Scientific African 23 (2024) e02032

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Experimental simulation and kinetic modeling of bioenergy potential of *Eichornia crassipes* biomass from the Volta River basin of Ghana under mesophilic conditions

Enoch Asante [a], Richard Arthur [a], Emmanuel Okoh Agyemang [a], Martina Francisca Baidoo [b], Nana Yaw Asiedu [b,*]

[a] *Department of Energy Systems, Koforidua Technical University, Eastern Region, Koforidua, Ghana*
[b] *Department of Chemical Engineering, Faculty of Mechanical and Chemical Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology, Ashanti Region, Kumasi, Ghana*

ARTICLE INFO

Editor by: DR B Gyampoh

Keywords:
Water hyacinth
Anaerobic digestion
Mesophilic
Kinetic models
Hydrolysis constant

ABSTRACT

The study presents the results of the laboratory experiment performed on the anaerobic digestion of water hyacinth biomass harvested from the Volta River basin of Ghana and Fruit waste sludge as the inoculum. Batch mode of experiment was performed under mesophilic conditions (29 ± 3 °C) with a hydraulic retention time of 61 days. The experimental setup was made up of three (3) fermenter bottles of 5.0 L capacity namely F1, F2 and F3. F1 served as the control whiles F2 and F3 served as the test fermenter bottles. Each of the fermenter bottles was fitted with BlueSens methane sensor and BlueVcount flowmeter for the measurement of methane composition and biogas volumes, respectively. The Theoretical Biomethane Potential (BMP) of the water hyacinth biomass was estimated to be 422.23 ml/gVS. The experimental BMP was determined to be 402.62 ml CH_4/gVS and 356.03 ml CH_4/gVS for F2 and F3, respectively. Consequently, a biodegradability value of 95.36 and 84.32 % was obtained from F2 and F3, respectively. Moreover, the F2 fermenter bottle recorded a cumulative net methane and biogas volumes of 5576.3 ml and 12,014 ml, respectively. Likewise, a total net cumulative methane and biogas volumes of 4931.0 ml and 11,384 ml were produced from the F3 fermenter bottle. Using the First order kinetic model, an average value of hydrolysis constant for water hyacinth biomass was determined as 0.051 day^{-1}. Furthermore, the modified Gompertz model, the logistic function model and Transference function models were used to fit the experimental cumulative biogas and methane production data. The outcome of the study shows that, the production of biogas from water hyacinth biomass harvested the Volta River basin of Ghana could offer sustainable control solutions to its invasion on water bodies whiles providing a cheap and reliable means of biofuel to the riparian communities.

Introduction

Eichornia crassipes which is mostly referred to as water hyacinth has been reported to be the world's most noxious, dreadful and aquatic invasive weeds which is able to produce 14 × 10^7 daughter plants yearly [1]. It is an aquatic plant which grows on the surfaces

* Corresponding author.
E-mail address: nyasiedu.coe@knust.edu.gh (N.Y. Asiedu).

https://doi.org/10.1016/j.sciaf.2023.e02032
Received 17 June 2023; Received in revised form 30 September 2023; Accepted 19 December 2023
Available online 21 December 2023

of open water such as slow-moving rivers, ponds and lakes. Water hyacinth could achieve a growth rate of 1.75 metric tons per hectare per day under favorable conditions [2]. Additionally, other reports have indicated that water hyacinth usually forms a densed mat on the surfaces of slowing moving water bodies whose population size doubles every 5–15 days or 6–18 days [3,4]. In Ghana, it is reported to be prevalent on River Oti arm of the Volta Lake, the lower Volta River, Tano River, Kpong Headpond and Odaw stream in Accra [5]. Elsewhere in Africa, the invasion of water hyacinth on major water bodies such as Lake Victoria in Kenya, Ologe Lagoon in Nigeria, Nile River in Egypt and the Zembezi River in Zambia have been reported [6].The contribution towards the reduction in the quantity and quality of water bodies by water hyacinth through evapotranspiration on the Roseta branch of the Nile River alone have been estimated to be 21.3 million m^3/year [7]. Further, the effect of the invasion of the densed mat of water hyacinth interrupts with navigation of water transport due to the clogging of waterways. The situation interferes with fishing and farming activities which impacts negatively on the socioeconomic life of the affected communities. Woefully, the densed mat of water hyacinth also creates a favorable environment for the breeding of disease vectors such as mosquitoes and snails [5]. Due to the difficulty associated with its eradication through biological, physical, and chemical means, there is a great divergence of thoughts among policy makers and environmental scientists with regards to the most effective control measure scheme to be adopted. Notable among the sustainable applications proposed as a form of mitigating the hazards caused by water hyacinth is the exploitation of its biomass for biogas production through anaerobic digestion process [8]. Anaerobic digestion (AD) is environmental friendly biological process in which microorganisms work synergistically to convert organic wastes into biogas and a stable product (soil conditioner) useful for agricultural practices without any detrimental effects on the environment [9]. The technology has been widely applied as a useful method for the bioconversion of complex substrates into renewable energy in a form of methane [10]. Moreover, the option for the conversion of complex organic substrates to renewable energy has largely been embraced especially in a dispensation of increasing demand for energy arising from the growth of human population, depletion of fossil fuels resources amidst environmental concerns emanating from the its combustion [11].

