Enhancing methane yield from duck waste by co-digestion with *Xyris capensis*

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Abstract. This study examined the possibilities of enhancing methane yield from anaerobic digestion of *Xyris capensis* and duck wastes based on improved feeding composition and the C/N ratio. Batch anaerobic digestion of *Xyris capensis* and duck wastes was conducted at mesophilic temperature (37 ± 2 °C) with the mixing ratios of 100:0, 75:25, 50:50, 25:75, and 0:100% of duck wastes: *Xyris capensis*. The highest methane yield of 301.17 mL CH_4/ gVS_{added} was recorded when the mixing ratio of 50:50% (duck wastes: *Xyris capensis*) and C/N ratio of 19.26 was digested. The biodegradability (BD) of duck wastes and *Xyris capensis* were 86.60 and 58.57%, respectively. The BD of duck wastes increases with the addition of *Xyris capensis*, and it started to decline after a 50:50% mixing ratio. A stronger synergistic influence of co-digestion was noticed compared to mono-digestion of the individual of each feedstock. This study showed a better performance of anaerobic co-digestion and can be used to enhance feeding composition and the C/N ratio. In general, methane production from duck wastes co-digested with *Xyris capensis* is a good strategy to generate renewable energy and minimize waste management challenges.

Keywords: Anaerobic co-digestion, duck wastes, *Xyris capensis*, methane.

1 Introduction

Reliance on fossil fuels as the primary energy is still prevalent in developing countries, and it is expensive and pollutes the environment [1]. One bright way to solve these challenges is to engage in biofuel production, a form of renewable and sustainable energy source. Bioenergy can be considered the most subsistent renewable energy origin because of its economic merits and remarkable capacity to substitute for fossil fuels. Bioenergy is renewable energy generated from biomass materials, and it can be released from various origins and generated with several technologies [2]. Biogas is an example of bioenergy that is produced through anaerobic digestion, and it is flexible to various biodegradable materials. Biogas production can assist in lowering greenhouse gas emissions and sustainable energy supply [3]. Anaerobic digestion improves the upcycling of organic waste materials into high-end outputs of biogas, and digestate that is rich in a nutrient that can serve as a nutrient source for plants [4]. Biogas clean energy is a potential, sustainable energy that can substitute for highly dependent fossil fuels, and digestate can replace chemical fertilizer and is a bright means of reducing the carbon footprint in the ecosystem [5].

Anaerobic digestion has been observed as an alternative to manure disposal in landfill sites; nevertheless, the low carbon to nitrogen (C/N) ratio in livestock wastes hinders anaerobic digestion. Therefore, for efficient anaerobic digestion of livestock wastes, there is a need to introduce carbon-rich feedstock to be co-digested to compensate for the carbon deficiency and enhance its characteristics for biogas production [6]. Lignocellulose feedstock includes agricultural residues, forestry wastes, etc., and they are potential feedstocks with a high carbon content that can compensate for carbon deficiency in livestock wastes. Lignocellulose feedstock digestion is restricted by their slow digestion and subsequent low methane production. Biogas production efficiency of lignocellulose feedstocks can be enhanced with different pretreatment methods nevertheless, pretreatment might make the process uneconomical [7]. Anaerobic co-digestion of livestock wastes, and lignocellulose feedstocks provides an opportunity to balance the C/N ratio of the anaerobic digestion feedstocks. Some of the merits of co-digestion include improving the buffering capacity, diluting the potentially toxic compounds, using the nutrients, bacterial adversity, and reducing ammonia risk [6,8]. Several works of literature have reported their findings on anaerobic co-digestion of livestock manure and lignocellulose feedstocks or other carbon-rich materials. Kaur and Kommalapati studied the methane potential from co-digestion of goat manure and cotton gin trash, and it was observed that methane yield was improved compared to mono-digestion of individual feedstock [9]. Co-digestion of swine manure and peanut hulls was reported that the C/N ratio significantly influences the methane yield, and the appropriate mixing ratio releases the highest methane yield [10].

It can be inferred from the literature that co-digestion of different feedstocks improves the methane yield, lowers the retention time, and enhances the unit's treatment capacity. Nevertheless, co-digestion of feedstock proportions and their subsequent methane potential for several organic materials for anaerobic

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digestion is yet to be ascertained, let alone optimization. Therefore, this study aimed to study the influence of *Xyris capensis* and duck waste co-digestion on methane yield, biodegradability, and synergetic effect index, which is still missing in the literature.

