PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 28 (10) 3007-3012 October, 2024

Enhancing Energy Efficiency and Mitigating Environmental Degradation through Anaerobic Co-digestion of Palm Oil Mill Effluent and Solid Residues

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ABSTRACT: The utilization of palm oil mill residues for sustainable biogas production presents a promising avenue to mitigate environmental challenges associated with waste disposal and energy demand in palm oil processing. The study explores the use of palm oil mill residues for sustainable biogas production, focusing on the impact of mixing ratios of POME and three raw milled residues on biogas yield through anaerobic co-digestion. Results indicate that co-digestion significantly enhanced biogas production compared to mono-digestion of POME alone. The highest biogas yield of 370 ml was recorded in the digester with 40% residues followed by 50% with a cumulative biogas of 190 ml. The two digesters were higher than 80 ml recorded for POME alone.The findings underscore the potential of integrating palm oil mill residues into biogas systems to achieve dual objectives of waste management and renewable energy generation.

DOI: https://dx.doi.org/10.4314/jasem.v28i10.7

Cite this Article as: AJAYI, O; OLALUSI, A. P: OLANREWAJU, O. O; IKHAZUAGBE, H. I; OLUGBEMIDE, A. D. (2024). Enhancing Energy Efficiency and Mitigating Environmental Degradation through Anaerobic Co-digestion of Palm Oil Mill Effluent and Solid Residues. *J. Appl. Sci. Environ. Manage.* 28 (10) 3007-3012

Dates: Received: 30 July 2024; Revised: 29 August 2024; Accepted: 21 September 2024 Published: 05 October 2024

Keywords: anaerobic co-digestion; biogas production; palm oil mill effluent; mesocarp fibers; palm kernel shells.

Anaerobic co-digestion is increasingly preferred over mono-digestion for biogas production from organic residues due to its higher yields and superior efficiency in waste management (Kumar et al., 2024). There have been numerous reports in the literature on the synergistic effects of codigesting substrates. Chomini et al. (2019) codigested cow dung with maize cob at three combination ratios, with a 75:25 ratio producing the highest biogas of 2522.40 ml. In another study conducted by Olugbemide et al. (2023), rice husk was co-digested with plantain peels under mesophilic conditions with 60:40 combination ratios, recording the highest biogas yield of 2880 ml. However, there remains a notable gap in research regarding the co-digestion of palm oil mill process residues in Nigeria, despite their significant environmental impact. This study addresses this gap by focusing on the urgent need for enhanced energy efficiency within medium-scale crude palm oil processing facilities through the bioconversion of

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these residues into useful products. This urgency stems from the steep rise in fossil fuel prices, which have quadrupled over the past two years, making traditional energy sources increasingly costly and environmentally detrimental (Holechek *et al.*, 2022).The production of crude palm oil is accompanied by substantial solid waste accumulation, often inadequately managed through land piling, and liquid effluents that are commonly discharged into rivers. This practice contributes significantly to environmental degradation. Recovering biogas from these underutilized solid and liquid residues via anaerobic codigestion (AcoD) presents a compelling opportunity to mitigate environmental harm while enhancing energy sustainability. It also offers a viable alternative to the unsustainable use of wood energy in the industry's energy mix (Sodri and Septriana, 2022).

The objective of this study was to investigate the potential of anaerobic co-digestion of palm oil mill effluent and raw solid residues for biogas production, with a focus on the effect of combination ratios on process efficiency and biogas yield.

MATERIALS AND METHODS

Samples collection: Palm mill solid residues, including empty fruit bunches (EFB), mesocarp fibers (MF), palm kernel shells (PKS), and palm oil mill effluent (POME), were collected from Leventis Palm Oil Mill in Weppa, Agenebode. The solid residues were sun-dried for three weeks on average, then milled into fine particles (<200 mm) before being taken to the laboratory for further experimentation.

Substrate characterization: The physicochemical characteristics of pome and three raw solid residues (EFB, MF, and PKS) from oil palm processing with solid residues were characterized for ash, total solid (TS), volatile solid (VS), cellulose, hemicellulose, lignin, carbon, and nitrogen according to standard methods (Singh *et al.* 2010).

Experimental Setup: Palm oil mill effluent and solid residue samples were collected for laboratory-scale co-digestion experiments conducted under varying mixture ratios in digesters to produce biogas. The digesters, labeled A, B, C, and D, each had a capacity of 1.5 liters with a working volume of one liter (Plate 1). The experiments were performed at an ambient temperature of 27±1°C for thirty days. The composition of the digesters is detailed in Table 1. Digester A, serving as the control, comprised 100% palm oil mill effluent, while the other digesters contained mixtures of palm oil mill effluent and the three solid residues in different percentages. Initial and final pH values were measured using a handheld digital pH meter by HANNA Instruments. The digesters were manually shaken to enhance microorganism-substrate contact. Daily biogas production was measured using the water displacement method.Plate 1 shows the laboratory experimental set-up.

