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FRUIT AND VEGETABLE WASTE MANAGEMENT THROUGH CO-DIGESTION WITH LOCAL MARKET WASTEWATER: OPERATING CONDITIONS AND SYSTEM KINETICS

Nqobile Mkhize[a*], Siphesihle Mangena Khumalo[b], Emmanuel Kweinor Tetteh[c], Sudesh Rathilal[d]

[a] Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Steve Campus, S3 L3, P.O. Box 1334, Durban 4000, South Africa, e-mail: 21555544@dut4life.ac.za, ORCID 0000-0003-4239-5138
[b] Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Steve Campus, S3 L3, P.O. Box 1334, Durban 4000, South Africa, e-mail: SiphesihleK1@dut.ac.za, ORCID 0000-0002-4486-3663
[c] Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Steve Campus, S3 L3, P.O. Box 1334, Durban 4000, South Africa, e-mail: emmanuelk@dut.ac.za, ORCID 0000-0003-1400-7847
[d] Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Steve Campus, S3 L3, P.O. Box 1334, Durban 4000, South Africa, e-mail: rathilals@dut.ac.za, ORCID 0000-0002-4677-5309

[*]*Corresponding author: e-mail: 21555544@dut4life.ac.za*

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ABSTRACT

Environmental pollution from fruit and vegetable waste (FVW) produced by local markets in South Africa is inevitable. Nevertheless, the current management strategy of disposing of FVWs in landfills contributes to the emission of greenhouse gases. Therefore, valorizing agricultural waste into bioenergy is critical for achieving zero waste and reducing the carbon footprint. In this study, parametric optimization of the co-digestion of FVWs with market wastewater (MW) was conducted using the Box–Behnken design (BBD) adapted from response surface methodology (RSM). The study identified optimal combinations of process variables, i.e., temperature, pH, hydraulic retention time (HRT), and organic loading rate (OLR), to produce biogas while reducing volatile solids (VS) and chemical oxygen demand (COD) from wastewater. At optimal operating conditions of 40°C, HRT of 10 days, pH of 7.2, and an OLR of 3.98 kg VS·m^{-3}·day^{-1}, a desirability of 100% was achieved. A biogas production rate of 717 mL·day^{-1} was reported, with VS and COD removals of 73.37% and 79.24%, respectively. The robustness of the predictive models developed using RSM was corroborated by R^2 values greater than 0.9 for all output variables. The Modified Gompertz model was well-fitted to the experimental data, yielding an R^2 of 0.995 and a lower root mean square error (RMSE) of 21.08. The findings of the present study suggest that the valorization of FVW through co-digestion with wastewater can be considered a promising, environmentally sustainable technology for agro-waste management and bioenergy production.

Introduction

Fossil fuels, linked to climate change impacts, have been the main global energy source for many years. The rising costs of fossil fuels, such as crude oil, have created an opportunity to reassess economic development and energy policies to explore new and sustainable energy alternatives (Kreps, 2020; Holechek et al., 2022; Ritchie et al., 2023). In the South African context, the energy sector is primarily dependent on coal, which constitutes 85% of the energy supply, while renewable energy accounts for only 5%, with the remainder comprising wind, solar, biofuels, hydrothermal, and other sources (Akinbami et al., 2021; Ukoba et al., 2023).

On the other hand, food security and increasing food demand have contributed to the growing production of fruits and vegetables. The most commonly produced and consumed fruits and vegetables in South Africa include apples, bananas, pears, avocados, oranges, grapes, potatoes, onions, tomatoes, carrots, and cabbages (DTIC, 2022). Approximately 33% of harvested fruits and vegetables are lost along the production and marketing chain – including harvesting, storage, packaging, and transportation – and end up as FVWs (FAO, 2019; Yahaya et al., 2019; Jun et al., 2022). In South Africa, an estimated 10.2 million tons of FVWs are produced annually (Machate, 2020). The production of substantial quantities of fruits and vegetables presents new challenges in handling the resulting waste. Innovative renewable approaches must be implemented to replace current management methods that harm the environment, such as landfilling and burning (Fredes et al., 2023).

Research into the valorization of fruit and vegetable waste (FVW) has led to the advancement of technologies such as incineration, anaerobic digestion (AD), gasification, pyrolysis, and hydrothermal methods (Kassim et al., 2022; Zhu et al., 2023). Among these technologies, AD is reported to be highly promising and environmentally friendly for valorizing FVWs by breaking down organic waste anaerobically into biogas (Bong et al., 2018; Wainaina et al., 2019; Almeida et al., 2021). Many researchers advocate for the use of two or more substrates, as this enhances synergy by balancing specific elements required for anaerobic digestion that might be deficient or excessive when using a single substrate, ultimately leading to increased biogas production (anaerobic co-digestion) (Scano et al., 2014; Bong et al., 2018; Kuczman et al., 2018; Chow et al., 2020). The co-AD process is influenced by various parameters and operational conditions, including volatile solids (VS), substrate mixing ratios, pH, temperature, hydraulic retention time (HRT), organic loading rate (OLR), and the carbon-to-nitrogen ratio (C/N) (Mao et al., 2015; Uddin et al., 2022; Agrawal et al., 2023; Agrawal et al., 2024). The temperature operating ranges can be either mesophilic (32-42°C) or thermophilic (50–65°C), with mesophilic conditions being more commonly used due to lower energy consumption and greater microbial adaptability, although thermophilic conditions allow for shorter retention times (Al-Rubaye et al., 2019; Aworanti et al., 2023; Duong et al., 2023). Therefore, it is essential to identify optimal operating conditions to reduce energy consumption and process duration (Mlaik et al., 2024).

