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Biogas production using dry fermentation technology through co-digestion of manure and agricultural wastes

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Abstract
Recently, dry anaerobic co-digestion is one of the mechanisms which have been increasingly used to improve the reactor's performance for treating livestock manure with agricultural crop residues. Due to carbohydrate, protein and lipid existing in agricultural wastes, biogas yield decreased with higher reactor volume when using wet anaerobic digestion. In this regard, the aim of this work was to achieve the production of biogas using the dry anaerobic technology through livestock manure co-digestion with agricultural waste (AW) such as potato peels, lettuce leaves and peas peels. The manure and AW were mixed at a ratio of 2:1 for 15 min before being introduced into the batch anaerobic system. The results indicated that the co-digestion of lettuce leaves and manure yielded the highest production of methane and biogas which were 6610.2 and 12756.7 ml, respectively, compared to the control (manure) that yielded 4689.9 ml and 11606.7 ml, respectively. Additionally, the results indicated that the co-digestion of lettuce leaves and manure yielded the highest specific production of methane and biogas which were 405.5 ml CH_4 g^{-1} VS and 782.6 ml biogas g^{-1} VS, respectively, compared to the mono-digestion of manure (control) that yielded 328 ml CH_4 g^{-1} VS and 633 ml biogas g^{-1} VS, respectively. Eventually, dry anaerobic co-digestion process is an effective approach to waste treatment.

Keywords Dry fermentation · Biogas · Co-digestion production · Crop residues · Livestock manure

1 Introduction

The production of agricultural wastes is anticipated to increase by 44% from 2005 to 2025 in the coming years, particularly in developing countries. Accordingly, these countries dispose the agricultural wastes by landfills or incineration. Consequently, it is required to improve or upgrade techniques that specify convenient handling of these bio-wastes

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(Melikoglu et al. 2013; Capson-Tojo et al. 2017). The agricultural wastes emission 3 Gt CO_2 equivalents of greenhouse gases (GHGs) that reported by the Food and Agriculture Organization (FAO) of the United Nations estimated 750 billion US dollars. Subsequently, wastes represent one of the greatest opportunities to produce renewable fuels (FAO 2013; Eriksson et al. 2017; Tayyab et al. 2019). In the European agricultural sector, animal manure and agro-industrial wastes are mainly released in liquid form, and continuous wet anaerobic digestion in continuous stirred tank reactor (CSTR) reactors is the dominant technology. Alternately, in the MENA region, wastes are often generated in solid form, due to extensive agricultural practices and dryer climate conditions. Furthermore, smaller amounts of waste are generated at community level; hence, biogas technology must be deployed at smaller scales (Abdelsalam et al. 2019, 2020; Anjum et al. 2016).

Anaerobic digestion is a naturally process that allows the growing of microbial communities in the absence of oxygen to accelerate the biological pretreatment of organic substrates. In addition, it is an effective and environmental-friendly treatment of organic wastes and their valorization in the form of several products (Abdelsalam et al. 2018; Xu et al. 2019; Hijazi et al. 2020a). One of the main problems facing the mono-digestion of substrates is the digester instability which found to be occurred because of the rapid degradation of organic nitrogen. This is could lead to decrease the biogas yield during the anaerobic digestion process of organic wastes (Pan et al. 2015; Giuliano et al. 2013; Sawatdeenarunat et al. 2015). There are different operators such as hydraulic retention time (HRT), temperature, carbon-to-nitrogen ratio (C:N ratio) and pH that effect on the consortium of microorganisms; these microorganisms represent the main player in the anaerobic digestion (AD) process (Ali et al. 2019; Tayyab et al. 2019; Abdelsalam and Samer 2019).

Recently, it was found the anaerobic co-digestion (ACoD) of lingo-cellulose with animal manure could improve the reactor's performance with balanced nutrients (Gabriel et al. 2017; Xu et al. 2019; Hijazi et al. 2020b). Moreover, the co-digestion of carbohydrate-rich lingo-cellulosic with nitrogen-rich in livestock manure offers a solution to equilibrium the C:N ratio of the substrate (Chiu and Lo 2016; Samer et al. 2019, 2020). Furthermore, ACoD can prevent the digestion of cellulose consequent from short the residence time of the substrates (Sawatdeenarunat et al. 2015).

