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Biogas Production from Plantain and Yam Peels: Modelling using Response Surface Methodology

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Abstract

The world's growing demand for energy and our concern to preserve the environment have prompted research into alternative sources of energy. Renewable energy from biomass is one such opportunity. The aim of this study is to model the production of biogas from the anaerobic digestion of plantain and yam peelings and cattle dung. A characterisation of these residues showed their good suitability for methanisation with good moisture contents (>70%), high volatile solids contents (>75%) and C/N ratios of between 20 and 30. In addition, methanisation trials under mesophilic conditions following a mixing plan generated quantities of biogas ranging from 128 to 565 mL with CH_4 contents of between 54.03 and 72.98%. The digester made up of 1/6 plantain peels + 2/3 yam peels + 1/6 cattle dung gave the best biogas yield with 565 mL for 67.52% CH_4. The model established from these results is highly significant with an F value (1268.01) having a probability significantly lower than 0.05. In addition to the coefficients R^2 (0.9994) and R^2 (0.9986) which adjust are very close to unity, there is a good correlation

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between the experimental results and those predicted. This prediction model is therefore reliable for explaining biogas production. However, further study of the kinetics of anaerobic digestion and biogas treatment remains important.

Introduction

Energy is an essential component of economic and social development (Deshaies and Kouadio [11]). It contributes to the permanent satisfaction of a number of needs such as food, education, housing, health, transport, etc. As part of this development trend, global demand for energy is increasing at a worrying rate (Kwietniewska and Tys [20]). Indeed, projections have shown that this need for energy over the course of this century has increased by a factor of 2 to 3 (Weiland [31]). However, fossil fuels are largely responsible for long-term environmental risks through greenhouse gas emissions (Boissin [6]). Faced with this situation, it is imperative to resort to other sources of energy that replace fossil fuels and protect the environment (Mckendry [24]). One of the solutions to this concern is anaerobic digestion. It appears to be a process that offers the possibility of combining waste treatment with the production of renewable biogas energy (Laskri *et al.* [22]). Plantain and yam are still the main source of food for many people in the West African subregion, particularly in Côte d'Ivoire (Bomisso *et al.* [7]) (Ettien and Tschannen [13]). Despite all the benefits that these foods provide, they generate a considerable amount of waste, including peelings, which are unsuitable for our environment. If left untreated, this waste becomes a potential source of disease (Prüss-Üstün and Corvalán [26]). In developing countries, their elimination poses a challenge to governments because of the weakness of their waste management systems (Mangoumbou *et al.* [23]). The aim of this study is to recover energy from plantain and yam peelings in order to contribute to new energy sources. Specifically, the aim is to develop a model that predicts the biogas yield from the anaerobic digestion of plantain and yam peelings and cattle dung using response surface methodology. To achieve our objective, we first carried out a physicochemical characterisation of plantain and yam peelings and cattle dung collected in the town of Yamoussoukro with a view to understanding the feasibility conditions for their methanisation. Anaerobic digestion tests were then carried out under mesophilic conditions using a conventional mixing plan. Finally, the experimental results were used to develop a model for predicting biogas yield.

Material and Methods

Substrates: The study material consisted of three samples: plantain peels, yam peels and cattle dung. The plantain and yam peels came from restaurants in the city of Yamoussoukro. The cattle dung comes from the farm of the Institut National Polytechnique-Houphouet Boigny (INP-HB) in Yamoussoukro. The plantain and yam residues were crushed in a blender for easy access to the micro-organisms. The dung was not pre-treated. Figure 1 shows the images of the samples. The samples were stored in a refrigerator at -4°C (Sajeena Beevi *et al.* [27]) until testing took place after exposure to room temperature.