Despite the available literature on the digestion of FVW for biogas production, studies on parametric optimization for the co-digestion of FVW with wastewater are limited. Accordingly, the present study focuses on the parametric optimization of biogas production through the co-digestion of FVW (i.e., apples, bananas, tomatoes, oranges, and spinach) with wastewater originating from a fruit and vegetable market. The interaction effects of operating parameters (i.e., hydraulic retention time, organic loading rate, pH, and temperature) were investigated using the Box–Behnken design (BBD) in response surface methodology (RSM). Furthermore, this study evaluates the performance of co-digesting FVW with market wastewater (MW) under optimal conditions by assessing the desired responses, i.e., volatile solids (VS) reduction (%), biogas production (mL·day^{-1}), and chemical oxygen demand (COD) removal (%). The study also examines the process kinetics of the co-digestion using the Modified Gompertz and First-Order kinetic models.

Materials and Methods

Sample collection and preparation

FVW samples were collected from a local market waste disposal station in Durban, South Africa, and included apples, bananas, tomatoes, oranges, and spinach. Prior to experimental runs, the mixed FVW samples were thoroughly washed using deionized water to eliminate any dirt and/or foreign organic material. Thereafter, the samples were preserved in a refrigerator at a temperature of ±3°C. Before the commencement of each experimental run, the samples were pulverized into smaller particles or pulp using a LOGIK blender, which was done to improve the hydrolysis process, thereby promoting greater microbial activity as well as biogas production, as reported by Oyaro et al. (2021). Similarly, MW samples were collected from the local market using 5 L blue-cap sample bottles and were transported in a cooler box to preserve the sample conditions between the sampling point and the laboratory. Activated sludge (AS) was also collected from an anaerobic digester at a local wastewater treatment plant and, to preserve the sludge conditions, it was transported in a cooler box at a temperature of ±5°C. It is worth noting that the collected activated sludge was used as an inoculum during the experimental runs.

Sample characteristics

Herein, sample characterization was conducted in accordance with the American Public Health Association standard methods, which included the determination of total solids (TS), volatile solids (VS), moisture content, and ash content (APHA, 2012). Characterization results are shown in Table 1. The calorific value of the mixed, pulverized FVW sample was determined using a bomb calorimeter (GLOMRO BXT-ZDHW9B, China). Wastewater and inoculum (i.e., activated sludge) samples were analyzed for COD, TS, VS, and pH, and the characterization results for wastewater and activated sludge samples are shown in Table 2. The pH was analyzed using a pH meter (Thermo Scientific Eutech Elite PTCS, United States of America), and COD analyses were conducted using a spectrophotometer (HACH DR3900, United States of America).

Table 1.
Composition of a FVW sample.

Parameter	Fruit and vegetable waste (FVW)
Volatile solids (%)	90 ± 6.30
Total solids (%)	15 ± 0.87
Moisture	87 ± 10.76
Ash	0.6 ± 0.05
Calorific value (MJ kg^{-1})	13.33 ± 1.53
C/N	23 ± 2.20

Table 2.
The physiochemical parameters of wastewater and activated sludge

Parameter	Market wastewater (MW)	Activated sludge (AS)
Volatile solids (%)	39 ± 8.12	74 ± 11.03
Total solids (%)	11 ± 1.03	20 ± 2.10
pH	6 ± 0.50	6.5 ± 0.80
COD ($mg·L^{-1}$)	1410 ± 50	6020 ± 175

Experimental procedure of co-digestion

Herein, the experimental procedure adopted in this study is detailed in our previous work (Mkhize et al., 2023). The generation of biogas (i.e., methane) was carried out using a laboratory-scale batch co-AD system, as depicted in Figure 1. A blue-cap Schott bottle was utilized with a working volume of 800 mL. The blue-capped bottle functioned as a bio-digester and was submerged in a water bath (United Scientific, WBST0001, South Africa) equipped with a temperature-control device to maintain mesophilic conditions within a temperature range of 32°C to 42°C. The bio-digester was equipped with a flexible pipe connected to a biogas collection system. The biogas collection system comprised a graduated flask inverted in a 10 L container of water, establishing a downward displacement connection between the outlet gas nozzle and the biogas collection system, as illustrated in Figure 1.

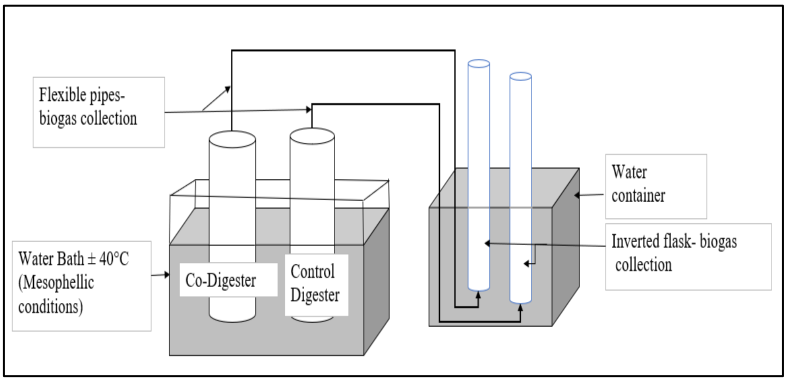

Figure 1. Co-AD experimental set-up, adopted from (Mkhize et al., 2023)

Please note that the biodigester underwent a 2-minute nitrogen gas flush in the headspace before the initiation of each run. This procedure aimed to establish anaerobic conditions by eliminating oxygen molecules from the system. The biodigester's temperature and pH were routinely monitored, and if the temperature fluctuated, adjustments were made to the water bath to maintain the required conditions.

