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Production of biomethane by co-digestion of food waste from Abidjan with tuna waste

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Abstract: Waste from the Abidjan district is rich in organic matter. This high organic matter content indicates a high potential for methane and carbon dioxide emissions. These greenhouse gases pose a real danger to the environment. The objective of this work is to evaluate the energy potential of biogas from food waste in Abidjan. Currently, information on the energy recovery of food waste from the Abidjan district is limited. Thus, the anaerobic co-digestion of food waste with tuna waste was carried out to evaluate their energy potential. Said anaerobic co-digestion revealed a specific biomethane yield of 257,9±3,2 mL / gSV. This corresponds to an electrical energy production capacity of up to 37 MW annually. This biomethane production corresponds to 9% of Ivorian butane gas consumption in 2017 and represents an important contribution, within the framework of sustainable development, to the 42% of renewable energy in the energy mix by 2030 of the Ivory Coast. Future studies will focus on a complete legal framework and a roadmap for the project to produce energy from waste in Côte d'Ivoire.

Keywords*: Waste, biomethane, energy, sustainable.*

1. Introduction

Industrial development requires the use of fossil fuels (oil, natural gas and coal) (Zhukovskiy *et al.*, 2021). However, their decreasing availability is a significant source of concern (Holechek *et al.*, 2022). Also, the use of fossil fuels has harmful consequences on the environment, particularly because of the production of greenhouse gases (GHG) which contribute to global warming (Wang *et al.*, 2024). The exploitation of renewable energies such as wind energy, solar energy, hydroelectricity and biogas constitutes an alternative solution to energy needs while preserving the environment (Ang *et al.*, 2022). Biogas has advantages over other types of energy (Czekała, 2022). These are its availability, ease of storage, distribution through existing gas infrastructure, direct use for domestic cooking and as a transportation fuel (Czekała, 2022). The production of biogas from fermentable waste can therefore contribute to solving the energy problem (Mthimunye *et al.*, 2024).

Although technologies for producing energy from waste have been developed in several countries around the world, in Côte d'Ivoire, studies to this effect are limited. In addition, waste from the Abidjan district, including food waste, is rich in organic matter (Kouakou *et al.*, 2021). This high organic matter content promotes a high potential for methane and carbon dioxide emissions (Kouakou *et al.*, 2021). In addition, waste from the fishing industry, particularly tuna waste, also stands out for its abundance, as Côte d'Ivoire is the second largest exporter of tuna in the world, with 250,000 tonnes of tuna processed by year. This is why the objective of this work is to evaluate the energy potential of biogas from food waste in Abidjan. For this study, anaerobic co-digestion of food waste with tuna waste was carried out in order to optimize their energy potential using an experimental plan. This study can be used as basic scientific information for the energy recovery of organic waste from the city of Abidjan.

2. Materials and methods

2.1. Waste and inoculum:

Food waste (lot 1) consisted of leftover fruit, vegetables, cereals, tubers, etc. As for the second batch, it consisted of tuna waste from the Adjamé market. Cow dung from the Port-Bouët slaughterhouse (Abidjan) was used as inoculum. The food and tuna wastes were ground separately using a Binatone brand blender and stored individually with the inoculum in a refrigerator at -4°C until the time required for the experiments. The waste was then thawed at room temperature for 24 h before experimental use.

2.2. Analysis methods

pH, total solids (TS), and volatile solids (VS) were analyzed according to standard methods of the American Public Health Association (APHA) (Canan *et al.*, 2021). Total Kjeldahl nitrogen (TKN) was analyzed using a Kjeldahl apparatus (Zhang *et al.*, 2022) (Kjeltec 2100, Foss, Sweden). Total organic carbon was determined following the Walkey-Black method, involving oxidation with 1 N potassium dichromate ($K_2Cr_2O_7$) solution and 96% sulfuric acid (H_2SO_4) solution for 30 minutes (Canan *et al.*, 2021). The total organic carbon content was calculated by titrating the excess dichromate with ammoniacal iron sulfate ($Fe(NH_4\text{-}SO_4)_2\cdot 6H_2O$) solution at 0.5 N. The organic carbon was then divided by total nitrogen to obtain the C/N ratio. Samples for metal analysis were prepared by acid digestion as previously described. Nitric acid was used for digestion. After digestion, samples were filtered using 0.22 µm filter paper and analyzed for metals using an air-acetylene flame atomic absorption spectrometer (Varian SpectrAA 20).