Water hyacinth biomass, under the classification of aquatic based waste material has been proposed as a potential feedstock for biogas production [12]. Water hyacinth as a potential biomass for biogas production is based on its abundant availability at low cost because it is naturally grown and it has relatively high cellulose (20 %) proportion, hemicellulose content of (33 %) with low lignin (10 %) content per unit volume of dry matter which enhances its biodegradability [2]. Again, the water hyacinth biomass as a potential feedstock is acknowledged for its highly rich content in nitrogen, essential nutrients and fermentable matter [13]. Subsequently, several research works have been undertaken to study the biogas and biomethane yield of water hyacinth using a suitable inoculum source at an optimized ratio. A good source of inoculum could further enhance anaerobic biodegradability, shorten lag phase, and ensure a more stable process. On the contrary, a low quality inoculum with a volatile solid content below 60 % could affect the stability of the anaerobic digestion process [14]. Several experimental works have been undertaken to enhance the biomethane production of water hyacinth using different inoculum sources. The combination of water hyacinth and primary sludge as an inoculum source at varying ratios have been investigated [13]. In another report, water hyacinth was co-digested with cow dung to assess its biomethane potential [15]. The mixing of water hyacinth with sheep waste at varying combinations has also been explored [16]. Further investigation into the biomethane potential of water hyacinth with rumen liquid have equally been reported [17]. Though several experimental procedures on the biomethane potential of water hyacinth have previously been reported, the simulation of biomethanation data of water hyacinth under the specific experimental conditions of (28–35 °C), employing fruit waste sludge as the source of inoculation using mathematical model equations has not yet been reported in the literature. In the course of the study, the hydrolysis constant parameter for water hyacinth biomass which is a rarely documented in literature was determined from the first-order kinetic model equation for biogas and methane production. Again, the innovation is centered on the utilization of a modern Bluevis BMP test apparatus for the experimental work. This equipment is equipped with digital flowmeters and methane sensors to measure biogas volume and methane concentration. In contrast, the traditional method for measuring biogas volumes primarily relied on the upward displacement of water, which is more prone to inaccuracies in volume measurements. In addition, sieving analysis procedure was exploited to determine the geometric mean diameter of the milled water hyacinth biomass. A Logistic model was also developed to determine the particle size (D) for a given cumulative percentage undersize (Ps) of the milled particles using the Orthogonal Distance regression iteration in Origin Pro 8 software. The paper aims to reveal the experimental biomethane potential data of the water hyacinth biomass located along the stretch of Lower Volta River in Ghana. The exploitation of the biomass for biogas production would offer a more sustainable control measure against the high rate of invasion of the biomass on the Volta river.