Moreover, biogas production was recorded daily using the water displacement method. The composition of the produced biogas, specifically the methane content, was analyzed using gas chromatography (GC-2014 SHIMADZU, Japan). The percentage removals of VS and COD were calculated using equations (1) and (2), respectively.

$$\text{VS reduction (\%)} = \frac{\text{VS}_i - \text{VS}_\text{f}}{\text{VS}_\text{i}} \times 100 \quad (1)$$

where: VS_i and VS_f are the initial and final VS amounts, respectively.

$$\text{COD Removal} = \frac{\text{COD}_\text{i} - \text{COD}_\text{f}}{\text{COD}_\text{i}} \times 100 \quad (2)$$

where: COD_i and COD_f are the initial and final COD concentrations, respectively.

Experiment design and development of the predictive model

In ascertaining the optimum operating conditions for biogas production, percentage reduction of VS, and removal of COD, the Box–Behnken Design (BBD) within the Response Surface Methodology (RSM) framework in Design Expert version 11.1 was employed. The BBD is a factorial design involving at least three factors, analyzed using randomized response surface methods. The parameters investigated for the optimization of biogas production, percentage reduction of VS, and COD removal are displayed in Table 3, which clearly shows the factors, codes, and levels of the factors. The number of experimental runs (N_er) in the BBD method is determined using equation (3), as reported by Madondo et al. (2022).

$$N_{er} = n_{fp} + P_{cp} = 2n_{iv}(n_{iv} - 1) + P_{cp} \quad (3)$$

where:

n_{fp} – represents the factorial points,

P_{cp} – is the number of center points,

n_{iv} – denotes the number of input variables.

Herein, the number of input variables i.e., n_{iv} was limited to 4 and the number of center points (P_{cp}) was 2. As such, the number of experimental runs as per equation (3) was 26.

Table 3.

Experimental range and levels of independent process variables.

Factor	Units	Code	Range and level of factors		
			-1	0	1
Temperature	(°C)	A	32	37	42
pH	(-)	B	6	7	8
HRT	(days)	C	10	15.5	21
OLR	(kg VS·m^{-3}·day^{-1})	D	1	2.5	4

For the present study, stepwise regression analysis was employed to examine the experimental data, and a second-order regression model was developed to achieve the best fit, aimed at identifying significant model terms as recommended by Madondo et al. (2022). It is important to note that in the BBD system, the second-order polynomial model can be represented by equation (4).

$$y_r = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{r=1}^{N_{er}} \beta_{rr} x_r^2 + \sum \sum_{i>r} \beta_{ri} x_r x_i + \epsilon \quad (4)$$

where:
β_0 – denotes the regression coefficient at $r = 0$,
β_i – is the i^{th} regression coefficient,
$i = 1,2,3, \dots .p$; x_i is the i^{th} input variable,
$\beta_{rr} x_r^2$ – denotes quadratic expressions,
$\beta_{ri} x_r x_i$ – denotes cross-product expressions,
ϵ – is the experimental error.

The validity of the fitted model was assessed using analysis of variance (ANOVA). The Design Expert software allows for the fitting of models with unknown coefficients. Herein, lack-of-fit, sequential F-tests, and adequacy measures were employed to determine the best regression equations.

Kinetic Modeling of the Co-Digestion Process

Kinetic studies of biogas production were conducted using equation (5) and equation (6) for the First-Order kinetic model and the Modified Gompertz kinetic model, respectively. These models are widely used to simulate biogas production, as reported by Córdoba et al. (2018); Oyaro et al. (2021).

$$\mathrm{Y(t)} = \mathrm{Y_m}\,[1 - \exp(\mathrm{kt})] \quad (5)$$

where:
Y(t) – is the cumulative biogas production, ($mL \cdot gVS^{-1}$)
Y_m – is the ultimate biogas production potential, ($mL \cdot gVS^{-1}$)
t – is time measured in days,
k – is the First-Order kinetic model constant, (day^{-1})

$$\mathrm{Y(t)} = \mathrm{Y_m} \exp\left\{-\exp\left(\frac{\mathrm{R_m - e}}{\mathrm{Y_m}}(\lambda - \mathrm{t}) + 1\right)\right\} \quad (6)$$

where:
Y(t) – is the cumulative biogas production, ($mL \cdot gVS^{-1}$)
Y_m – is the ultimate methane production, ($mL \cdot gVS^{-1}$)
t – is the time in days,
R_m – is the maximum biogas production rate, ($mL \cdot gVS \cdot day^{-1}$)
e – is a constant equal to 2.7183,
λ – is the lag phase time, (days)

The kinetic constants were determined using non-linear regression in OriginLab (2019 version) software. The study presents four validation statistical parameters, i.e., root mean square error (RMSE), residual sum of squares (RSS), coefficient of determination (R^2), and adjusted R^2 (Lübken et al., 2015; Ajayi-Banji et al., 2021; Leite et al., 2024).

$$RMSE = \sqrt{\frac{RSS}{n}} \tag{7}$$

where:
RSS – is the residual sum of squares,
n – is the number of datasets.

$$RSS = \sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \tag{8}$$

where:
N – represents the number of measurements,
y_i – is the experimentally collected data,
$\hat{y}_i$ – is the output projected by the model.

