Anaerobic Valorisation of Kplala *(Corchorus olitorius)* Residues Through Co-digestion with Leftover Food for Enhanced Biogas Generation

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ABSTRACT

The organic-rich waste from Abidjan District has high methane and carbon dioxide emission potential, posing environmental risks. This study aims to assess the impact of incorporating kplala, a leafy biomass, on the biogas yield and methane content derived from food waste. Batch experiments were conducted under mesophilic conditions (37°C), testing various mixing ratios of food waste and kplala. This approach achieved a specific biomethane yield of 327.57±4 mL/gVS, corresponding to an annual electricity generation with a maximum potential of 23 megawatts. This finding is likely due to a more balanced nutrient profile and increased biodegradability of the co-substrate mixture. Furthermore, the combined treatment of these organic wastes presents a promising and Eco-friendly strategy for urban waste management, while simultaneously supporting renewable energy generation. These outcomes highlight the potential for developing tailored anaerobic digestion solutions suitable for the Ivorian context.

Keywords: Biodegradability, Biogas, Codigestion, Co-substrate.

INTRODUCTION

Industrial growth largely depends on the consumption of fossil fuels[1]. Still, their availability raises important concerns[2]. The reliance on non-renewable energy sources leads to negative ecological impacts, especially through the emission of global warming gases that drive climate change[3].

As a result, research has been conducted worldwide on energy from renewable natural sources since these energy forms generate fewer pollutants or waste[4-5]. Biogas, among renewable energy sources, offers advantages compared to other types of energy[6], such as its availability, ease of storage, distribution via existing natural gas infrastructure, and its direct use for domestic cooking and as

transport fuel[6]. Thus, biogas production can contribute to addressing energy challenges[7].

Furthermore, population growth and rapid urbanization in cities, especially in developing countries, have led to an exponential increase in the production of municipal solid waste, posing a major challenge for environmental management. Among these wastes, food waste is fermentable, producing biogas that can be used for heat and electricity generation, as well as digestate that can be used as compost in agriculture[8,9].

While waste-to-energy (WtE) technologies have seen broad adoption across numerous nations, studies in this field are limited in Côte d'Ivoire. As a result, data regarding the conversion of food waste into usable energy within the Abidjan area are notably limited.

The organic-rich waste from Abidjan district has high methane and carbon dioxide emission potential, posing environmental risks[10-12]. Therefore, this study aims to assess the impact of incorporating kplala, a leafy biomass, on the biogas yield and methane content derived from food waste. Batch experiments were conducted under mesophilic conditions (37 °C), testing various mixing ratios of food waste and kplala *(Corchorus olitorius).* Additionally, a face-centred composite design methodology was used to optimize biogas production. This study highlight the potential for developing tailored anaerobic digestion solutions suitable for the Ivorian context.

EXPERIMENTAL

Sample Preparation

Two batches of waste from the city of Abidjan were prepared. The first batch, food waste, consisted of fruit, vegetable, cereal, and tuber residue, among other items. The second batch was made up of kplala waste collected in "marché gouro" (Adjamé municipality). biological inoculant was sourced from manure of cows collected in the aforementioned city. Employing machine that crushes, leftovers and kplala were crushed independently and then preserved in a fridge at -4°C addition to the biological inoculant. The materials were allowed to defrost for a full day at ambient temperature before the test began.

Techniques of analysis

pH, total solids (TS), and volatile solids (VS) were analyzed following the standard methods outlined by the American Public Health Association (APHA)[13,14]. Total Kjeldahl nitrogen (TKN) was determined using a Kjeldahl apparatus[15] (Kjeltec 2100, Foss, Sweden). Total organic carbon was measured using the Walkey-Black method[13,14]. Carbon-to-nitrogen proportion (C/N) was determined by calculating the ratio of organic carbon (C) to total nitrogen(N).