2.3 Anaerobic digestion tests

Batch anaerobic digestion tests were carried out in triplicate at (37±1°C) for 45 days. The composite samples were digested in three batch digesters of 1200 mL with a working volume of 1000 mL. After adding inoculum and food waste, the digester was filled to 1000 mL with tap water. The digesters were sealed with a rubber septum and screw cap. Two control digesters containing only inoculum were also incubated at the same temperature to correct for the biogas produced by the inoculum. Each digester was mixed manually for two minutes, twice a day to avoid the formation of a layer on the surface of the digester. The digester is equipped with two orifices, the first for taking liquid samples using a syringe, and the other for recovering and measuring the volume of biogas produced. The total volume of biogas was measured by the water displacement method (Singh *et al.*, 2021). The determination of the CH_4 content in the biogas was made by dissolving CO_2 and H_2S in a basic solution (KOH) (Muntaha et al., 2022). The biogas yields relative to the volatile solid (RBS) was determined by the following equation (Khan et al., 2021):

$$RBS = \frac{DB}{SV_{added}} \qquad \textbf{Eqn. 1}$$

DB: biogas flow rate (mL); SV_{added}: volatile solid of the substrate (g).

For each test, a constant inoculum mass of 47.8g (8gSV) was used in the digester. That of the substrate varied depending on the type of test.

Tests were carried out to determine the experimental biomethanogenic potential (PBM) of each substrate. The different masses of the substrates used are 33.6g and 53.1g respectively for food waste (DAL) and tuna waste (TH). In each test the ratio $\frac{SV_{substrat}}{SV_{inoculum}} = 1$ was kept because it is the standard value applied (Khadka et al., 2022).

In the co-digestion tests, the effects of the Substrate / Inoculum ratio on the biogas yield produced were studied. Food waste (DAL) and tuna waste (TH) were mixed in a ratio of $\frac{SV_{DAL}}{SV_{TH}} = 1$. The different ratios (S/I) $\frac{SV_{substrat}}{SV_{inoculum}}$ used for the codigestion tests are 1/4, 1/1, 1.5/ 1 and 2/1 respectively for mixtures named T-0.25 ; T-1; T-1.5 and T-2.

Response surface methodology (MSR) was used to optimize the studied parameters C/N and residence time). Thus, the standard deviations and the calculated responses (Ycalc) were determined using the NEMROD-W software, version 9901.

3. Results and discussion

3.1. Anaerobic digestion of food waste from Abidjan

3.1.1. Monodigestion of waste

3.1.1.1. Evolution of the pH and VFA concentration of the different types of mixtures in the digesters

Figure 1 shows the evolution of the pH of the different types of mixtures M_1 and M_2 during anaerobic digestion (M_1: mixture consisting of food waste; M_2: mixture consisting of tuna waste). Taking into account the different pH values of the mixtures, it was necessary at times to carry out pH corrections of the two solutions by adding 10 mL of a $Ca(OH)_2$ solution with a concentration of 1 mol/L to each time the pH was below 6.5; indeed, the optimal pH range for anaerobic digestion is (6.5–8.5). However, M_2 required less lime for correction. pH is therefore an important parameter to control during anaerobic digestion (Chew et al., 2021). The observed pH drops are primarily due to the acidic nature of the waste and to the formation of organic acids and volatile fatty acids during the degradation of various substrates. In fact, the pH drop most often occurs during acidogenesis and hydrolysis. During these stages, particulate matter is broken down into soluble compounds, which are then converted into acetate, hydrogen, carbon dioxide, propionate, and butyrate (Swetha et al., 2023).

3.1.1.2. Biogas yield of different types of waste per gram of volatile dry matter

Biogas yields from organic waste per gram of volatile dry matter as a function of time are shown in **Figure 2**. Analyzing the results, it appears that after 45 days of methanization, the highest specific biogas production was obtained with tuna waste (302.5 mL/g SV) followed by food waste (205.9 mL/g SV).

