Journal of Environmental Protection, 2025, 16(4), 273-291
https://www.scirp.org/journal/jep
ISSN Online: 2152-2219
ISSN Print: 2152-2197

Optimization of Biomethane Production from Vegetable Waste Collected in Ouagadougou Markets and "Yaars" Using the Response Surface Method (RSM)

Joseph M. Makaya[1*], Mahamadi Nikiema[2], Nombamba Ouéda[2], Sonagnon H. S. Kouhounde[3], Marius Kounbèsiounè Somda[4]

[1]Laboratory of Sciences and Technologies, New Dawn University, Ouagadougou, Burkina Faso
[2]Higher Institute of Sustainable Development (HISD), University Yembila Abdoulaye TOGUYENI, Fada N'Gourma, Burkina Faso
[3]Research and Training Unit, New Dawn University, Bobodioulasso, Burkina Faso
[4]Laboratory of Microbiology and Microbial Biotechnology, Research Center in Biological Food and Nutrition Sciences (CRSBAN), Department of Biochemistry and Microbiology, University Joseph KI-ZERBO, Ouagadougou, Burkina Faso
Email: *makaya.joseph7@gmail.com

How to cite this paper: Makaya, J.M., Nikiema, M., Ouéda, N., Kouhounde, S.H.S. and Somda, M.K. (2025) Optimization of Biomethane Production from Vegetable Waste Collected in Ouagadougou Markets and "Yaars" Using the Response Surface Method (RSM). *Journal of Environmental Protection*, **16**, 273-291.
https://doi.org/10.4236/jep.2025.164014

Received: January 21, 2025
Accepted: April 6, 2025
Published: April 9, 2025

Abstract

Large quantity of vegetable waste is produced in Ouagadougou' markets and "yaars", causing damage to the environment and, consequently the risks of to some diseases. Reusing methane in the production system could constitute one of the best options for the management of this waste. The objective of this study is to contribute to the energy recovery of vegetable wastes produced in Burkina Faso cities. Thus, a sampling of vegetable wastes was carried out at vegetable sales points in Ouagadougou. The physicochemical characterization of vegetable waste samples was investigated using standard methods. The response surface method through an experimental design implemented by the Expert Design software was used to determine the optimal production conditions of biogas in codigestion with cattle dung. A pilot scale production was carried out in a digester of 5 liters based on the optimal parameters obtained by the response surface method. The biogas was estimated through the volume of the torus and its composition determined by a biogas analyzer. The physicochemical parameters showed that the vegetable wastes contained 84.84% of dry matter (DM), 88.28% of volatile dry matter (VDM), 11.70% of ash, 1.5% of total nitrogen (TN) and 50.73% carbon content. The carbon-to-nitrogen (C/N) ratio was 33.82. These data show that vegetable wastes are potential substrates for anaerobic digestion however, they can be co-digested with animal manures to balance the low nitrogen content. The pilot production tests in the laboratory, based on the optimized model, produced an average volume of biogas equal to 30525.326 cm^3 with 57.61% as the proportion of methane. The production yield was 3540 L CH_4/kg VDM. These data obtained show that the codigestion of cattle dung with vegetable waste would have an increasing effect on biogas production. Also, the experimental production yield, higher than theoretical yield generated by the optimization equation, allows us to admit that this study has given satisfactory results.

Keywords

Vegetable Waste, Cattle Dung, Response Surface Method, Biomethane, Markets and "Yaars", Ouagadougou

1. Introduction

Empirical studies conducted worldwide have shown that the agriculture and livestock sectors are the largest producers of organic waste, considering all related activities [1] [2]. In Burkina Faso, these two sectors contribute approximately 40% to the country's Gross Domestic Product (GDP) and employ more than 86% of the active population [3] [4].

Trivially, the consumption of agricultural products generates significant quantities of waste. The production of these wastes is further amplified with the increase of the population, particularly in urban areas. Current statistics show that more than 57% of the world's population lives in cities. According to demographic projections, this value could exceed 68% by 2050, mainly due to the exponential urban growth in Africa and Asia [5].

According to the recent census, the population of Burkina Faso has almost doubled after two decades [3]. The country's population is predominantly rural, however, the number of people living in cities is increasing. Ouagadougou and Bobo-Dioulasso are the two largest urban centers in the country. These two cities represent more than half of the urban population (62.2%). The district of Ouagadougou is the capital city and the main economic center of Burkina Faso. Industry, trade, agriculture and, livestock breeding, etc. constitute the main economic activities [6].

In the context of West African cities where population growth remains constant, markets and "yaars" represent the primary source of food supply for households [7]. The growing these points of sale proportionally to the population' growing contributes thus to the production of significant quantities of organic waste, particularly that of damaged fruits and vegetables [8]. Inappropriate management of this waste could increase the risks of diseases related to the poor living environment.

Also, the scope of waste management services in countries is progressing due to global environmental and technical-economic issues [9] [10]. Methods such as landfill and incineration are the most used for the treatment of municipal solid waste. However, these methods of waste management could lead to various pollutions and losses of energy and material resources [11]. Anaerobic digestion, then appears to be a sustainable solution for waste management [12] [13]. It consists to the degradation of organic matter in the absence of oxygen, which can lead to the production of biogas and digestate [14]. This biogas can be used as a source of renewable energy, for the production of electricity and heat. The resulting digestate can be used as an organic fertilizer. Anaerobic digestion could contribute to the reduction of organic waste through recovery. The physicochemical or biological pretreatment of substrates as well as their codigestion promote the obtaining of better biomethane production yields [15]-[17]. Generally, the parameters such as temperature, pH, substrate load and agitation influenced biogas production yields during anaerobic digestion processes [18] [19].

Theoretical models have been used to refine product design and production processes, where interactions between factors can be complex and non-linear, as anaerobic digestion process. The Response Surface Method appears to be an advanced design of experiments technique that is used to explore and optimize the relationship between several input variables (factors) and an output variable (response). It aims to understand how the response varies depending on the levels of factors and to identify the optimal conditions for the desired response. The software allowed the generation of experimental designs and mathematical models to determine the optimized values of the parameters [20] [21]. The objective of our study is to optimize the production of biogas from vegetable waste collected in Ouagadougou markets and "yaars" using the Response Surface Method (RSM).

2. Materials and Methods

2.1. Sampling

Figure 1. Sample of vegetable waste, (a, b) Vegetable waste (fresh), (c) Dried vegetable waste, (d) Shredded vegetable waste

The wastes collected during this study consisted of the leaf wastes of cabbage, beans, and sorrel. Samples were obtained from three locations corresponding to vegetable sales outlets in the Ouagadougou commune, namely "Paglayiri", "Nabiyaar" and "Cité an II" markets. At the moment of sampling campaign, the vegetables wastes were collected and subsequently dried in the sun. The dried waste was then ground by an electric grinder to obtain a suitable refined powder (see **Figure 1**).

2.2. Determination of the Physicochemical Parameters of Shredded Vegetable Waste

The hydrogen potential (pH) was determined using the pH-meter (HI 99121) according to the method of Nout *et al.* [22]. The dry matter content was obtained by drying 5 g of material, placed in an oven at 105˚C for 24 hours until a constant weight (M2) was obtained [23]. Ash was determined by calcination in an oven at 550˚C for 6 hours [23]. Volatile dry matter (VDM) is estimated by measuring the weight loss of dry matter after calcination. The total organic carbon (TOC) content was determined from the ratio VDM/TOC = 1.74 [24]. Total nitrogen was determined using the Kjedahl method. After mineralization with pure sulphuric acid and in the presence of a catalyst (K_2SO_4 and $CuSO_4$), the nitrogen compounds are mineralized to ammonium sulphate. The ammonia displaced by the soda is vaporized and measured out with sulphuric acid. This method gives the percentage of total nitrogen (% Nt) in the sample.