The dry anaerobic digestion is assessed as a new technology and a promising approach for small-scale biogas production from solid waste in the agriculture sector (Bayrakdar et al. 2017). The most important features of this technology are the small size, easy maintenance and simplicity of the digester process; it doesn't occasion any troubles for foam, surface crust and sedimentation furthermore. Also, it doesn't require any additional energy for stirring (Alper et al. 2017; Xu et al. 2019).

Based on above, some researchers reported an increasing of 65%, 58% and 16% of methane production by using of AcoD with sugar beet, some grass and several straws tops, respectively. Also, the cumulative methane yield was increased by 26.64% from cow's manure and straw from oat during AcoD process (Lehtomäki et al. 2007; Zhao et al. 2018; Ning et al. 2019). Furthermore, the addition of limonite to the dry AD techniques of wasted organic could lead to increase both of the biodegradation efficiency and the rate of protein methane generation. In addition, methane production from organic wastes can be used as a basis of environmentally friendly and clean energy for the transportation, industries and residential premises (Matheri et al. 2017; Xu et al. 2019).

The equalization between production and inhibition was a mix of 40% v/v roadside grass cuttings and 60% v/v solid cattle manure at experiment scale when using co-digestion by the dry process (André et al. 2019). On the other hand, the most important material containing high value of nitrogen element was goat manure and it could produce the highest biogas yield from different co-substrates such as 30 goat manure:70 corn stalks, 70 goat manure:30 corn stalks, 30 Goat manure:70 rice straw and 50 Goat manure:50 rice straw (Zhang et al. 2013), while the highest methane yield was produced from food waste co-digested with cattle manure. Furthermore, the highest quality and quantity of bio-manure with highest nutrients can be achieved by using dry anaerobic digestion Arelli et al. (2018) and Yang et al. (2015). In another way, mixing 2 or more substrates can improve the methane yield by ACoD as outcome of increased biodegradability. For instance, blending a (65–70%) of yogurt whey and wheat straw with a C:N ratio of (26–27.5) with chicken litter (30–35%) realized maximum methane production (Zahan et al. 2017).

In view of the foregoing, the purpose of this study was examining the production of biogas using the dry fermentation technology through livestock manure co-digestion with agricultural waste (AW) such as potato peels, lettuce leaves and peas peels. In addition, this paper aims at reducing the knowledge gaps in the dry anaerobic co-digestion process.

2 Materials and methods

2.1 Fresh manure and agricultural wastes samples

Feces and urine as fresh raw manure were collected at random from cows housed in livestock cowsheds at the Experiment Station of the Faculty of Agriculture at Cairo University. Furthermore, the following 3 agricultural wastes (AW) potato peels, lettuce leaves and peas peels were selected for co-digestion with cow manure as shown in Table 1, where the mixing ratio of cow manure to an agricultural waste was 2:1 (weight basis).

2.2 Substrate analysis

The substrate pH (initial and final) was detected by an electrode (QIS, proline B210, Oosterhout, Netherlands). Also, organic carbon, ash, volatile solid (VS) and total solids (TS) were estimated during the standard methods (EPA METHOD 1684, 2001) utilizing muffle furnace (Vulcan D-550, Ney Tech, York, USA).

2.3 Experimental setup

In this research, a biogas production system (Fig. 1) was commissioned following recommendations of Samer (2010). This batch consists of: (1) a biodigester is 1000 ml screw cap bottle (Borosilicate glass, Simax, Czech Republic) plugged into gas outlet

Table 1 Characteristics of different wastes used in co-digestion experiment

Item	Manure	Potato peels	Lettuce leaves	Peas peels
Total solids, TS%	22.92	20.57	5.77	16.55
Volatile solids, VS%	14.32	18.73	4.19	15.47
VS (% as TS)	62.52	91.07	72.73	93.46
Ash (%)	8.59	1.84	1.57	1.08
Organic carbon (%)	36.26	52.83	42.19	54.21
pH	6.27	5.75	5.34	5.23