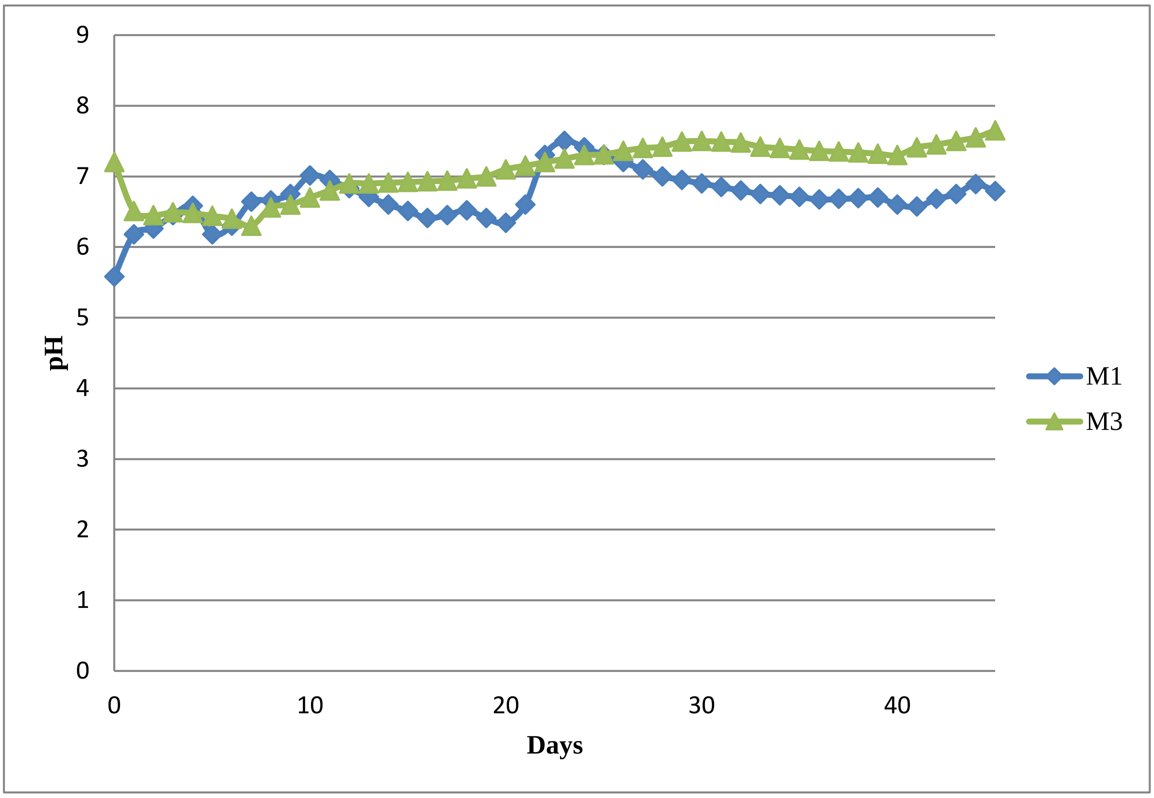


Figure 1. Variation in the pH of mixtures M_1 and M_2 during anaerobic digestion.

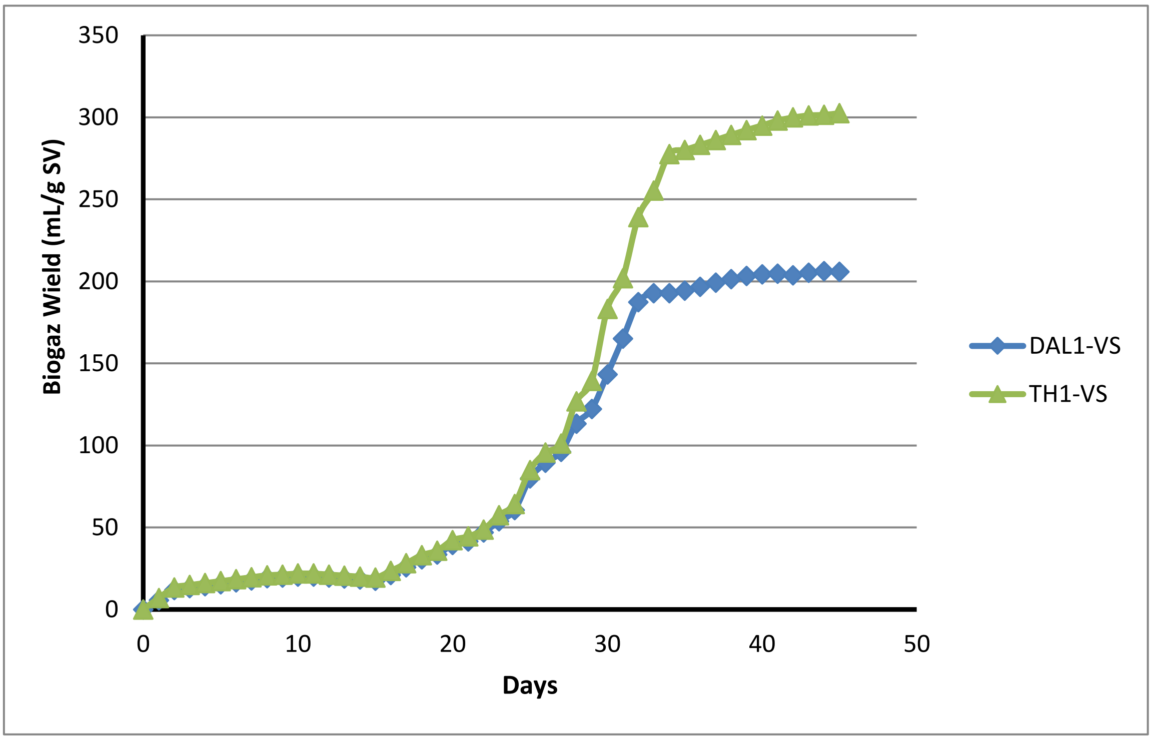


Figure 2. Specific biogas yields of each mono-substrate

The high specific biogas yield of tuna waste compared to that of food waste would certainly be linked to a greater accumulation of VFA (decrease in pH) in the digesters containing food waste compared to those containing tuna waste (Maurus *et al.*, 2021), (Haririchi *et al.*, 2022). The biomethanogenic potentials are 161.6 ± 2.5 and 211.8 ± 4.9 mL CH_4/gSV for food waste and tuna waste respectively.

