Fruit Waste Anaerobic Co-Digestion with Market Wastewater: Process Kinetics

Nqobile Mkhize, Emmanuel Kweinor Tetteh and Sudesh Rathilal

***Abstract*—** South Africa today has an issue of high demand for energy, water, and waste management. Herein, valorisation of fruit wastes (FWs) to produce biogas present alternative energy source with sustainable waste management solutions. Conventionally, landfilling as waste practices comes with environmental risks with the emissions of greenhouse gases (such as carbon dioxide and methane). In addressing this concern, this study explored co-digestion of FWs and market wastewater (MWW) obtained from a local fruit and vegetable bulk market in Durban, South Africa, to produce biogas. The FWs including the apples, and bananas wastes were co-digested to establish degradability kinetic conditions with MWW. Results of the reduction in volatile solids (VS), among the FWs range from 69% to 72%. Biogas of 940 mL.day^{-1} produced by the apple waste was greater than the bananas waste of 830 mL.day^{-1} as compared to the MWW control of 500 mL.day^{-1}. The kinetics of the co-digestion of FWs and MWW favoured the Modified Gompertz kinetic principles in comparison with the First Order kinetics principle. The findings of this study are significant in understanding the mechanisms involved in the management of fruit waste via co-digestion.

***Keywords*—** Co-Digestion, Fruit Wastes, Apples, Bananas, Biogas, Kinetics.

I. Introduction

Stakeholders in South Africa's agriculture sector and government policy makers diligently strive to generate large amounts of fruit to address food security and food demand challenges. The economic and social advantages derived from huge production are essential; however, they entail negative repercussions, as the agricultural sector grapples with managing the significant fruit wastes (FWs) generated. This therefore results to land degradation, alterations in runoff, disruption of groundwater discharge, water quality deterioration, and accessibility issues with water and land for many applications [1]. An alternate framework is based on the circular economy, a system that decreases material consumption and waste generation while promoting the recycling and reuse of wastes to create new resources [2-4]. The idea of transforming waste into a resource is intriguing in terms of environmental sustainability and waste management towards circular economy.

Nqobile Mkhize, Emmanuel Kweinor Tetteh and Sudesh Rathilal, Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and The Built Environment, Durban University of Technology, Durban, 4001, South Africa

Organic wastes, such as food, fruits, and vegetables and wastes produced by restaurants, daily markets, and biological wastes from businesses, are frequently used as feedstocks to produce biogas by anaerobic digestion (AD) [5]. This application is mainly linked to the significant moisture content and remarkable degradability of the organic wastes, fruits included [6]. Biogas is globally acknowledged as a conventional form of off-grid energy. The use of biogas for electricity generation is made possible by technological developments, less reliance on fossil fuels, and a decrease in greenhouse gas emissions [7]. There is still a significant gap to close in transitioning South Africa's energy sector into sustainable energy sources such as biogas. The actual utilisation of biogas in South Africa, as in other African countries, have been restricted by a lack of investments, efficient government policies, a scarcity of locally accessible and appropriate technologies as well as insufficient research [8-10]. Approximately 300 installations are primarily small-scale domestic AD installations with a capacity of less than 10 m^3 [11, 12]. In 2023, the National Energy Regulator of South Africa (NERSA) registered 30 biogas projects in commercial and industrial sectors in South Africa [13].

Banana and apple waste has been reported by researchers to be a potential organic waste feedstock for the production of biogas [14, 15]. Biogas production can be enhanced through the co-digestion (Co-AD) process, where a co-substrate is added, preferable another waste material, to stabilise the anaerobic process [16]. The process of co-digestion is a complex process and needs to be studied further, the process kinetics will help in understanding the process further.

This study compares the combined digestion of banana waste with local market waste and apple waste with the local market wastewater. The process kinetics using the First Order and Modified Gompertz model equations were developed for the comparison.

II. Materials and methods

A. Co-substrates and inoculum specifications

Bananas and apples from a nearby bulk market waste dumpsite made up the fruit waste. The waste was gathered, separated into each of the fruits, and transported to the lab. The highly organic wastewater generated by the market is

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kept in septic tanks within the market. It was collected, placed in 25-litre containers, and then taken to a laboratory where it was kept at low temperatures. Activated sludge from a nearby wastewater treatment facility was used to create the inoculum anaerobically.

B. Feedstock preparation and characterisation

The sample was characterised according to the standard techniques set by the American Public Health Association [17]. These comprised determining the total solids (TS), volatile solids (VS) and moisture content. [17]. Table I shows the results obtained after characterisation. Samples of the market wastewater and activated sludge were tested for pH, TS, VS and Chemical Oxygen Demand (COD) and the results are shown in are shown in Table II. A pH meter (Thermo Scientific Eutech Elite PTCS, United States of America) was used to measure the pH, and a spectrophotometer (HACH DR3900, United States of America) was used to measure the COD.