Results and Discussion

Box-Behnken Design (BBD) Model Development

In this study, the effects of temperature (A), pH (B), HRT (C), and OLR (D) were investigated on biogas production (Y_{R1}), VS reduction (Y_{R2}), and COD percentage removal (Y_{R3}) for the co-digestion of FVW with market wastewater using activated sludge. Biogas production, VS reduction, and COD removal were selected as dependent variables to evaluate the influence of process variables on the system's performance. Using experimental data generated from the RSM–BBD, which comprised 26 experimental runs, predictive models for the responses – biogas production, VS percentage reduction, and COD percentage removal – were developed, as shown in Equations (9), (10), and (11), respectively. The experimental data obtained were subjected to statistical analysis to validate the predictive ability of the developed models. This was done to ensure that the models provided an adequate approximation of the actual system, as reported by (Khumalo et al., 2023b)

$$Y_{R1} = 464.29 + 72.50A + 22.08B - 37.08C + 155.83D + 40.BD - 53.04B^2 \tag{9}$$

$$Y_{R2} = 58.70 + 1.20A + 4.20B - 4.63C + 7.94D + 3.95AB + 0.81AC - 0.76AD - 3.02BC \tag{10}$$

$$Y_{R3} = 70.74 + 1.93A + 3.99B - 2.22C + 3.74D - 2.70AC + 7.30BD - 4.17B^2 - 3.13D^2 \tag{11}$$

Analysis of Variance (ANOVA)

Herein, predictive models developed from the RSM–BBD matrix were subjected to statistical analysis using the analysis of variance (ANOVA) approach to ascertain their significance, as presented in Tables 4-7. It is worth noting that through the application of ANOVA, it was possible to examine the interactions between the dependent variables (i.e., Y_{R1}, Y_{R2}, and Y_{R3}) and the independent variables, i.e., A, B, C, and D. The developed predictive models were evaluated by considering essential statistical parameters, as depicted in Table 4.

Table 4.
ANOVA summary of results for the developed model's responses

Parameter	Biogas production	VS reduction	COD removal
Coefficient of determination (R^2)	0.991	0.978	0.977
Adjusted R^2	0.988	0.966	0.966
Predicted R^2	0.984	0.939	0.936
Adequate precision	62.14	31.23	35.34
Standard deviation	14.16	1.37	1.09
Mean	439.81	58.70	67.38
Coefficient of variance (CV, %)	3.22	2.33	1.61

The overall significance of the developed predictive models was evaluated by considering both the coefficient of determination (R^2) and the adjusted R^2 values. Statistically, R^2 is a measure of the total variation of predicted values relative to the mean. As such, in a model with good predictive efficiency, the R^2 value should be close to 1. For the present study, R^2 values greater than 0.97 (see Table 4) were recorded for all three models, suggesting that the developed models satisfactorily predict biogas production, VS reduction, and COD removal. Moreover, the adjusted R^2 parameter was used to evaluate the models' efficiency on the basis that it corrects the R^2 value for sample size and the number of terms in the model, as discussed by (Khumalo et al., 2023a). Here, the signal-to-noise ratio was measured using adequate precision; the recorded values of greater than 4 for all responses clearly indicate an adequate signal, suggesting that the developed models can be used to navigate the design space of the experimental study.

The significance of a parameter was evaluated based on its F-value, which should be comparatively high, and its p-value, which should be less than 0.05 (Alimohammadi et al., 2017). From the ANOVA results presented in Tables 5, 6, and 7, all model terms – i.e., A (temperature), B (pH), C (HRT), and D (OLR) – and selected combinations recorded p-values of less than 0.05, confirming their significance at the 95% confidence level.

Table 5.
ANOVA results for the biogas production predictive model

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	4.014E+05	6	66902	333	< 0.0001	significant
A	63075	1	63075	314	< 0.0001	
B	5852	1	5852	29	< 0.0001	
C	16502	1	16502	82	< 0.0001	
D	2.914E+05	1	2.9E+05	1452	< 0.0001	
BD	6400	1	6400	31	< 0.0001	
B^2	18174	1	18174	90	< 0.0001	
Residual	3811	19	200			
Lack of fit	3611	18	200	1.00	0.6687	not significant
Pure error	200	1	200			
Cor total	4.052E+05	25				

Furthermore, the OLR parameter (D) recorded higher F-values of 1452 and 404.05 for biogas production and VS reduction, respectively, implying its greater significance when compared to temperature (A), pH (B), and HRT (C). On the other hand, pH (B) recorded an F-value of 161.88 for COD removal, confirming its significance. It is worth noting that all three models recorded p-values of less than 0.05, indicating their statistical significance for predicting biogas production, VS reduction, and COD removal.