Experimental setup for biogas production

Experiments setup for biogas production occurred per triple at 37±1°C over forty-five days. Three anaerobic bioreactors operating in batch mode, offering a total capacity of 1,2 L and a usable capacity of 1 L were used to digest the mixture of substrate and inoculum. The bioreactor was topped up with public water supply to a final volume of 1000 mL, after the mixture of substrate and inoculum were added. A threaded lid and elastic sealing plug were used to firmly seal the bioreactors. To isolate the contribution of gas from the biological inoculant alone, 2 bioreactors that contain only the seeding material were kept under identical thermal conditions as the experimental units. To prevent a surface layer from forming, every bioreactor was manually stirred two times daily, for a duration of 2 minutes. The bioreactor had two ports: one for extracting liquid samples with a syringe and the other for the recovery and measuring the quantity of biogas produced. The total quantity of gas was determined using the water volume shift[16]. To measure the methane concentration in biogas, carbon dioxide and hydrogen sulfide were absorbed using a potassium hydroxide solution[17,18]. The quantity of biogas produced per unit of volatile solids (RBS) was calculated according to the next formula[19].

$$RBS = \frac{DB}{SV_{ajouté}} \qquad (1)$$

Where:
RBS = Methane yield (mL/gVS);
DB = Rate of biogas throughput (mL);
SV_{added} = Organic fraction of the feedstock (g).

It should be noted that the inoculum production was subtracted from the total production of the substrate and inoculum. For each test, a constant inoculum mass of 47.8 g (8 gVS) was used in the digester, while the substrate mass varied according to the type of test.

Experimental assays were performed to assess the biochemical methane potential (BMP) of every feedstock. The quantities of feedstock applied were 53.1 g and 33.6 g for kplala residues (KP) and leftovers (LF), respectively. For every experimental assay, substrate-to-inoculum ratio was maintained at 1, as it is the standard value applied[20].

During the simultaneous anaerobic digestion of the two substrates, an investigation was conducted to assess how varying the proportion between feedstock and biological inoculant influences the volume of biogas produced. Leftovers (LF) and kplala (KP) were blended according to a proportion of $\frac{SV_{DAL}}{SV_{KP}}$ = 1. The different substrate/inoculum ratios (S/I) used for co-digestion trials were 1/4, 0.5/1, 1/1, and 1.5/1, respectively for the mixtures named K-0.25, K-0.5, K-1, and K-1.5.

A face-centered central composite design (FCCCD) was employed to optimize the parameters under investigation, namely the carbon-to-nitrogen ratio and retention time. The NEMROD-W program, edition 9901, was used for the computation of predicted answers (Ycalc) and dispersion measures.

RESULTS AND DISCUSSION

Digesting leftovers anaerobically
Anaerobic digestion of monosubstrate
Variations in the acidity levels of monosubstrates throughout the anaerobic digestion process

Figure 1 illustrates variations in the acidity (pH) of the composite samples, M_1 and M_2, during anaerobic digestion (M_1: composite sample of leftovers; M_2: composite sample of kplala residue.
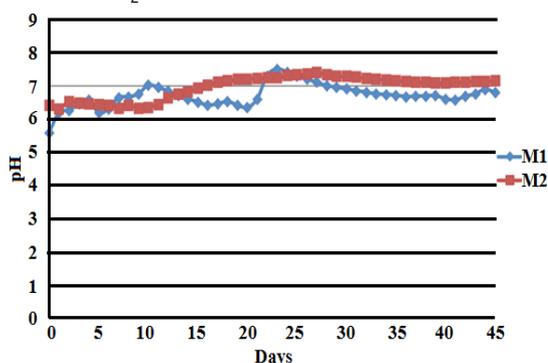

Fig. 1. pH variation of mixtures M_1 and M_2 during anaerobic digestion

The pH levels ranged from 5.58 to 7.65 for all types of mixtures at the beginning of digestion. The minimum pH values were 5.50 and 6.29 for mixtures M_1 and M_2, respectively. As for the maximum values, they reached 7.50 and 7.41 for M_1 and M_2, respectively. During the initial phase of anaerobic digestion, the pH values of mixtures M_1 and M_2 were 5.58 and 6.30, respectively. The pH of mixtures M_2 and M_1 exceeded 6.5 after 11 and 21 days of adjustment, respectively. Both drops and increases in pH were observed throughout the digestion process. The observed pH reductions are primarily due to the inherent acidity of the leftovers and the generation of short-chain volatile fatty acids occurs as the different feedstocks break down. These drops typically occur during the hydrolysis and acidogenesis phases, where solid particles are transformed into freely dissolvable materials. These compounds are then further converted into various substances[21].