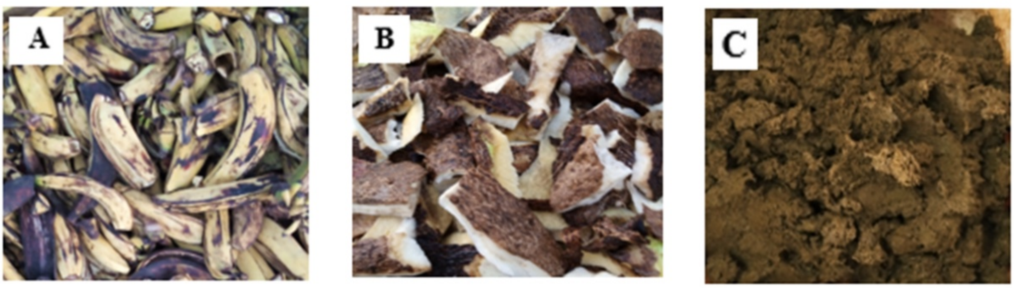

Figure 1. Plantain peels (A); Yam peels (B); Cattle dung (C).

Moisture content (H): For the evaluation of the moisture content, a mass (m_0) of sample was oven dried at 105°C for 24 hours (Kra *et al.* [19]). The moisture loss (H) was evaluated between the mass m_0 and that obtained after drying m_1 according to the following relationship (1):

$$H(\%) = \frac{m_0 - m_1}{m_0} * 100 \quad (1)$$

H: moisture content;

m_0: initial mass of the sample before drying;

m_1: mass of the sample after drying for 24 hours at 105°C in the oven.

Total Solids (TS): The determination of the total solids content is a function of the moisture content.

$$ST(\%) = 100 - H \qquad (2)$$

ST: total solids content;

H: moisture content.

Volatile solids content (VS): The volatile solids content of a sample is assessed after measuring its water content. The dried sample (m_1) was placed in a muffle furnace at 550 °C for 6 hours giving a mass m_2. Subsequently, this content was measured as the percentage weight loss of the dried sample (M'Sadak and M'Barek [25]) according to equation (3):

$$VS(\%) = \frac{m_1 - m_2}{m_1} * 100 \qquad (3)$$

VS: volatile solids content;

m_1: mass of sample after oven drying for 24 hours at 105°C;

m_2: mass of sample calcined at 550°C for 5 hours after drying.

Determination of pH: The hydrogen potential (pH) of each waste (substrate) was determined by dissolving the waste in a waste/distilled water ratio of 1:10 (Traore *et al.* [29]). Thus, 5 g of waste was suspended with 50 mL of distilled water in a 250 mL beaker under constant stirring for 5 min using a magnetic stirrer. The suspension was left to stand for 30 min for pH measurements using a HANNA HI 8424 pH meter.

Carbon and nitrogen content of substrates: The determination of carbon (C) was carried out by the Walkley and Black method (Walkley and Black [30]) which consists of an oxidation of the organic matter by an excess amount of potassium dichromate ($K_2Cr_2O_7$) in a cold sulphuric medium, in the presence of a coloured indicator (diphenylamine). The carbon concentrations are given as a percentage according to the following equation (4):

$$C(\%) = (V_1 - V_2) * \frac{0{,}897}{M} \qquad (4)$$

V_1: volume of iron sulphate used to titrate the blank;

V_2: volume of iron sulphate used to titrate the sample;

M: mass of the sample in grams;

0.897: dilution correction factor.

The determination of the nitrogen content was done by hot (300°C) and acidic mineralization of the organic matter according to the Kjeldhal method (Bremner [8]). This is a three-step assay: mineralization of the organic nitrogen into ammoniacal nitrogen, distillation and titration of the mineralisate. The nitrogen content is given by the relation (5):

$$N(\%) = \frac{0{,}14 \times 1000 \times C \times (V_e - V_b)}{m} \times 10 \quad (5)$$

m: test sample mass in grams;

V_e: volume of soda added for the sample determination;

V_b: volume of soda added for the blank determination;

C: concentration of the soda solution used.

The organic carbon was divided by the total nitrogen to obtain the C/N ratio.

Experimentation matrix: The experimentation matrix is given in Table 1.

Table 1. Experimentation matrix.