Materials and methods

Analytical methods

The pH measurements were determined using Hanna Combo pH/EC/EC/TDS and Temperature tester (Model 198129 low range). The standard method [18] was strictly followed to determine the Total solid (TS) content where each of Water Hyacinth (WH) and Fruit Waste Sludge (FWS) was dried at a temperature of 105 °C for 8 h using a Fisher Isotemp Senior model size Oven. In a similar manner, the Volatile Solids (VS) content of the WH and FWS was determined according to the standard method [19] by heating to a constant mass at a temperature of 550 °C for 5 h using a Thermo Scientific Thermolyne benchtop muffle furnace. The compositional structural analysis for cellulose, hemicellulose and lignin was performed using the modified form of the Direct Method procedure adopted by Auma et al. [3] at the Physiology Laboratory of the Cocoa Research Institute of Ghana (CRIG). The alkalinity tests were performed strictly according to the standards proposed by APHA [20].The detection and the quantitative determination of elemental traces such as (C, H, N, O, S, Mg, Mn, Ni, Fe) suspected in the WH and FWS was performed using Atomic Absorption Spectroscopy

(AAS) method as exposited by Ref. [21].

Characterization of water hyacinth

Water hyacinth (WH) was considered as the main substrate for the study of the biomethane potential test analysis. It is an aquatic lignocellulose plant, which is mainly made up of cellulose, hemicellulose and lignin as structural components. Samples were harvested along the stretch of Lower Volta River at Kpong in the Eastern region of Ghana, whose geographical location lies within the borders reported by Nyamekye et al. [22]. The entire plant (root, stem and leave) was cleaned from debris and dried using a Fisher Isotemp Senior model size Oven at temperature of 50 °C. The dried samples were milled in batches at a duration of 15 min to obtain particles whose mean diameter was 197 μm using CИTRONIC High Speed Bleeder machine (Model No. CTC-17135). The milling process was performed to ensure relative ease of handling, promote fluidity in the fermenter bottle and lastly, increase the surface area to enhance microbial accessibility to the biodegradable cellulose and hemicellulose components of the WH. The powdered samples of WH were subsequently analyzed for moisture content, total solids, volatile solids, and elemental traces according to analytical method procedure mentioned previously.

Particle size analysis of water hyacinth

The assessment of the particle size distribution of the water hyacinth was carried out using sieving analysis referenced to the procedure outlined by Jillavenkatesa et al. [23]. Accordingly, the finely milled water hyacinth particles were subjected to vigorous shaking as it passed through series of mounted sieves having different opening sizes. The sieves were successively arranged in decreasing order of mesh size from top to the bottom. The nominal sieve size openings used were 4000, 3350, 2000, 1700, 1400, 1180, 850, 710, 600, 500, 425, 300,212, 150, 106, 90, 75 and 45 μm. Initially, the retained mass of particles on each sieve opening was determined. The obtained value was then expressed as a percentage of the total mass of sample used for the analysis. A semi log graph of retained mass of particles against the particle geometric mean diameter was plotted. Besides, another semi-log graph of the percentage of cumulative passing against the nominal sieve opening was also drawn to determine the geometrical mean diameter (D_{50}) of the particles.

Characterization of the inoculum

Fruit Waste Sludge (FWS) from a mesophilic biodigester plant (28–35 °C) plant was used as the inoculum source. This was obtained from the Fresh and Dry Fruit Processing Company located at Adeiso in the Eastern region, Ghana. The biodigester plant operates at a hydraulic retention time (RHT) of (18) days under ambient temperature conditions. The FWS was subjected to a hunger phase of (15) days at room temperatures between 26 and 29 °C to expel as much as possible the available carbon (IV) oxide and methane present. The raw FWS was flocculated according to the procedure outlined by Scherer et al. [24] where Synthofloc 5840 VS was used as the flocculation agent. The practice tends to increase the total solid content of the raw FWS, reduce the interspatial distance and enhance synergistic activities among the microorganisms to boost biogas production. The flocculation process was performed by adding 500 ml of prepared flocculent solution of concentration 6.0 g/l to 60 L of raw FWS. The contents were thoroughly stirred gently and allowed to stay at room temperature (26–28 °C) for 24 h. The supernatant developed after the flocculating process was separated from the solid residue (flocculated sludge). The flocculated FWS was characterized for parameters such as total solids, volatile solids, alkalinity, pH and total organic carbon. The buffering capacity of the flocculated FWS was enhanced by adding 20 ml of 1 M of sodium hydrogen carbonate before it was introduced into the fermenter bottles.

