each sample.

2.2 Biomethane Potential (BMP) Assay

The biochemical methane potential (BMP) assay was done in triplicate for each sample and a blank. Serum bottles (125 ml) are flushed with nitrogen gas for 2 minutes. The substrates and inoculum are filled with a ratio of 2:1 for each sample. S/I ratio stated in Table 1 below was calculated based on g VS basis. In order to standardize the working volume of reactor used, the volume of substrates and volume of inoculum in term of Liters (L) have been fixed but the value of Volatile Solid (VS) for each substrate are different, hence the S/I ratio also tun into different. Phosphate buffer (700 µl), micronutrients (42 µl) and macronutrients (420 µl) are added into the mixture as supplements based on the nutrient list from [14]. Distilled water is added until the volume reached 70 ml. Then, the serum bottles are flushed again with nitrogen gas and immediately sealed with the rubber cover provided with the bottle. The serum bottles are incubated at 37 °C.

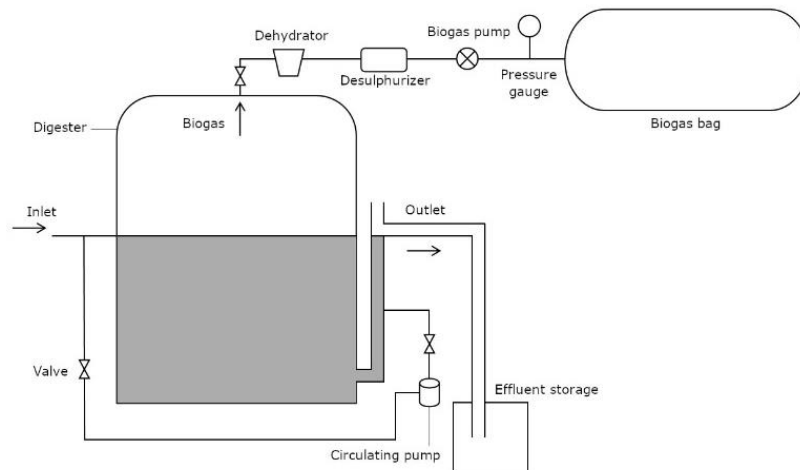
In order to measure the amount of biogas produced in each serum bottle, a 20 ml syringe is inverted straight into the lid of each serum bottle. The serum bottles are shaken once to twice a day. The reading of biogas volume for each bottle is recorded daily and the experiment are terminated after the volume of the biogas did not increase. Table 1 below shows the experimental setup for the biochemical methane potential (BMP) test of different substrates.

Table 1 - Experimental setup for Biochemical Methane Potential (BMP) test of different substrates

Parameter	Rice waste (R)	Vegetable Waste (WV)	Coconut Meat Residue (CMR)
<i>Operation Conditions</i>			
No. of replications	3	3	3
Reactor working volume (ml)	125	125	125
Mass substrates (g VS/L)	0.1631	1.1690	1.0059
Volume substrates (L)	0.0140	0.0140	0.0140
Mass inoculum (g VS/L)	1.1285	1.1285	1.1285
Volume inoculum (L)	0.0070	0.0070	0.0070
S/I (g VS)	0.2891	2.0718	1.7827
<i>Characteristics</i>			
Initial pH	7.52	6.49	7.12
Final pH	6.74	5.33	6.07
Initial COD (mg/L)	212,300	59,600	47,300
Final COD (mg/L)	26,700	49,300	41,700

2.3 Reactor Setup

Next, for the pilot plant performance of a substrate chosen, a 1.2 m³ reactor is used. In this reactor, the weight ratio of substrate to inoculum is 2:1 since the substrate that have been chosen from BMP assay was rice waste. The experiment is carried out for about 43 days. The substrate is being fed once in a week into the reactor and the COD of the effluent from the anaerobic digestion process is analysed and recorded daily. From the COD value, the value of COD removal is calculated. Fig. 1 shows the diagram of the anaerobic digester set up.