Table 6.
ANOVA results for the VS reduction predictive model

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	1346.99	8	168.37	89.94	< 0.0001	significant
A	17.35	1	17.35	9.27	0.0073	
B	211.85	1	211.85	113.17	< 0.0001	
C	257.61	1	257.61	137.62	< 0.0001	
D	756.36	1	756.36	404.05	< 0.0001	
AB	62.41	1	62.41	33.34	< 0.0001	
AC	2.59	1	2.59	1.38	0.2555	
AD	2.33	1	2.33	1.24	0.2805	
BC	36.48	1	36.48	19.49	0.0004	
Residual	31.82	17	1.87			
Lack of fit	31.82	16	1.99	235.32	0.0512	not significant
Pure error	0.0085	1	0.0085			
Cor total	1378.81	25				

Table 7.
ANOVA results for the COD removal predictive model.

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	839.65	8	104.96	89.08	< 0.0001	significant
A	44.66	1	44.66	37.91	< 0.0001	
B	190.72	1	190.72	161.88	< 0.0001	
C	58.96	1	58.96	50.05	< 0.0001	
D	167.93	1	167.93	142.53	< 0.0001	
AC	29.05	1	29.05	24.66	0.0001	
BD	213.01	1	213.01	180.80	< 0.0001	
B^2	105.93	1	105.93	89.91	< 0.0001	
D^2	59.53	1	59.53	50.52	< 0.0001	
Residual	20.03	17	1.18			
Lack of fit	19.14	16	1.20	1.35	0.5974	not significant
Pure error	0.8844	1	0.8844			
Cor total	859.68	25				

Influence of input factors and their interactions on responses

The co-digestion process is influenced by independent variables, i.e., pH, temperature, OLR, and HRT. The interaction of two independent variables was used to examine their combined influence on the responses, i.e., biogas production, VS reduction, and COD removal. Figure 2 depicts a 3D plot showing the interactive effect of organic loading rate and pH on the predicted response for biogas production in mL·day^{-1}. The impact of the organic loading rate (1–4 kgVS·m^{-3}·day^{-1}) and pH (6–8) shows that an increase in both OLR and pH results in an increase in predicted biogas production. Biogas production increases with OLR, reaching a maximum at 4 kgVS·m^{-3}·day^{-1}, whereas a rapid increase in pH toward the upper range of 8 leads to a reduction in predicted biogas production. The decrease in biogas production is attributed to elevated OLR, which leads to the accumulation of undesirable high amounts of volatile fatty acids (VFAs), and the findings of the current study align with those reported by Nkuna et al. (2022). The study findings also indicate that an increase in pH leads to a rise in ammonia (NH_3) concentration, which may cause undesirable ammonia inhibition, as similarly reported by Cai et al. (2021).

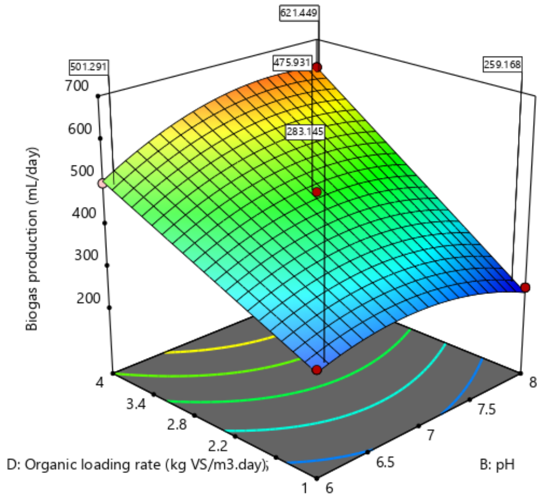

Figure 2. 3D plot showing interactive effect between OLR and pH in the biogas production

Figure 3 shows a 3D plot of the interaction effect between pH and temperature on VS reduction. It can be observed that VS reduction decreased under low pH conditions. Previous studies suggest that a combined increase in temperature and pH leads to an increase in VS reduction. This increase is attributed to the fact that elevated temperature accelerates anaerobic digestion (AD) mechanisms (i.e., hydrolysis, acetogenesis, etc.), while increased pH results in reduced production of undesirable volatile fatty acids (VFAs) (Zhuo et al., 2012; Dev et al., 2019; Nie et al., 2021). The production of VFAs hinders biochemical reactions, thereby compromising the efficiency of a typical AD process in the context of biogas production.

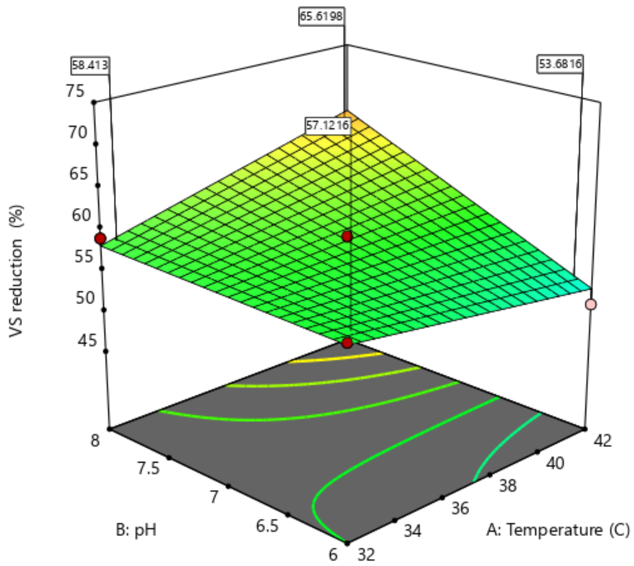

Figure 3. 3D plot showing the interactive effects of temperature and pH on VS reduction

From Figure 4, increasing the temperature while decreasing the HRT has a positive impact on COD removal. This is corroborated by previous studies which have demonstrated that the efficacy of COD removal through anaerobic digestion of untreated wastewater decreases as the system temperature deviates from its optimal mesophilic value (dos Santos, 2018).

