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Anaerobic Co-Digestion of Wastewater Activated Sludge and Rice Straw in Batch and Semi Continuous Modes

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Abstract

Co-digestion of sewage sludge with rice straw may be attractive option from energetic, as well as, environmental viewpoints. In this study, co-digestion of wastewater activated sludge (WWAS) with grinded rice straw at different ratios (0.5, 1.0, 1.5 and 3.0%), straw to WWAS based on weight, was performed using batch reactors. Moreover, a semi-continuous model was developed for sludge digestion and co-digestion with rice straw. The results showed that the co-digestion of WWAS with rice straw improved the carbon to nitrogen ratio (C/N) and consequently increased biogas production compared to sludge digestion. Moreover, total solids, total volatile solids and chemical oxygen demand were reduced by digestion during the reaction time. Furthermore, the biogas yield increased by increasing mixing ratio in co-digester and reached four times at maxing ratio 3.0% compared to sludge digestion. The semi-continuous model showed that the co-digestion increased total biogas amount continuously and methane was the main component in biogas released from digester and co-digester.

Keywords: Co-digestion; Activated sludge; Rice straw; Biogas production

Introduction

Anaerobic digestion has been traditionally used as an effective, environmental sustainability and economical technology for the biological treatment of sewage sludge which enables energy production as heat, electricity and/or vehicle fuel, as well as stabilization of volume reduction of sludge [1,2] (Figure 1).

In Egypt, about 2.0 × 10^6 tons of sewage sludge are produced annually from 303 wastewater treatment plants (WWTPs) [3,4]. One of the most important WWTP in Egypt is Al Gabel Asfer that having a current sewage treatment capacity of 1.8 × 10^6 m^3/day, which is expected to be doubled in 2020 [3]. The application of anaerobic digestion technology for sludge stabilization and power generation in Al-Gabel Al-Asfer WWTP has achieved good results and considerable experience of operation and maintenance has been gained. A large portion of the biogas produced is currently used for the operation of hot water boilers, which are used to heat the raw sewage sludge in the primary digesters. Dual fuel generators use the excess digested gas to generate electricity that representing about 37-68% of the power consumed by this WWTP [3].

In anaerobic digester, proper carbon to nitrogen (C/N) ratio is important for efficient digestion [2]. However, unbalanced C/N ratio in the sewage sludge inhibits the anaerobic digestion efficiency due to the formation of ammonia and volatile fatty acids, which, if accumulate too much in the digester, would inhibit the methanogen activity [5]. Typically, the C/N ratio of sewage sludge is ranged between 6-16 [6]. However, the optimal C/N ratio for anaerobic digestion should be in the range of 20-30 [7]. Recently, different organic waste materials with higher content of organic carbon have been mixed with sewage sludge in anaerobic digester (anaerobic co-digester) to improve C/N ratio [8]. Therefore, the combination is leading to an increase in biogas production [1,5,9-12].

Anaerobic co-digestion of sewage sludge with different organic waste material has been studied such as: source-sorted organic fraction of municipal solid waste [12,13], confectionery waste [14], municipal solid waste [9,15], food waste [11,16-18], sludge from pulp and paper industry and enzyme production [19], lixiviation of sugar beet pulp [20], grease trap sludge from a meat processing plant [1], macroalgae from the lagoons [21], sterilized solid slaughterhouse waste [22], corn straw [23], and rice straw [2,5,24,25].

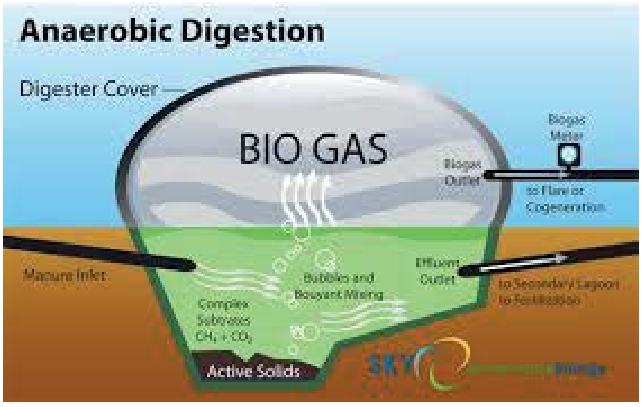

Figure 1: Graphic abstract.