2.3. Determination of Optimum Biogas Production Parameters

- **Response Surface Method (RSM)**

Based on the work of Nikiema *et al.* [25], the Response Surface Method was used to determine the optimum parameters for biogas production. The centred composite design (CCD) method with three independent variables was used to determine the effect of inoculum proportion (X1), substrate quantity (X2) and temperature (X3) on biogas and biomethane (CH_4) production (**Table 1**). Biogas, biomethane and carbon dioxide represent the responses.

Table 1. Coded levels for independent variables in factorial designs.

Variables	Symbol	Unit	Ranking and level	
			Level − 1	Level + 1
Inoculum	X1	%	2	20
Substrate	X2	g	0	80
Temperature	X3	˚C	25	50

- **Experimental design**

The experimental set-up consisted of a 230 ml glass bottle used as a batch bioreactor. A total of 20 formulations were generated using Expert Design software. The different formulations were used as shown in **Table 2**.

Table 2. Model design based on factorial design.

Std	Serial	Block	Substrate (g)	Bovine dung (%)	Temperature (˚C)
19	1	Block 1	11	40	37.5
1	2	Block 1	2	0	25
3	3	Block 1	2	80	25
2	4	Block 1	20	0	25
10	5	Block 1	26,1	40	37.5
12	6	Block 1	11	107,3	37.5
4	7	Block 1	20	80	25
11	8	Block 1	11	0	37.5
13	9	Block 1	11	40	16.5
14	10	Block 1	11	40	58.5
20	11	Block 1	11	40	37.5
18	12	Block 1	11	40	37.5
15	13	Block 1	11	40	37.5
5	14	Block 1	2	0	50
8	15	Block 1	20	80	50
6	16	Block 1	20	0	50
7	17	Block 1	2	80	50
16	18	Block 1	11	40	37.5
17	19	Block 1	11	40	37.5
9	20	Block 1	0	40	37.5

- **Monitoring biogas production during the experimental design**

Biogas production was monitored for 48 days under laboratory conditions and the product was analyzed every 4 days. The biogas was measured using a SEFRAM Paris gas chromatograph. The volume of produced biogas was estimated using the Liquid Displacement Method. The gaseous products (CO_2 and CH_4) were analyzed using a gas chromatograph (Girdel series 30 with catharometer fitted with a thermal conductivity detector [TCD] equipped with a SERVOTRACE type SEFRAM Paris 1mV potentiometric recorder).

The operating conditions for the determination of CH_4 and CO_2 are: Injector temperature 90˚C, column temperature 60˚C, detector temperature 100˚C, filament current 150 mA, carrier gas pressure 1 bar, attenuation 32, paper unwinding speed 10 mm/min, volume of 1 ml of the gas phase is taken and then injected into the chromatograph using a graduated leakproof syringe. The CH_4 and CO_2 contents were determined using standard curves established from CH_4 and CO_2 standards.

2.4. Experimental Set-Up for Pilot-Scale Biogas Production

The optimum conditions obtained from the RSM for optimal biomethane production were used on a pilot scale. The experimental set-up consisted of a fermentation reactor with a capacity of 5 liters and a biogas collection system is an air chamber and flexible conductive pipes (Figure 2). The inoculum/substrate ratio was set according to the optimal model derived from the experimental design. The substrate consisted of shredded vegetable waste and the inoculum of diluted cattle dung. The experiment was carried out in triplicate. The pH was monitored regularly at an interval of three-day using samples from the digesters. Biogas production was assessed each time the air chamber by formula 1. Neglecting the effect of temperature, the volume of biogas was determined using formula 2.

$$V = 4\pi^2 \times R \times r^2 \quad (1)$$

with R: radius and r: cross-section of the torus

$$V \text{ biogas} = V \text{ chamber} \times \Delta P \quad (2)$$

where V chamber: volume of the air chamber and ΔP: relative atmospheric pressure of the biogas in the air chamber.

The composition of the biogas for the pilot tests in the digester was determined using an OPTIMA7 gas analyzer.

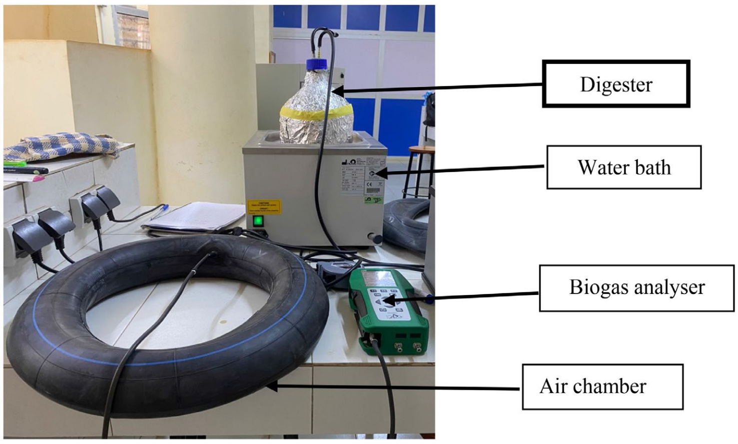


Figure 2. Experimental pilot plant.

2.5. Data Analysis

Expert design software was used to determine the optimum conditions for biogas production using the Central Composite Design (CDD) method.

3. Results

3.1. Physicochemical Parameters of Vegetable Waste Shredded Material

The values of the physicochemical parameters of the vegetable waste shredded material are presented in Table 3. The shredded vegetable wastes used as substrate for our study had a dry matter content of 84.84%, an ash content of 11.70%, a volatile dry matter content of 88.28%, a total nitrogen content of 1.50%, a total organic carbon content of 50.73% and a C/N ratio of 33.82.

Table 3. Vegetable waste physicochemical parameters.

Physicochemical parameters	Unit	Average
Dry matter	%	84.84 ± 0.68
Ash	%	11.70 ± 0.56
Volatile solid	%	88.28 ± 0.56
Total nitrogen	%	1.50 ± 0.62
Total organic carbon	%	50.73 ± 0.32
C/N ratio	-	33.82 ± 0.30

3.2. Parameters for Optimising Biogas Production: Model Fitting

Factorial design is a statistical, theoretical and mathematical technique for building models to optimize the level of independent variables [26].

The effect of the independent variables (substrate concentration, inoculum proportion and temperature) on biogas (Y1) and CH_4 (Y2) production is shown in Table 4. The coefficients of the polynomial equation were calculated from the experimental data to predict the values of the response variable. The regression equations for each response variable, obtained from the response surface methodology, are given in equation (3) and (4):

$$\begin{aligned}\%\ \text{Biogas} = {} & +350.84 - 53.15 * X1 + 130.85 * X2 + 74.34 * X3 - 38.17 * X1 * X2 - 24.48 * X1 * X2 \\ & +47.65 * X2 * X2 - 56.01 * X1^2 - 77.73 * X2^2 - 58.43 * X3^2 - 42.52 * X1 * X2 * X3\end{aligned} \tag{3}$$

$$\begin{aligned}\%\ CH_4 = {} & +240.48 - 58.76 * X1 + 103.26 * X2 + 51.54 * X3 - 15.66 * X1 * X2 - 28.29 * X1 * X3 \\ & +34.24 * X2 * X3 - 26.87 * X1^2 - 63.03 * X2^2 - 46.93 * X3^2 - 33.66 * X1 * X2 * X3\end{aligned} \tag{4}$$