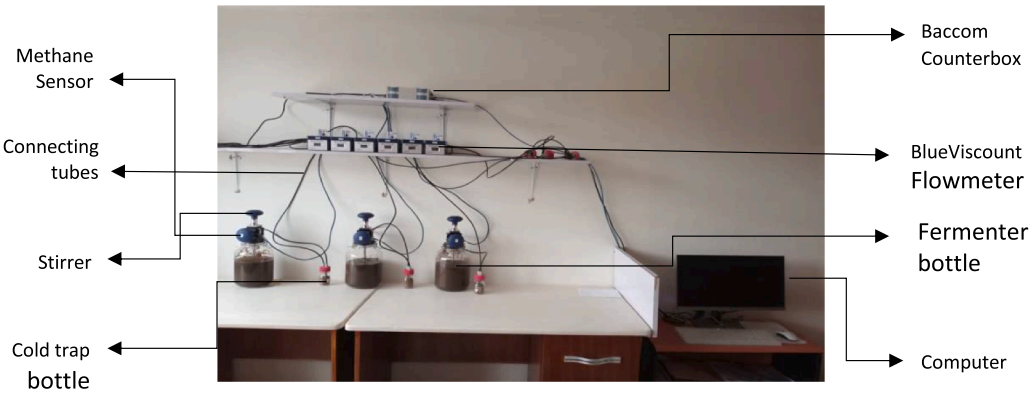

Fig. 1. Anaerobic batch fermentation set-up.

Description of experimental setup

The BMP setup consists of three (3) glass fermentation vessels namely F1, F2 and F3 as presented in Fig. 1. Each vessel has a capacity of 5.0 L. However, only 60 % of the full capacity was occupied by the mixture of the inoculum and the water hyacinth biomass whiles the remaining capacity served as headspace volume. The fermentation process was allowed to proceed at mesophilic conditions of 29 ± 3 °C under atmospheric pressure for 61 days. Each of the fermentation vessel is connected to a distinct cold trap bottle which is filled iron oxide adsorbent granules for the adsorption of H_2S gas and a BlueVCount flowmeter. These accessories are linked by a rubber hose having an internal and external diameter of 4 mm and 6 mm, respectively. In addition, a BCP-CH_4 sensor (BlueSens, Germany) which measure the concentration of methane in the biogas produced is directly mounted on the opening of the fermentation vessels and held firmly by a supporting clip. The setup is also equipped with Counterbox BACCom which serves as a data logger. A dedicated computer installed with a BlueVis 4.0 bioprocess software program captures and processes the volume and the concentration of methane in the biogas produced from the fermentation vessels. The BlueVcount gives an online measurement of the biogas volume produced. The device has a volume measuring unit which consist of a sealed lubricated cylinder fitted with a magnetic piston. The measurement of the produced gas volume is based on the displacement meter principle.

A built-up pressure of 3.0 mbar by the produced gas from the fermentation vessel causes the magnetic piston to rise in the guided cylinder until a marked volume (0.6 ml) in the measuring cylinder is reached. At this point, the presence of a micro-controller in the measuring unit signals a magnetic sensor to activate the opening of the outlet valve and the volume of gas that exits is measured spontaneously.

The process of methane production in the fermentation bottle is accomplished through the four main stages namely; hydrolysis, acidogenesis, acetogenesis and methanogenesis which occur concurrently. At the hydrolysis stage, the cellulose and hemicellose structural components of the water hyacinth are broken down largely into glucose monomers and other basic organic structures such as amino acids. The newly formed basic organic structures (glucose, amino acids and lipids) at the hydrolytic stage are converted to acetate, carbon dioxide and hydrogen including alcohol and volatile fatty acids (VFA) by the acidogenic bacterial at the acidogenesis stage. During the acetogenesis stage, the alcohol and volatile fatty acids formed in the acidogenesis stage is converted to methanogenic substrates such as acetate, hydrogen and carbon dioxide. At the methanogenesis stage, about 70 % of the methane is produced from the acetate formed at the acetogenesis stage. The remaining 30 % of the methane production is formed from the available carbondioxide and hydrogen [25].

Experimental design

The fermentation vessel (F1) served as the control which contained only the inoculum. An Inoculum to substrate ratio (ISR) of 10 was chosen for the test fermentation vessels (F2) and (F3) which contained the inoculum and the water hyacinth.