**Fig. 1 - Anaerobic digester set up**

2.4 Other Analysis

For the characterization of substrates and inoculum samples, the samples were analyzed for their pH, total solids (TS), volatile solids (VS), volatile fatty acid (VFA), and chemical oxygen demand (COD). Total solids (TS), volatile solids (VS), pH, volatile fatty acid (VFA), chemical oxygen demand (COD), and soluble chemical oxygen demand (SCOD) analysis were carried out according to standard methods [15].

3. Results and Discussion

3.1 Characterization of different substrates and Inoculum

A key parameter of designing and operating anaerobic reactors is the characteristics of feedstock, which strongly affect the biogas yield and anaerobic process stability. The initial physicochemical characteristics of inoculum and substrates in this study including analysis of total solid (TS), volatile solids (VS), chemical oxygen demand (COD), pH and volatile fatty acid (VFA) were summarized in Table 2 and Table 3, respectively. From the data in Table 2, inoculum (I) was at pH 6.58, which is within the optimum range for anaerobic digestion (AD) process [5]. It also can

be seen that inoculum (I) has a very low range of VFA concentration which is 109.60 mg/L, in which as reported by [16] in their previous study that the value of VFA within the optimum range (173-193 mg/L) did not cause inhibition during digestion period since most of VFAs produced were consumed by methanogens.

Table 2 - The characteristics of inoculum used in this research

	pH	% Total Solid (g/L)	% Volatile Solid (g/L)	Volatile Fatty Acids (VFA)*	Chemical Oxygen Demand (COD)
Inoculum (I)	6.58	1.28	55.81	109.60	40,600 mg/L

Based on mg/L acetic acid equivalent [HAceq]

Results from Table 3 shows that coconut meat residue (CMR) contained the highest percentage of TS, which is at 7.32%, followed by 7.02%, 2.40%, and 1.28% for rice (R), vegetable waste (VW) and inoculum (I) respectively. Interestingly, substrate rice (R) has the highest percentage of VS compared to coconut meat residue (CMR) and the other two substrates and inoculum. The percentage of VS for rice (R), vegetable waste (VW), coconut meat residue (CMR), and inoculum (I) are at 95.35%, 81.81%, 14.02%, and 55.81% respectively. According to [17] value of total TS and VS of substrates can be used to predict the anaerobic digestion process efficiency and biogas yield. Hence, the value of VS for substrate rice (R) portrays that rice waste (R) has a high potential to produce a huge amount of biogas production in the anaerobic digestion (AD) process.

The data presented in Table 3 shows that coconut meat residue has the lowest COD concentration, which is at 10,700 mg/L compared to substrate rice (165,300 mg/L) and vegetable waste (21,300 mg/L). Surprisingly, substrate rice (R) has the highest percentage of sCOD/COD but has the lowest percentage of VS/TS. According to [18], soluble chemical oxygen demand (sCOD) used to analyze the amount of soluble organic material in the subjected substrate and express the readiness of materials to be converted into methane through the AD process. Therefore, the high percentage of sCOD/COD of substrate rice waste (R) supports the finding reported by [19], in which the highest value of COD solubilization would significantly affect the biogas production.

Table 3 - The characteristics of different substrates used in this research

Parameter	Rice (R)	Vegetable Waste (VW)	Coconut Meat Residue (CMR)
pH	6.34	5.88	6.08
Total Solid (g/L)	17.55	32.14	14.58
% Total Solid (g/L)	7.02	2.40	7.32
Volatile Solid (g/L)	0.8155	5.85	5.03
% Volatile Solid (g/L)	95.35	81.81	14.02
% VS/TS (g/l)	5	18	34
COD (mg/L)	165,300	21,300	10,700
sCOD (mg/L)	112,380	11,200	4,010
sCOD/COD (%)	67.99	52.58	37.48

3.2 Biogas Generation from Biomethane Potential (BMP)

Table 4 shows the overall performance of BMP of different substrates. Fig. 2 shows the cumulative and specific biogas yields of three substrates in mono digestion of the BMP setup. Biogas values presented are the average results of triplicate trials at standard temperature and pressure after control correction.