Order of tests	Factor 1	Factor 2	Factor 3
Standard	X1: Plantain	X2: Yam	X3: Cattle dung
2	0	1	0
9	0.167	0.667	0.167
10	0.167	0.167	0.667
6	0	0.5	0.5
5	0.5	0	0.5
13	0	0	1
3	0	0	1
8	0.667	0.167	0.167
15	0.5	0	0.5
14	0.5	0.5	0
4	0.5	0.5	0
7	0.333	0.333	0.333
12	0	1	0
11	1	0	0
1	1	0	0

The mixtures for the anaerobic digestion trials were based on the volatile matter contained in plantain peels, yam peels and cattle dung. The mass of volatile solids in the substrates was therefore the factor used in the mixtures. We set a total mass of 16gVS per trial. Henry Scheffé's Simplex-centroid design was adopted. For the three substrates, this design requires ten trials with different proportions of substrates determined by the Design Expert software 11. However, the first five trials were repeated.

Anaerobic digestion tests according to the mixing plan: All trials were conducted in batch type digesters for 40 days. The experimental digester is a 1200 mL vessel with a usable volume of 1000 mL and a headspace of 200 mL. It has two ports, one for syringe sampling of liquids and one for collecting and measuring the volume of biogas produced. Once the waste is in the digester, the final volume is adjusted with distilled water. The digester is then sealed with a screw cap and placed in a thermostat at 37 ± 1°C. Each digester is manually stirred twice a day for two minutes to homogenise the anaerobic medium. The biogas is collected in graduated tubes (gasometers) inverted by the water displacement method (Kouakou *et al.* [17]) to determine the volume collected.

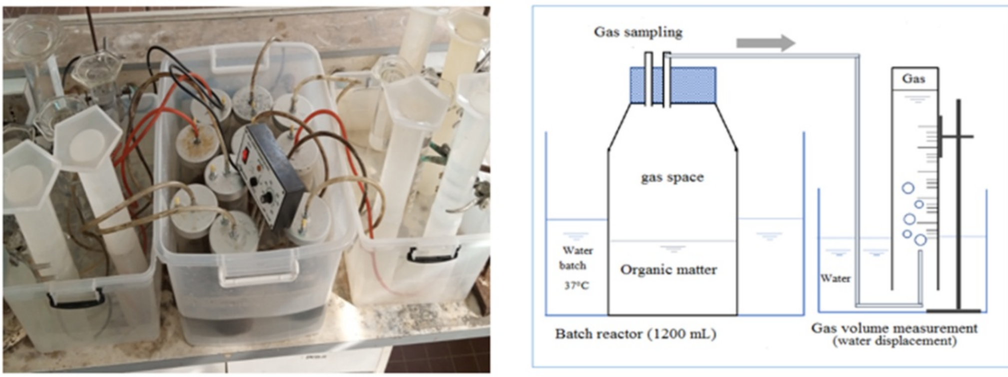

Figure 2. Anaerobic digestion test setup.

Results and Discussion

Physical and chemical parameters: The results of the analysis of the physico-chemical parameters of the waste before the tests are presented in Table 2.

Table 2. Physico-chemical characteristics of substrates.

Substrates	pH	H (%)	TS (%)	VS (%)	C (%)	N (%)	C/N ratio
Plantain peelings	5,27	87,01	12,98	86,07	38,72	1,36	28,47
Yam peelings	5,78	74,34	25,65	94,57	30,19	1,23	24,54
Cattle dung	8,14	86,90	13,09	76,97	42,83	1,66	25,80

The pH values obtained according to Table 2 are 5.27, 5.78 and 8.14 for plantain peelings, yam peelings and cattle dung in that order. It should be noted that only dung has a pH within the range recommended for good anaerobic digestion, i.e. between 6.5 and