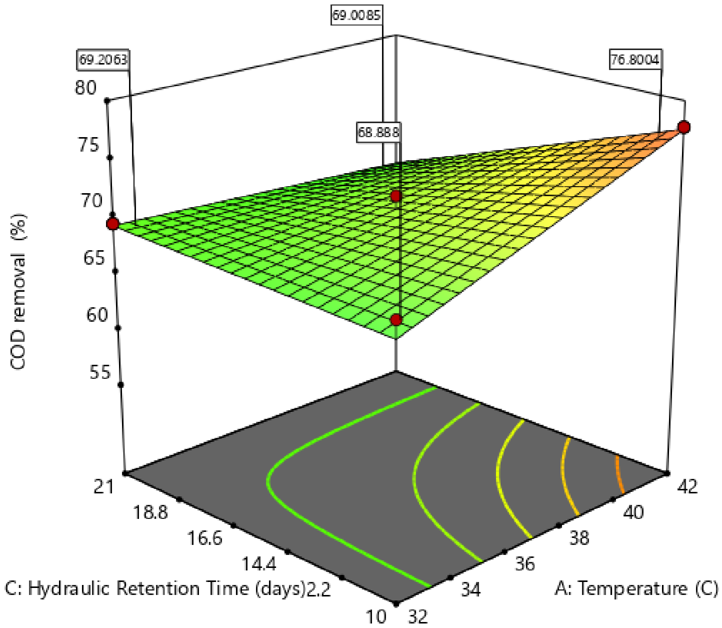

Figure 4. 3D plot showing interactive effects of temperature and HRT on the COD removal

Model validation

Figure 5 shows the actual vs. predicted plots for biogas production, VS reduction, and COD removal responses to evaluate the three models and determine whether the errors were negligible and within the specified operational limits. All developed models were found to be appropriate. This was supported by the actual vs. predicted plots, where the reduced quadratic model for biogas production, the reduced two-factor interaction (2FI) model for VS reduction, and the reduced quadratic model for COD removal showed that the predicted and actual data were randomly distributed close to the 45° line, validating that all experimentally obtained results were within the boundaries of the predicted results and, therefore, the response variables required no modification (Montgomery, 2017; Khumalo et al., 2023a).

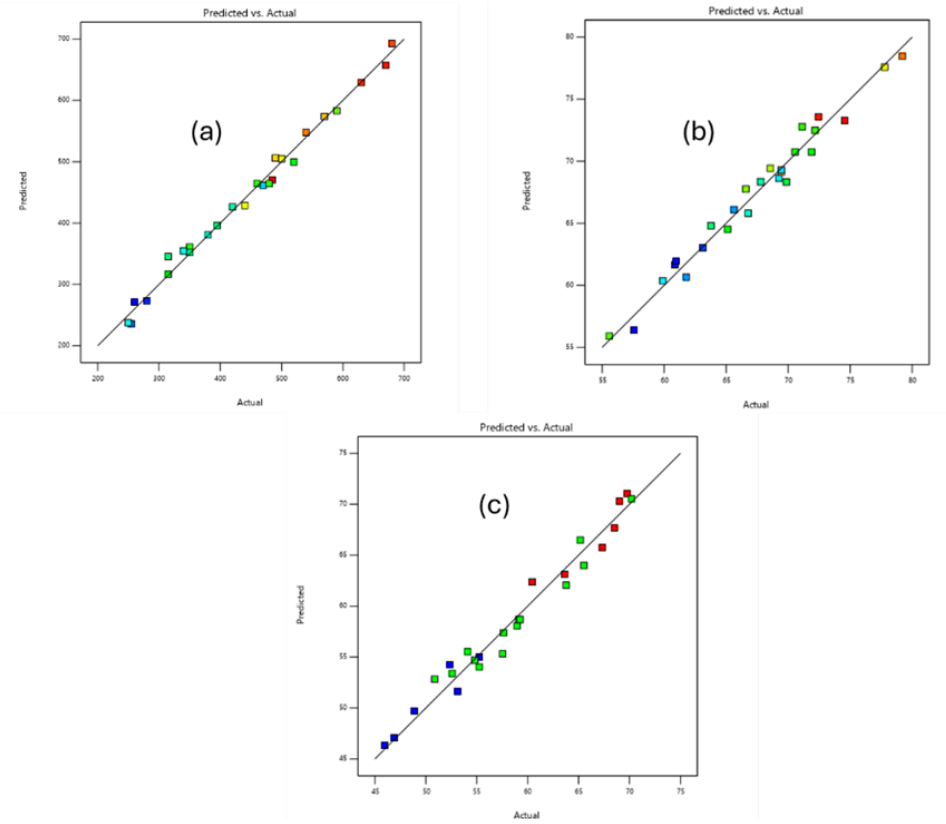

Figure 5. The actual vs predicted plots of biogas production (a), VS reduction (b), and COD removal (c)