Table 4 - Biomethane Potential (BMP) performance of different substrates

Parameter	Rice (R)	Vegetable Waste (VW)	Coconut Meat Residue (CMR)
Time (Days)	7	7	8
Cumulative Biogas Production (mL)	76	22	15
Specific biogas yield (L/kg VS)	0.0587	0.0094	0.0007
COD removal (%)	87.42	17.28	11.84

Under the optimal ratio of substrate/inoculum (S/I) of 0.2891 with a total organic load of 1.2916 g VS/L, the highest cumulative biogas production (CBP) reached 76 mL/day when substrate rice was placed in serum bottle of BMP to undergo the process of mono digestion for 7 days. The specific biogas yields (SBY) of three substrates of rice (R), vegetable waste (VW), and coconut meat residue (CMR) were 0.0587, 0.0094, and 0.0007 L/kg VS respectively. The mono digestion of rice (R) had the highest cumulative and specific biogas yield among all, while substrate coconut meat residue (CMR) yielded the lowest biogas (Fig. 2). Specific biogas yield (SBY) of rice (R) was 16.01 and 11.92 %

higher than substrate vegetable waste (VW) and coconut meat residue (CMR), respectively. The value of COD removal (%) for mono digestion of substrate rice (R) is the highest among all which is 87.42 % and it shows the ability of the substrate to lower down the COD influent of 212,300 mg/L to 26,700 mg/L after the end of 7 days digestion periods.

Specific biogas yield (SBY) and cumulative biogas production (CBP) was the highest from substrate rice (R), as it has the highest percentage of VS and the highest percentage of sCOD/COD. Meanwhile, the lowest of Specific biogas yield (SBY) and cumulative biogas production (CBP) is from substrate coconut meat residue (CMR). It can be seen from the collected data in Table 3 that coconut meat residue (CMR) has a low percentage of TS. Thus, these results confirmed the finding reported by [20] mentioned that coconut meat residue (CMR) found to have a high percentage of moisture content due to the high water-holding capacity, water retention, and swelling capacity of itself compared to other dietary fibers. The high percentage of VS/TS of coconut meat residue (CMR) indicates that the fast degradation of VS, which leads to rapid acidification and VFAs accumulation, hence resulted in lower down the cumulative biogas production (CBP).

Furthermore, according to [21] there is about 17-24 % of extractable oil content found in coconut meat residue (CMR) after coconut milk extraction. This result may explain the reason behind the lowest cumulative biogas production (CBY) from coconut meat residue (CMR) due to the high loading of lipids, which resulted in a decrease in the degradation of carbohydrates and protein. High lipids lead to process failure by the formation of oil floc and absorption to microbial cells that affect the methanogen activity and biogas production. However, few parameters may affect the biogas production such as C/N ratio, pH instead of the effect of lipid content in the substrate itself [22].

