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Anaerobic co-digestion of alkali-pretreated groundnut shells and duck waste for methane yield optimization and sustainable environment

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Abstract: This study investigated the effect of the anaerobic co-digestion of duck waste and alkali-pretreated groundnut shells at mesophilic temperature for methane yield optimization and waste management. Co-digestion of duck waste and alkali-pretreated groundnut shells was carried out using 100, 75: 25, 50: 50, 25: 75, and 100% duck waste: alkali-pretreated groundnut shells in a laboratory-batch digester at mesophilic temperature. The results indicated that anaerobic co-digestion of duck waste and alkali-pretreated groundnut shells is possible since no negative influence was observed during the joint digestion. It was observed that co-digestion released higher methane yield compared to mono-digestion. The optimum cumulative methane yield of 290 mL CH_4 g/ VS_{added} was recorded from a 75: 25% ratio of duck waste: alkali-pretreated groundnut shells. This mixing ratio improved methane yield by 38%. This study confirms that the anaerobic co-digestion of duck waste and alkali-pretreated groundnut shells can produce low-carbon fuel and economical waste management to maintain a sustainable environment.

Keywords: Renewable energy, anaerobic co-digestion, duck waste, groundnut shells, alkali pretreatment, methane.

1 Introduction

The demand for clean and sustainable energy is increasing daily due to the increase in population and industrialization. Fossil fuel is the major source of energy, and its combustion poses a direct threat to the environment and causes damage to the ecosystem [1]. Sourcing for a new novel green energy is the main challenge in the world at present. In this background, renewable energy from organic wastes can be the potential green energy for the future. It can be produced from organic waste and is a safe source for sustainable future productions [2]. The energy generated from biomass and other biodegradable materials is bioenergy. Replacing fossil fuels with these fuels that are renewable and free from impurities will help in reducing the environmental effect of waste and energy in use.

Anaerobic digestion technology for biogas production has existed for a long time, and it is simple and readily available for application at both household and commercial levels. Biogas is eco-friendly, renewable, cheap, clean, versatile, and high-quality fuel that is regarded as an alternative green energy source that can be used for different energy needs like transportation fuel, heating, and electricity generation [3].

Groundnut is a major leguminous crop grown in semiarid and tropical countries. In 2020, around 53,638,932 tonnes of groundnut were produced globally [4]. It is a pod made of about 65-75% seed, and the covering layer, referred to as the shell, is between 25 – 35% [5]. The main product of groundnut in most countries is oil because of its excellent protein content. After the groundnut processing, the bye products are shells and cake, and the potential of these bye products is not primarily used excellently [6]. Large quantities of groundnut shells are left on the farm or burnt off during processing annually, and the inherent energy is lost [7]. Research has shown that groundnut shells have excellent potential for biogas production. This potential can be part of the global path to zero-waste generation and low-carbon energy [8]. Groundnut shells are made of lignocellulose material, and their resistance to microbial attack during anaerobic digestion is a major challenge. Therefore, pretreatment before anaerobic digestion can influence the process and make it economical [9].

A large quantity of waste released from livestock production is a potential feedstock for generating clean and sustainable energy like biogas. In 2020, about 1 154 933 000 heads of duck were produced globally [10]. It has been observed that anaerobic digestion of animal waste can save about 20% of the energy required in their facility [11]. Despite their biogas production potential,

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animal waste could inhibit the activities of methanogenic bacteria because of their high content of nitrogen that produces ammonia during anaerobic digestion [12]. Co-digestion of animal manure and lignocellulose could improve and optimize the anaerobic digestion of feedstock with complementary/different characteristics [2]. Groundnut shells are rich in carbon, and animal manure is a potential feedstock to supplement nitrogen shortage during anaerobic digestion, including the supply of vital nutrients and minerals.