8.5 (Kouadio [16]). Such a pH is favourable to the growth of methanogenic bacteria (Kalloum *et al.* [15]) and can raise the pH of the anaerobic environment in the context of co-digestion with acidic substrates (Kpata [18]). The moisture contents (H) of the different substrates are 87.01, 74.34 and 86.90% for plantain peelings, yam peelings and cattle dung, respectively. This high moisture content indicates that the residues are highly fermentable and therefore suitable for anaerobic fermentation (Afilal *et al.* [2]). As volatile solids (VS), the proportions obtained are 86.07%, 94.57% and 76.97% for plantain peelings, yam peelings and cattle dung respectively. It can be seen that these contents are high. For plantain and yam peelings, they are almost identical to those obtained by Thomsen *et al.* [28] as part of their work on biofuel production from West African agricultural residues. They determined 85.20% and 94.80% as organic matter contents for plantain and yam peelings. Compared with the work of Lacour [21], where the volatile solid content of the dung was 55%, our dung is the richest in organic matter. This high organic load is favourable to methanisation technology. The C/N ratios were 28.47, 24.54 and 25.80 for plantain and yam peels and cattle dung. These values suggest that the biological conversion processes are stable, as they fall within the range recommended by Gunaseelan [14], i.e. between 20 and 30. This stability would be enhanced by the use of cattle dung, whose C/N ratio is close to the optimum value of 25. Analysis of these physico-chemical parameters highlights certain properties specific to the substrates that could favour the possibility of co-digestion between them.

Results of the anaerobic digestion tests: The results of the anaerobic digestion tests are shown in Table 3. They show that the biogas yield ranged from 128 to 565 mL. Trial 9 (1/6 banana; 2/3 yam; 1/6 dung) recorded the highest amount of biogas with 565 mL. In contrast, trial 11 (Plantain) provided the least amount with 128 mL. These data were used to establish the biogas yield prediction model.

Table 3. Quantities of biogas from the different tests.

Order of tests	Experimental results
Standard	Biogas (mL)
2	373
9	565
10	502
6	556
5	241

13	407
3	410
8	370,5
15	249
14	491,4
4	485
7	555,6
12	368,2
11	128
1	133

Biogas quality: The composition of the biogas was determined by a portable biogas analyser of the BOSEAN type. The values provided by this device are shown in Table 4.

Table 4. Composition of biogas by digester.

Digesters	CO_2 (%)	CH_4 (%)	H_2S (ppm)	CO (ppm)
1	33,17	54,03	>5	37
2	35,97	56,83	>5	34
3	16,02	72,98	0,02	7
4	30,72	59,51	>10	45
5	30,49	57,51	2	27
6	32,67	62,33	1,8	24
7	22,06	65,94	2,2	19
8	30,49	63,28	> 5	23
9	21,48	67,52	1,5	17
10	27,51	69,49	0,08	10
11	32,59	55,17	>5	35
12	35,27	54,94	>5	35
13	17,12	72,85	0,04	6
14	29,83	56,61	>10	43
15	28,26	59,24	2,14	27

This table shows that the biogas from the various digesters consists of carbon dioxide (CO_2), methane (CH_4), hydrogen sulphide (H_2S) and carbon monoxide (CO). The CH_4 and CO_2 contents of these biogases are in line with the general composition of biogas (50 to 75% CH_4 and 25 to 50% CO_2) (Adjiri *et al.* [1]). As regards the most important gas sought in biogas (CH_4), the highest content comes from the digester containing only cattle dung (72.98%). Apart from this digester, the CH_4 proportions are also good in the codigestion digesters containing cattle dung (between 57.51 and 69.49%). However, the digesters without dung showed the lowest CH_4 contents (between 54.03 and 59.51%). We can say that cattle dung improved the CH_4 quality of the biogas in the codigestion digesters. It is therefore an important co-substrate for the anaerobic digestion of plantain and yam peels. In addition, CO_2, H_2S and CO are impurities found in these biogases. If this biogas is to be used, it will need to be purified.

Biogas production modelling: Using the response surface methodology, we were able to build a predictive model of biogas quantity from the test results (Table 3). The model that could explain the relationship between substrates and biogas quantity is of the special quartic form. After fitting, its equation is given by the relationship (6). The coefficients of the model and their significances were evaluated by Design Expert 11 software.

$$\mathbf{Y} = +\,130.84\mathbf{X1} + 370.94\mathbf{X2} + 408.84\mathbf{X3} + 951.98\mathbf{X1X2} - 96.62\mathbf{X1X3} + 669.93\mathbf{X2X3} + 1440.20\mathbf{X1^2X} + 2581.83\mathbf{X1X2^2X3} + 3168.63\mathbf{X1X2X3^2} \quad (6)$$

In this equation, X1, X2 and X3 are the coded values of the proportions of plantain peels, yams and cattle dung, respectively, with Y being the amount of biogas. The positive sign in face of a term indicates a synergistic effect on the other hand, any negative sign indicates an antagonistic effect on the response (Alahiane *et al.* [3]). Thus, with the exception of the interaction term X1X3 showing an antagonistic effect, the other terms have synergistic effects on biogas production. As a result, the effects of the independent variables X1, X2 and X3 as well as those of the terms X1X2, X2X3, $X1^2X2X3$, $X1X2^2X3$ and $X1X2X3^2$ increase biogas yield while a strong X1X3 interaction decreases this yield.