TABLE I
FRUIT WASTE CHARACTERISATION

	TS (%)	VS (%)	Moisture (%)
Banana waste	19.8 ± 2.15	88 ± 6.88	75 ± 5.97
Apple waste	21 ± 3.66	90 ± 8.96	82 ± 7.69

TABLE II
MARKET WASTEWATER AND ACTIVATED SLUDGE CHARACTERISATION

	COD	pH
Market wastewater (MWW)	2010 ± 95	6.10 ± 0.7
Activated sludge (AS)	5860 ± 102	6.35 ± 0.45

C. Co-digestion Biochemical potential tests (BMP)

A BMP study was conducted utilising a laboratory-scale Co-AD system, where a water bath (United Scientific, WBST0001, South Africa) fitted with a temperature control to maintain a mesophilic temperature range of 40°C was used. An organic loading rate (OLR) of 4 $kgVS.m^{-3}.day^{-1}$, with a hydraulic retention time (HRT) of up to 12 days was used as operating conditions. A blue-cap Schott served as a co-digester and was immersed in the water bath. The Schott bottles were fitted with a flexible pipe linked to a biogas collection system which was connected to the inverted graded flask within a 10 L water container. The co-digester experienced a 2-minute nitrogen gas purge in the headspace prior to the commencement of each session to create anaerobic conditions by removing oxygen molecules from the system and the biogas collection apparatus. The feedstock mixing ratio (FW:MWW:AS) was 2:1:2. Furthermore, it is important to note that biogas generation was documented everyday utilising the water displacement approach. Gas chromatography (GC-2014 SHIMADZU, Japan) was employed to analyse the methane content of the biogas that was generated.

Equations (1) and (2) were used to determine the percentage removals of VS and COD, respectively.

$$\mathbf{VS\ RED.}(\%) = \frac{\mathbf{VS}_i - \mathbf{VS_f}}{\mathbf{VS_i}} \times \mathbf{100} \tag{1}$$

Where VS_i and VS_f are the initial and final VS quantities, respectively.

$$\mathbf{COD\ REM.}(\%) = \frac{\mathbf{COD_i} - \mathbf{COD_f}}{\mathbf{COD_i}} \times \mathbf{100} \tag{2}$$

Where COD_i and COD_f are the initial and final COD values, respectively.

D. Kinetic study: models

The kinetic models such as the First Order kinetic model and the Modified Gompertz kinetic models are widely used to simulate biogas production [18, 19]. Kinetic studies for biogas production were carried out using equations (3) and (4) for the First Order and Modified Gompertz kinetic models, respectively.

$$\mathbf{Y(t)\ =\ Y_m\ [1\ -\ exp(kt)]} \tag{3}$$

Where Y(t) is the cumulative biogas production ($mL.gVS^{-1}$), Y_m is the maximum biogas production potential ($mL.gVS^{-1}$), t is time in days and k is the First Order kinetic model constant (day^{-1}).

$$\mathbf{Y(t) = Y_m\ exp\left\{-exp\left(\frac{R_m - e}{Y_m}(\lambda - t) + 1\right)\right\}} \tag{4}$$

Where Y(t) is the cumulative biogas production ($mL.gVS^{-1}$), Y_m is the maximum methane production ($mL.gVS^{-1}$), t is the time in days, R_m is the rate of the maximum biogas production ($mL.gVS^{-1}.day^{-1}$), *e* is a constant (2.7183), and λ is the lag phase time (days).

The non-linear regression in Origin Lab software (2019 version) was used to determine the kinetic constants. The statistical validation utilised statistical parameters such as coefficient of determination (R^2), and modified coefficient of determination (adjusted R^2) and root mean square error (RMSE) [20-22].

$$RMSE = \sqrt{\frac{RSS}{n}} \tag{5}$$

Where RSS is the residual sum of squares and *n* number of datasets.

III. RESULTS AND DISCUSSION

A. Fruits co-digestion BMP

The performance of apple and banana wastes in the performance in biogas production was assessed by the BMP Co-AD method utilising MWW. Fig. 1 illustrates the biogas production and methane concentrations (%) for the co-digestion of fruit waste (banana and apple waste) alongside the control with mono-substrate (without fruit waste). During the digestion phase, biogas production from banana and apple waste continuously exceeded that of the control. Apple waste yielded the maximum biogas production at 940 $mL.day^{-1}$, whilst the banana waste management systems produced 830 $mL.day^{-1}$and 500 $mL.day^{-1}$, respectively. Both banana and apple waste generated substantial quantities of biogas, aligning with previous research indicating that fruit waste is highly effective in biogas production due to elevated moisture content and volatile solids [6].