Table 1: The composition of the digesters

Digester	Composition (%)
A	100 POME
B	70 POME/10EFB/10MF/10PKS
C	60POME/15EFB/15MF/10PKS
D	50POME/20EFB/20MF/10PKS

Plate 1: Laboratory experimental set-up

RESULTS AND DISCUSSION

Physicochemical Properties: The physicochemical properties of the feedstocks are presented in Table 2. The physicochemical characteristics of palm oil mill effluent (POME) and solid residues (EFB, MF, and PKS) are crucial in determining their potential for biogas production through anaerobic co-digestion. These properties, including moisture content (MC), ash content, total solids (TS), volatile solids (VS), carbon (C), nitrogen (N), C/N ratio, initial pH (pHi), and lignocellulosic composition (lignin, cellulose, and hemicellulose), significantly influence the efficiency and biogas yield of anaerobic digestion.

Moisture content (MC) is a critical factor in anaerobic digestion, as it affects microbial activity and the overall efficiency of the digestion process. High MC generally facilitates microbial activity and substrate breakdown, whereas low MC can hinder these processes (Liang *et al.*, 2003). In this study, sample B exhibited the highest MC (5.24 ± 0.03%), which could enhance its digestibility and biogas production potential. In contrast, samples C (0.97±0.00%) and D (2.57±0.03%) had significantly lower MC, which might require pre-treatment or co-digestion with higher MC substrates to optimize biogas production.Ash content represents the inorganic matter in the substrates, which can affect biogas yield. High ash content can reduce the organic fraction available for microbial digestion, potentially lowering biogas production efficiency (Olugbemide *et al.*, 2022). Among the substrates, sample C had the highest ash content (15.02±0.24%), which may hinder its biogas production efficiency. Conversely, samples B (8.63±0.02%) and D (6.49±0.02%) had lower ash content, suggesting a higher potential for biogas production.

Total solids (TS) indicate the total concentration of solids in the substrate, which is essential for assessing the potential for biogas production. High TS can enhance biogas production by providing more organic material for microbial digestion (Cazier *et al.*, 2015). PKS had the highest TS (103.59±0.51 mg/l), suggesting a high biogas production potential. However, extremely high TS might also inhibit microbial activity if not managed properly, indicating a need for careful balance. Sample A had a higher TS content than samples B and C.

Volatile solids (VS) represent the fraction of total solids that can be degraded by microorganisms (Peces *et al.*, 2014). The VS of the solid residue samples was significantly higher than the POME, which justified the use of these residues as co-substrates to compensate for the deficiency.

The carbon-to-nitrogen (C/N) ratio is critical in maintaining the balance between carbon and nitrogen, which affects microbial growth and activity (Wang *et al.*, 2019). An optimal C/N ratio for anaerobic digestion is typically between 10 and 30. The C/N of all the solid residues was outside the optimal range recommended for the AD process, indicating potential issues with nitrogen balance. These results suggest that changing the C/N ratio by co-digesting with nitrogen-rich substrates or additives could make biogas production more efficient.

pH is a crucial parameter for the stability of the anaerobic digestion process (Sodri and Septriana, 2022). The optimal pH range for anaerobic digestion is between 6.5 and 7.5. The initial pH values of all substrates were below this optimal range, indicating acidity that could inhibit microbial activity. The pH of the mono and codigestion substrates are shown in figure 1. Both samples A and B had an initial pH of 4.69±0.00, sample C had a slightly higher pH of 4.93±0.04, and D had the highest pH of 5.36±0.03. These low pH values suggest the need for pH adjustment or buffering agents to create a more favourable environment for anaerobic digestion. However, pH adjustment was intentionally omitted in this study to understandthe indigenous behaviours of the samples under experimental conditions.