Microorganisms involved in hydrolysis and acidogenesis can adapt to lower pH levels, whereas methanogenic bacteria tend to lose activity in such conditions. As a result, methanogenesis may be significantly inhibited when pH levels are too low. The observed increases in pH are mainly due to the addition of lime for pH correction. Specifically, when the pH drops below 6.5, 10 mL of a 1 mol/L $Ca(OH)_2$ solution is added to the digester to prevent inhibition of methanogenesis[22]. The longer it takes to adjust the pH back above 6.5, the faster biogas production is inhibited. In the case of M_1, inhibition was more rapid due to the 21-day delay in pH correction. This highlights the importance of maintaining proper pH control throughout the anaerobic digestion process[23].

Quantity of biogas produced per unit of volatile solids (RBS)

Figure 2 illustrates the quantity of biogas produced per unit of mass of volatile solids (RBS).

Analysis indicates that after fifty-five days of anaerobic digestion, food waste yielded the highest quantity of biogas produced per unit of mass at 205.9 mL per gram of volatile solids (VS), with kplala residue *(Corchorus olitorius)* following at 180.4 mL/g VS.
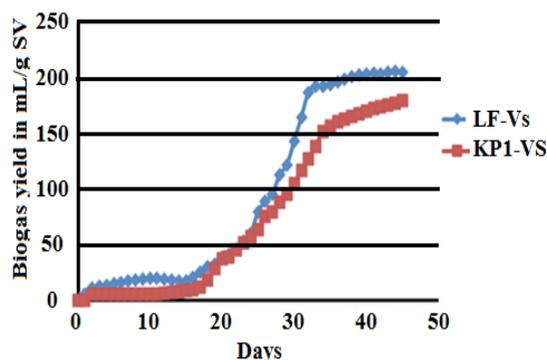
Fig. 2. Quantity of biogas produced per unit of
mass of volatile solids for each mono-substrate

The higher quantity of biogas produced per unit of mass of volatile solids from leftovers by comparison with kplala is likely due to a lower pH-resulting from a greater accumulation of volatile fatty acids-in digesters fed with kplala waste than in those fed with food waste[24,25]. The biomethane potentials were 161.6 ± 2.5 and 142.2 ± 4.2 mL CH/g VS for leftovers and kplala, respectively.

Anaerobic co-digestion of leftovers with kplala residues
pH variation

The variation of pH over time for the mixtures K-0.25, K-0.5, K-1, and K-1.5 during anaerobic digestion is presented by figure 3. K-0.25, K-0.5, K-1, and K-1.5 refer to digestion mixtures of cosubstrate such as leftovers and kplala, with respective substrate-to-inoculum volatile solids ($SV_{substrate}/SV_{inoculum}$) ratios of 1/4, 0.5/1, 1/1, and 1.5/1.
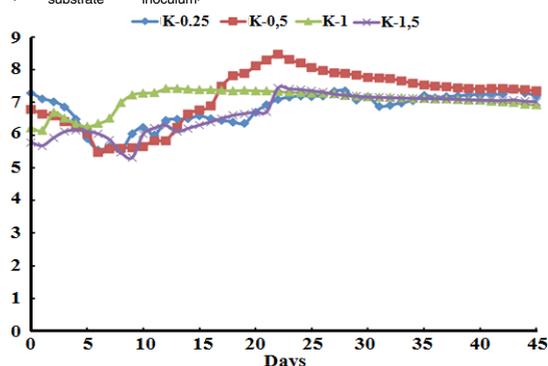

Fig. 3. pH variation in the composite samples
K-0.25, K-0.5, K-1 and K-1.5

The pH values ranged from 5.30 to 8.47 for all mixtures: K-0.25, K-0.5, K-1, and K-1.5. At the beginning of anaerobic digestion, the pH values were 7.28, 6.78, 6.22, and 5.77, respectively. The pH of mixture K-0.25 remained higher than those

of mixtures K-0.5, K-1, and K-1.5 throughout the digestion process. The pH values of mixtures K-0.5 and K-1 exceeded 6.5 after 7 and 14 days of degradation, respectively. As for mixtures K-0.25 and K-1.5, their pH values remained above 6.5 after 18 days. At the final stage of the decomposition process, each of pH values fell in the ideal range. The reduction in pH occurred more gradually when the substrate-to-inoculum ratio was equal to or exceeded 1, in contrast to the faster decline observed at ratios less than 1.