3.1.2. Co-digestion of food waste with tuna fish waste

3.1.2.1. Evolution of pH over time

Figure 3 shows the evolution of the pH as a function of time of the T-0.25 mixtures; T-1; T-1.5 and T-2 during anaerobic digestion. T-0.25; T-1; T-1.5 and T-2 are mixtures of co-digestion of food waste and tuna respectively at ratios $\frac{SV_{substrat}}{SV_{inoculum}}$ of 1/4, 1/1, 1.5/1 and 2/1.

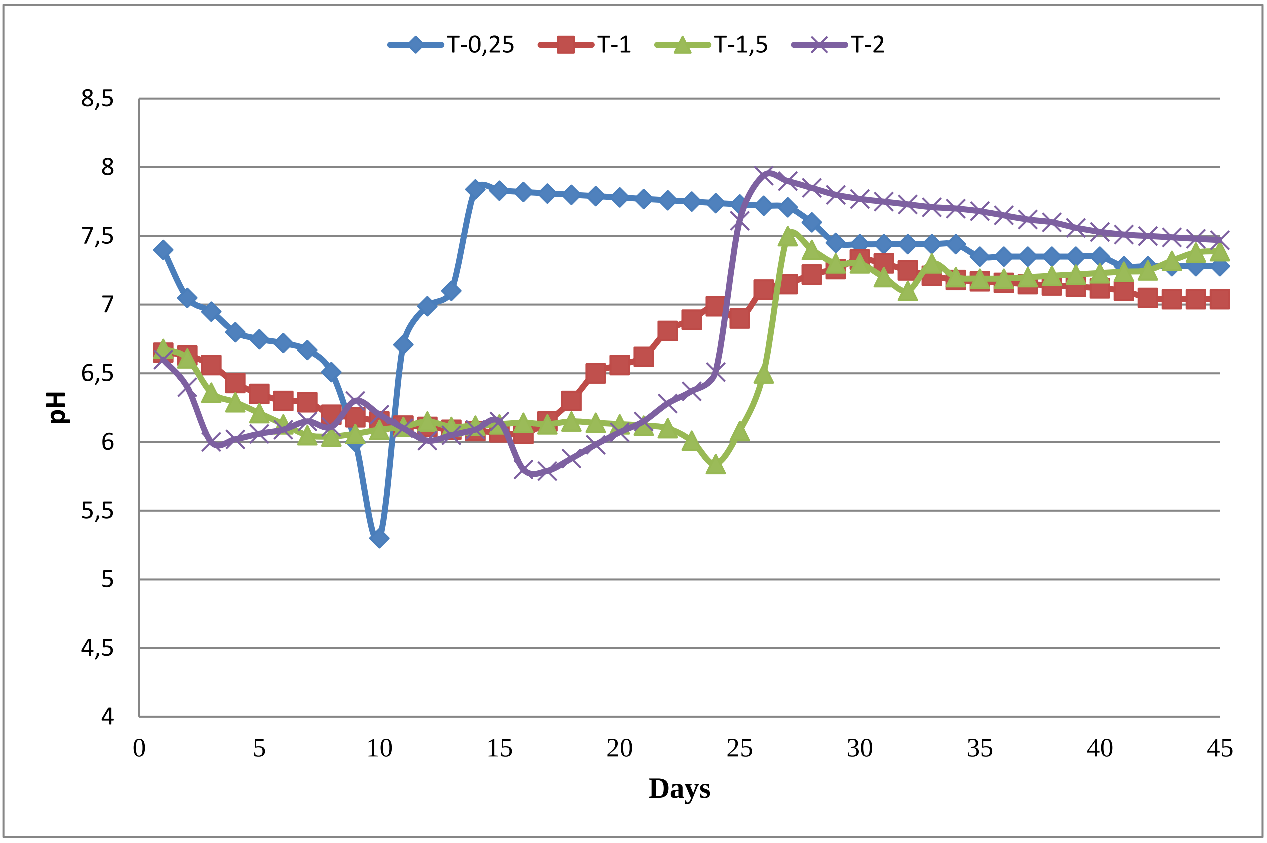


Figure 3. Evolution of the pH of mixtures T-0.25; T-1; T-1.5 and T-2

pHs are between 5.30 and 7.94 for all types of T-0.25 mixtures; T-1, T-1.5 and T-2. The pH of these mixtures is respectively 7.40; 6.65; 6.68 and 6.60 at the start of anaerobic digestion. The pH of the T-0.25 mixture is the highest and all of these pHs are above 6.5. The pH of the T-0.25 mixtures remained above 6.5 after 10 days of digestion. As for the pH of the T-1 mixture, it is greater than 6.5 after 19 days of digestion. The pH of the other mixtures T-1.5 and T-2 remained above 6.5 after 26 days and 23 days of digestion respectively. At the end of anaerobic digestion, all pHs are within the optimal pH range. A slower decline in pH at Substrate/Inoculum ratios greater than or equal to 1 was observed compared to Substrate/Inoculum ratios less than 1. Compared to the results obtained for food waste alone (pH=5.58), these results indicate pHs that are generally within the optimal range indicated for anaerobic digestion (6.5-8.5) (Ajayi-Banji *et al.*, 2022). The advantage of using tuna waste in the proportions used in this study is the adjustment of the pH of food waste to values above 6.5. This leads to a reduction in the use of lime for pH adjustment and therefore saves money.

The observed pH drops would be due to the aforementioned reasons. They could also be linked to the use of fresh cow dung as an inoculum (Hamzah *et al.*, 2024). Indeed, fresh cow dung is believed to contain more acidogenic bacteria than methanogenic bacteria, so the imbalance between these two microbial groups could disrupt anaerobic digestion (Abid *et al.*, 2021). Thus, a higher quantity of acidogenic bacteria in fresh excrement would lead to a rapid and higher concentration of volatile fatty acids (VFAs). These VFAs, which cannot be consumed as quickly by methanogenic bacteria as by acidogenic bacteria, accumulate and cause a pH drop in the digester (Al-Sulaimi *et al.*, 2022).

The slower pH decrease observed could be due to a slow acid production for Substrate/Inoculum ratios ≥ 1, because in this case, the digesters contain less inoculum (Kassongo *et al.*, 2022) .

3.1.2.2. Specific yield of biogas per gram of volatile dry matter

The specific biogas yields per gram of volatile solids of the four substrate mixtures T-0.25; T-1; T-1.5 and T-2 are shown in **Figure 4**.