Therefore, this study aimed at widening and improve knowledge in the anaerobic co-digestion of complementary feedstocks, giving insight into the influence of animal waste and pretreated lignocellulose feedstock. Anaerobic co-digestion of underutilized groundnut shells and readily available duck waste that is missing in literature was examined in a batch digester under different mixing ratios. This study is expected to provide insight into the long-term anaerobic digestion of lignocellulose feedstocks and animal wastes and provide sustainable green energy production and economical waste management.

2. Materials and Methods

2.1 Feedstocks and inoculum

Groundnut shells and duck waste used for this study were sourced locally. The groundnut shells were dried at room temperature and stored in zipped plastics. Duck waste was checked for stones, feathers, and other impurities and stored at -20 °C to prevent decomposition. Inoculum used was collected from a nearby biogas plant and stored at 4 °C. The feedstock and inoculum were investigated for total solids, volatile solids, C/N ratio, Sulphur, hydrogen, and oxygen according to the AOAC official standard [13].

2.2 Groundnut shells pretreatment

This study adopted alkaline pretreatment using NaOH as a pretreatment agent to enhance the lignocellulosic degradation of groundnut shells during biogas production. Pretreatment was carried out according to the process reported in our previous study [14]. The groundnut shells were soaked in 3% w/w NaOH for 15 min at 90 °C (using a dry weight basis) with a solid-to-liquid ratio of 1: 10.

2.3 Anaerobic digestion

The anaerobic co-digestion was carried out in a laboratory-scale batch digester according to VDI 4630 at mesophilic temperature (37 ± 2 °C) [15]. Five bottles were used as digesters, each having a total capacity of 1000 ml and a working volume of 800 ml. The quantity of alkali-treated groundnut shells and duck waste were measured in the digester as calculated from 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 [16]. The digestion was replicated twice, and two digesters with only inoculum were run parallel to ascertain the quantity of gas released from the inoculum. Nitrogen gas was used for flushing out the oxygen in the digester to set up the anaerobic conditions, and the process took place at mesophilic (37 ± 2 °C) conditions. The gas released was collected inside calibrated gas bottles mounted on the digester bottles, and the volume of gas released was determined from downward water displacement. Reading of the gas volume was taken daily, and gas composition was determined at intervals using a gas analyzer (BioGas, Geotech GA5000, Warwichshire, UK). Gas yield from the parallel digesters was subtracted from the digesters with substrate and inoculum, to determine 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 less than 1% of the cumulative gas yield.

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

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 [15].

Table1. Anaerobic co-digestion digesters with different feedstock ratio

Digester	Duck waste (%)	Alkali-treated groundnut shell (%)
A	100	0
B	75	25
C	50	50
D	25	75
E	0	100

3. Results and Discussion

3.1 Physicochemical properties of alkali-pretreated groundnut shells and duck waste.

The physicochemical properties of alkali-pretreated groundnut shells and duck waste were determined using the official methods of AOAC [13], and the findings are presented in Table 2. It can be observed from the result of characterization that the TS and VS of alkali-pretreated groundnut shells are 93.00 and 94.62%, respectively, while it is 91.61 and 47.18% for duck waste, respectively. It can be noticed that the TS and VS of alkali-pretreated groundnut shells are higher than that of duck waste. Previous studies reported the TS and VS of untreated groundnut shells to be 95.51 and 91.27%, respectively [17]. This implies that alkali pretreatment using NaOH reduced the TS and VS of the substrate. The TS of duck waste is high compared with cow dung experimented with (15.32%), but the VS in the same cow dung was high (77.50%) compared to duck waste considered in this study [18]. The higher percentage of TS indicates low moisture content in the feedstock [19]. The value of VS indicates the available portion of the feedstock for biogas and methane yield. It can be noticed from the feedstocks considered that their VS are not the same; that of alkali-pretreated groundnut shell is almost double that of duck waste. This is one of the advantages of anaerobic co-digestion of two or more feedstocks.