This was necessary to minimize the effect of the biogas production from inoculum on the net biogas production from the test fermentation vessels. The ISR represents the ratio of inoculum to the water hyacinth biomass in terms of gram mass of the volatile solid content. The gram mass of the volatile solid content of the inoculum is determined using the percentages of total solids (TS), the volatile solids (VS), density and active volume of the fermentation vessel which is 3000 ml in the current study. As an illustration for a basis of 100 g of inoculum, the masses of the total solids and volatile solids present were determined from the percentage of total solids and volatile solids (Table 1) using Eq. (1) and Eq. (2), respectively. In order to establish a basis for calculating the volatile solid mass of the inoculum expected in the active volume of the fermentation vessel, the volume occupied by the 100 g of inoculum was determined from its density using Eq. (3). Therefore, the gram mass of volatile solids present in the inoculum (138.52 gVS) as shown in Table 2 that could be found in the active volume of the fermenter vessel was determined using equation Eq. (4). Moreover, the actual mass of inoculum likely to contain the estimated volatile solid content of 138.52 gVS was determined from Eq. (5).

$$Mass\ of\ TS\ of\ Inoculum\ (M_{TS}) = \frac{\%\ TS}{100} \times\ 100g\ of\ inoculum \tag{1}$$

$$Mass\ of\ VS\ of\ Inoculum(M_{VS}) = \frac{\%\ VS}{100} \times Mass\ of\ TS\ of\ Inoculum\ (TS_m) \tag{2}$$

$$Volume\ of\ inoculum(V_i) = \frac{mass\ of\ inoculum\ (M_i)}{Density(\rho_i)} \tag{3}$$

Table 1
Physical properties of water hyacinth and inoculum.

Parameters	Unit	Inoculum (flocculated sludge)	Water hyacinth
Moisture	%	94.32	35.27
Total solid content	%	5.68	64.73
Volatile matter content	%	84.67	53.73
Density	g/ml	0.96	–

Table 2
Determined gram mass of volatile solids for inoculum and water hyacinth.

Fermenter	Inoculum mass (gVS)	Water hyacinth mass (gVS)	Total feedstock mass (gVS)	Inoculum actual mass (g)	Water hyacinth actual mass (g)	ISR
F1 (control)	138.52	–	138.52	2880.00	–	–
F2	138.52	13.85	152.37	2880.00	39.83	10.00
F3	138.52	13.85	152.37	2880.00	39.83	10.00

gVS: gram mass of volatile solids.

$$Mass\ of\ VS\ of\ inoculum\ in\ the\ active\ volume\ of\ fermenter\ vessel = \frac{Active\ fermenter\ vol.}{Inoculum\ vol.} \times Mass\ of\ VS\ of\ Inoculum(M_{VS}) \quad (4)$$

$$Actual\ Mass\ of\ inoculum = \ Density(\rho_i) \times Active\ fermenter\ vol. \quad (5)$$

An ISR of 10 indicates that, the proportion by mass in terms volatile solids of the water hyacinth biomass in feed mixture constitutes one tenth (13.85 gVS) of the total gram mass of the volatile solid (138.52 gVS) present in the inoculum. Referencing a basis of 100 g of water hyacinth biomass, the mass of total solids and volatile solids of the water hyacinth were calculated from the percentage values (Table 1) using Eqs. (6) and (7). The gram mass of volatile solids present in the 100 g of the water hyacinth obtained from Eq. (7) was used as the basis for calculating the mass of water hyacinth that would contain 13.85 gVS using Eq. (8). As a result, 39.83 g of water hyacinth biomass was added to the inoculum in the test fermentation vessels (F2 and F3) at an ISR of 10 as shown in Table 2.

$$Mass\ of\ TS\ of\ water\ hyacinth\ (M_{TS}) = \frac{\%\ TS}{100} \times \ 100g\ of\ water\ hyacinth \quad (6)$$

$$Mass\ of\ VS\ of\ water\ hyacinth\ (M_{VS}) = \frac{\%\ VS}{100} \times Mass\ of\ TS\ of\ Water\ hyacith(TS_m) \quad (7)$$

$$Mass\ water\ hyacinth\ \left(M_g\right) \ = \frac{13.85gVS}{Mass\ of\ VS\ of\ water\ hyacinth\ (M_{VS})} \times \ 100g \quad (8)$$