This regression model can be materialised by a response surface (Aydram *et al.* [5]). Figure 3 is an illustration of the special quartic model developed in this study. In this figure, the vertices of the triangle indicate the maximum proportions of the different factors. As one moves to the side, this percentage decreases. Also, the colouring of the triangle reflects the different values taken by the response. The responses are given from the lowest to the highest, from blue to red. The area where the red colour is more pronounced implies a high biogas yield due to the good digestibility of the organic matter. On the 2D graph, there are also lines called contour lines. Each curve shows the same response for all the mixing points on it. However, this model was subjected to an analysis of variance (ANOVA) to judge its quality.

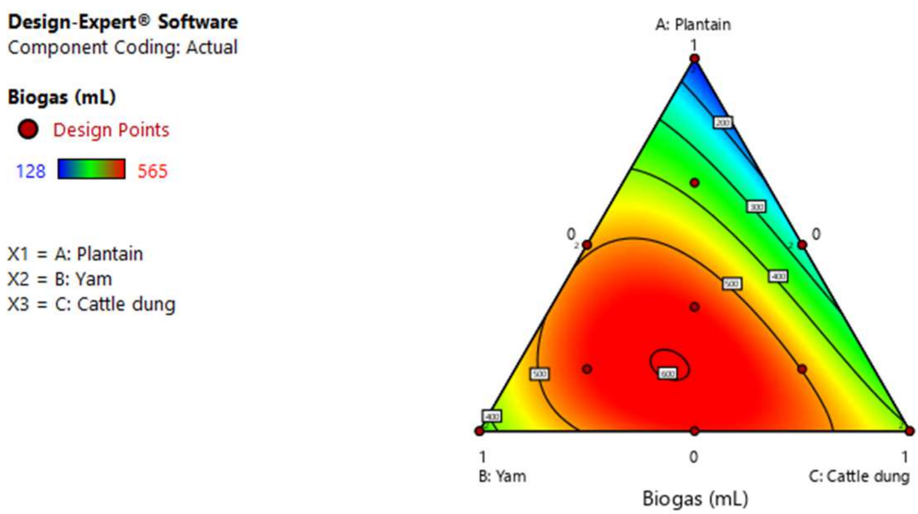

Figure 3. 2D representations of the response surface.

Statistical analysis: In order to determine the significance of the special quartic model, an analysis of variance (ANOVA) of the model was performed as shown in Table 5.

Table 5. ANOVA results of the special quartic model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	295900	8	36984,15	1268,01	< 0.0001	significant
Residual	175,00	6	29,17			
Lack of Fit	94,00	1	94,00	5,80	0,0609	not significant
Pure Error	81,00	5	16,20			
Cor Total	296000	14				

Std. Dev	5,40	R^2	0,9994
Mean	388,98	adjusted R^2	0,9986
C.V(%)	1,39	predicted R^2	0,9771
	Adeq Pecision	103,0158	

The ANOVA was performed with the Design Expert 11 software to determine the relevance and significance of the model. The model and the model terms are considered significant when their probability values (p-value) are less than 0.0500 (Briton *et al.* [9]). This table reveals that our model is highly significant due to an F-value of 1268.01 having a probability significantly less than 0.0001. Besides that, the predicted R^2 of 0.9771 is in reasonable agreement with the adjusted R^2 of 0.9986, i.e. the difference is less than 0.2 (Deepanraj *et al.* [10]). Also, the coefficient of variation (C.V) has a low value (1.39). This value gives the model a high degree of accuracy and good reliability (Sajeena Beevi *et al.* [27]). The adequate accuracy (Adeq Precision) of the model is very high (103.0158) and shows an adequate signal to noise ratio. It therefore implies that the model can be used to navigate the design space.