Compared to the pH measured when only leftovers was used (pH = 5.58), the current results indicate values that mostly fall within the optimal range for methanisation (6.5–8.5)[26]. In the ratios applied in these experiments, the use of kplala helped increase the pH of leftovers beyond 6.5. This reduces the need for lime for pH correction, leading to potential cost savings.

Specific biogas yield per unit of mass of volatile solids

The quantity of biogas produced per unit of volatile solids for the four composite samples K-0.25, K-0.5, K-1, and K-1.5 are shown in Figure 4.
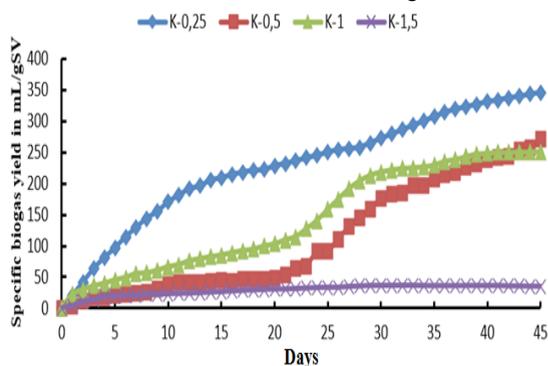

Fig. 4. Quantity of biogas produced per unit of mass of
volatile solids by the K-0.25, K-0.5, K-1, and K-1.5 mixtures

The specific biogas yields were 346, 271, 251, and 35 mL/gVS for the K-0.25, K-0.5, K-1, and K-1.5 mixtures, respectively (Fig. 4). The K-0.25 mixture produced the highest specific biogas yield, while K-1.5 resulted in the lowest. The quantity of biogas produced per unit of mass of volatile solids of the K-0.25 mixture was 1.54 times greater than that of K-0.5.

The amount of organic matter used determines the precise biogas production. The higher quantity of biogas observed for the

K-0.25 mixtures may be attributed to the better biodegradability of their substrates compared to the others[26], and to the Substrate/Inoculum (S/I) ratio. In fact, as leftovers becomes more biodegradable, the quantity of biogas produced per unit of mass of volatile solids tends to grow[26].

It is worth noting that the specific biogas yield from the mono-digestion of food waste at a S/I ratio of 1 was 205.9 mL/gVS. This yield is significantly lower than those obtained from the co-digestion of food waste with kplala residues at S/I ratios of 2/8 and 4/8, which reached 346 and 271 mL/gVS, respectively. The co-digestion of food waste and kplala residues thus increased the specific biogas yield by 68.32% and 22% at S/I ratios of 2/8 and 4/8, respectively.

The specific methane yields from the different co-substrate mixtures were 272±6, 212±4, 195±5, and 27±1 mL CH /gVS for the K-0.25, K-0.5, K-1, and K-1.5 mixtures, respectively. The highest methane yield was recorded for the K-0.25 mixture.

At this performance level, methane

production corresponds to an annual energy output of approximately 98 GWh (11 MW) for the K-0.25 mixture[27], considering an annual food waste generation of 1,624 million tonnes.

These findings show that the generation of biogas was improved by the co-digestion of leftovers with kplala residues. This improvement is strongly influenced by the C/N ratio[21,28]. A proportion of carbon to nitrogen that is ideal is essential because anaerobic bacteria need a balanced nutritional content to develop and sustain an appropriate ecosystem. However, for industrial-scale application, further research is needed to determine the ideal C/N ratio and retention time that maximize biogas production from the co-digestion of leftovers and kplala residues.