Fig. 1 Biogas production system

that attached the gas holder with 1/400 connectors via 8 mm polyethylene tube; (2) a water bath (Raypa, BAD-12, Barcelona, Spain) equipped with thermostat that controls water temperature, wherever mesophilic condition was maintained (37.5 ± 0.3 °C); (3) gas measurements; the biogas volume was daily determined using transparent graduated polypropylene (PP) tube (1000 ± 10 ml, Azlon, Staffordshire, UK) attached to gas outlet by polyethylene tube (8 mm)to the bottom and inversely inserted in a second PP tube (2000 ml, Azlon) filled with water. In addition, CO_2 and CH_4 concentrations were measured by a multigas analyzer (Biogas 5000, Geotech, Warwickshire, UK). Dual-wavelength infrared cell used to calculate CH_4 and CO_2 with reference channel.

2.4 Experimental design

Batch operation used 1000-ml biodigesters as laboratory experiments. Each AW was grinded and mixed thoroughly for 15 min with manure to obtain the co-digestion substrates under dry fermentation condition at total solids TS > 20% as shown in Table 2. Manure + potato peels (M + Pot), manure + lettuce leaves (M + Let) and manure + pea peels (m + Pea) were used in system of production biogas (Abdelsalam et al. 2018) under mesophilic condition (37.5 °C) for 45 days of anaerobic digestion, in addition to manure only as control.

Table 2 Characteristics of different wastes used in co-digestion experiment under dry fermentation condition

Item	Manure (control)	M + Pot (2:1)	M + Let (2:1)	M + Pea (2:1)
TS, %	22.9	35.5	21.8	34.4
VS, %	14.3	29.2	16.3	28.4
VS (% as TS)	62.5	82.1	74.2	82.3
Ash (%)	8.6	6.3	5.5	6.0
Organic carbon (%)	36.3	47.6	43.0	47.7
pH	6.3	6.1	6.1	6.1

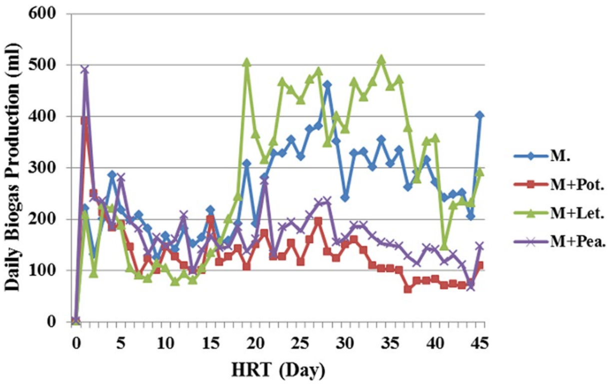


Fig. 2 Daily production of biogas affected by different agricultural wastes as co-digestion with manure

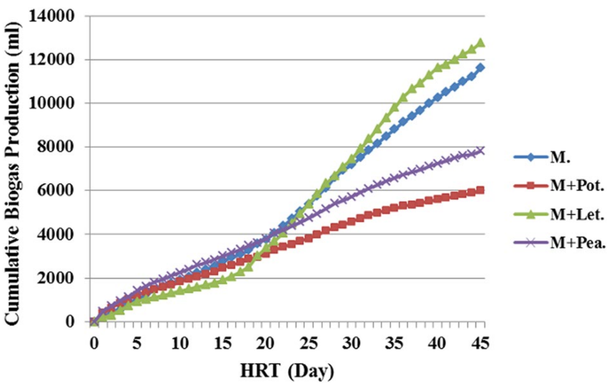


Fig. 3 Cumulative production of biogas affected by different agricultural wastes as co-digestion with manure

2.5 Statistical analysis

Each treatment was launched in triplicates to conduct the statistical analysis study for assessing production of biogas production and concentration of methane concentration by using dry anaerobic co-digestion, and analyzed using least significant difference (LSD, SPSS software version 19) at a significance level of $p < 0.05$.