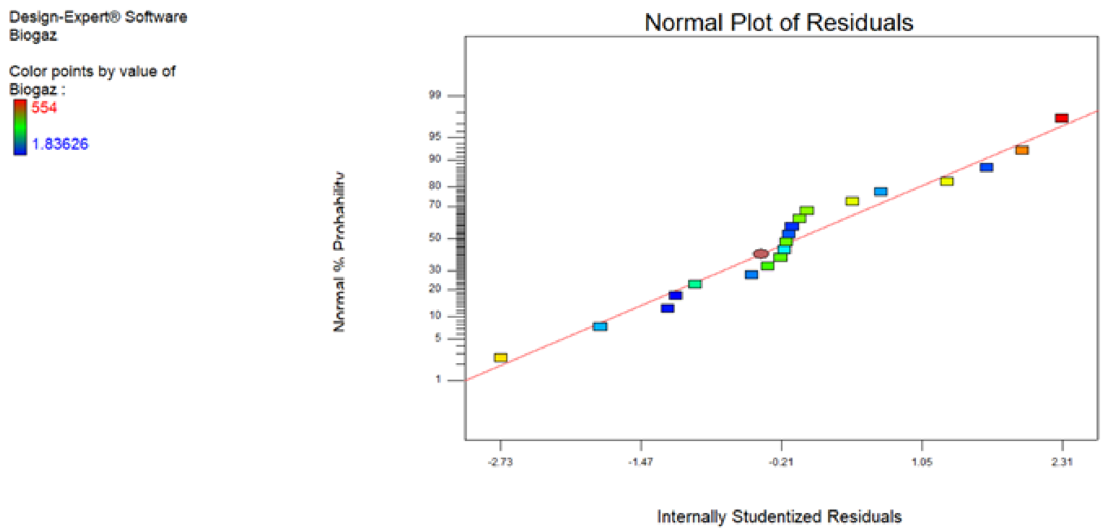
Legend: A: Substrate, B: Bovine dung, C: Temperature.

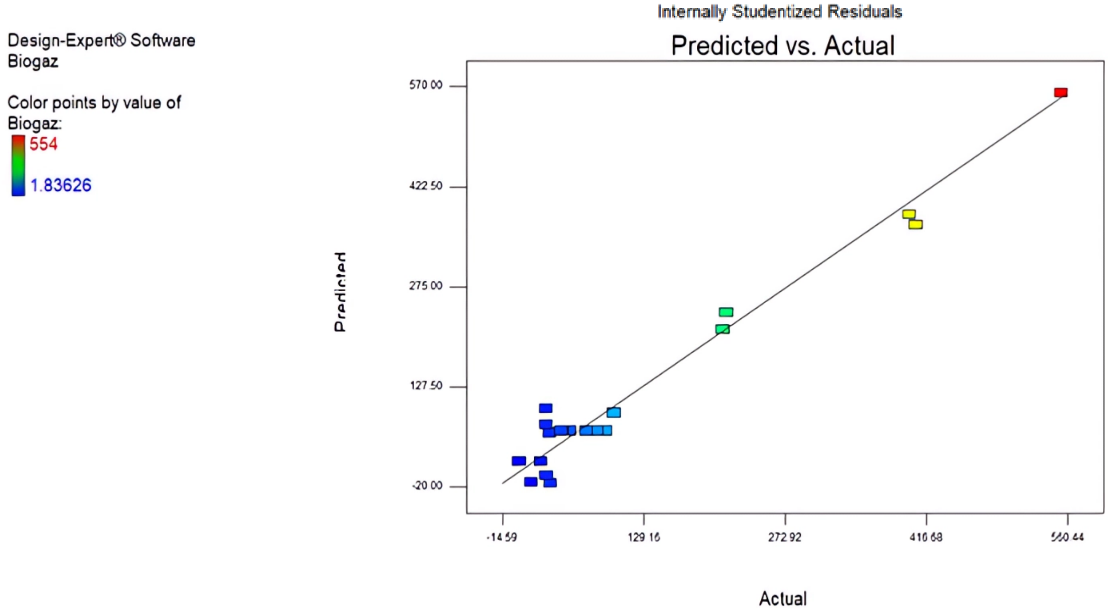
Table 4. Regression analysis of variance (ANOVA) of the model.

	Source	Sum of Squares	Df	Mean Square	F Value	p value Prob > F	R^2
Biogas	Model	280132.914	10	28013.2914	2.49650599	0.0922	Not significant
	X1-Substrate	40140.4235	1	40140.4235	3.57725931	0.0911	0.96
	X2-Cattle dung	113237.916	1	113237.916	10.0916073	0.0112	
	X3-Temperature	36282.0439	1	36282.0439	3.23340583	0.1057	
	X1 X2	1963.11211	1	1963.11211	0.17494985	0.6856	
	X1 X3	6402.21077	1	6402.21077	0.57055621	0.4693	
	X2 X3	9376.91764	1	9376.91764	0.835658	0.3845	
	X^2	7191.60355	1	7191.60355	0.64090581	0.4440	
	X^2	35625.673	1	35625.673	3.17491096	0.1085	
	X^2	32228.555	1	32228.555	2.87216448	0.1244	
	X1 X2 X3	9065.89887	1	9065.89887	0.80794043	0.3921	
	Model	13837.9032	10	1383.79032	10.6335228	0.0008	Significant