The maximum methane concentration attained (67%) occurred in the digester containing apple waste and municipal wastewater. The banana waste had 65% methane content. The control exhibited the lowest methane production of 53%. The results indicate the necessity of the co-digestion process and the synergistic effects of using market wastewater as a co-substrate. The low methane compositions from the control system utilising solely MWW align with other research, which reported a methane composition of 58% using the wastewater (sewage sludge) and activated sludge [23].

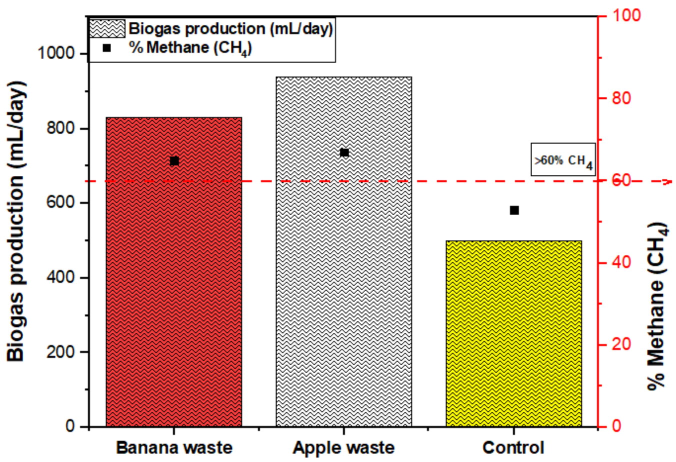

Fig. 1 Biogas production for co-digestion BMP systems with OLR of 4 $kgVS.m^{-3}.day^{-1}$, a temperature of 40° C and an HRT of 12 days.

Fig. 2 exhibits the reactors' performance and efficiency in terms of COD elimination and VS reduction percentages. The decrease in volatile solids (VS) for the control, banana waste, and apple waste was recorded at 52%, 69.49%, and 72.22%, respectively. A The significant VS removal can be attributed to the higher moisture content of the FWs, specifically when moisture levels are ≥ 75% [24, 25]. The VS removal produced is within the performance as achieved by other studies [15]. The COD removal was quantified, revealing that apple waste achieved the highest COD removal rate of 80.65%

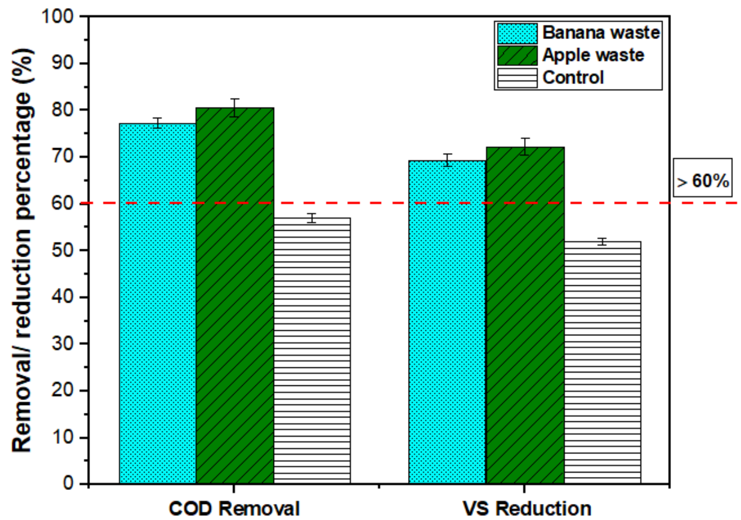

Fig. 2 COD removal (%) and VS reduction (%) of BMP systems with with OLR of 4 $kgVS.m^{-3}.day^{-1}$, a temperature of 40° C and an HRT of 12 days.

B. Kinetic study of the banana waste and apple waste co-AD systems

The kinetics of the co-digestion BMP process in the banana and apple waste digesters were generated by fitting their cumulative biogas production to First Order and Modified Gompertz models, as illustrated in Equations (3) and (4). The Modified Gompertz and First Order models have been utilised as the kinetic modelling for biogas production, based on the premise that the biogas generation rate in batch mode is exactly proportional to the specific growth rate of methanogenic bacteria within the biodigester [26, 27].