3 Results

3.1 Biogas production

Figures 2 and 3 illustrate the cumulative and daily of biogas production by different agricultural wastes as co-digestion with manure. At the beginning, the most biogas produced substrates with manure and pea peels which yielded 490 ml at the first day of HRT. Furthermore, the top value of the production was 503.3 ml biogas with manure with lettuce leaves. In addition, manure with lettuce leaves treatment delivered the highest production of biogas until day 40. Moreover, biogas production from manure delivered the highest till day 45 which is the last day of the experiment. However, the accumulative value of biogas yielded from the co-digestion of manure with lettuce leaves delivered the highest biogas yield at 45 days of HRT and 12756.7 ml compared with other treatments. In addition, the yield of biogas using mono-digestion of manure reached 11606.7 ml.

The results indicated that the co-digestion of lettuce leaves and manure yielded the highest production of methane and biogas which were 6610.2 and 12756.7 ml, respectively, compared to the control (manure) that yielded 4689.9 ml and 11606.7 ml, respectively. Additionally, the results indicated that the co-digestion of lettuce leaves and manure yielded the highest specific production of methane and biogas which were 405.5 ml CH_4 g^{-1} VS and 782.6 ml biogas g^{-1} VS, respectively, compared to the mono-digestion of manure (control) that yielded 328 ml CH_4 g^{-1} VS and 633 ml biogas g^{-1} VS, respectively.

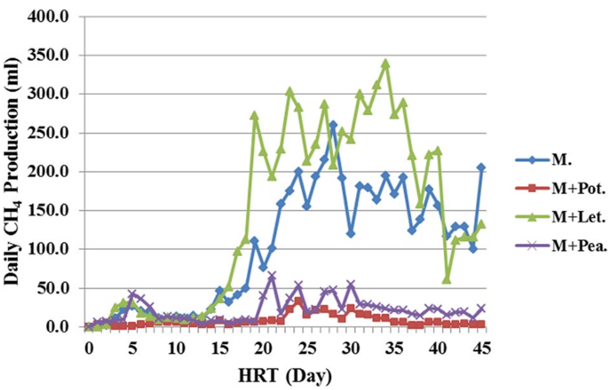
3.2 Methane concentration

All different treatments are explained in Fig. 4 to show the CH_4 concentration. The manure with lettuce leaves delivered the highest CH_4 contents during the dry anaerobic co-digestion process and recorded 45.4% CH_4 of HRT as average of the first 20 days. Moreover, this treatment accomplished the maximum peak of CH_4 contents during days from 30 to 36, while no other treatments achieved as high as this treatment.

3.3 Methane production

The manure with lettuce leaves achieved the top daily production of methane on day 34, where it yielded 340 ml. Furthermore, the daily methane production was achieved when the treated with manure which realized 259.76 ml. While, no other treatments achieved as high as this treatment (Figs 5, 6). In addition, the cumulative production of methane curves stated that the manure with lettuce leaves and manure increased the methane production at 45 days of HRT and 6610.2 and 4689.9 ml, respectively, in comparison with the manure with pea peels and manure with potato peels which yielded 993.7 and 376.9 ml, respectively. On the other hand, Table 3 briefs the overall average of organic matter analysis before and after digestion.

Fig. 4 CH_4% affected by different agricultural wastes as co-digestion with manure



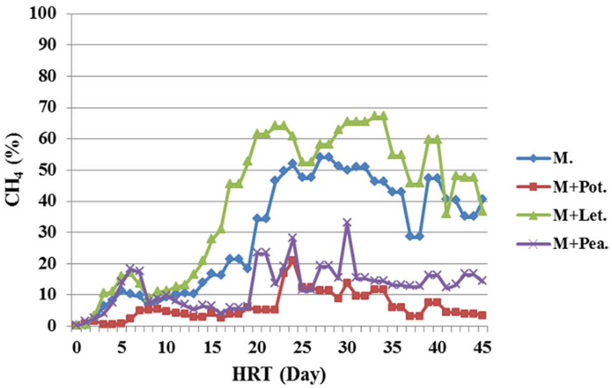


Fig. 5 Daily production of methane affected by different agricultural wastes as co-digestion with manure