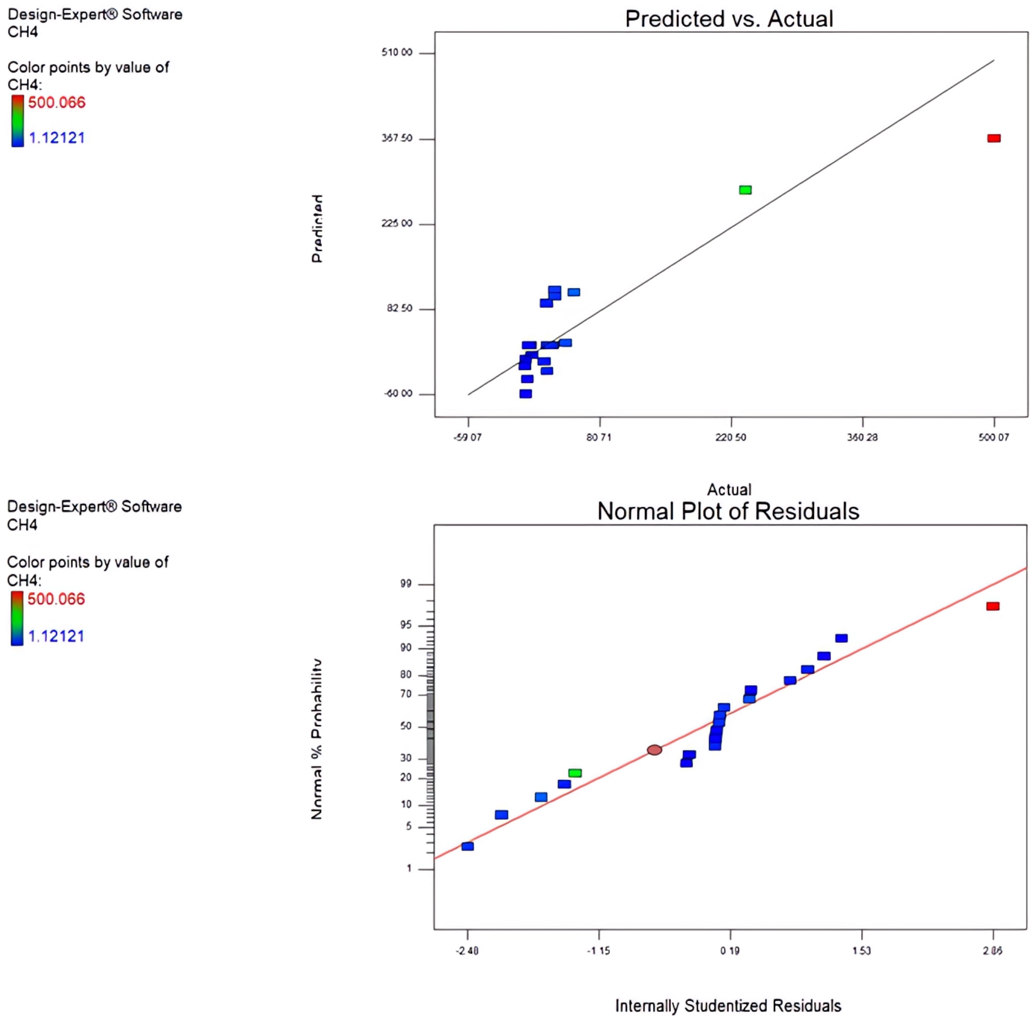
Continued

	X1-Substrate	4262.78933	1	4262.78933	32.7567457	0.0003	
Biogas	X2-Cattle dung	3568.03925	1	3568.03925	27.4180461	0.0005	0.81
	X3-Temperature	915.415565	1	915.415565	7.03436941	0.0264	
	X1 X2	1509.88949	1	1509.88949	11.6025124	0.0078	
	X1 X3	493.971267	1	493.971267	3.79584584	0.0832	
	X2 X3	445.141463	1	445.141463	3.42062077	0.0974	
CH_4	X^2	609.613096	1	609.613096	4.68447761	0.0586	
	X^2	244.702268	1	244.702268	1.88037676	0.2035	
	X^2	795.887075	1	795.887075	6.1158712	0.0354	
	X1 X2 X3	0.09696294	1	0.09696294	0.0007451	0.9788	





(a)



(b)

Figure 3. (a) Plot of residuals and normal probability and plot of actual vs predicted values for Biogas, (b) Plot of residuals and normal probability and plot of actual vs predicted values for methane.

The lack of fit was insignificant ($p \leq 0.05$) compared to the pure error for all variables, indicating that our model is statistically accurate. If the R^2 value is closed to 1, this indicates a better fit of the model to the actual data. Conversely, lower R^2 values indicate that the response variables were not appropriate to explain the variation in behaviour according to Myers *et al.* [27]. In our study, the high R^2 value demonstrates that the influence of substrate concentration (X1), inoculum proportion (X2) and temperature (X3) on the response variables can be adequately described by a quadratic polynomial model. The significance level of the coefficients of the quadratic polynomial model was determined by analysis of variance (ANOVA). A smaller p-value and a larger F-value indicate a highly significant effect of a term on the response variable [28]. The results of the analysis of variance of the regression are shown in **Table 4**.

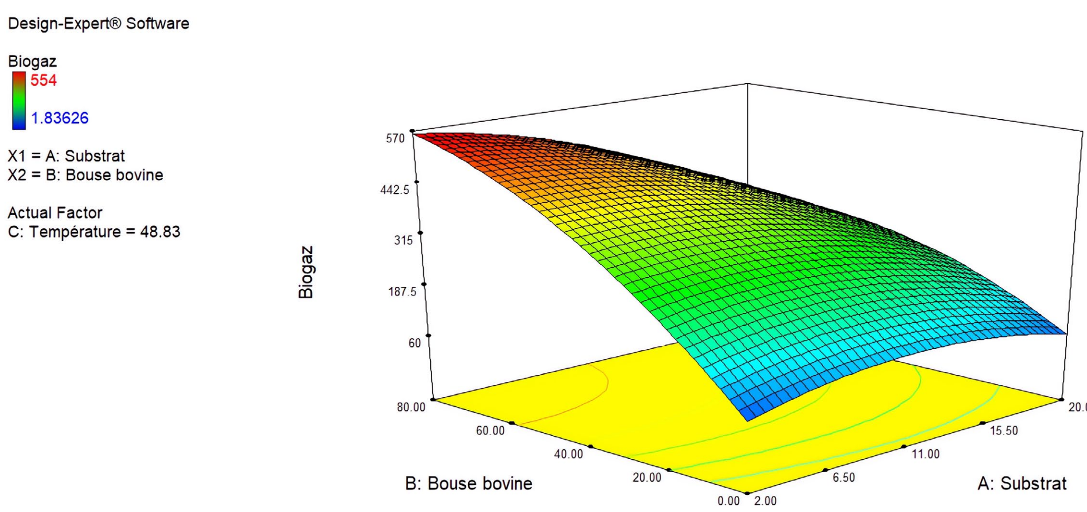
In this study, the coefficient of determination values for biogas (Y1) and CH_4

(Y2) were 0.96 and 0.81, respectively. Which means that these different models could explain 96% and 81% of variability in responses, respectively for biogas and CH_4. Among the two models, only that of CH_4 production is significant with a p-value = 0.0008. On the other hand, the biogas production model has a high p-value (p = 0.0922) and is therefore not significant. The value of the linear model value ((X1, X2, and X3) was significant, while the other values of the quadratic model ($X1^2$, $X2^2$ and $X3^2$) and the interactive model (X1 X2 X3) were not significant with p-values > 0.05. Each of Figure 3(a-b), shows the normal probability plot of the residuals and the predicted biogas and methane yield versus the actual yield. The graphs show that there are no anomalies in the proposed experimental work. The model therefore successfully predicts methane yield.

3.3. Interactive Effect of Process Variables' Ratios on Biogas and Methane Yield

The response values for the inoculum, substrate and temperature parameters are shown in Table 5. Numerical optimization was performed by the desirability function using Design Expert software. Twenty (20) different solutions were found containing different levels of independent variables. The solution with the highest desirability value was selected as the optimized condition for biogas and methane production. The proportion of inoculum varied from 0 to 107.3 ml with biogas and CH_4 values ranging from 1.84 to 554.00 and 1.12 to 235.63 ml/g volatile dry matter (VDM) respectively. In fact, the inoculum is a source of microorganisms for anaerobic digestion. Substrate concentrations varied from 0 to 26.1 g per unit volume. The residuals of the difference between the predicted and actual values are practically zero for biogas and CH_4, 0.011 and 0.025 respectively.

The combined conditions for optimized methane production were: an inoculum volume of 40 ml, a substrate concentration of 11% at a temperature of 37.5˚C. The response values for the optimized preparation conditions were 399.33 liters biogas and 235.65 liters methane per kilogram of volatile dry matter. The influence of the various parameters on biogas and methane production is shown in Figures 4-5.