In particular, rice straw is one of the most problematic agriculture wastes in Egypt, where it is generated in huge amounts (3.0 to 7.0 × 10^6 tons/year) over a limited harvesting period, representing the largest amount of unused agriculture residues by a wide margin [26-28]. A small amount of rice straw being used for livestock feedstuff of

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fertilizer and the majority of the waste is burned in open field, causing great impact on the greenhouse aspect as gas emissions as well as air pollution and consequently affects public health [29]. Moreover, the utilization of rice straw as a source of energy production is urgently needed in Egypt [26].

Komatsu et al. [5] investigated the feasibility of anaerobic co-digestion of sewage sludge and rice straw via mesophilic and thermophilic digesters using feeding ratio 1.0:0.5 based on the total solids (TS) of sewage sludge to rice straw and the results showed that the presence of rice straw increased methane production by 66-82% in case of mesophilic digester that was more effective than thermophilic one. Lei et al. [25] studied the influence of the effect of phosphate supplementation to anaerobic sludge in the presence of rice straw and the results showed that the phosphate seemed to have a little evident effect of the performance of anaerobic co-digestion, such as total volume of biogas or methane and accelerated the process. Kim et al. [2] investigated effective biohydrogen production process through anaerobic co-digestion of rice straw and sewage sludge via batch test. Based on their results, adding of rice straw showed that the C/N ratio of 25, pH range of 4.5-5.5, and untreated sludge were optimum for H_2 production. El-Bery et al. [24] studied the effect of thermal pre-treatment on inoculum sludge for continuous H_2 production from alkali hydrolyzed rice straw by using two mesophilic anaerobic baffled reactors with untreated and thermally treated sludge, ABR1 and ABR2, respectively; at a constant hydraulic retention time 20 h and organic loading rate 0.50-2.16 g chemical oxygen demand (COD)/Ld. They reported that thermal pretreatment of sludge slightly improved H_2 production around 212 and 261 mL H_2/g for ABR1 and ABR2, respectively, and COD removal for both reactors. Furthermore, Maroušek et al. [30-33] have studied different methods to improve the biogas production from different residues such as pre-treatment methods (hot maceration, steam explosion, and pressure shockwaves) and found that the self-standing hot maceration did not significantly increase the methane yield, however, steam explosion has potential to significantly increase the methane yields, furthermore, the pressure shockwaves are capable of high methane yield.

From this background, the main objectives of this study are to investigate the effect of adding rice straw with different ratios to anaerobic digester of wastewater activated sludge (WWAS) on biogas production, analyze the chemical composition of the biogas production and study the effect of co-digestion on characteristics of digested material using batch and semi-continuous reactors.

Materials and Methods

Materials

Wastewater activated sludge samples were obtained from Altal-Alkabeer wastewater treatment plant, Ismailia Government, Egypt. Samples of WWAS were stored in cold (4°C) until their use. Rice straw samples were collected from El-Sharkia Government, Egypt with approximately length of 1.0 m. The rice straw was shredded to 2.0 mm and was stored at ambient temperature far from heat and moisture, for subsequent use.

Experimental methods

Batch experiment: The batch reactor consisted of a reactor connected to gas collector with P.V.C. tube and the gas collector was attached to an open jar by a tube with valve to measure the volume of water collected due to the pressure of the biogas production. The batch reactor was placed in a glass basin equipped with a heater and thermostat to maintain a constant temperature (35°C) (Figure 2A). Five batch reactors were used in this experiment, each reactor contained 2.5 Kg WWAS and the first reactor was used as control contained sludge only. The other reactors contained WWAS mixed with rice straw at ratios 0.5, 1.0, 1.5, and 3.0% (straw to WWAS based on weight). The batch reactors were static except for daily mixing by hand after gas measurements.