The C/N ratio of alkali-pretreated groundnut shells and duck waste were observed to be 79.62 and 10.49, respectively. These values observed are relatively different compared to other investigations. The value for the alkali-pretreated groundnut shells was higher, while duck waste was lower [20,21]. Lower nitrogen values in feedstocks indicate a higher C/N ratio [22]. As previously observed in the literature, the C/N ratio for the optimum anaerobic process is 20 – 30. An inappropriate C/N ratio can result in higher volatile fatty acids (VFAs), ammonia nitrogen, or free ammonia [23]. Higher VFAs and ammonia concentrations in the anaerobic reactor will increase the process's pH, producing a toxic environment for the microbes and inhibiting their growth [24]. The result from this study indicates that alkali-pretreated groundnut shells have a high C/N ratio, while duck waste was low. This shows that appropriate mixing of these feedstocks is required through anaerobic co-digestion for optimum biogas and methane release.

Table 2. Physicochemical characteristics of alkali-pretreated groundnut shells and duck waste

Parameter	Alkali-pretreated groundnut shells	Duck waste
Total Solids (TS) (%)	93.00	91.61
Volatile Solids (VS) (%)	94.62	47.18
Carbon Content (%)	48.57	34.42
Nitrogen Content (%)	0.61	3.28
C/N Ratio	79.62	10.49
Hydrogen (%)	5.86	4.37

3.2 Daily methane yield of anaerobic co-digestion of alkali-pretreated groundnut shells and duck waste.

The daily methane released by mono-digestion and co-digestion of alkali-pretreated groundnut shells and duck waste is illustrated in Table 3 and Figure 4. It can be noticed from the Figure that the highest daily methane released peak values were 43.33, 53.33, 36.67, 43.33, and 33.33 mL CH_4/g VS_{added}, for treatments A, B, C, D, and E, respectively. It can be noticed that all these peak values were recorded on day 2 of the experiment. Treatment B was the co-digestion of 75% duck waste and 25% alkali-pretreated, releasing the highest daily methane. In contrast, mono-digestion of alkali-pretreated groundnut shells (treatment E) released the least daily methane yield. All the treatment has 4 different peaks except treatment C, that have 5 peaks, and the methane released can be observed to follow the same patterns. The methane yield can be noticed to decline steadily until the digesters stop producing methane. Our findings corroborate what was observed when food waste and livestock waste were co-digested, whereby multiple daily methane yield peaks were noticed [25]. Aboudi *et al*. reported multiple peaks of daily methane yield when sugar beet by-product was co-digested with animal manure in a long-term continuous assay [20].

3.3 Cumulative methane yield of anaerobic co-digestion of alkali-pretreated groundnut shells and duck waste.

The total methane yield of anaerobic co-digestion of alkali-pretreated groundnut shell and duck waste is presented in Figure 2. Figure 2 shows that cumulative methane yields of 280, 290, 236.67, 230.00, and 210 mL CH_4/g VS_{added} were released by treatments A, B, C, D, and E, respectively, at the end of 23 days retention period. The electrical potential estimation of the cumulative methane released was determined using 1 m^3 methane will produce 36 MJ, and electric conversion rate of 35%; thereby, 1m^3 of methane will produce 10 kWh [26]. Therefore, the cumulative methane yield released by treatments A, B, C, D, and E will generate 0.0028, 0.0028, 0.0024, 0.0023, and 0.0021 kWh of electricity. It can be observed from this result that mono-digestion of duck waste releases about 33.33% more methane yield compared to mono-digestion of alkali-pretreated groundnut shells.

Table 3. Daily methane yield of anaerobic co-digestion of alkali-pretreated groundnut shells and duck waste