2 Material and method

2.1 Materials sourcing

Xyris capensis and duck waste used for this study were sourced locally. The *Xyris capensis* was chopped into small sizes (2 – 4 mm), dried at room temperature, stored in zipped plastics, and kept in the laboratory for further processing. Stones, feathers, and other impurities in the duck waste were removed and then stored at -20 °C to prevent decomposition. The inoculum used was collected from a nearby biogas digester and stored at 4 °C. The feedstock samples and inoculum were investigated for total solids, volatile solids, C/N ratio, Sulphur, hydrogen, and oxygen according to the AOAC official standard [11].

2.2 Experimental setup

The anaerobic co-digestion of *Xyris capensis* and duck waste was experimented with in a laboratory-scale batch digester according to VDI 4630 at mesophilic temperature (37 ± 2 °C) [12]. Five Schott Duran were utilized as digesters, each having a total capacity of 1000 ml and a working volume of 800 ml. The amount of *Xyris capensis* and duck wastes were charged into the digester as calculated with equation 1, using volatile solids of 2: 1 of solid: inoculum. The mixing ratio charged into each digester was presented in Table 1, according to the earlier study, with slight adjustments [13]. The digestion was duplicated twice, and two digesters with only inoculum were run parallel to determine the volume of gas generated by the inoculum. Nitrogen gas was utilized to flush out the oxygen in the digester to set up the anaerobic conditions. The digesters were placed in the water bath set at 37 ± 2 °C, and the gas produced was stored inside calibrated gas bottles mounted on the digester bottles. The gas-generated volume was ascertained from downward water displacement. Reading of the gas volume generated was taken daily and gas quality was measured at intervals using a gas analyzer (BioGas, Geotech GA5000, Warwichshire, UK). The gas released from the parallel digesters was removed from the digesters with substrate and inoculum to ascertain the actual yield from the substrates. Atmospheric temperature and pressure were also noted daily, and the digesters were shaken manually once daily for homogeneity, to break scum, and to remove trapped gases. The experiment was terminated by day 24 when it was discovered that the daily gas yield was below 1% of the total gas produced.

$$M_s = \frac{M_i C_i}{2C_S} \quad (1)$$

Where: M_s = Mass of the substrate (g), M_i = Mass of inoculums (g), C_s = Concentration of substrate (%), C_i = Concentration of inoculum (%). The inoculum required is 80% of the reactor volume [12].

Table1: Anaerobic co-digestion digesters with different feedstock ratio

Digester	Duck waste (%)	*Xyris capensis* (%)
A	100	0
B	25	75
C	50	50
D	75	25
E	0	100

2.3 Theoretical methane yield (TMY)

The theoretical methane yield of duck waste and *Xyris* capensis were calculated from the chemical composition of the feedstocks using Buswell Muller's relations presented in equation 2 [14].

$$C_aH_xO_yN_z + \left(a - \frac{x}{4} - \frac{y}{2} - \frac{3z}{4}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{x}{8} - \frac{y}{4} - \frac{3z}{8}\right) CH_4 + \left(\frac{a}{2} - \frac{x}{8} + \frac{y}{4} + \frac{3z}{8}\right) CO_2 + zNH_3 \quad (2)$$

$$TMY \left(\frac{mLCH_4}{gVS}\right) = \frac{22.4\ X\ 1000\ X\ \left({}^{a}/_{2} + {}^{x}/_{8} - {}^{y}/_{4} - {}^{3z}/_{8}\right)}{12a + x + 16y + 14z} \quad (3)$$

2.4 Biodegradability

The volatile portion of a feedstock converted to methane during anaerobic digestion is referred to as anaerobic biodegradability (BD). The biodegradability of the co-digestion at different mixing percentages was calculated using the experimental cumulative methane yield (EMY) observed from the experiment and the theoretical methane yield (TMY) as presented in equation 4 [15].

$$BD\ (\%) = \frac{EMY_{CO}}{(TMY_1\ X\ V_1) + (TMY_2\ X\ V_2)}\ X\ 100 \quad (4)$$

Where: EMY_{co} is the methane potential of co-digestion; TMY_1 is the theoretical methane potential of *Xyris capensis*; TMY_2 is the theoretical methane potential of duck waste; V_1 is the volatile solid portion of *Xyris capensis*; and V_2 is the volatile solid portion of duck waste.