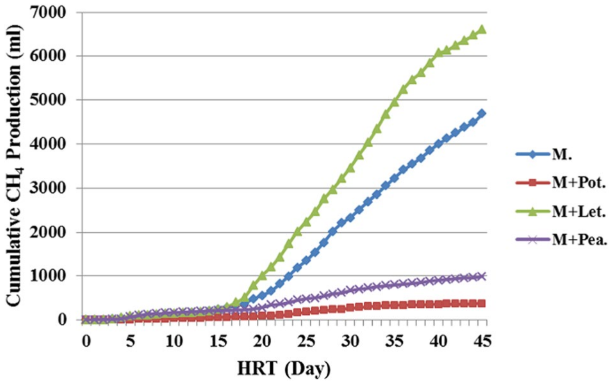


Fig. 6 Cumulative production of methane affected by different agricultural wastes as co-digestion with manure

Table 3 Overall average of organic matter analysis before and after digestion

Item	Manure		M + Pot (2:1)		M + Let (2:1)		M + Pea (2:1)	
Total solids, TS%	22.9	17.6	35.5	19.1	21.8	13.5	34.4	18.3
Volatile solids, VS%	14.3	8.9	29.2	12.6	16.3	7.4	28.4	12.0
VS (% as TS)	62.5	49.8	82.1	66.0	74.2	55.0	82.3	65.8
Ash (%)	8.6	8.7	6.3	6.5	5.5	6.1	6.0	6.3
Organic carbon (%)	36.3	28.9	47.6	38.3	43.0	31.9	47.7	38.1
pH	6.3	7.0	6.1	6.8	6.1	7.8	6.1	6.6

3.4 Results of the statistical analysis

Table 4 indicates that there is significant difference ($p < 0.05$) in the results for biogas production between manure and manure with potato peels, also there is significant difference ($p < 0.05$) between manure and manure with pea peels, but there is no significant difference ($p > 0.05$) between manure and manure with lettuce leaves. On the other hand, there is significant difference ($p < 0.05$) when comparing manure with potato peels

Table 4 Yield of biogas (dependent variable) compared to the different treatments

(I) Treatment	(J) Treatment	Mean difference (I-J)	Sig
M	M + Pot	124.593*	4.7E−10
	M + Let	−25.556	1.93E−01
	M + Pea	84.296*	2.1E−05
M + Pot	M	−124.593*	4.7E−10
	M + Let	−150.148*	9.4E−14
	M + Pea	−40.296*	4.06E−02
M + Let	M	25.556	1.93E−01
	M + Pot	150.148*	9.4E−14
	M + Pea	109.852*	3.5E−08
M + Pea	M	−84.296*	2.1E−05
	M + Pot	40.296*	4.06E−02
	M + Let	−109.852*	3.5E−08

*Significant difference ($p < 0.05$)

to manure with lettuce leaves and manure with pea peels. In addition, there is significant difference ($p < 0.05$) between manure with lettuce leaves and manure with pea peels.

The results for methane production (Table 5) showed that there is significant difference between manure (control) and all other treatments. However, there is significant difference between manure with potato peels and manure with lettuce leaves, but there is no significant difference between manure with potato peels and manure with pea peel.

4 Discussion

Several studies have investigated the co-digestion of different substrates. Wang et al. (2018) investigated the effect of addition of biogas slurry of initial mushroom slag for anaerobic fermentation of deer manure on biogas production, where they found that the addition of biogas slurry increased biogas production from deer manure, whereas Li et al. (2020)

Table 5 Yield of methane (dependent variable) compared to the different treatments