Time (Days)	Methane yields (mL CH_4/g VS_{added})				
	A	**B**	**C**	**D**	**E**
1	0.00	0.00	0.00	0.00	0.00
2	43.33	53.33	36.67	43.33	33.33
3	36.67	33.33	26.67	30.00	26.67
4	13.33	10.00	6.67	10.00	10.00
5	6.67	6.67	3.33	6.67	3.33
6	26.67	20.00	20.00	16.67	13.33
7	16.67	16.67	10.00	13.33	10.00
8	3.33	10.00	3.33	3.33	3.33
9	10.00	6.67	6.67	6.67	6.67
10	20.00	20.00	13.33	16.67	16.67
11	10.00	10.00	6.67	6.67	6.67
12	3.33	3.33	6.67	3.33	3.33
13	6.67	3.33	10.00	6.67	6.67
14	10.00	6.67	6.67	10.00	6.67
15	13.33	16.67	13.33	10.00	10.00
16	10.00	13.33	10.00	13.33	13.33
17	26.67	23.33	20.00	6.67	6.67
18	3.33	10.00	3.33	3.33	10.00
19	3.33	3.33	6.67	6.67	3.33
20	3.33	6.67	13.33	6.67	6.67
21	3.33	6.67	3.33	3.33	6.67
22	6.67	6.67	6.67	3.33	3.33
23	3.33	3.33	3.33	3.33	3.33

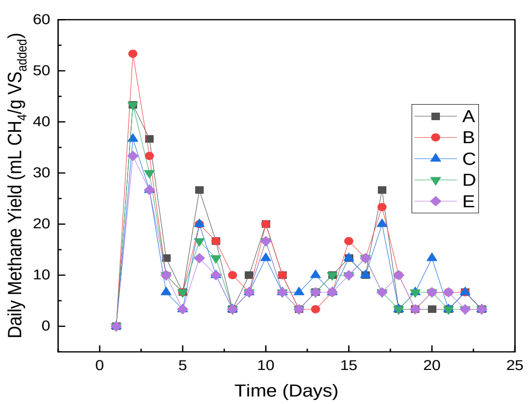

Figure 1. Daily methane yield of anaerobic co-digestion of alkali-pretreated groundnut shells and duck waste

This can be traced to the groundnut shells as lignocellulose materials that are not easily accessible to microorganisms. Duck waste is easily accessible for methanogenic bacteria, enabling them to use all its potential as biogas feedstock, unlike groundnut shells that are not wholly digested despite pretreatment application. Mono-digestion of alkali-pretreated groundnut shells improved the methane yield by about 738%, compared to the methane yield of untreated groundnut shells [17]. This supports what was reported in a previous study that pretreatment methods improve the biogas and methane yield of lignocellulose feedstocks [27]. Combined pretreatment of corn stover before anaerobic digestion was reported to increase the methane yield by 40.0 and 56.40% [28]. Hydrogen peroxide pretreatment of sorghum bicolor stalk was observed to enhance the biogas yield by 65% and reduce the lag time by 5 days [29]. The improvement in methane yield of groundnut shells can be observed to be higher than some of the results of the previous studies, indicating the effectiveness of the method used.

Compared to mono-digestion of alkali-pretreated groundnut shells (treatment E), the methane yield was improved by 33, 38, 12.7, and 9.5% for treatments A, B, C, and D, respectively. It can be inferred from this study that anaerobic co-digestion of alkali-pretreated groundnut shells with duck waste can improve the methane yield. This agreed with what was previously reported when sodium hydroxide pretreated Napier grass was co-digested with food waste [30]. The result shows that the highest cumulative methane yield was recorded when 75% of duck waste was combined with 25% alkali-pretreated groundnut shell (75: 25%, duck waste: alkali-pretreated groundnut shells) (treatment B). This indicates that 75% of duck waste provides a comfortable environment for the methanogenic bacteria colostra to grow and degrade the complex carbohydrates into simple sugars and then to methane. This could be traced to the ability of co-digestion to balance the nutrient in the digester, as observed in the previous study [16]. Mono-digestion of 100% duck waste also showed better methane yield compared to co-digestion with other percentages of alkali-pretreated groundnut shells. The yield is low compared to treatment B, which can be linked to the low carbon content of the duck waste and the imbalance of nutrients, especially the C/N ratio, during digestion. Another reason that could lead to lower methane yield in treatment A compared to treatment B is the percentage of volatile solids available for methane production. Duck waste has a low volatile solid (47.18%) compared to the alkali-pretreated groundnut shells. But when 25% of alkali-pretreated groundnut shells were added to 75% duck waste, the process was buffered, and the potential to release more methane yield was noticed. It can be observed from the methane yield of treatments C and D that as the percentage of alkali-pretreated groundnut shells increases, the volume of methane yield decreases. This is an indication that an increase in alkali-pretreated shells and a reduction in duck waste caused nutrient imbalance which reduced the activities of methanogenic bacteria and subsequent methane yield.