2.5 Synergistic effect index

Equation 5 was used to calculate the synergistic effect index (SEI) of the anaerobic co-digestion of *Xyris capensis* and duck waste as prescribed by Li et al. [15].

$$SEI\ (\%) = \frac{EMY_{CO} - (EMY_1\ X\ V_1 + EMY_2\ X\ V_2)}{(EMY_1\ X\ V_1 + EMY_2\ X\ V_2)}\ X\ 100 \qquad (5)$$

Where: EMY_{co} is the methane potential of co-digestion; EMY_1 is the methane potential of *Xyris capensis*; EMY_2 is the methane potential of duck waste; V_1 is the volatile solid portion of *Xyris capensis*; and V_2 is the volatile solid portion of duck waste.

3 Result and Discussion

3.1 Physicochemical characteristics of feedstocks and inoculum

The feedstocks and inoculum were characterized for total solid (TS), volatile solid (VS), nitrogen content, carbon content, percentage hydrogen, and C/N ratio, and the findings are in Table 2. It can be observed from the Table that the TS of *Xyris capensis* and duck waste are 84.62 and 91.61%, respectively. Compared with similar feedstocks, rice straw, and wheat straw have 94.09 and 86.10%, while chicken manure and dairy manure have 26.80 and 14.40%, respectively [16,17]. It can be noticed that the percentage of TS reported for both *Xyris capensis* and duck waste is higher compared with other similar lignocellulose materials and livestock wastes. Total solid is a crucial parameter that affects the anaerobic digestion process. TS of 25 – 30% has been observed to lead to the formation and release of effluent associated with mass losses [18]. A total solid between 28 and 40% is mostly reported as a rough estimate for optimum biogas production. The total solid of these feedstocks was observed to be higher than the recommended percentage. Therefore, the calculated volume of water was added to reduce the TS to the recommended percentage [12]. The percentage VS observed for *Xyris capensis*, and duck waste are 95.00 and 47.18%, respectively. These values are higher compared to similar feedstocks, rice straw (80.50%), wheat straw (90.60), digested cow dung (32.62%) but lower to groundnut shell (99.87%) and swine manure (74.80%) [10,16,17,19]. This high VS implies a high buffering capacity for microorganisms' degradation and sufficient methane potential of the feedstock [19]. The C/N ratios of 28.02 and 10.49 were observed for *Xyris capensis* and duck waste, respectively, and this was calculated from the percentage of carbon and nitrogen observed during elemental analysis. These C/N values are lower compared to similar substrate rice straw (43.00%), peanut hull (48.00%), cow manure (13.20%), and pig manure (13.50%) [10,17,20]. A higher percentage of carbon indicates sufficient carbon for methane production. In contrast, a lesser percentage of nitrogen reduces microbial activity since microorganisms need a considerable quantity of nitrogen to maintain growth, which can slow down the process. Literature has it that a C/N ratio of 20 – 30 is the most suitable range for anaerobic digestion. Outside this range, an increase in ammonia nitrogen, overaccumulation of volatile acids (VFAS), and free ammonia are possible [16]. Overaccumulation of VFAs or ammonia concentration in the digester will alter the pH of the process and make the environment toxic to the methanogenic bacteria and inhibit growth and subsequent reduction in methane yield [21]. It can be observed from Table 2 that the C/N ratio of *Xyris capensis* is within the recommended range, but duck waste has a low C/N ratio, whereas inoculum has a value above the recommended range, therefore anaerobic co-digestion of the feedstocks with the inoculum will assist in balancing the C/N ratio. These values of the C/N ratio have shown that the feedstocks and inoculum are suitable for anaerobic digestion.

Table 2: *Xyris capensis*, duck waste, and inoculum characterization

Parameter	*Xyris capensis*	Duck waste	Inoculum
Total solid (%)	84.62	91.61	19.12
Volatile solid (%)	95.00	47.18	91.67
Carbon (%)	41.47	34.42	42.57
Nitrogen (%)	1.48	3.28	1.23
Hydrogen (%)	5.38	4.38	5.50
Oxygen (%)	46.15	47.92	0.60
C/N ratio	28.02	10.49	34.61

3.2 Daily methane yield

The daily methane yields for mono and co-digestion of *Xyris capensis* and duck wastes are presented in Fig. 1. The Figure shows that the daily peak values differ in most of the treatments. It can be observed that daily methane yields of 25.00, 31.25, 28.57, 25.00, and 21.85