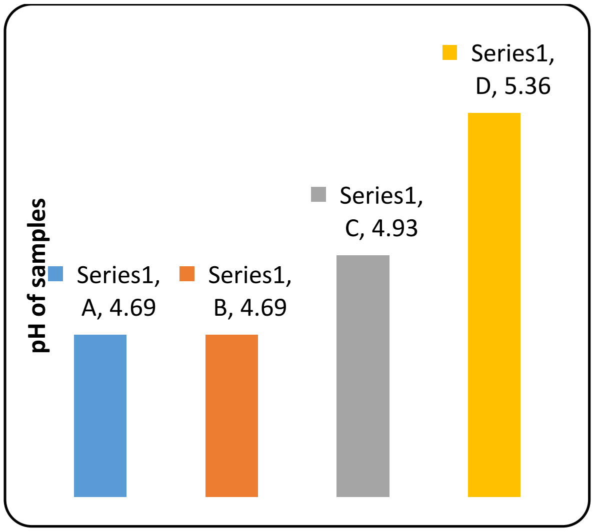

Fig. 1: the initial pH values of mono and codigestion substrates

The lignocellulosic composition (lignin, cellulose, and hemicellulose) of the solid residues significantly influences their biodegradability (Sodri and Septriana, 2022). High lignin content can hinder biogas production due to its resistance to microbial degradation. EFB, MF, and PKS exhibited high lignin content (59.42±1.41%, 57.64±1.38%, and 62.16±0.42%, respectively), which might impede biogas production unless pre-treatment methods are applied. Cellulose and hemicellulose are more easily degradable and contribute positively to biogas production. EFB and PKS had moderate cellulose content (21.86±0.75% and 18.20±0.29%, respectively), while MF had high hemicellulose content (32.52±1.21%), indicating varying degrees of biodegradability and potential for biogas production. Pre-treatment methods, such as mechanical, chemical, or biological treatments, could enhance the digestibility of these lignocellulosic materials and improve biogas yields.

In general, the physicochemical properties of POME and solid residues from palm oil mills indicate varying potentials for biogas production through anaerobic co-digestion. POME, with its high moisture content, low ash content, high VS/TS ratio, and moderate C/N ratio, appears to be the most favourable substrate. However, its low initial pH needs adjustment for optimal microbial activity. The solid residues, particularly EFB and PKS, exhibit properties that could hinder biogas production, such as high ash and lignin content and suboptimal C/N ratios. To enhance the biogas production potential, pre-treatment methods and strategic co-digestion with POME or other substrates with complementary properties may be necessary. Addressing these factors through innovative strategies and careful substrate management can significantly improve the efficiency and sustainability of biogas production from palm oil mill effluent and solid residues.

Table 2: Physicochemical properties of effluent co-mixed with solid process residues

Parameter	Unit	POME	EFB	MF	PKS
MC	(%)	ND	5.24 ± 0.03	0.97 ± 0.00	2.57 ± 0.03
Ash		ND	8.63 ± 0.02	15.02 ± 0.24	6.49 ± 0.02
TS	(mg/l)	86.29 ± 0.27	83.55 ± 0.27	84.75 ± 0.04	103.59 ± 0.51
VS	(%)	3.94 ± 0.37	96.86 ± 0.01	91.37 ± 0.02	93.62 ± 0.01
C	(%)	1.91 ± 0.01	50.76 ± 0.01	47.21 ± 0.08	51.95 ± 0.01
N		ND	0.65 ± 0.00	1.16 ± 0.01	0.82 ± 0.01
C/N		ND	78.09 ± 9.21	40.69 ± 9.40	63.35 ± 0.50
Lignin		ND	59.42 ± 1.41	57.64 ± 1.38	62.16 ± 0.42
Cellulose		ND	21.86 ± 0.75	9.84 ± 1.84	18.20 ± 0.29
Hemicellulose		ND	18.71 ± 0.21	32.52 ± 1.21	19.64 ± 0.88

(Note: ND - Not Determined)

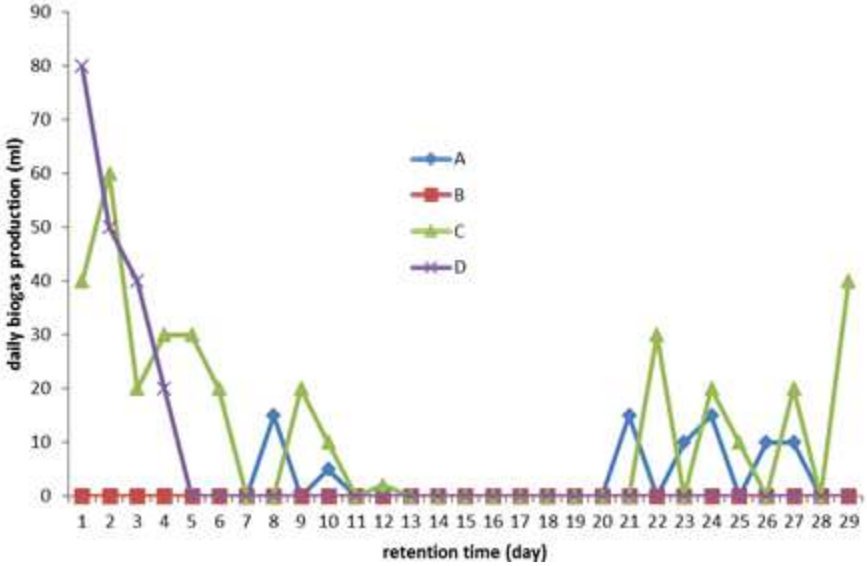

Fig.2: Daily Biogas Production Over 30 Days from Anaerobic Co-Digestion of Palm Oil Mill Effluent (POME) with Empty Fruit Bunches (EFB), Mesocarp Fibers (MF), and Palm Kernel Shells (PKS) in Laboratory-Scale Digesters