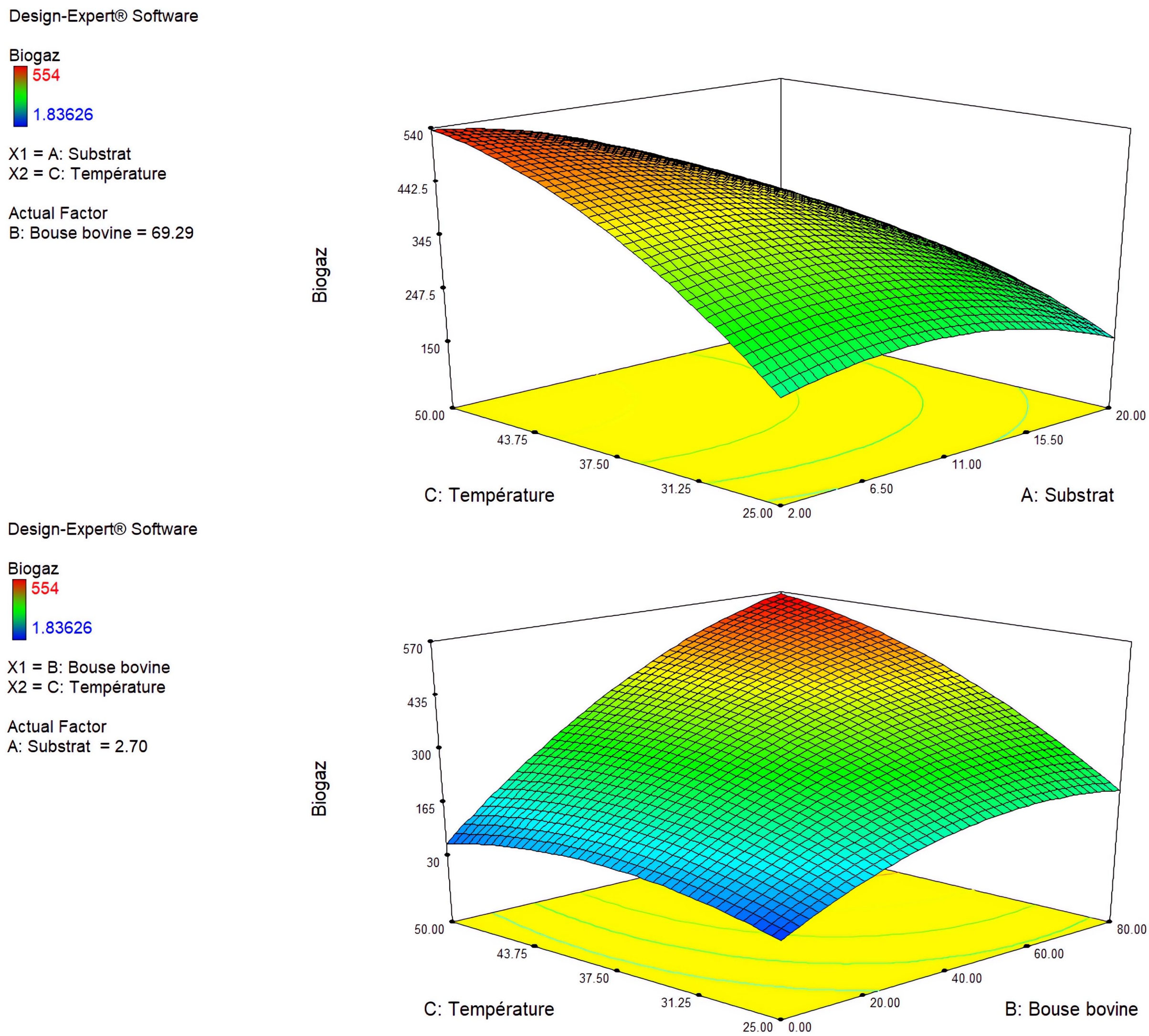
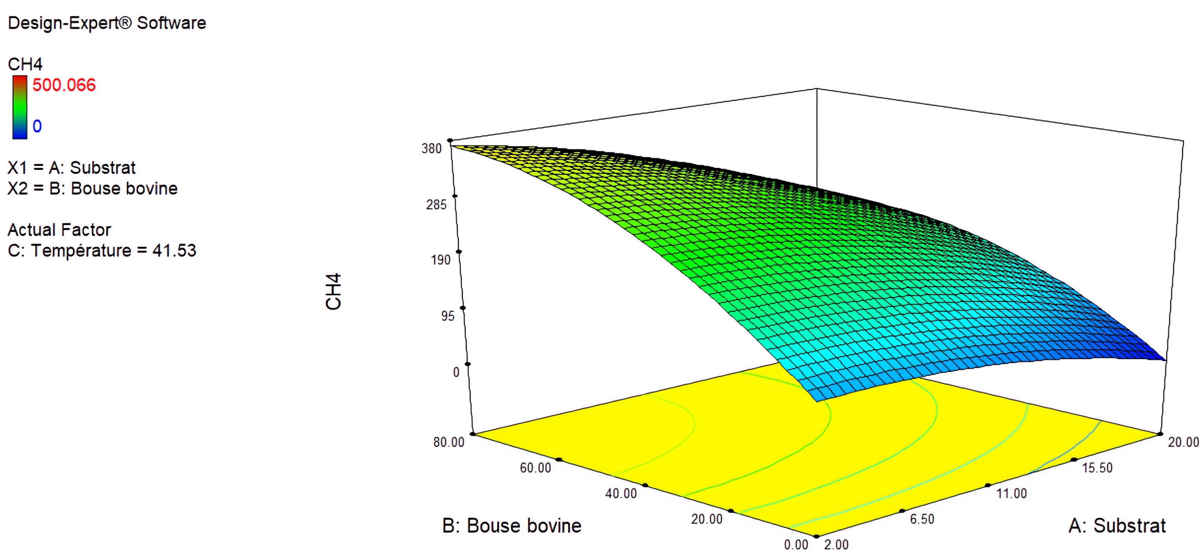


Figure 4. Biogas volume a function of temperature (˚C), substrate loading (% m/v) and inoculum proportion (v/v).



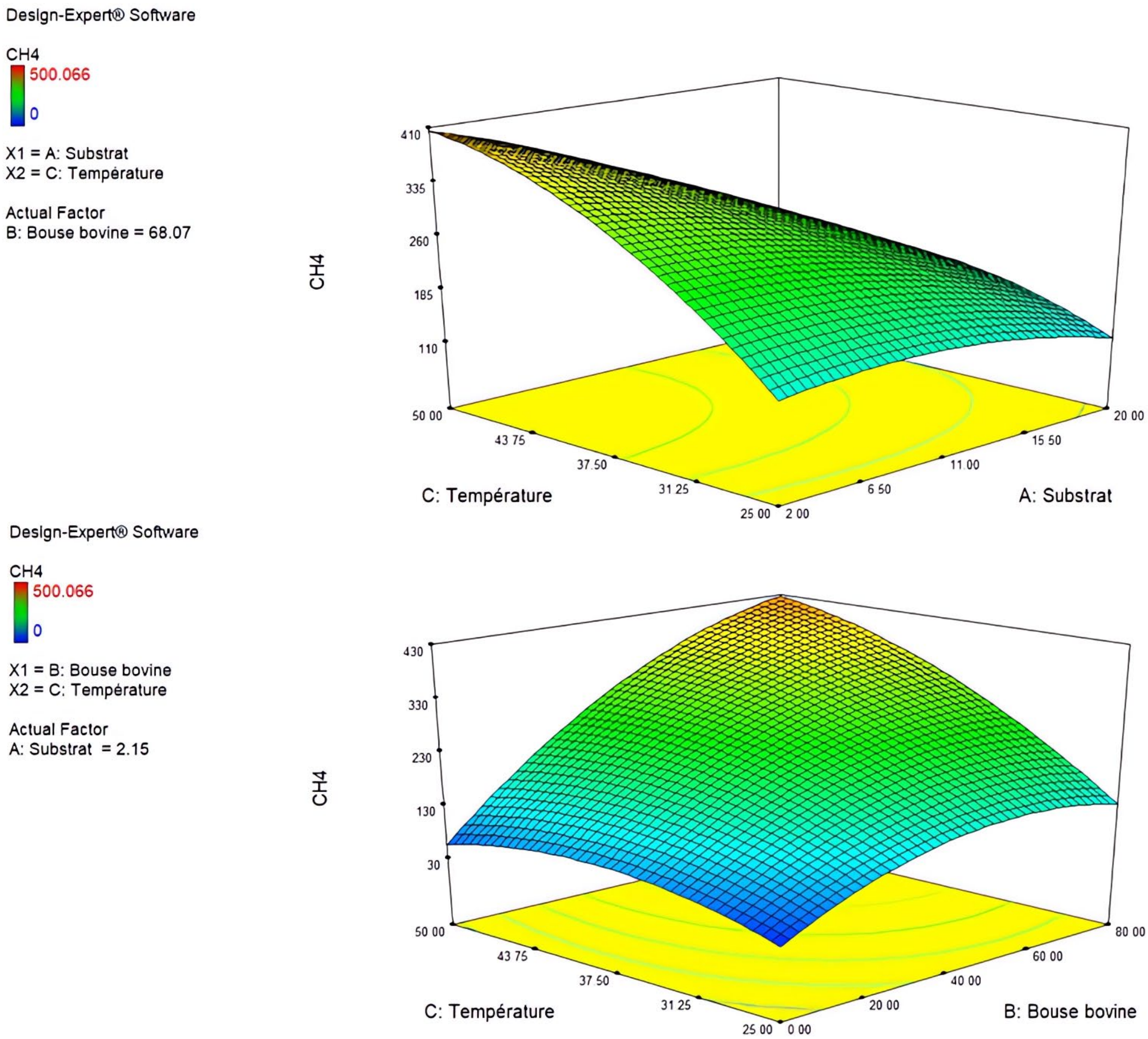


Figure 5. Methane volume as a function of temperature (˚C), substrate loading (% w/v) and inoculum proportion (v/v).