Experimental values compared with predicted values: In addition to the statistical analysis, the predictive ability of the regression model was assessed by plotting the prediction against the experiment. This plot was obtained using the graphical interface of the Design Expert 11 software. Analysis of this graph is used to estimate the predictive quality of the model and its relevance for validation (Armah *et al.* [4]). In Figure 4 we observe a strong correlation between the theoretical and experimental results as all points tend to be close to the regression line. This fact reflects the agreement between the theory used and the mixing design used to develop our model (Diarrassouba *et al.* [12]). This confirms that the model is robust and therefore very effective for predicting biogas yield. We can therefore use it to determine the amount of biogas at any point in the study area.

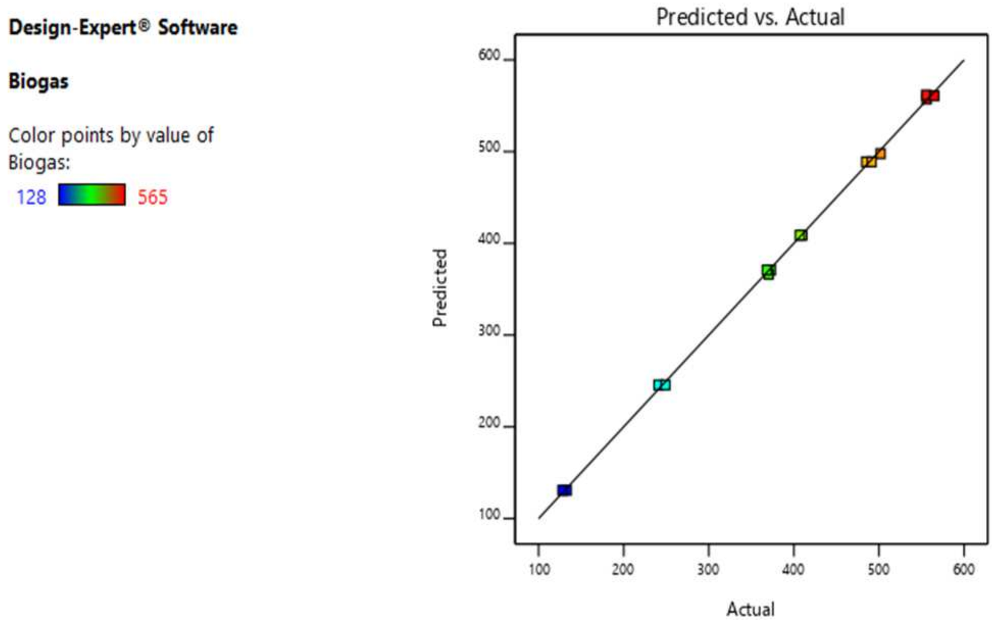

Figure 4. Prediction versus experience.

Conclusion: This study showed that biogas production from the anaerobic digestion of plantain and yam peels and cattle dung can be explained by a model. To do this, a physico-chemical characterisation of the substrates was carried out. This revealed that they are suitable for the anaerobic digestion process, given their high water and volatile matter content and good C/N ratios. With anaerobic digestion tests under mesophilic conditions and in batch mode, the quantities of biogas collected ranged from 128 to 565 mL. Analysis of the different quantities of biogas revealed CH_4 contents ranging from 54.03 to 72.98%. Based on the experimental results, a biogas quantity prediction model was established. An analysis of variance showed that the model is highly significant. In addition, the plot of the prediction against the experiment shows a strong correlation between the theoretical and experimental results. The model is therefore robust in explaining the biogas yield from anaerobic digestion of banana peels, yams and cattle dung under mesophilic conditions. However, a study of the kinetics of anaerobic digestion and a biogas purification process to complement this model would be required as part of a project.