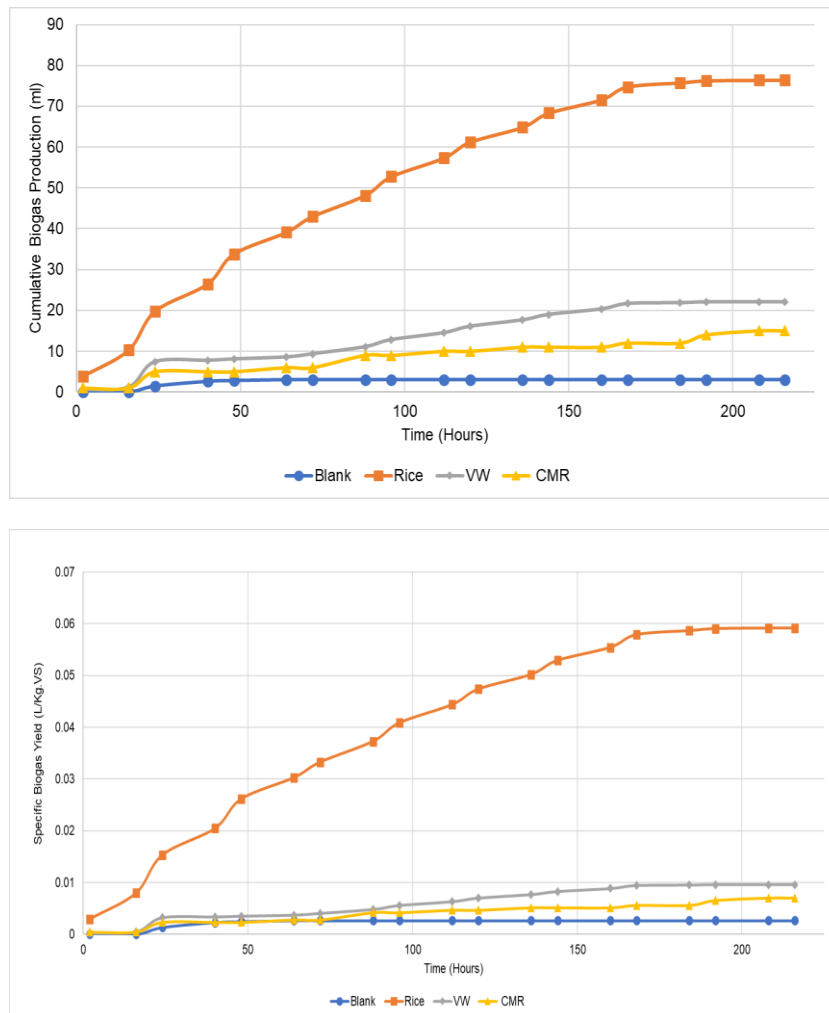


Fig. 2 - Cumulative (top) and specific biogas yields (below) of substrate mixtures during BMP test

3.3 Reactor Performance: COD Removal Efficiency (%) of Substrate Rice Waste (R)

Overall, reactor performance in terms of COD removal efficiency of mono digestion substrate rice (R) is illustrated in Fig. 3. Three substrates of rice (R), vegetable waste (VW), and coconut meat residue (CMR) were analyzed in the biomethane potential (BMP) test in order to evaluate the potential of each substrate to produce biogas. It has been observed that substrate rice (R) had the highest cumulative and specific biogas yield among all of the two other

substrates. According to [23] common operational issues for the anaerobic digestion (AD) of food waste is process instability, hence microbial management, process monitoring, and control were used to overcome the instability and increase the energy conversion efficiency of anaerobic digesters.

As shown in Table 5, the COD concentration of influent and effluent in the reactor on the 0th day is about 32,000 mg/L, which resulted in 0 % of COD removal efficiency. The feeding of rice waste for the reactor is started on the 1st day of the digestion period, with about 165,000 mg COD/L. The circulation system of the reactor is operated once the loading of rice waste to determine the mixture homogeneity of substrate and inoculum. On the next day, the COD concentration of effluent is decreasing from 165,000 to 64,000 mg/L, which indicates the positive result of COD removal efficiency, in which about 68 % of COD from the reactor is successfully removed.

The reactor was not fed with rice waste until day 7th of digestion period and as can be seen in Fig. 3, there has been a steep fall of COD effluent concentration. The same amount of COD concentration of rice waste was fed on day 8th and the trends shows the similar result as in day 1st of digestion period. The COD removal efficiency drop to 64 % due to increasing of COD influent concentration on the feeding day but simultaneously there are gradually drop of COD effluent concentration from day 9th to day 14th, in which it is a good indicator of reactor performance.