Table 5. Optimisation of independent variables for biomethane production.

Std	Serial	Block	Substrate (g)	Cattle dung (%)	Temperature ˚C	Biogas L/kg VDM	CH_4 L/kg VDM
19	1	Block 1	11	40	37.5	45.66	27.57
1	2	Block 1	2	0	25	29.15	24.57
3	3	Block 1	2	80	25	33.02	23.82
2	4	Block 1	20	0	25	29.15	1.75
10	5	Block 1	26.1	40	37.5	70.40	4.85
12	6	Block 1	11	107.3	37.5	80.99	30.42
4	7	Block 1	20	80	25	44.63	6.87
11	8	Block 1	11	0	37.5	13.95	3.52
13	9	Block 1	11	40	16.5	29.75	1.72
14	10	Block 1	11	40	58.5	405.95	53.35
20	11	Block 1	11	40	37.5	399.33	235.63

Continued

18	12	Block 1	11	40	37.5	52.95	24.35
15	13	Block 1	11	40	37.5	209.59	32.56
5	14	Block 1	2	0	50	1.84	1.12
8	15	Block 1	20	80	50	98.39	43.98
6	16	Block 1	20	0	50	89.46	30.87
7	17	Block 1	2	80	50	33.52	21.54
16	18	Block 1	11	40	37.5	213.06	32.79
17	19	Block 1	11	40	37.5	23.82	8.35
9	20	Block 1	0	40	37.5	554.00	500.07

3.4. Changes in Parameters in the Pilot Digester

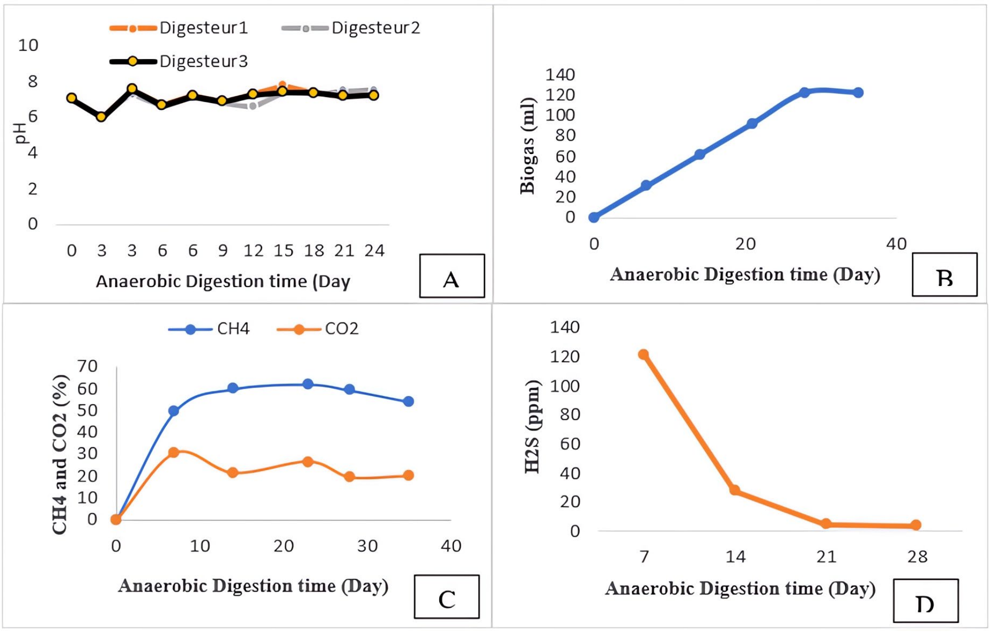


Figure 6. Monitoring of anaerobic digestion parameters: (A) pH; (B) Biogas production; (C) Changes in the proportion of CH_4 and CO_2 in the biogas and (D) Changes in H_2S.

At regular intervals of three (3) days, the pH was monitored in the digester and adjusted if the value was not close to neutral. After day 24, the pH was no longer monitored as it had become stable. **Figure 6(A)** shows the evolution of the pH in each of the three digesters over 24 days. The quantity of biogas produced was 30525.3216 cm^3 or 30.525 L. It was determined under normal temperature and pressure conditions using formula 1 for the torus. The quantity of biogas produced was monitored for 28 days, at the end of which we obtained a total production volume of 122.1 L with a yield of 3540 L CH_4/kg. **Figure 6(B)** shows the evolution of the quantity of biogas produced during our study. The proportion of methane is greater than that of carbon dioxide during the anaerobic digestion process, and the curves for these two products are almost parallel (**Figure 6(C)**). The curve for the production of hydrogen sulfide (H_2S), from **Figure 6(D)**, shows a drop in concentrations during anaerobic digestion towards zero at the end of the process.

4. Discussion

4.1. Physicochemical Parameters of Vegetable Waste from Markets and "Years"

The average pH value of vegetable waste shreds is 7.36 ± 0.15. This pH is close to neutral, and therefore suitable for anaerobic digestion. Methanogenic bacteria can tolerate pH values of between 6 and 8, with optimum activity around 7 [29]. The average rate of volatile dry matter obtained in our study was 88.28%. Volatile dry matter represents the quantity of organic matter volatilized during combustion. These high dry matter values indicate that the shredded vegetable waste consists mainly of organic matter. The values for dry matter and volatile dry matter in our study are close to those obtained by Tong *et al*. [30] on dried forage shreds, which were equal to 88.20% and 95.80% respectively. The low ash content (11.70%) could be explained by the fact that appropriate sorting was carried out on the samples prior to analysis, as shown by Nikiema *et al*. [31]. Furthermore, the ash contents obtained in our study are higher than those obtained from kitchen waste, fish waste and poultry viscera [32] [33]. The C/N ratio was 33.82, slightly higher than the optimum, which is between 25 and 30 [34]. This relatively high value could mean that the vegetable waste collected in the markets and "yaars" of the city of Ouagadougou has a low nitrogen content. Deublein and Steinhauser [35] reported that a low C/N ratio in the substrate for anaerobic digestion would lead to an increase in the production of ammonia, considered to inhibit the process. Similarly, a high C/N ratio would have a negative impact on microbial metabolism, since nitrogen is necessary for the formation of cellular proteins. When the C/N ratio is high, biomethane production drops due to a lack of nitrogen [36] [37]. This nitrogen deficiency could be made up for with other substrates, such as animal waste, through codigestion [38]-[40].