Biogas yield optimization in the context of anaerobic codigestion
Examination of contributing factors

Table 1 outlines the outcomes of design of the experiment. Table 2 displays the corresponding coefficients. Y1 represents the specific biogas yield generated by codigestion of food waste and kplala *(Corchorus olitorius).*

Table 1: Outcomes of the central composite design that is face-centered

Experiences	1	2	3	4	5	6	7	8	9	10	11	12	13
Y1	144,6	201,0	204,6	410,5	91,8	190,6	157,8	336,8	111,6	114,5	109,7	108,9	112,8

Table 2: An overview of the primary, interaction, average, and quadratic coefficients from the several experiments

Coefficients	b_0	b_1	b_2	b_{11}	b_{22}	b_{12}
Y1 Values	278,738	34,800	58,200	-13,283	-45,183	15,100

The specific biogas yield ranges from 144.6 to 410.5 mL/g VS in the context of co-digestion of leftovers with kplala *(Corchorus olitorius)* residues. For Y1, the coefficients range from 11.922 to 118.022. The p-values associated with these coefficients are all below 0.001, indicating that every coefficient in the model is statistically significant (p<0.05). Moreover, a noticeable variability in specific biogas yield is observed across the factor variation domains. This is confirmed by the standard deviation of 2.275 associated with the responses for Y1. The mean coefficient value is b_0= 116.579.

The mean coefficient value (b_0 = 116.579) indicates that these co-digestion processes can

yield over 116.579 mL/g VS of biogas. The p-values associated with each coefficient are all below 0.001, which confirms that all variables, and their interactions throughout the investigated range, significantly (p<0.01) affect the specific biogas production rate. Since the individual p-values are all under 0.05, every term in the model is considered statistically significant. It is important to understand that smaller p-values indicate a larger influence of that term on the model.

This next formula represents the model:

$$Y = 116.579 + 60.183X + 74.750X + 11.922X^2 + 118.022X^2 + 37.375X\ X \qquad (2)$$

Where X_i represents the coded values of the variables.

In the context of biogas production, the combined influence denoted by b_0 amounts to 15.100. This effect is interpreted based on the graphical representation of factor interaction.

Combined influence between variables

An analysis focusing on how variables influence one another provides a better understanding of how the selected factors influence one another. The impact of the variables on biogas production, while Fig. 5 provides a depiction of how these factors influence one another when combined.
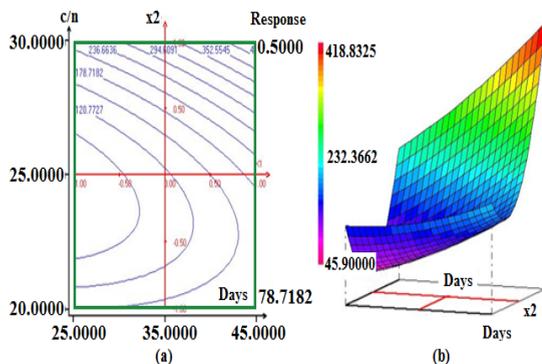

Fig. 5. Response surface plot of Y_1 as a function of the interaction b_{12} for the quadratic model (a), and isoresponse contour plot of the specific biogas yield Y_1 from the codigestion of food waste and kplala residues (b)

The specific biogas production initially decreases and then increases with both hydraulic retention time and the C/N ratio. When the C/N ratio ranges between 20 and 25, the biogas yield tends to decrease. However, C/N ratios above 25 lead to an increase in biogas production (Fig. 5). Therefore, higher values of retention time and C/N ratio (greater than 25) are associated with improved biogas production.

It is worth noting that the increase in specific biogas yield becomes almost negligible when the retention time exceeds or equals 35 days. This negligible increase at longer retention times suggests that considerable energy savings could be achieved at this duration by maintaining the temperature at 37°C.

Among the studied parameters, the C/N ratio appears to have the most significant influence on specific biogas production. These findings also highlight the combined influences of hydraulic retention time and the C/N ratio. Codigesting leftovers with kplala residues at a C/N ratio of 23 does not appear to be economically viable.

Model adjustment of the studied phenomenon

It is essential to assess how well the obtained models fit the experimental data. This is achieved by examining the relationship between the answers obtained from the experiments (Yexp) and the predicted values (Ycalc) (see Fig. 6 and Table 1).
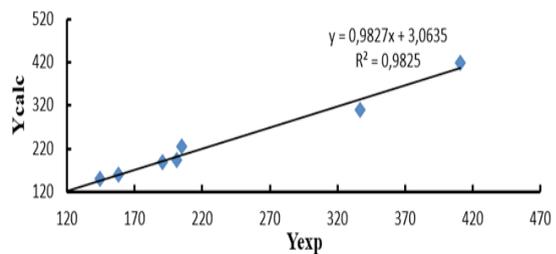