References

[1] Adjiri, A., Koudou, A., Soro, G., & Biemi, J. (2018). Étude du potentiel de valorisation énergétique du biogaz de la décharge d'Akouédo (Abidjan, Côte d'Ivoire). *Environnement, Ingénierie & Développement*, N°77 - September 2018. https://doi.org/10.4267/dechets-sciences-techniques.3784

[2] Afilal, M. E., Elasri, O., & Merzak, Z. (2014). Caractérisations des déchets organiques et évaluation du potentiel biogaz. *Journal of Materials and Environmental Science*, *5*(4), 1160-1169.

[3] Alahiane, S., Qourzal, S., Sennaoui, A., El Ouardi, M., & Assabbane, A. (2016). Modélisation et optimisation de la photoélimination du rouge réactif 120 en milieu aqueux en présence de TiO_2 supporté. *Journal of Materials and Environmental Science*, *7*(2), 638-647.

[4] Armah, E. K., Chetty, M., & Deenadayalu, N. (2020). Biogas production from sugarcane bagasse with South African industrial wastewater and novel kinetic study using response surface methodology. *Scientific African*, *10*, 1-17. https://doi.org/10.1016/j.sciaf.2020.e00556

[5] Aydram, R., Alizade, H. H. A., Rasouli, M., & Shadidi, B. (2021). Simplex centroid mixture design for optimizing and promoting the anaerobic co-digestion performance of sheep blood and cheese whey. *Journal of Renewable Energy and Environment*, *8*(3), 8-15. https://doi.org/10.30501/jree.2021.251583.1151

[6] Boissin, O. (2021). Développement durable : Des chiffres et des étoiles Vol. 2 : Noire Magie. HAL Id : hal-03459396.

[7] Bomisso, E. L., Seydou, T., & Ake, S. (2018). Effet du mélange de pelure de banane plantain et de compost de fiente de poules sur la croissance en pépinière de rejets écailles de bananier plantain, variété Big Ebanga (Musa AAB sg Plantain). *Journal of Applied Biosciences*, *130*, 13126-13137. https://doi.org/10.4314/jab.v130i1.1

[8] Bremner, J. M. (1996). *Nitrogen-Total*. Chapter 37, pp 1085-1117

[9] Briton, B. G. H., Yao, B. K., Richardson, Y., Duclaux, L., Reinert, L., & Soneda, Y. (2020). Optimization by using response surface methodology of the preparation from plantain spike of a micro-/mesoporous activated carbon designed for removal of dyes in aqueous solution. *Arabian Journal for Science and Engineering*, *45*(9), 7231-7245. https://doi.org/10.1007/s13369-020-04390-0

[10] Deepanraj, B., Senthilkumar, N., Ranjitha, J., Jayaraj, S., & Ong, H. C. (2021). Biogas from food waste through anaerobic digestion: optimization with response surface methodology.

Biomass Conversion and Biorefinery, *11*(2), 227-239. https://doi.org/10.1007/s13399-020-00646-9

[11] Deshaies, M., & Kouadio, A. (2019). Les enjeux du développement des énergies renouvelables pour la production d'électricité en Côte d'Ivoire. *Revue Espace Géographique et Société Marocaine*, *26*, 249-272.

[12] Diarrassouba, F., Koné, M., Bamba, K., Traoré, Y., Koné, M. G.-R., & Assanvo, E. F. (2019). Development of predictive QSPR model of the first reduction potential from a series of tetracyanoquinodimethane (TCNQ) molecules by the DFT (density functional theory) method. *Computational Chemistry*, *07*(04), 121-142. https://doi.org/10.4236/cc.2019.74009

[13] Ettien, J. B., & Tschannen, A. (2003). Evaluation de nouvelles variétés d'igname en Côte d'Ivoire: bilan de trois ans d'expérience avec des génotypes améliorés par l'IITA. In avanes africaines: des espaces en mutation, des acteurs face à de nouveaux défis. Actes du colloque, Garoua, Cameroun, (7p.).

[14] Gunaseelan, V. N. (2007). Regression models of ultimate methane yields of fruits and vegetable solid wastes, sorghum and napiergrass on chemical composition. *Bioresource Technology*, *98*, 1270-1277. https://doi.org/10.1016/j.biortech.2006.05.014

[15] Kalloum, S., Khelafi, M., Djaafri, M., Tahri, A., & Touzi, A. (2007). Etude de l'influence du pH sur la production du biogaz à partir des déchets ménagers. *Revue Des Energies Renouvelables*, *10*, 539-543.