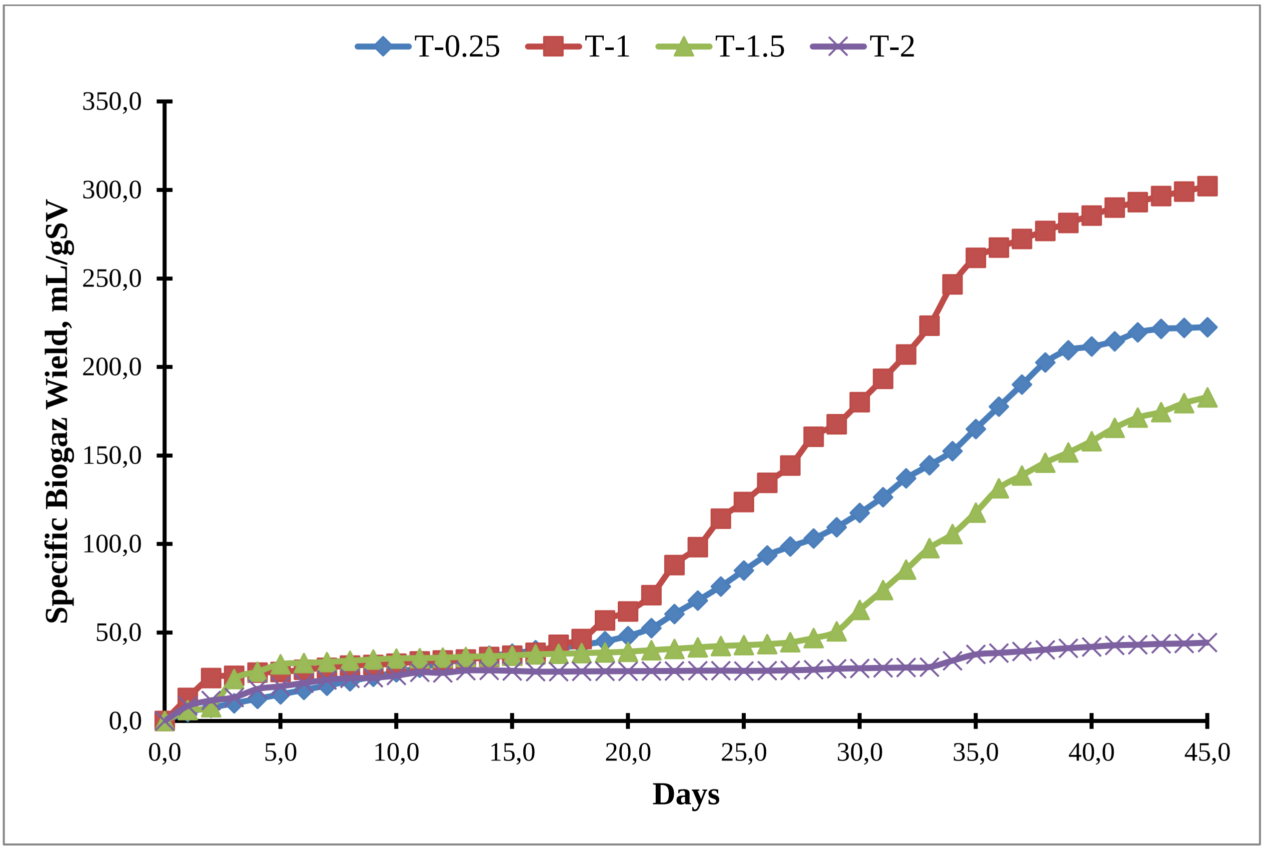


Figure 4. Specific yield of biogas from the co-digestion of T-0.25 mixtures; T-1; T-1.5 and T-2

The specific biogas yields are 222.5; 302.1; 180.1 and 44.3 mL/g SV respectively for the T-0.25 mixtures; T-1; T-1.5 and T-2 (**Figure 4**). The T-1 mixture has the highest specific biogas yield, while the T-2 mixture gives the lowest specific biogas yield. The specific biogas yield of the T-1 mixture is higher than those of the T-0.25 mixtures; T-1.5 and T-2 respectively by 36%, 68% and 58.2%. The results of this study are comparable to those of other studies where the biogas yields are 99.18 mL/g SV and 225 $mLCH_4/gVS$ after 27 days of digestion at 37°C (Mota-Panizio *et al.*, 2021).

The specific yield of biogas depends on the quantity of organic matter used. The higher specific biogas yields of T-1 mixtures could be due to the biodegradability of the substrates of T-1 mixtures compared to other mixtures (Chen *et al.*, 2024), at the Substrate/Inoculum ratio. Indeed, the specific yield of biogas increases with the biodegradability of food waste (Chen *et al.*, 2024).

It should be noted that the specific yield of biogas in the case of monodigestion of food waste for a Substrate/Inoculum ratio of 1 is 205.9 mL/g SV. This specific yield is much lower than those obtained in the case of the co-digestion of food waste and tuna waste for substrate/inoculum ratios of 1 and 2/8, which are respectively 302.1 and 222.5 mL/g. SV. The co-digestion of food waste and tuna waste therefore made it possible to increase the specific yield of the biogas produced from food waste by 47% and 8% respectively for the Substrate/Inoculum ratios of 1 and 2/8.

The specific methane yields of the different types of co-substrates are 166±2; 222±4; 131±3 and 22±1 mL CH_4/ gVS respectively for the T-0.25 mixtures; T-1; T-1.5 and T-2. The best yield was obtained for the T-1 mixture. The best methane yields correspond to annual energy productions of 216 GWh (26MW) for T-1 