Fig. 6. Graph showing the relationship between Ycalc and Yexp for Y1

The determination coefficient calculated is 0.9825 for the codigestion with kplala *(Corchorus olitorius)* residue. This suggests a good fit of the model. The relationship involving several linear predictors coefficient further confirms the quality of this fit. The linear correlation coefficient R, with a value of 0.991, is close to 1, suggesting that the model accounts for 99.1% of the observed variability. This correlation coefficient can also be derived from the plot of experimental values (Yexp) versus predicted values (Ycalc), as shown in Fig. 6. The adjusted R^2 value calculated is 0.970 for Y , this reflects a high level of consistency between the measured and estimated biogas yields. The statistical evaluation, including ANOVA, indicates that the models are statistically significant, as demonstrated by the extremely low p-values (less than 0.05). This confirms that the suggested nonlinear model is well-suited and aligns closely with the observed experimental results. Moreover, the results confirm that a second-degree quadratic model is appropriate for explaining the phenomenon under study.

Enhancing the efficiency of biogas generation

After successfully calibrating the model, the subsequent phase involves determining the most favorable conditions. Throughout the present work, the goal is to determine the hydraulic retention time and the carbon-to-nitrogen (C/N) ratio that maximize the

specific biogas yield. Based on the previous results, equation (2) presents the expression used to estimate the specific biogas yield, represented by Y_1.

Figure 5 (b), which displays the isoresponse curves, makes it possible to visually identify the region that leads to the highest biogas production. A multi-response optimization was performed using Excel's spreadsheet tool to determine the optimal conditions for anaerobic digestion aimed at maximizing biogas yield (Fig. (5(b)). This numerical optimization technique identifies the point that maximizes the objective function and the corresponding conditions. This method of numerical optimization determines the set of conditions under which the objective function reaches its maximum value. It concerns:

$$Y_{1MAX} = 418.83 \text{ mL/gVS for } X_1 = 0.998 \text{ and } X_2 = 0.99$$

As a result, the highest estimated specific biogas output, based on the quadratic model of the second degree, is 418.9 ± 2.3 mL/gVS for the co-digestion of leftovers and kpala residues. This outcome is associated with a hydraulic retention time of around 45 days and a carbon-to-nitrogen ratio of 29.99. This response corresponds to a hydraulic retention time of approximately 45 days and a C/N ratio of 29.99.

Verification of the model

Experimental trials were carried out using the theoretically optimal input parameters to assess the model's accuracy. The actual biogas yield of 415.7 ± 4.0 mL/gVS (see Table 3) was in reasonable agreement with the calculated value, which supports the accuracy and relevance of the chosen models. The methane content (%) was 78.8 ± 0.6.

Table 3: Experimental Verification of the Model's Validity

Experiences	Y1(mL/gSV)
1	412
2	415
3	420

This methane production is equivalent to 197 GWh (23 MW) of electricity in year, derived from an annual generation of 1.624 million tonnes of food waste[29]. This output represents approximately 5% of Côte d'Ivoire's national butane gas consumption, drawing on figures released in 2017 by the Ministry in charge of Petroleum, Energy, and the Development of Renewable Resources.

CONCLUSION

This study aims to evaluate the impact of incorporating kpala, a leafy biomass, on the biogas yield and methane content derived from food waste. The analysis indicates that biodegradable residue produced in the city possesses biomethane potentials of 161.6 mL/gVS for leftovers (LF) and 142.2 mL/gVS for kplala residue (KP). When these two waste types are co-digested, the process achieves a peak specific methane output of 328 mL/gVS, translating to an estimated energy potential of 197 GWh, equivalent to 23 MW.

The findings indicate that generating electricity from biogas presents a viable approach to waste management. The amount of energy produced is considerable, adequately covering the operational requirements of a biogas facility and offering the potential to contribute surplus electricity to the public power grid. The information provided here offers essential insights and serves as a knowledge base for future decision-making regarding municipal solid waste management. Additionally, it may be applied in the development of integrated solid waste management plans in Abidjan, aligning with Côte d'Ivoire's objectives for sustainable development and the transition to renewable energy.

Conflict of interest

The author declare that we have no conflict of interest.

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