Semi-continuous experiment: Figure 2B showed a schematic diagram for a semi-continuous reactor, it was similar to the batch reactor, in addition to influent and effluent tubes, moreover, shaking water bath was used to keep the reactor in continuous mixing and fixed temperature (35°C) during the reaction time. Two reactors were used in this experiment, the first reactor contained 2.5 Kg WWAS solo and operated as a control, meanwhile, the second one contained the same amount of WWAS mixed with rice straw (mixing ratio 1.5% based on weight) and retention time was 25 days for both reactors. Samples were withdrawn from effluent of both reactors around 100 mL and were replaced with the same volume of substrate prepared daily for each reactor.

Analytical methods: TS, total volatile solids (TVS), and COD samples were measured according to the procedure mentioned in the standard methods. Phosphorous was measured by the method described by Murphy and Riley [34] using spectrophotometer model UV-160A-SHIMADZU. Potassium was determined spectrophotometrically in the acid digested samples via Atomic Absorption Spectrophotometer model UNICAM 969a by the method of Nation and Robinson [35]. Finally, the organic carbon content was determined by the method of Walkley and Black [36]. The pH was measured using pH meter (pHep, HI 98107 pocket-sized pH Meter).

The biogas production was calculated by measuring the volume of the displaced water due to the pressure of biogas. Samples of the biogas produced were analyzed using gas chromatograph, LNG analyzer Varian 3800 cp (Liquefied natural gas analyzer) to determine its composition.

Results and Discussion

Characteristics of raw material

The physical and chemical characteristics of WWAS and rice straw are summarized in Table 1. The WWAS has a high COD ranged between 17.0 to 20.5g/L and a few-solid substrate, with a total solid content ranged from 1.29 to 1.39%, while the rice straw contains 93.63%. The majority of TS present were TVS, 64.74 to 69.09 and 74.10 for WAS and rice straw, respectively. The C/N ratio of WWAS was 6.59-9.40, however, it was 72.90 for rice straw. These values indicated the importance of rice straw in anaerobic co-digester due to its high carbon content that may adjust the optimum digestion C/N ratio to improve the biogas production. Furthermore, P and K were observed in both raw materials constituent and they are considered as macronutrients and required for functioning of many microorganisms in biological processes.

Batch experiment

Figure 3 showed the cumulative biogas produced from digestion of WWAS and mixture of WWAS with rice straw at ratios (0.5, 1.0, 1.5, and 3.0%), finding that the rate of biogas production was elevated during the first 20 days of reaction time, especially in the presence of rice straw with different mixing ratios. Then, the rate decreased with higher reaction time up to 60 days, and then it was negligible at higher reaction time.

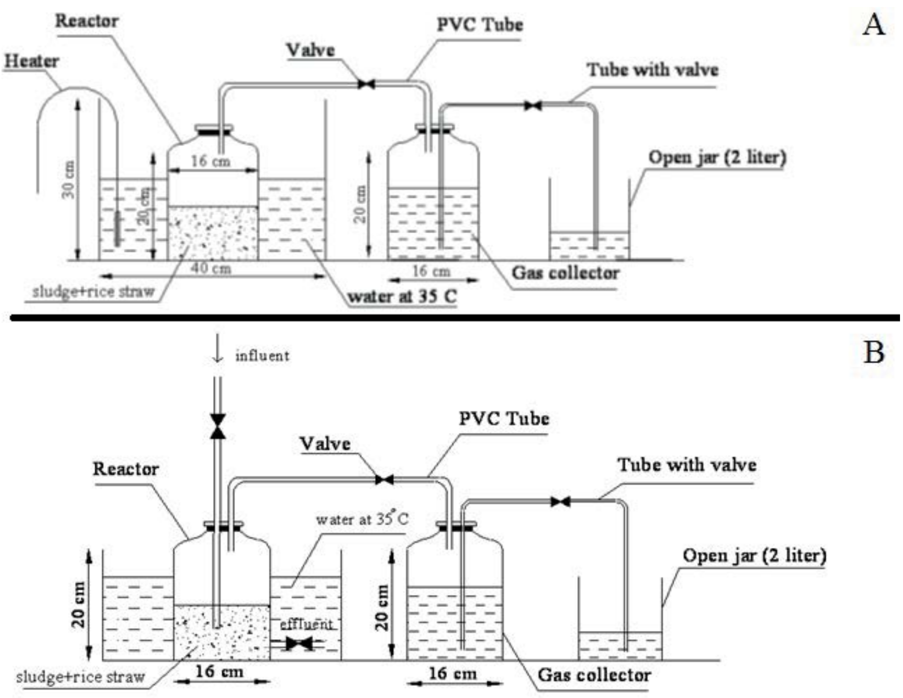

Figure 2: A schematic diagram of anaerobic co-digester reactors. A. The batch reactor and B. The semi-continuous reactor.