mL CH_4/ g VS_{added} were produced for treatments A, B, C, D, and E, respectively, at days 3, 3, 4, 4, and 9. It can be observed that treatment A has two daily peaks on days 3 and 4, and treatment B also has two daily peaks on days 3 and 6. It can be observed that all other treatments reached their daily peak yield between days 3 and 4 except treatment E (100% *Xyris capensis*), which was delayed till day 9. The daily peak methane yield observed in this study is higher than all the daily yields recorded when goat manure was co-digested with cotton gin trash [9]. It can be inferred from the result that duck waste was digested faster than the *Xyris capensis*; 100 and 75% of duck waste produced their first daily peak yield by day 3. But a further increase in the percentage of *Xyris capensis* increased the daily peak to day 4, while the daily peak methane yield for 100% *Xyris capensis* released its daily peak methane yield on day 9. This can be traced to the availability of the organic content of duck waste early in the digestion, such that methane release commenced immediately. *Xyris capensis* is a lignocellulose material with lignin and hemicellulose that prevents the cellulose from microorganisms' accessibility, thereby delaying methane release [7]. It can also be observed that co-digestion of *Xyris capensis* assisted in the startup of the methane yield, and the higher the percentage of duck waste, the earlier the daily peak of methane yield. It can be observed from Figure 1 that different compositions for co-digestion and mono digestion have other different daily peaks but are not up to the first daily peak discussed above. After 15 days, no other significant daily peak was noticed, and the daily methane yield declined steadily until day 25, when the experiment was terminated. This result agreed with a previous study that identified different daily peak values during anaerobic co-digestion [16]. This study corroborates a previous study that reports that anaerobic co-digestion lowers the retention time and improves daily methane yield compared to mono-digestion [8,20].

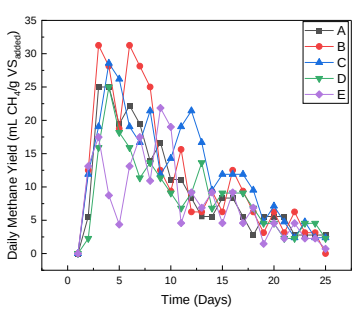

Fig. 1. Daily methane yield of mono and co-digestion of Xyris capensis and duck waste.

3.3 Cumulative methane yield.

The cumulative methane yield for mono and co-digestion of *Xyris capensis* and duck waste after 25 days of retention time is presented in Figure 2. It can be observed that methane yield of 241.67, 293.75, 309.52, 218.18, and 198.51 mL CH_4/ gVS_{added} for treatments A, B, C, D, and E. Compared with mono-digestion of *Xyris capensis*, it can be noticed that methane yield was improved by 21.74, 47.98, 55.92, and 9.91% for treatments A, B, C, and D, respectively. When the mono-digestion of the substrates was considered, it can be inferred that mono-digestion of duck waste produced higher biogas yield than mono-digestion of *Xyris capensis*. Studies have shown that lignocellulose feedstocks are recalcitrant, and this characteristic hinders the accessibility of methanogenic bacteria, thereby increasing the retention time and reducing the methane yield [7]. When 25% of *Xyris capensis* was co-digested with 75% duck waste, it can be observed that the methane yield was improved by 47.98% compared to mono-digestion of *Xyris capensis*, and 21.55% increase compared to mono-digestion of duck waste. This could be traced to the ability of co-digestion to balance the nutrient in the digester, as observed in the previous study [13]. The optimum cumulative methane yield of 309.52 mL CH_4 /gVS_{added} was recorded when 50% of *Xyris capensis* was combined with 50% of duck waste. This result represents a 28.08% improvement compared to the mono-digestion of duck waste and a 55.92% increase in methane yield compared to the mono-digestion of *Xyris capensis*. This implies that *Xyris capensis* and duck waste co-digestion can improve the methane yield once the appropriate mixing ratio is selected. Although, no investigation reports the co-digestion of *Xyris capensis* and duck waste before this study.

Nonetheless, several studies reported the influence of co-digestion of lignocellulose materials and livestock waste. Anaerobic co-digestion of cotton gin trash and goat manure was observed to release the optimum methane yield when the combination was 70% cotton gin trash and 30% goat manure [9]. In another related study, the highest methane yield was observed when pineapple waste was co-digested with cow dung at 50: 50% [22], as observed in this study. During the anaerobic co-digestion of sugar beet by-products and animal manure using a long-term continuous assay, it was observed that co-digestion reduced the retention time and improved methane yield by 70% [20]. Co-digestion of rice straw with food waste was observed to increase the methane yield by 71.09% compared to mono-digestion of either feedstock [16]. It can be noticed that from all the literature compared, the methane yields were improved compared to the mono-digestion, which aligned with the result from this study. Anaerobic co-digestion can overcome some of the

limitations associated with mono-digestion and improve energy recovery efficiency from co-digestion and managing various wastes together [16]. This process is a practical method to overcome feedstock characteristics and process optimization issues. The co-digestion of different feedstocks has been reported to provide nutrient balance, maintain stability, and improve the methane yield, but also minimize the cost of multiple waste treatments [9].