mixtures (Alao *et al.,* 2022), taking into account an annual production of food waste of 1624 million tonnes. These results show that anaerobic co-digestion of food waste with tuna waste increased biogas production. This production is significantly affected by the C/N ratio (Budiyono *et al.,* 2023). An optimal C/N ratio is necessary because a proper nutrient balance is required by anaerobic bacteria for their growth as well as for maintaining a stable environment. However, for an application on an industrial scale, it would be necessary to determine the C/N ratio as well as the residence time which gives the best biogas yield for the anaerobic co-digestion of food waste with tuna waste.

3.2. Optimization of biogas yield in the case of co-digestion

3.2.1. Factor Analysis

The experimental plan made it possible to achieve the results summarized in Table 1. The different coefficients are recorded in Table 2. Y_1 is the specific yield of biogas from the co-digestion of food and tuna waste.

Table 1. Results of the face-centered composite design

Experiences	1	2	3	4	5	6	7	8	9	10	11	12	13
Y1	149.2	181.2	232.4	325.0	220.0	304.0	168.9	291.3	279.6	284.2	274.9	283.5	278.4

Table 2. Summary of the average, main, interaction coefficients and quadratic coefficients of the different tests.

	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
	Probability	<0.0001	<0.0001	<0.01	0.001	<0.001	<0.001

The specific biogas yield is between 149.2 and 325 mL/g SV in the case of co-digestion of food and tuna waste. The coefficients vary between -45.183 and 278.738 for Y_1. The probabilities p for these coefficients to be zero are all less than 0.01. All the coefficients of the model are therefore significant ($p < 0.05$). Furthermore, we note a significant variability in the specific yield of biogas at the level of the areas of variation of the factors. This is confirmed by the standard deviations of the responses which are 6.658 for Y_1. The value of the average coefficient is $b_0 = 278.738$.