Parameter	Sewage sludge		Rice straw
	Batch test	Semi-continuous test	
pH	7.2	6.9	N.D.
COD (g/L)	17	20.5	N.D.
TS (%)	1.29	1.39	93.63
TVS (%)*	64.74	69.09	74.1
C/N	6.59	9.4	72.9
K (%)*	0.3	0.38	1.82
P (%)*	1.4	0.69	0.05

N.D. Not determined. *Percentages from TS.

Table 1: Characterization of raw materials used in the experiments.

In general, co-digestion of WWAS with rice straw increased the amount of biogas produced which can be explained as the addition of rice straw improved C/N ratio and this ratio increased with increasing of straw content, (Figure 4), consequently enhanced biogas production by 150, 200, 250, 400% at mixing ratios 0.5, 1.0, 1.5, and 3.0%, respectively, in comparison to WWAS only. These results are similar to pervious works [5,9,10].

The relation between mixing ratio and biogas production has been proved by the following linear equation [11]:

$$Y = A \times X + B \quad (1)$$

Where, Y is the total amount of biogas predicted from anaerobic co-digester at equilibrium within boundary conditions (0.5 to 3.0% and 80 days), X is the mixing ratio, B is the total amount of biogas predicted from anaerobic digester at equilibrium, and A is the constant represented the relation between the mixing ratio and gas production. Equation coefficients have been found 8.10 and 7.51 for A and B, respectively, and the deviation percentage was calculated (1.64%) with

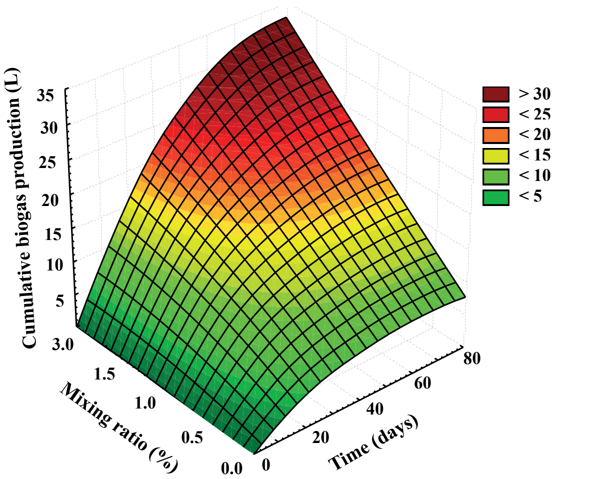

Figure 3: Variation in cumulative biogas production from batch reactors with different mixing ratios of rice straw and reaction time.

the following equation:

$$\%D = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{V_{exp} - V_{pred}}{V_{exp}}\right| \times 100\% \quad (2)$$

where, V_{exp} is the value of experiment data and V_{pred} is the value of predicted data, Furthermore, C/N showed similar linear equation in relation to mixing ratio and the equation coefficients were 4.91 and 7.13 for A and B, respectively, and % D was 3.36 %, as shown in Figure 4.

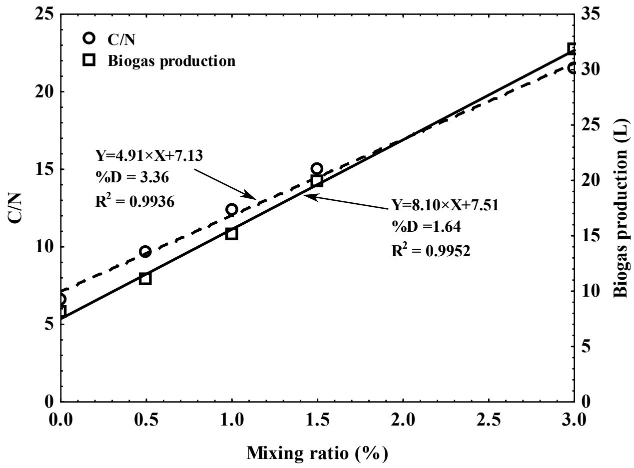

Figure 4: Variation in total biogas production and C/N ratio with different mixing ratios between WAS and rice straw.