Numerical determination of optimum conditions

The numerical and graphical optimization techniques were developed using Design Expert to identify the conditions of the input variables that significantly impacted the responses. The system generated 100 conditional solutions with 100% desirability at a 95% confidence level. The optimum conditions of the input factors are shown in Figure 6, where an optimum OLR of 3.98 kgVS·m^{-3}·day^{-1}, a temperature of 40°C, an HRT of 10 days, and a pH of 7.2 will result in a biogas production of 716.53 mL·day^{-1}. Additionally, there will be a VS reduction of 73.37% and a COD removal of 79.24%. Consequently, triplicate model validation experimental investigations were performed under the obtained optimum conditions, achieving a biogas production of 730 ± 30.12 mL·day^{-1}, a VS reduction of 74.70 ± 10.02%, a COD removal of 80.51 ± 10.02%, and a methane composition of 73%. The minimal standard deviation indicates that the implementation of BBD in RSM produced a strong correlation between the experimental and projected values.

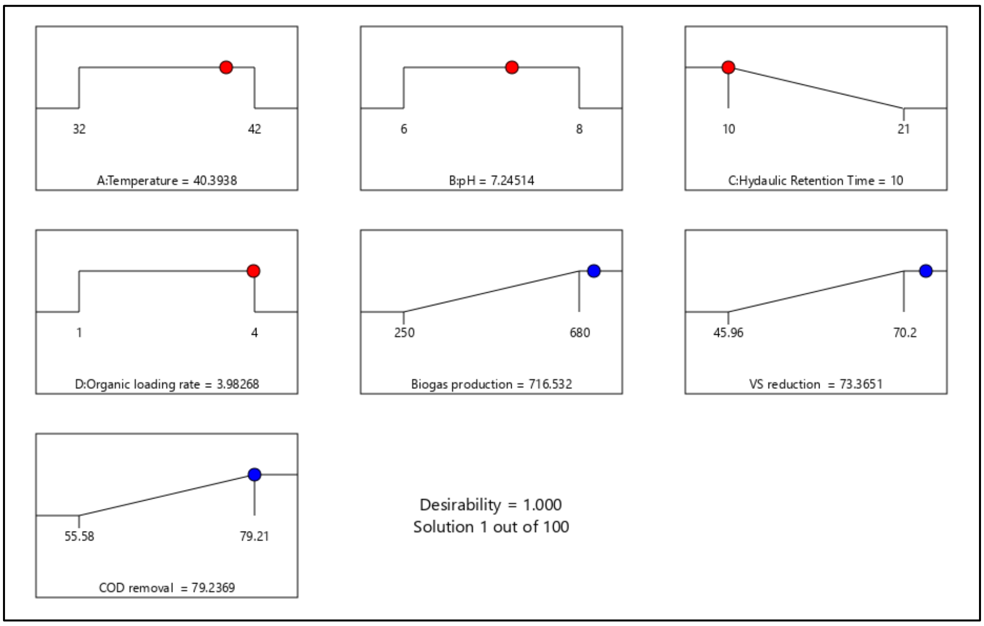

Figure 6. Ramp plots showing optimum conditions of the co-digestion BMP system

Co-digestion process kinetics

The kinetic models can be used to evaluate the behavior and effectiveness of the co-digestion BMP system. For this purpose, the First-Order and Modified Gompertz kinetic models were utilized. Table 7 summarizes the kinetic analysis, confirming that the Modified Gompertz model provides a more accurate description of the kinetics and dynamics of the BMP co-digestion systems. The maximum biogas production rate (k) was determined to be 0.08 day^{-1} for the Modified Gompertz model. The experimental biogas production was found to be 715 $mL \cdot gVS^{-1}$, while the predicted biogas yields were 733.59 and 686.00 $mL \cdot gVS^{-1}$ for the Modified Gompertz and First-Order models, respectively. The correlation coefficient (R^2) was 0.995 for the Modified Gompertz model, confirming its robustness. The robustness of the Modified Gompertz model and its superior fit were further validated by a lower RMSE of 21.08, indicating reduced variation between experimental and predicted data (Morais et al., 2021; Avinash et al., 2024). A lag phase (λ) of 0.90 days was also observed, and other studies have reported similarly small λ values – as low as 0.85 and 0.594 days – when using FVW co-digested with other substrates such as coffee grounds and landfill leachate (de Quadros et al., 2023). The low lag phase suggests that the breakdown of organic materials began shortly after the incubation period, as microorganisms in the mixture rapidly adapted to their environment, although higher lag phases have also been associated with more efficient biogas yields (Zhao et al., 2016; de Quadros et al., 2023). Figure 7 displays a graphical representation of the findings obtained by fitting the cumulative biogas production data to the two models, demonstrating that the Modified Gompertz model is well-suited.