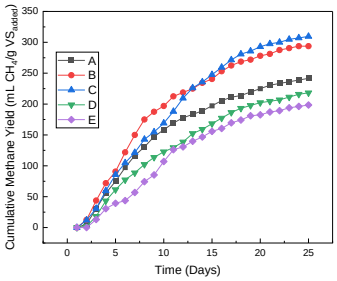

Fig. 2: Cumulative methane yield of mono and co-digestion of *Xyris capensis* and duck waste.

3.4 Biodegradability and synergetic effect

Table 3 presents the C/N ratio, theoretical and experimental methane yield, biodegradability, and synergistic effect of anaerobic digestion of duck waste and *Xyris capensis* for mono-digestion and co-digestion. It was noticed that the mixing ratio improves the C/N ratio of the feedstock compared to the mono-digestion of individual feedstocks. When the theoretical and experimental yield of the process was compared, it can be noticed that none of the combinations could release its total methane yield. This can be traced to factors such as lignin content, C/N ratio, the toxicity of the feedstock, etc. Co-digestion was observed to improve the methane release, which could result from balancing the C/N ratio, reducing toxicity, and lowering the resistance of the lignin portion. It can be inferred that with the increase of the feedstock with higher lignin content (*Xyris capensis*) beyond 50%, the experimental methane yield started declining. This can be traced to the rigidity of *Xyris capensis* due to the high lignin content that resists the activities of methanogenic bacteria [7]. It can be observed from the Table that the biodegradability of mono-digestion of duck waste and *Xyris capensis* are 86.60 and 58.57%, respectively. It can be noticed from the result that the rate of digestion of duck waste is higher than *Xyris capensis*, which can be traced to the level of lignin percentage of the individual feedstock. It can be inferred that biodegradability improved when 25% of *Xyris capensis* was combined with 75% duck waste. This can be linked to improvement in the C/N ratio of the process at this mixing ratio. It can also be observed from the Table that there is a small difference between the BD of 50:50% and 75:25% combination. It was noticed that an increase in the percentage of *Xyris capensis* slows down the rate of digestion of the co-digestion process. The best SEI value of 77.53% was recorded when the mixing ratio was 75: 25%. *Xyris capensis* utilized for this study was observed to have a lignin content of 30.23%, as observed in our previous study. Several pieces of literature have reported that feedstock with high lignin content lowers biodegradability and prolongs the retention time during anaerobic digestion [15,19]. Therefore, the low biodegradability of the mixing ratio with a higher percentage of *Xyris capensis* could be due to the lignin richness of the feedstock.

Table 3: Elemental formular, C/N ratio, theoretical and experimental biomethane potential, biodegradability, and synergistic effect index of duck waste and *Xyris capensis*.

DCW/XC	Elemental formular	C/N ratio	TMY (mL/g VSadded)	EMY (mL/g VSadded)	BD (%)	SEI (%)
100:0	$C_{12.17}H_{19.04}O_{13.04}N$	10.49	279.05	241.67	86.60	-
75:25	$C_{11.01}H_{17.21}O_{11.35}N$	14.87	296.95	293.75	98.92	77.53
50:50	$C_{9.85}H_{15.37}O_{9.65}N$	19.26	309.52	301.17	97.30	31.58
25:75	$C_{8.68}H_{13.54}O_{7.96}N$	23.64	316.47	218.18	68.94	50.43
0:100	$C_{7.52}H_{11.70}O_{6.26}N$	28.02	338.95	198.51	58.57	-

DCW – duck waste, XC – *Xyris capensis*, C/N ratio – carbon/nitrogen ratio, TMY – theoretical methane yield, EMY – experimental methane yield, BD – biodegradability, and SEI – synergistic effect index.

4 Conclusion

This study investigated the anaerobic co-digestion of *Xyris capensis* and duck wastes, and it was discovered that the co-digestion performed better than mono-digestion due to improved C/N ratios. Despite the high resistance of *Xyris capensis* to methanogenic bacteria, the highest methane yield was recorded at 50:50 of *Xyris capensis*: duck wastes. The complex structure of *Xyris*

capensis slows down the hydrolysis stage and the efficiency of the process can be improved by applying pretreatment methods. Therefore, the process is proven to be a successful means of waste management and can turn around 'waste to wealth', resulting in total usage of renewable energy resources in minimizing energy challenges, making it accessible, and reducing the environmental pollution.

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