Figure 5 presented the variation of pH, COD, TS, and TVS that occurred during the reaction time. The results showed that pH for all cases before and after digestion varied between 7 and 7.5 (Figure 5A), which nearly lied in the optimum pH range (6.5-7.5) for anaerobic digestion [37-39]. COD values decreased for all cases with about 50%, meanwhile, the reactor contained WWAS only recorded around 82 % reduction percent, which can be explained that WWAS reactor contained lower organic matter than co-digester reactors, due to the absence of rice straw (Figure 5B), that was completely degraded before the others co-digester reactors and it was confirmed by the produced biogas that almost stopped after 50 days of reaction time (Figure 3). The reduction in TS and TVS due to digestion and co-digestion varied in their percentages, however, the reduction percentages reached to about 40% and 53%, respectively (Figures 5C and 5D).

Semi-continuous experiment

Biogas production: From application stand point of view, semi-continues reactor was investigated. As a result obtained from batch reactor, co-digestion of 3.0% mixture of WWAS and rice straw recorded the highest amount of biogas production among the studied ratios; semi-continuous experiment for the same ratio was investigated, however, at this ratio, the reactor was stopped many times because clogging of tubes due to the high percent of rice straw, thus the ratio 1.5% was investigated and showed a flexibility in movement. Figure 6 showed the cumulative biogas production that was obtained from digestion co-digestion with 1.5% of rice straw. The amount of biogas released from co-digestion was 2.5-folded higher than that from digestion. This may due to higher C/N ratio in co-digester (16.0) than that in digester (9.4). Furthermore, the continuous increase in the total amount of biogas is attributed to the daily substrate feeding, consequently, continuous decomposition of organic compounds into biogas by anaerobic bacteria activation [40,41].

Biogas analysis: Samples of biogas produced from both reactors were collected and analyzed to determine its composition. Table 2 shows the composition of the biogas production from anaerobic digester and co-digester. It has been found that the main component in produced biogas was methane and followed by CO_2, then N_2. It was observed that there was no significant effect on methane content in produced biogas via co-digester. However, the released volume of methane based on the produced biogas from co-digester was around 2.5-fold higher than that anaerobic digester, similar results were found by Komatsu et al. [5].

Digested samples analysis: At constant period time (every 10 days), digested samples were taken from both reactors to measure TS, TVS, COD, TN, and pH during the digestion time. Figures 7A and 7B showed the variation of TS and TVS contents, they showed similar behavior for both reactors and were higher (2-fold) for co-digester compared to digester due to the presence of rice straw which has high contents of TS and TVS. It was observed that the decrease in their contents was higher in case of co-digester compared to digester only up to 40 days, may be due to the higher organic content in the co-digester than the digester which converted to biogas by anaerobic bacteria activation [40,41], and then remained virtually constant at a higher digestion time for both reactors. Figure 7C showed variations in COD during the reaction time for both reactors. The presence of rice straw in co-digester increased COD value by about 49% of that at digester due to the presence of rice straw, moreover, it was observed a similar trend for both reactors during digestion time and there was no difference between the both reactors for the removing of COD (around 12 g/L) during the reaction time.

Concentration of TN was found higher in the co-digester than that in digester, due to the presence of rice straw in co-digester (Figure 7D). However, a marked decrease in TN was detected for co-digester and digester up to 30 days of reaction time, and this is because the nutrients as nitrogen are conserved and mineralized to more soluble and biologically available forms [42] and can also be explained due to the conversion of some nitrogen into nitrogen gas during anaerobic decomposition, meanwhile, a slight increase was observed in co-digester at 40 days that may be related to the formation of ammonium ion (NH_4^+) during the biological processes [41,43].