4.2. Modelling Biogas Production from Vegetable Waste

In the context of optimizing biogas production, the overall model does not appear to be significant with a p-value of 0.092 (**Table 4**). Only the cattle dung variable (B) is significant with a p-value of 0.0112, which is less than 0.05. This means that cattle dung has a significant impact on biogas production. For methane production, the model shows significance with a p-value of 0.0008, indicating that the model as a whole is significant. The interactions (AB) substrate plus cattle dung and the temperature variable showed significance with p-values of 0.0078 and 0.0264. In terms of CH_4 production, the model was also significant with a p-value of 0.008. Temperature was significant with a p-value of 0.0264. The results show that cattle dung has a significant impact on biogas production, temperature and AB interactions (substrate plus cattle dung) have an impact on CH_4 production and percentage methane.

The best biogas and methane production in this trial was obtained with cattle dung and vegetable waste, with a biogas yield of 399.33 L/kg VDM and a methane yield of 235.63 L/kg VDM. These results are in agreement with those of Traoré *et al.* [33], who obtained better production by codigestion of mango waste and pig dung. The higher biogas and methane yields obtained by Traoré *et al.* [33] could be explained by the difference in the constituents of the substrates used in co-management. The that fact codigestion was not used in our study could explain the low biogas and methane yields obtained. Certainly, mixing substrates creates a compensatory effect, which could prevent inhibition of anaerobic digestion due to excessive production of ammonia or volatile fatty acids, which are limiting factors in the digestion of substrates taken separately [33]. Codigestion stabilized the process and increases biogas production. Optimum production was obtained at a mesophilic temperature of 37.5˚C. Several studies have shown that mesophilic temperature is more stable because it tolerates stress factors [38]-[40].

4.3. Pilot Biogas Production Using the Optimal Mathematical Model

The quantity of biogas produced during the trials was 30.525 normo-liters (NL), *i.e.* a yield of 1005.16 NL biogas/kg VDM. Our results are much better than those of Castaing *et al.* [41].

In batch reactor trials, these authors found high yields for pig slurry and agro-industrial waste, between 250 and 330 Nm^3 CH_4/t VDM. Confirmation of these authors' results on a pre-industrial scale from codigestion trials carried out on the 150 m^3 digester led to an average biogas production of 90 Nm^3/d (normo-cubic meter per day), obtained with a methane content of 63%. The methane content of 57.61% obtained in our study is lower than the content found by Castaing *et al.* [41]. These differences could be explained by the quality of the substrates used in codigestion. The substrates have different bio-methanogenic potentials [42]. Chidikofan *et al.* [40] have shown that gross biogas production with chicken droppings is 12% higher than with cattle dung. According to Pouech *et al.* [43], the methanogenic potential of livestock effluents varies between 187 and 652 NL CH_4/kg organic matter (OM); that of agro-industrial effluents varies between 173 and 738 NL CH_4/kg OM. The decrease in the quantity of CO_2 during anaerobic digestion could be explained by the fact that some of the carbon dioxide is reduced to methane [31].

5. Conclusion

Our study on the energy recovery of vegetable waste by anaerobic digestion highlighted the importance of anaerobic fermentation of organic matter as a promising technique for the management of vegetable waste. Physicochemical analyses carried out on vegetables wastes from markets and "yaars" have shown that they constitute a substrate favourable to anaerobic digestion, but could be improved by codigestion with nitrogen-rich substrates such as animal manure. The response surface method (RSM) was used to generate the biomethane production optimization equation. The ANOVA statistical analysis allowed us to verify that the coefficients of the linear model used in our study are statistically significant. The best biogas and methane production was obtained by codigestion of cattle dung and vegetable waste, with a biogas yield of 399.33 L/kg VDM and a methane yield of 235.63 L/kg VDM. A model has been identified, thus making it possible to optimize production. Laboratory-scale production with the 5-liter reactors resulted in high yields of 1005.16 NL biogas/kg VDM. This model could be used on a larger scale to produce biomethane in quantity from vegetable waste.

Acknowledgements

The authors thank the Research Center in Biological Food and Nutrition Sciences (CRSBAN) for technical support in carrying out this study. They sincerely thank the New Dawn University for its financial support.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Bon, H., Parrot, L. and Moustier, P. (2010) Sustainable Urban Agriculture in Developing Countries. A Review. *Agronomy for Sustainable Development*, **30**, 21-32. https://doi.org/10.1051/agro:2008062

[2] Food and Agricultural Organization of the United Nations (FAO) (2018) Livestock Production Systems Spotlight: Cattle and Poultry Sectors in Burkina Faso. http://www.fao.org/3/I8492EN/i8492en.pdf

[3] Institut National de la Statistique et de la Démographie (INSD) (2022) Cinquième recensement général de la population et de l'habitation du Burkina Faso. Rapport, Ouagadougou/Burkina Faso.

[4] Bassinga, H., Lankoandé, B.Y., Sawadogo, Y. and Soura, A.B. (2024) Geography of the Elderly in Ouagadougou-Burkina Faso. *Remses*, **9**, 67-91. http://revues.imist.ma/?journal=REMSES&page=index

[5] Department of Economic and Social Affairs (UN-DESA) (2024) Annual Highlights Report 2023-2024. https://www.un.org/en/desa

[6] Bagbila, A.J. (1993) Les marchés urbains de Ouagadougou. Rapport, Université de Ouagadougou, Burkina Faso.

[7] De Loma-Ossorio, E., Lahoz, C., Luis, F. and Portillo, L.F. (2014) Assessment on the Right to Food in the ECOWAS Region. Food and Agricultural Organization of the United Nations. https://openknowledge.fao.org/handle/20.500.14283/i4183e

[8] Diallo, R. (2024) Insalubrité à Ouagadougou, Burkina Faso: Une gestion parfois catastrophique dans certains marchés et yaars. https://lefaso.net/spip.php?article130356

[9] Durand, A., Leborgne, G., Robert, C., Barrault, S. and Bort, T. (2020) Gaz à effet de serre-Changements climatiques.

[10] Le Bris, C. and Coutard, O. (2009) Les réseaux rattrapés par l'environnement? Dévelop-

pement durable et transformations de l'organisation des services urbains. *Flux*, **74**, 6-8. https://doi.org/10.3917/flux.074.0006

[11] Thonart, P., Diabaté, S.I., Hiligsmann, S. and Lardinoi, M. (2005) Guide pratique sur la gestion des déchets ménagers et des sites d'enfouissement technique dans les pays du sud. Institut de l'énergie et de l'environnement de la Francophonie (IEPF), 121.

[12] Deepanraj, B., Sivasubramanian, V. and Jayaraj, S. (2014) Biogas Generation through Anaerobic Digestion Process: An Overview. *Research Journal of Chemistry and Environment*, **18**, 80-93.

[13] Fagerström, A., Al Seadi, T., Rasi, S. and Briseid, T. (2018) The Role of Anaerobic Digestion and Biogas in the Circular Economy. In: Murphy, J.D., Ed., *IEA Bioenergy Task* 37, IEA Bioenergy, 1-24.