Table III presents a summary of the kinetics investigation, indicating that the greatest biogas production rate (k) for the Modified Gompertz model of banana waste was established at 0.11 day^{-1}. The experimental production of biogas from banana waste under these conditions was measured at 830 $mL.gVS^{-1}$, whereas the predicted biogas outputs were 810.43 and 848.35 $mL.gVS^{-1}$. The experimental biogas production from apple waste was 940 $mL.gVS^{-1}$, while the First Order and Modified Gompertz models generated 985.91 $mL.gVS^{-1}$ and 946.56 $mL.gVS^{-1}$, respectively. The results indicated a robust correlation between the projected biogas production and the actual biogas production for both the First Order and Modified Gompertz Models, with the predicted data from the Modified Gompertz model exhibiting a closer alignment with the experimentally measured data, consistent with other studies [27, 28]

TABLE III
KNTEIC STUDY SUMMARY: FRUIT WASTE CO-DIGESTION

	Banana Waste		Apple waste	
Parameter	First Order	Modified Gompertz	First Order	Modified Gompertz
Exp[a]. (mLgVS^{-1})	830	830	940	940
Pred[b]. (mL.gVS^{-1})	810.34	848.35	985.97	946.56
R^2	0.953	0.992	0.976	0.996
Adjusted R^2	0.948	0.990	0.973	0.994
RMSE[c]	29.63	26.73	25.28	20.33
k[d] (day^{-1})	0.07	0.11	0.08	0.06
Rm /Ym[e] (mL.gVSday^{-1})	1580.63	1068.05	1574.63	1085.47
λ[f] (days)		1.40		1.02

[a]Exp. (Experimental biogas production)
[b]Pred. (predicted biogas production)
[c]RMSE (root mean square error)
[d]k (rate constant)
[e]Y_{m} / R_{m} (Maximum predicted biogas production
[f]λ (Lag phase)

Fig. 3 illustrates the fitted curves of the modified Gompertz model, First Order, and the associated experimental data for the apple waste system It also illustrates the fitted models and experimental data for the banana waste system The correlation coefficient (R^2) values for the modified Gompertz model (>0.99) exceeded those of the First Order kinetic model (>0.95). The R^2 number indicates the optimal fit of the statistical models, both of which were statistically valid. The lag phase (λ) of 1.40 for banana waste and 1.02 for apple waste, as predicted by the Modified Gompertz model, was relatively low, aligning with laboratory investigations and supporting other studies that reported a lag phase as low as 0.01 days [24]. The Modified Gompertz model's adaptability and optimal fit were confirmed by the got lower RMSE values of 20.33 for apple waste and 26.73 for banana, indicating less variation between experimental and predicted data.

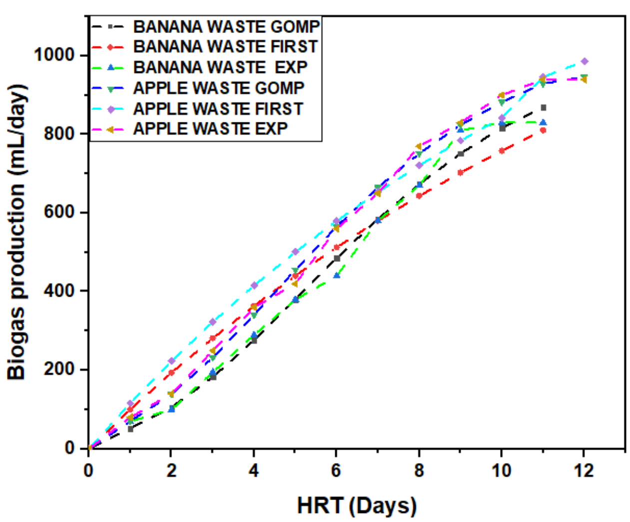

Fig. 3 Fitting biogas production on First Order and Modified Gompertz models

IV. CONCLUSION

The co-digestion of fruit waste and market wastewater demonstrated viability, with apple waste yielding the highest biogas production of 940 mL.day^{-1} and a methane composition of 67%, compared to the control system (MWW only), which produced 500 mL.day^{-1} and had a methane composition of 55%. The Modified Gompertz model was found more suitable for the experimental data derived from apple and banana wastes, which established the co-digestion degradation kinetics conditions. The results were further corroborated by the superior performance shown by the observed $R^2 > 0.99$ for all the Modified Gompertz data. The kinetic modelling yielded results indicating that the lag phase for the two systems, bananas (1.4 days) and apples (1.02 days), exhibited great biodegradability. It can be concluded that the co-digestion of agricultural waste and market wastewater to optimise the anaerobic digestion process for biogas production is highly viable by augmenting the methane potential .Findings of this study will serve as a foundation of co-digestion various wastes with inoculated wastewater for biogas production.

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