Figure 7E showed that the pH was almost constant for digester during the digestion time, however, a marked decrease was observed for co-digester after ten days of digestion time. This may be attributed to acidogenic bacteria that produce organic acid which tend to lower the pH under normal conditions. The pH value increased at 40 days, reaching to the initial value. This increase may be explained due to the bicarbonate produced by methanogens [37] and the formation of ammonia, which usually formed in anaerobic processes as a result of mineralization of organic nitrogen [41], moreover, prolific methanogenesis may result in a higher concentration of ammonia [44]. Then pH values remained constant at higher digestion time. These results were similar to results obtained by Lei et al. [25].

However, the pH values through digestion process for both reactors were relatively in optimum range (6.5-7.5) which is favorable for the performance, stability, and to obtain maximal biogas yield [37-39].

Conclusions

Wastewater activated sludge and rice straw are produced in large quantities with serious effects on the environment. In this study, co-digestion of WWAS with grinded rice straw at different ratios (0.5-3.0%) was performed using batch model to investigate the effect of co-digestion of on biogas production. The results showed that the co-digestion of WWAS with rice straw improved biogas production compared to sludge digestion. Moreover, the biogas yield increased with the increasing of the rice straw content, it reached at 3.0% mixing ratio four times the amount released from the digested sludge only. The obtained results from semi-continuous reactor showed that the co-digestion increased total biogas amount continuously and no significant effect on the digested material characteristics which was

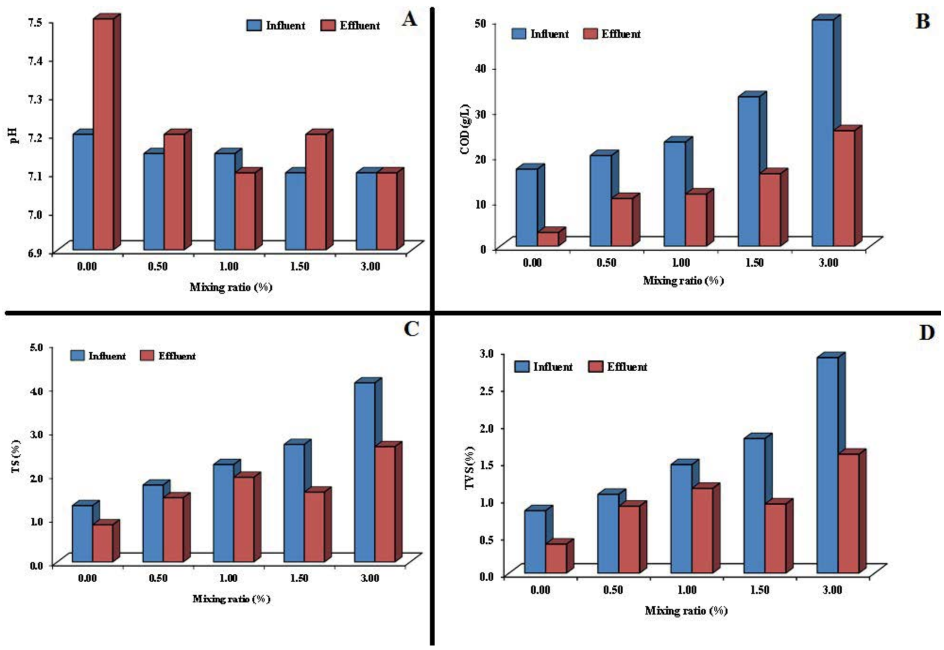

Figure 5: Characteristics of influent and effluent for the batch model with digestion time (80 days). A. pH. B. COD. C. TS. D. TVS.

Components	Composition %	
	Digester	Co-digester
Nitrogen	2.21	5.6
Methane	62.11	60.85
Carbondioxide	35.68	33.55

Table 2: The composition of the released biogas from digester and co-digester.