Table 7.
Summary of the kinetic study conducted from the co-digestion process under predicted optimum conditions

Parameter	First-Order	Modified Gompertz
R^2	0.990	0.995
Adjusted R^2	0.989	0.993
k (day^{-1})	0.02	0.08
Y_{EXP}. ($mL \cdot gVS^{-1}$)	715	715
Y_m. ($mL \cdot gVS^{-1}$)	686.00	733.59
RSS	5978.31	3556.18
RMSE	25.75	21.08
R_m ($mL \cdot gVS^{-1} day^{-1}$)	1856.98	949.82
λ(days)	-	0.90

*Y_m (model Predicted biogas production, Y_{EXP} (Experimental measured biogas production, λ (Lag phase), R_m (Maximum predicted biogas production, k (rate constant), R^2 (Correlation coefficient and RSS (Sum of residual squares)

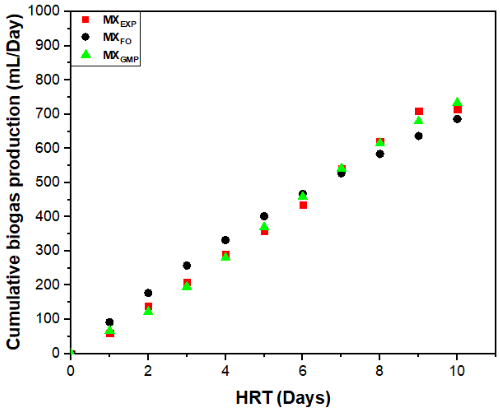

Figure 7. Comparison of Modified Gompertz and First-Order models for the mix-WW co-digestion process. MX_{EXP}. (experimental), MX_{FO} (First-Order), MX_{GMP} (Modified Gompertz)

Conclusions

This study examined the formulation of predictive models and kinetic models in the anaerobic co-digestion of fruit and vegetable waste with locally generated market wastewater. The optimal conditions for the system were analyzed and expressed as a mathematical function of the input variables through ANOVA, yielding statistically significant regression coefficients ($R^2 > 0.93$ for all responses) at a 95% confidence level. The optimal conditions achieved were an OLR of 3.98 $kgVS \cdot m^{-3} \cdot day^{-1}$, a temperature of 40°C, an HRT of 10 days, and a pH of 7.2, which resulted in a biogas production of 716.53 $mL \cdot day^{-1}$, a VS reduction of 73.37%, and a COD removal of 79.24%. The Modified Gompertz model effectively fit the experimental data and was deemed more suitable for this process, as it exhibited a lower RMSE of 21.08 and an R^2 of 0.995. The co-digestion of fruit and vegetable waste with market wastewater to optimize the anaerobic digestion process for biogas production is highly viable and enhances the efficiency of anaerobic digestion by increasing biogas yield and methane content. Co-digestion presents a promising solution for mitigating fruit and vegetable waste while repurposing wastewater. The pursuit of environmental sustainability and zero-waste management in support of a circular economy is a global challenge, and the co-digestion of fruit and vegetable waste can contribute to feasible and impactful solutions.

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ZAGOSPODAROWANIE ODPADÓW Z OWOCÓW I WARZYW POPRZEZ KOFERMENTACJĘ ZE ŚCIEKAMI Z LOKALNYCH TARGOWISK: WARUNKI EKSPLOATACJI I KINETYKA SYSTEMU

Streszczenie. Zanieczyszczenie środowiska odpadami z owoców i warzyw powstających na lokalnych targowiskach w Republice Południowej Afryki jest nieuniknione. Co więcej, obecna strategia utylizacji tego rodzaju odpadów przyczynia się do emisji gazów cieplarnianych. Dlatego wykorzystanie odpadów rolniczych do produkcji bioenergii ma kluczowe znaczenie dla osiągnięcia celu „zero odpadów" i zmniejszenia śladu węglowego. W tym badaniu przeprowadzono parametryczną optymalizację kofermentacji odpadów ze ściekami komunalnymi przy użyciu modelu Boxa-Behnkena, zaadaptowanego z metodologii powierzchni odpowiedzi (RSM). W badaniu ustalono optymalne kombinacje zmiennych procesowych, tj. temperatury, pH, hydraulicznego czasu retencji i wskaźnika obciążenia organicznego do produkcji biogazu przy jednoczesnym zmniejszeniu lotnych ciał stałych i chemicznego zapotrzebowania na tlen ze ścieków. W optymalnych warunkach pracy, przy temperaturze 40°C, czasie retencji 10 dni, pH 7,2 i zapotrzebowaniu na tlen rzędu 3,98 kg $VS \cdot m^{-3} \cdot dzień^{-1}$, uzyskano pożądaną wydajność 100%. Odnotowano wskaźnik produkcji biogazu na poziomie 717 $ml \cdot dzień^{-1}$ przy czym poziom redukcji lotnych ciał stałych i chemicznego zapotrzebowania na tle wyniosło odpowiednio 73,37% i 79,24%. Solidność modeli predykcyjnych opracowanych przy użyciu RSM została potwierdzona wartościami R^2 większymi niż 0,9 dla wszystkich zmiennych wyjściowych. Zmodyfikowany model Gompertza był dobrze dopasowany do danych eksperymentalnych, dając R^2 na poziomie 0,995 i niższy średni błąd kwadratowy (RMSE) wynoszący 21,08. Wyniki niniejszego badania pokazują, że zagospodarowanie odpadów z owoców i warzyw poprzez kofermentację ze ściekami można uważać za obiecującą, zrównoważoną środowiskowo technologię zarządzania odpadami rolniczymi i produkcji bioenergii.

Słowa kluczowe: odpady owocowe i warzywne; kofermentacja; biogaz; ścieki; metodologia powierzchni odpowiedzi; kinetyka