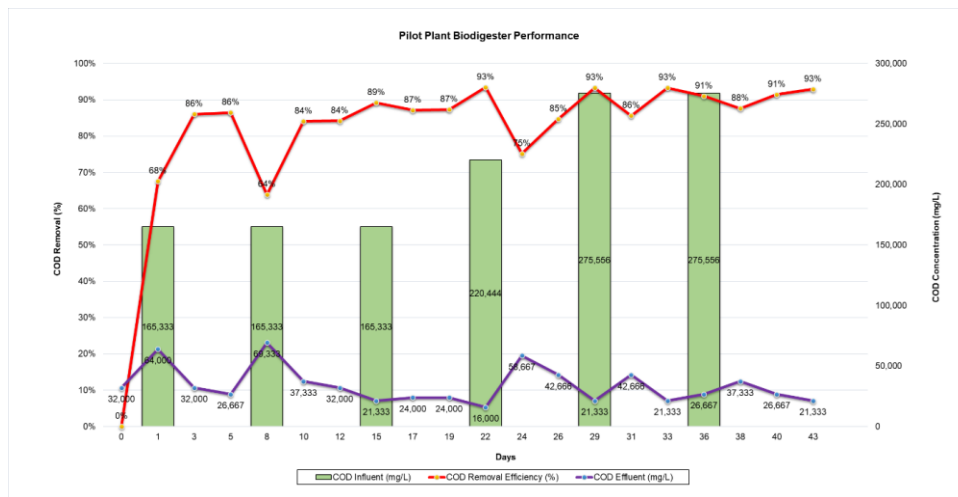


Fig. 3 - COD removal Efficiency (%) of substrate rice (R)

Table 5 - COD Removal Efficiency (%) of 1.2 m³ reactor Anaerobic Digestion (AD)

Days	Influent COD concentration (mg/L)	Effluent COD concentration* (mg/L)	COD Removal Efficiency (%)
0	32, 000	32, 000	0
1 st	165, 300	64, 000	68
8 th	165, 300	69, 300	64
15 th	165, 300	21, 300	89
22 nd	220, 400	16, 000	93
29 th	275, 500	21, 300	93
36 th	275, 500	26, 600	91
43 rd	-	21, 300	93

* Effluent COD concentration was taken the next day after each new feeding/influent addition

The third time of feeding is on day 15th with the same amount of COD concentration of rice waste. Previous trend shows a day after feeding there will be increasing of COD removal efficiency which indicate the good performance of reactor but surprisingly the third feeding result does not show the same trend as previous. The COD removal efficiency keep increasing even though there are new loading of rice waste, thus decreasing the COD concentration of effluent on the next day. This finding indicates that the consortium of microbes in the reactor system have possibility to digest more higher concentration of rice waste and the reactor did not reach its maximum performance yet. Hence, the new COD concentration of rice waste was introduced into the reactor on the day 22nd.

As can be seen in Fig. 3, the COD removal efficiency on the feeding day of 22nd increasing from 87% to 93% thus lowered the reading of COD effluent on the next day again. Interestingly, this result shows that microbes in the reactor actively digest the organic substrates hence, the higher COD concentration of rice waste was introduced on the next feeding day. As have been expected, the trend remains the same until the feeding day on 29th in which it is the good

indicator of stability of the anaerobic digestion (AD) in the reactor. Strong evidence of the hypothesis was found when there is a slightly increasing COD removal efficiency even after introducing a new COD concentration of influent. As the result, the COD concentration of effluent gradually decrease over the time.

A similar COD concentration of rice waste, 275 556 mg/L was fed in the reactor on day 36th and the result shows there is slightly fall of COD removal efficiency from 93% to 91% on the feeding day. This result can be seen as in the first phase of feeding period specifically on day 8th which the COD removal efficiency drastically fall right on the feeding day. This situation explains how the stability of anaerobic digestion process occurred in the reactor. In conclusion, the stability of the AD process in 1.2 m³ reactor during digesting the substrate rice waste (R) can be reached up to 93% of efficiency in order to remove the maximum COD concentration of 275,556 g COD/L of rice.

4. Conclusions

The following conclusions can be drawn from the present research:

- The inoculum used for this study performs very well and seems does not give any effect digesting food waste from palm oil mill effluent.
- Specific biogas yield (SBY) and cumulative biogas production (CBP) was the highest from substrate rice (R) at 0.0587 L/kg VS and 76 mL, respectively, compared to other substrates.
- High COD removal efficiency of pilot plant bio-digester (up to 93 %) using rice (R) as the sole substrate.
- Best on this excellent performance, mono-digestion of food waste (Rice) give promising results for the operation of bio-digester.

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