The influence of a factor on biogas yield is called factor effect. This effect is estimated by the coefficient bi. All effects are estimated by the coefficient b0, the interaction effects by the coefficient bij and the quadratic effects by the coefficient bii. With this plan, it is the overall quality of the model that is taken into account and not the influence of individual variables. The average coefficient value ($b_0 = 278.738$) indicates that these co-digestions can produce more than 278.738 mL/gSV of biogas respectively. The probabilities p for these coefficients to be zero are all less than 0.01. This means that all variables as well as their interactions have a significant influence ($p<0.01$) on the specific yield of biogas in the areas considered. Based on individual p-probability values less than 0.05, all terms in the model are significant. It should be noted that lower p-values mean greater influence of the term for the model. The model can be described by the following equation:

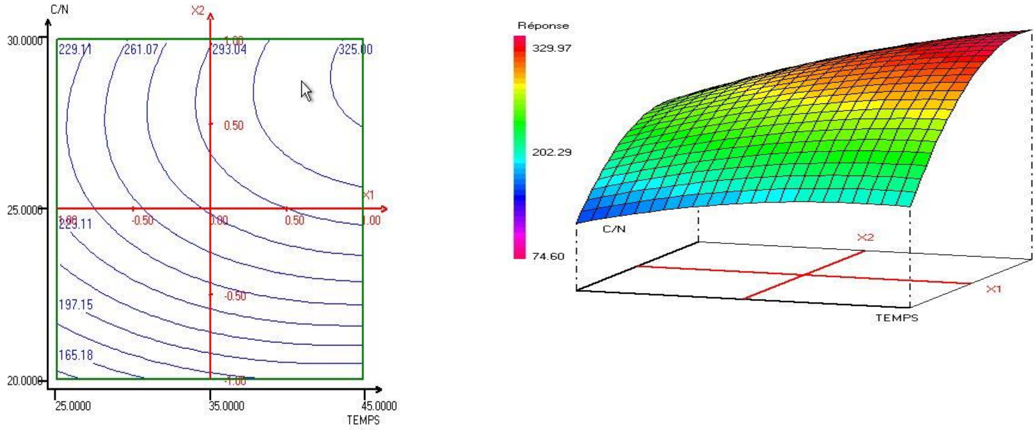
$$Y_1 = 278{,}738 + 34{,}8X_1 + 58{,}2X_2 - 13{,}283X_1^2 - 45{,}183X_2^2 + 15{,}1X_1 X_2 \qquad \textbf{Equ. 2}$$

With Xi designating the variables as coded values

The b_{12} interaction effect in biogas production is 15,100. Its interpretation is made from the graph of interaction effects.

3.2.2. Interaction effects

The study of interaction effects allows a better interpretation of the interactions between the different factors chosen. The influence of the variables represented in the production of biogas and their interaction effects are illustrated in **Figure 5**.



v.

(a) **(b)**

Figure 5. Graph of the Y1 response as a function of the b12 interaction for the quadratic model (a) and Isoresponse curve of the specific yield Y1 of biogas su from the co-digestion of food waste and tuna (b)

As the residence time and C/N ratio increase, the specific biogas yield increases, except for the range 28–30 where the yield is reduced (**Figure 5**). Thus, higher values of the residence time and the C/N ratio (greater than 25) correspond to higher biogas yields. It should be noted that the increase in the specific yield of biogas obtained for a residence time greater than or equal to 35 days Y_1 is almost negligible. The negligible increase in specific biogas yield at residence times greater than or equal to 35 would mean that significant energy savings can be achieved at these residence times to maintain the temperature at 37°C. It appears that the parameter having the most influence on the specific yield of biogas is the C/N ratio. These results further demonstrate the interactive effects between residence time and C/N ratio. Co-digestion of food waste with tuna waste in the C/N ratio of 20 is not cost-effective.

3.2.3. Adjustment of the model of phenomenon studied

It is necessary to study the perfect match between the models obtained and the experiment. This is done from the study of the correlation between the experimental (Yexp) and calculated or expected (Ycalc) responses (**Figure 6** and **Table 1**).