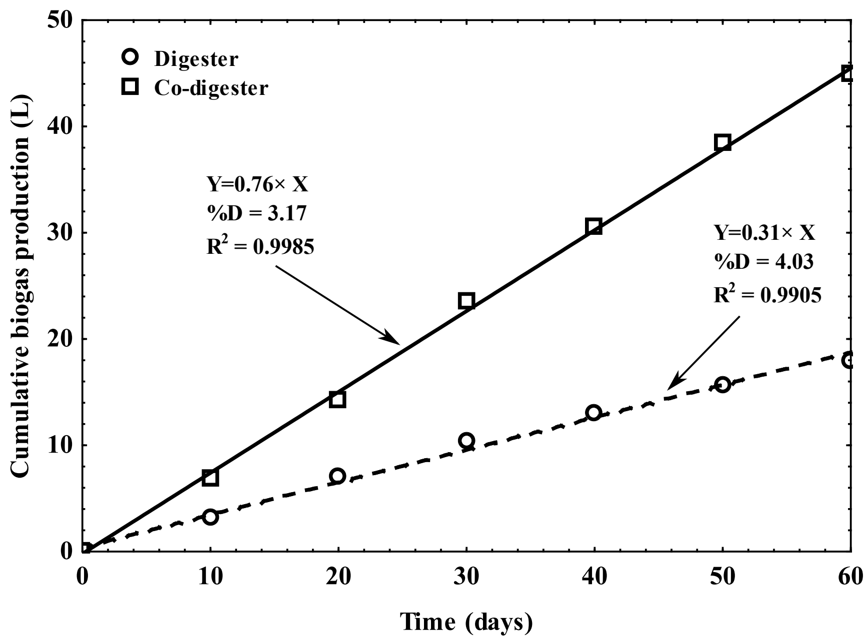

Figure 6: Cumulative biogas production via digestion and co-digestion for semi-continuous model.

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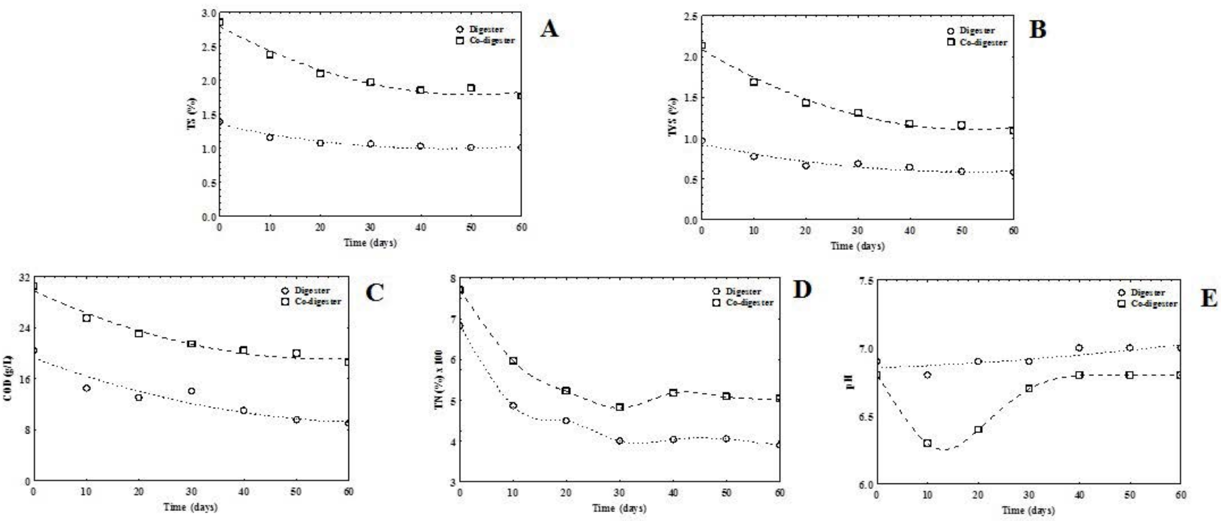

Figure 7: Characteristics variation of digested samples from digestion and co-digestion reactors during the digestion time in semi-continuous model. A. TS. B. TVS. C. COD. D. TN. E. pH.

noticed with the increase of the digestion time, although, no significant effect on methane percentage in the produced biogas was observed but its volume was increased due to the increase in the volume of produced biogas. Thus, the co-digestion of WWAS with rice straw using the existing digester is attractive option and could be beneficial to increase biogas production.

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