(I) Treatment	(J) Treatment	Mean difference (*i*–*j*)	Sig
M	M + Pot	95.84481*	7.75E−13
	M + Let	−42.67267*	1.15E−03
	M + Pea	82.13830*	6.44E−10
M + Pot	M	−95.84481*	7.75E−13
	M + Let	−138.51748*	5.12E−24
	M + Pea	−13.70652	2.94E−01
M + Let	M	42.67267*	1.15E−03
	M + Pot	138.51748*	5.12E−24
	M + Pea	124.81096*	4.10E−20
M + Pea	M	−82.13830*	6.44E−10
	M + Pot	13.70652	2.94E−01
	M + Let	−124.81096*	4.10E−20

*Significant difference ($p < 0.05$)

studied of the performance of biogas production by mixed fermentation of cow dung, deer manure and mushroom fungus, where they found that the mixed fermentation of livestock manure and mushroom fungus is made up for the inadequacy of its separate fermentation performance and was also an effective method to improve the biogas rate and comprehensive utilization rate of livestock manure. Such studies have stimulated further investigations of agricultural wastes co-digestion such as the present study.

According to the results of the present study, it was found that the co-digestion of the manure and AW at the ratio of 2:1 enhanced the anaerobic digestion process. In addition, the highest amount of methane (6610.2 ml) and biogas (12756.7 ml) was produced from manure with lettuce leaves compared to the control (manure) which yielded 4689.9 ml and 11606.7 ml, respectively. This result can be attributed to VS removal and pH temporal evolution of multiple wastes (livestock waste, agricultural residue and organic fraction of household waste) which can lead to increase the production of methane and biogas. These results are in agreement with the statements of the literature (Yang et al. 2015; Gabriel et al. 2017; Ning et al. 2019; Xu et al. 2019), where they found that one of the main reasons for improving biogas and methane production is the initial mixing of different materials with digestate because this determined an efficient inoculum of AD bacteria. On the other hand, the recirculation of leachate encourages for determining further inoculum, transporting and spreading microorganisms and metabolites in the media, increasing moisture content and therefore increasing and improving the production of biogas (Shahriari et al. 2012; Andrè et al. 2015). Moreover, our results are supported by Wu et al. (2010) and Zhang et al. (2013) as well as Chiumenti et al. (2018) where they found an increasing production of biogas and net CH_4 volumes at all C:N ratios in the co-digesting of manure (swine or goat) with different types of agricultural wastes. Also, our results are in agreement with Wu et al. (2010) for maximizing the process performance, where the quantity of added materials is depending on the requirement of C:N ratio, while Zahan et al. (2017) showed increasing concentrations of substrate lead to decrease the production of biogas. In contrast to our results, Chiumenti et al. (2018) concluded that the production of biogas is comparable in wet and dry digestion process.

The results of the present study indicated that the co-digestion of lettuce leaves and manure yielded the highest specific production of methane and biogas which were 405.5 ml CH_4 g^{-1} VS and 782.6 ml biogas g^{-1} VS, respectively, compared to the mono-digestion of manure (control) that yielded 328 ml CH_4 g^{-1} VS and 633 ml biogas g^{-1} VS, respectively. According to the literature, Dima et al. (2020) found that the experimental methane yield of the anaerobic co-digestion of manure with agricultural wastes was 358.4 ml CH_4 g^{-1} VS which is comparable to the results of the present study. Additionally, Meng et al. (2020) found that vinasse straw co-digestion showed the cumulative biogas yield was 633.4 ml g^{-1} VS which is comparable to the results of the present study. Besides, Zahan and Othman (2019) found that the anaerobic co-digestion of chicken litter with agricultural and food wastes produced biogas of 321.6 ml g^{-1} VS which is comparable to the results of the present study.

5 Conclusions

Based on the outcomes of this work, these inferred that manure with lettuce leaves yield the highest production of biogas and methane, whereas manure with potato peels and manure with pea peels produce lowest production of biogas and methane compared to the control (manure only). Therefore, this study can recommend using dry anaerobic co-digestion process in the biogas production, whereas the highest production of methane and biogas was 6610.2 and 12756.7 ml, respectively, compared to the control (manure) that yielded 4689.9 ml and 11606.7 ml, respectively. Dry anaerobic co-digestion process is an effective approach to waste treatment that can be incorporated into existing biogas production systems.

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