Quantification of Biogas Production Potential: Figures 2 and 3 show daily and cumulative biogas production from the four samples under mesophilic conditions. There was no lag phase in biogas production in samples C and D but sample A had a lag phase of seven days while digester B produced no biogas. The implication of this observation was that the microorganisms in samples C and D acclimatized rapidly to the substrates in these digesters. The failure of digester B could signal the antagonistic effect of the combination ratio of the major and minor substrates during anaerobic codigestion process. Digester had its peak value of 15 ml on day 8 while digesters C and D had their peak values of 60 and 80 ml on day 2 and day 1 respectively. Cumulative biogas production of the samples is shown in figure 3. There was no production in sample B as earlier stated, this could be as a result of formation of inhibitors at this combination ratio. The primary cause of anaerobic digester upset or failure is often attributed to a substantial quantity of inhibitory substances. Some of the most commonly encountered inhibitors in anaerobic digesters include heavy metals, light metal ions, organic compounds, and ammonia (Awe et al., 2018). The monodigestion digester produced 80 ml of biogas which was significantly lower than 370 and 190 ml reported for codigestion digesters C and D which represents 270 and 137.5% increase respectively. Codigestion ratios at these two combinations had positive effect on AD process which led to the substantial increase in biogas production. The better performance of these codigestion digesters C and D in comparison to monodigestion digester signals the possibility of improved waste management of residues from palm oil processing industries using an environmentally-benign technology like AD. The low biogas yields from these digesters could be partly due to the high content of lignin in the co-substrates, which, as earlier mentioned are difficult for microorganisms to degrade.

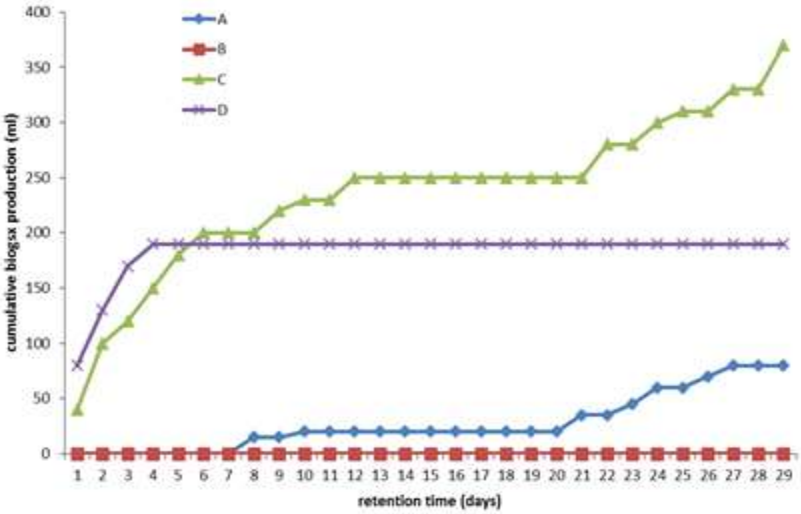

Fig. 3: Cumulative Biogas Production from Anaerobic Co-Digestion of Palm Oil Mill Effluent with Empty Fruit Bunches, Mesocarp Fibers, and Palm Kernel Shells Over 30 Days

A comparison of the two graphs reveals that the choice of co-substrates significantly impacts both the rate and total volume of biogas produced. Daily production data is crucial for understanding the kinetics of the digestion process, identifying peak production periods, and detecting operational issues such as substrate inhibition or nutrient limitations. This kinetic information is essential for optimizing the anaerobic digestion process to ensure steady and high biogas yields.

Conclusion: The study explores the use of palm oil mill effluent (POME) with empty fruit bunches (EFB), mesocarp fibers (MF), and palm kernel shells (PKS) for sustainable biogas production. It found that co-digestion significantly increases biogas yields compared to mono-digestion. EFB showed the highest biogas production, indicating its potential. The study suggests that integrating these residues in biogas systems can manage agricultural waste, generate renewable energy, and reduce environmental impact.

Acknowledgment: The authors would like to sincerely appreciate Tertiary Education Trust Fund (TETFUND) for funding this research with a Grant Number TETF/DR&D/POLY/AUCHI/IBR 2023/VOL.11

Declaration of Conflict of Interest: The authors declare no conflict of interest.

Data Availability Statement: Data are available upon request from the corresponding author.

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