[16] Kouadio, M. C. (2020). Caractérisation physico-chimique et énergétique de la décharge d'Akouédo. Thesis. Université Félix Houphouët-Boigny (Côte d'Ivoire).

[17] Kouakou, A. R., Abollé, A., Kouadio, M. C., Akossi, M. J. C., Donatien, E. A., & Kouassi, E. K. (2022). Estimation of the energy potential by anaerobic digestion of food waste at Nangui Abrogoua University: Codigestion of food waste with cow dung. *Journal of Ultra Chemistry*, *18*(3), 37-43. https://doi.org/10.22147/juc/180301

[18] Kpata, N. E. (2014). Valorisation des effluents issus de la production d'attiéké par digestion anaérobie avec l'urine humaine comme co-substrat.

[19] Kra, E. K. F., Lebi, & Adama, O. (2018). Characterization of waste from "attiéké" (*Cassava semolina*) process for the dimensioning of bio-methane's digester. *International Journal of Applied Science and Research*, *1*(3).

[20] Kwietniewska, E., & Tys, J. (2014). Process characteristics, inhibition factors and methane yields of anaerobic digestion process, with particular focus on microalgal biomass fermentation. *Renewable and Sustainable Energy Reviews*, *34*, 491-500. https://doi.org/10.1016/j.rser.2014.03.041

[21] Lacour, J. (2012). Valorisation de résidus agricoles et autres déchets organiques par digestion anaérobie en Haïti. https://tel.archives-ouvertes.fr/tel-00825479/document https://doi.org/10.54226/uniq.edse.28312

[22] Laskri, N., Hamdaoui, O., & Nedjah, N. (2007). Traitement et valorisation des déchets par procédé de digestion anaérobie : production du biogaz. *Revue des Energies Renouvelables CER'07 Oujda,* 23-26.

[23] Mangoumbou, G., Bekabeka, A., & Ngouma, D. (2023). Gestion des déchets et impacts sanitaires dans les campus de Brazzaville en République du Congo. *Revue Espace Géographique et Société Marocaine*, *67*, 105-122.

[24] Mckendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, *83*, 37-46. https://doi.org/10.1016/s0960-8524(01)00118-3

[25] M'Sadak, Y., & M'Barek, A. Ben. (2013). Caractérisation qualitative du digestat solide de la bio méthanisation industrielle des fientes avicoles et alternative de son exploitation agronomique hors sol. *Revue des Energies Renouvelables*, *16*(1), 33-42.

[26] Prüss-Üstün, A., & Corvalán, C. (2007). Prévenir la maladie grâce à un environnement sain: une estimation de la charge de morbidité imputable à l'environnement. http://apps.who.int/iris/bitstream/10665/43615/1/9242594201_fre.pdf

[27] Sajeena Beevi, B., Jose, P. P., & Madhu, G. (2014). Optimization of process parameters affecting biogas production from organic fraction of municipal solid waste via anaerobic digestion. *International Journal of Bioengineering and Life Sciences, 8*(1), 43-48.

[28] Thomsen, S. T., Kádár, Z., & Schmidt, J. E. (2014). Compositional analysis and projected biofuel potentials from common West African agricultural residues. *Biomass and Bioenergy*, *63*, 210-217. https://doi.org/10.1016/j.biombioe.2014.01.045

[29] Traore, D., Nikiema, M., Somda, M. K., Sawadogo, J. B., & Dayeri, D. (2016). Contribution à la biométhanisation de la biomasse végétale : cas des résidus de légumes au Burkina Faso. *Int. J. Biol. Chem. Sci.*, *10*(1), 35-47. https://doi.org/10.4314/ijbcs.v10i1.4

[30] Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, *37*(1), 29-38. https://doi.org/10.1097/00010694-193401000-00003

[31] Weiland, P. (2010). Biogas production: current state and perspectives. *Appl. Microbiol. Biotechnol.*, *85*, 849-860. https://doi.org/10.1007/s00253-009-2246-7