The nutrients in the digester are vital to parameters that define the stability and granulation of the digestion process. Therefore, methanogenic bacteria perform based on the environment they find themselves. These microorganisms require essential nutrients to carry out their activities that yield methane release [21]. The result from this study indicates that a higher percentage of alkali-pretreated groundnut shells (>25%) reduced the methane yield because of the production of inhibitory compounds that could result from nutrient imbalance. Mono-digestion of duck waste also showed fast hydrolysis due to its availability to microorganisms, resulting in over-accumulation of volatile fatty acids (VFAs) that significantly influence the process's pH. pH values of the anaerobic digestion process that is far from neutral (6 – 8) due to over-accumulation of VFAs will harm the methanogenic bacteria and lower the subsequent methane yield [31]. Only the mixing ratio of 75: 25%, duck waste: alkali-pretreated groundnut shells that provide suitable nutrients for microbe's activities, enhancing the methane yield. In a similar study, when cassava biomass was co-digested with winery solid waste, it was observed that co-digestion of the substrate released better methane yield compared to individual digestion, and the optimum methane yield was observed when the mixing ratio was 70: 30% of cassava biomass: winery solid waste [32]. Akilu and Waday investigated the influence of anaerobic co-digestion of alkali-treated corn stover and poultry manure, and it was reported that optimum methane yield was recorded at 80: 20 of poultry manure: alkali-pretreated corn straw [2]. The result from this study is in the same range as the previous studies, and the differences noticed in the mixing ratio can be traced to variations in the physicochemical characteristics of the feedstock and differences in the structural arrangement of the feedstock. It can be observed that an appropriate mixing ratio of alkali-pretreated groundnut shells and duck waste can improve methane yield.

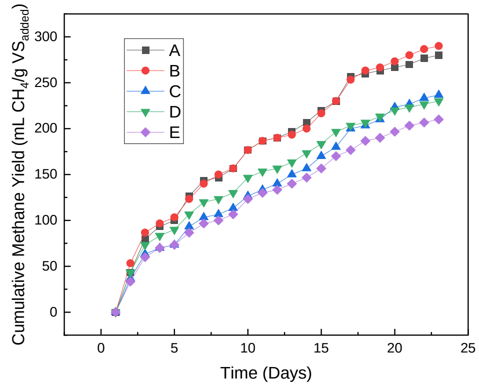

Figure 2. Cumulative methane yield of anaerobic co-digestion of alkali-pretreated groundnut shells and duck waste

4. Conclusion

Large quantities of groundnut shells and duck waste are released to the environment globally every year through agricultural activities. These residues pollute the environment and contaminate the groundwater. They are organic materials that can be converted into methane through anaerobic digestion. This study has shown that co-digesting alkali-pretreated groundnut shells can improve methane yield with duck waste. Co-digestion produced better methane yield than mono-digestion when selecting an appropriate mixing ratio. The optimum cumulative yield (290 mL CH_4/g VS_{added}) was recorded when the mixing ratio of 75: 25% of duck waste: alkali-pretreated groundnut shells. The process is economical, considering the availability of the feedstocks and the cost of chemicals used for pretreatment. Therefore, anaerobic co-digestion of duck waste and alkali-pretreated groundnut shells can effectively manage waste and produce renewable and sustainable energy for a sustainable environment. This technology can be scaled up and applied at a commercial scale. Nevertheless, the influence of NaOH pretreatment on the environment is scarce, and this poses a question on the environmental benefits of the economic motivation to propel better extensive implementation. It is recommended that future study should consider the effect of biogas residue of chemical pretreatment on the external environment.

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