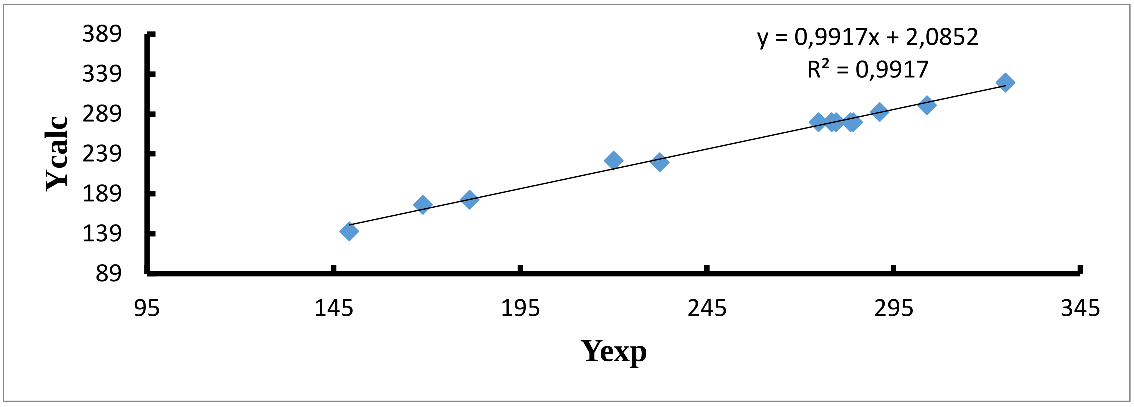


Figure 6. Correlation curve between Ycalc and Yexp for Y1

The coefficient of determination obtained is 0.991 for co-digestion with tuna waste. This indicates that the model is well adjusted. The multiple linear correlation coefficient indicates the very good quality of fit. This value of the linear correlation coefficient R is 0.996. It is close to 1. This indicates that the model explains the phenomenon studied at 99.6%. This correlation coefficient can also be obtained by the plots Yexp (measured responses) as a function of Y_{calc} (responses predicted by the model) presented in **Figure 6**. The adjusted R^2 value obtained is 0.986 for Y_1, which suggests good agreement between the experimental and predicted values of the biogas potential. According to the statistical analysis and ANOVA results, these models are highly significant with very low p-values ($p < 0.05$). All these findings suggest the adequacy between the postulated nonlinear model and the experiment. Furthermore, this confirms the use of a second-degree quadratic model to explain the phenomenon studied.

3.2.4. Optimization of biogas production

When the model is well fitted, the next step is to search for optimal conditions. Concerning this study, this concerns the residence time and the C/N ratio making it possible to maximize the specific yield of the biogas. According to the results obtained previously, the predicted responses of the specific biogas yield are in the form indicated in **Equ. 2** for Y_1. The graphic representation of the isoresponse curve (**Figure 5 b**) of the models makes it possible to graphically determine, with certainty, the best zone leading to maximizing biogas production. Simultaneous optimization of multiple responses was carried out by the Excel spreadsheet in order to find the optimal anaerobic digestion conditions for maximum biogas yield (**Figures 5a and 5b**). This numerical optimization technique determines a point that maximizes optimal function and conditions. These are :

- Y_{1MAX}= 329,97 mL/gSV pour X_1 =0,998 et X_2 = 0,811 **Equ. 3**

Thus, the maximum value of the specific biogas yield predicted by the second degree quadratic model is 330±5 mL/gSV for mixtures of food waste and tuna. This response corresponds to a residence time of approximately 45 days with a C/N ratio of 29.01.

3.2.5. Model validation

In order to validate the model, experiments were carried out based on optimal theoretical values obtained for the factors. The specific biogas yields of 330.7±3.2 mL/gSV (**Table 3**) for Y1 reasonably close to the predicted value. This demonstrates the validity and adequacy of the selected models. The methane content (%) is 78.1± 0.4

Table 3. Experimental verification of the validity of the model

Experience	Y_1(mL/gSV)
1	333
2	332
3	327

This methane production corresponds to an electricity production of 207 GWh (24 MW) for Y_1 (according to Equ. 2) for an annual production of food waste of 1.051 million tons according to Ivorian authorities. This production therefore corresponds to 6% of Ivorian butane gas consumption according to figures for 2017 from the Ministry of Petroleum, Energy and the Development of Renewable Energy of Côte d'Ivoire.

Conclusion

Study carried out aims to evaluate the energy potential of biogas from Abidjan waste by anaerobic digestion.

The results indicate that fermentable waste from Abidjan revealed biomethanogenic potentials (mL/gSV) of 161.6 and 211.8 for food waste (DAL) and tuna waste (TH) respectively. The results of DAL-TH codigestion present maximum specific methane yields (mL/gSV) of between 216 and 330. These yields correspond to a maximum energy potential of 207 GWh (24MW).

These results show that the conversion of biogas to electricity can be an attractive management policy. The energy production is considerable not only to cover the consumption of a biogas plant, but also to sufficiently supply the network. The results presented above constitute valuable and essential information. They constitute a knowledge base that can be taken into account in future decisions regarding household solid waste management. In addition, they can be used for studies on the integrated management plan for urban solid waste in Abidjan as part of sustainable development and for an energy transition in Côte d'Ivoire.

Outlook

The results obtained in this study should be supplemented to better understand the implementation of the project to recover biogas from waste. For this, it would be desirable:

- ✓ to carry out a study on the conservation of biogas;
- ✓ to conduct a study on a comprehensive legal framework and roadmap for the energy-from-waste production project in Côte d'Ivoire, which will incorporate adequate human capacity building for the effective management of MSW for the production of energy.

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