[14] Michaud, S., Bernet, N., Buffière, P. and Delgenès, J.P. (2005) Use of the Methane Yield to Indicate the Metabolic Behaviour of Methanogenic Biofilms. *Process Biochemistry*, **40**, 2751-2755. https://doi.org/10.1016/j.procbio.2004.12.017

[15] Cavinato, C., Bolzonella, D., Pavan, P., Fatone, F. and Cecchi, F. (2013) Mesophilic and Thermophilic Anaerobic Co-Digestion of Waste Activated Sludge and Source Sorted Biowaste in Pilot- and Full-Scale Reactors. *Renewable Energy*, **55**, 260-265. https://doi.org/10.1016/j.renene.2012.12.044

[16] Xie, Y., Chen, J., Xiao, A. and Liu, L. (2017) Antibacterial Activity of Polyphenols: Structure-Activity Relationship and Influence of Hyperglycemic Condition. *Molecules*, **22**, Article 1913. https://doi.org/10.3390/molecules22111913

[17] Lo, M., Sonko, E.h.M., Dieng, D., Ndiaye, S., Diop, C., Seck, A., *et al*. (2020) Co-Composting of Faecal Sludge with Vegetable and Fish Waste in Dakar (Senegal). *International Journal of Biological and Chemical Sciences*, **13**, 2914-2929. https://doi.org/10.4314/ijbcs.v13i6.38

[18] Ward, A.J., Hobbs, P.J., Holliman, P.J. and Jones, D.L. (2008) Optimisation of the Anaerobic Digestion of Agricultural Resources. *Bioresource Technology*, **99**, 7928-7940. https://doi.org/10.1016/j.biortech.2008.02.044

[19] Kwietniewska, E. and 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

[20] Jiang, F., Li, J., Yan, L., Sun, J. and Zhang, S. (2010) Optimizing End-Milling Parameters for Surface Roughness under Different Cooling/Lubrication Conditions. *The International Journal of Advanced Manufacturing Technology*, **51**, 841-851. https://doi.org/10.1007/s00170-010-2680-9

[21] Manohar, M., Joseph, J., Selvaraj, T. and Sivakumar, D. (2013) Application of Desirability-Function and RSM to Optimise the Multi-Objectives While Turning Inconel 718 Using Coated Carbide Tools. *International Journal of Manufacturing Technology and Management*, **27**, 218-237. https://doi.org/10.1504/ijmtm.2013.058899

[22] Nout, M.J.R., Rombouts, F.M. and Havelaar, A. (1989) Effect of Accelerated Natural Lactic Fermentation of Infant Good Ingredients on Some Pathogenic Microorganisms. *International Journal of Food Microbiology*, **8**, 351-361. https://doi.org/10.1016/0168-1605(89)90006-8

[23] AFNOR (1985) Fertilizing Materials and Crop Supports: Sampling, Chemical Analyzes and Physicochemical Tests. Organic Amendments and Culture Media-Determination of Total Organic Matter-Calcination Method. AFNOR, 1-4.

[24] Allison, L.E. (1965) Organic Carbon. Methods of Soil Analysis. 2e Partie, American Society of Agronomy.

[25] Nikiema, M., Somda, M.K., Sawadogo, J.B., Bambara, S., Barsan, N., Maiga, Y., *et al*. (2024) Optimization for Improved Biomethane Yield from Cashew Nut Hulls through Response Surface Methodology. *Biomass Conversion and Biorefinery*, **15**, 4013-4024. https://doi.org/10.1007/s13399-024-05577-3

[26] Homayoonfal, M., Khodaiyan, F. and Mousavi, M. (2015) Modelling and Optimising of Physicochemical Features of Walnut-Oil Beverage Emulsions by Implementation of Response Surface Methodology: Effect of Preparation Conditions on Emulsion Stability. *Food Chemistry*, **174**, 649-659. https://doi.org/10.1016/j.foodchem.2014.10.117

[27] Myers, R., Montgomery, D.C. and Anderson-Cook, C.M. (2011) Response Surface Methodology: Process and Product Optimization Using Designed Experiments. 3rd Edition, John Wiley & Sons.

[28] Quanhong, L. and Caili, F. (2005) Application of Response Surface Methodology for Extraction Optimization of Germinant Pumpkin Seeds Protein. *Food Chemistry*, **92**, 701-706. https://doi.org/10.1016/j.foodchem.2004.08.042

[29] Hilkiah Igoni, A., Ayotamuno, M.J., Eze, C.L., Ogaji, S.O.T. and Probert, S.D. (2008) Designs of Anaerobic Digesters for Producing Biogas from Municipal Solid-Waste. *Applied Energy*, **85**, 430-438. https://doi.org/10.1016/j.apenergy.2007.07.013

[30] Tong, X., Smith, L.H. and McCarty, P.L. (1990) Methane Fermentation of Selected Lignocellulosic Materials. *Biomass*, **21**, 239-255. https://doi.org/10.1016/0144-4565(90)90075-u

[31] Nikiema, M., Sawadogo, J.B., Somda, M.K., Traore, D., Dianou, D. and Traore, A.S. (2016) Optimization of Biomethane Production from Municipal Solid Organic Wastes. *International Journal of Biological and Chemical Sciences*, **9**, 2743-2756. https://doi.org/10.4314/ijbcs.v9i5.43

[32] Afilal, M.E., Elasri, O. and Merzak, Z. (2014) Organic Waste Characterization and Evaluation of Its Potential Biogas. *Journal of Materials and Environmental Science*, **5**, 1160-1169.

[33] Traore, D., Nikiema, M., Somda, M.K., Sawadogo, J.B., Dayeri, D. and Traore, A.S. (2016) Contribution to the Biomethanisation of Plant Biomass: Case of Vegetable Residues in Burkina Faso. *International Journal of Biological and Chemical Sciences*, **10**, 35-47. https://doi.org/10.4314/ijbcs.v10i1.4

[34] Ostrem, K. (2004) Greening Waste: Anaerobic Digestion for Treating the Organic Fraction of Municipal Solid Wastes. Thesis in Earth Resources Engineering, Columbia University.

[35] Deublein, D. and Steinhauser, A. (2008) Biogas from Waste and Renewable Resources: An Introduction. WILEY-VCH.

[36] Yadvika, Santosh, Sreekrishnan, T.R., Kohli, S. and Rana, V. (2004) Enhancement of Biogas Production from Solid Substrates Using Different Techniques––A Review. *Bioresource Technology*, **95**, 1-10. https://doi.org/10.1016/j.biortech.2004.02.010

[37] Guarino, G., Carotenutoa, C., Cristofaroa, F., Papab, S., Morronea, B. and Minalea, M. (2016) Does the C/N Ratio Really Affect the Bio-Methane Yield? A Three Years Investigation of Buffalo Manure Digestion. *Chemical Engineering Transactions*, **49**, 463-468.

[38] Girault, R., Peu, P., Béline, F., Lendormi, T. and Guillaume, S. (2013) Caractéristiques des substrats et interactions dans les filières de co-digestion: Cas particulier des co-

substrats d'origine agro-industrielle. *Sciences Eaux & Territoires*, **12**, 44-53. https://doi.org/10.3917/set.012.0044

[39] Aboubakar, Boli, Z. and Mbofung, C.M.F. (2016) Etude du potentiel biogaz des déjections animales: Bouses de bovins et fientes de volailles d'un centre zootechnique à Maroua-Cameroun. *Revue des Energies Renouvelables*, **19**, 447-464.

[40] Chidikofan, D.M.G.F., Adjakpa, J.B., Gnanga, H. and Assouma, N. (2023) Valorization of Digestate from Organic Waste Methanization in Market Gardening in Benin. *Revue Ivoirienne des Sciences et Technologie*, **41**, 11-29.

[41] Castaing, J., Pouech, P. and Coudure, R. (2002) Digestion anaérobie de lisiers de porcs en mélange avec des déchets agro-industriels. *Journées Recherche Porcine*, **34**, 195-202.

[42] Lacour, J., Bayard, R., Emmanuel, E. and Gourdon, R. (2011) Evaluation du potentiel de valorisation par digestion anaérobie des gisements de déchets organiques d'origine agricole et assimilés en Haïti. *Environnement, Ingénierie & Développement*, **60**, 31-41. https://doi.org/10.4267/dechets-sciences-techniques.2890

[43] Pouech, P., Coudure, R. and Marcato, C.E. (2005). Intérêt de la codigestion pour la valorisation des lisiers et le traitement de déchets fermentescibles à l'échelle d'un territoire. *Journées Recherche Porcine*, **37**, 39-44.