Theoretical developments

Estimation of theoretical biomethane potential

Theoretical BMP values could be predicted either as a function of the elemental composition such as carbon, hydrogen, oxygen, nitrogen and sulfur or based on the presence of organic family groups such carbohydrate, lipids and proteins present in the substrate [26]. The Buswell and Mullers equation (Eq. (9)) can be used for the prediction of the of BMP based on the chemical equation represented below. The equation only factors the presence of carbon, hydrogen and oxygen as the only elemental components of the substrate and CH_4 and CO_2 as the products of the anaerobic digestion process. The indexes a, b and c are determined from the ratio of the percentage mass compositions of carbon, hydrogen and oxygen in the substrate to their respective atomic masses.

$$C_aH_bO_c + \left(a - \frac{b}{4} - \frac{c}{2}\right)H_2O \rightarrow \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4}\right)CO_2 \ + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right)CH_4$$

$$BMP_{Th} = \frac{\left[\left(\frac{a}{2}\right) + \left(\frac{b}{8}\right) - \left(\frac{c}{4}\right)\right] \times \ 22400}{12a + b + 16c}\left[\frac{mL}{gVS}\right] \quad (9)$$

The BMP estimation by the Boyles equation (Eq. (10)) modifies the Buswell and Mullers equation to include nitrogen and sulfur atoms in the substrate and the release of NH_3 and H_2S in addition to CH_4 and CO_2 as products of the anaerobic digestion [27].

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{4}\right)H_2O \rightarrow \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} + \frac{3d}{8} - \frac{e}{4}\right)CH_4 + dNH_3 \ + eH_2S$$

$$BMP_{Th} = \frac{\left[\left(\frac{a}{2}\right) + \left(\frac{b}{8}\right) - \left(\frac{c}{4}\right) - \left(\frac{3d}{8}\right) - \left(\frac{e}{4}\right)\right] \times \ 22400}{12a + b + 16c + 14d + 32e}\left[\frac{mL}{gVS}\right] \quad (10)$$

Though the estimation of BMP using the elemental composition has been reported to be relatively fast, an ideal situation is always assumed that there is a complete conversion of all the organic matter present in the substrate to biomethane production. As a result, the approach fails to account for the fraction of the organic matter that is utilized for the growth of the microorganisms [26]. Though, the theoretical methane yield prediction based on the organic composition of the substrate has been exploited, the identification of the organic groups by chemical analysis have been reported to be time consuming [26]. Generally the experimental determined BMP values are always lower than theoretical BMP values due to limitations such as the utilization of substrate for the synthesis of bacterial mass, limitation of essential nutrients and inaccessibility of portions of the organic matter by microorganisms [28]. The theoretical BMP was predicted based on the elemental composition of the water hyacinth biomass using the Boyles equation. According to the Boyles equation, the general chemical formula of the substrate is represented as $C_aH_bO_cN_dS_e$. In the present study, the chemical formula $C_{1.94}H_{3.15}O_{1.38}N_{0.15}S_{0.01}$ was determined for the water hyacinth biomass. The indexes of the chemical formula were obtained by dividing the mass percentage composition of carbon, hydrogen, oxygen, nitrogen, and sulfur atoms using the results from the ultimate analysis test by the respective atomic masses as indicated below.

$$a = \frac{\%\ mass\ compostion\ of\ carbon}{Atomic\ mass\ of\ carbon} = \frac{\%\ mass\ compostion\ of\ carbon}{12.00}$$

$$b = \frac{\%\ mass\ compostion\ of\ hydrogen}{Atomic\ mass\ of\ hydrogen} = \frac{\%\ mass\ compostion\ of\ carbon}{1.01}$$

$$c = \frac{\%\ mass\ compostion\ of\ oxygen}{Atomic\ mass\ of\ oxygen} = \frac{\%\ mass\ compostion\ of\ carbon}{16.00}$$

$$d = \frac{\%\ mass\ compostion\ of\ nitrogen}{Atomic\ mass\ of\ nitrogen} = \frac{\%\ mass\ compostion\ of\ nitrogen}{14.01}$$

$$e = \frac{\%\ mass\ compostion\ of\ sulfur}{Atomic\ mass\ of\ sulfur} = \frac{\%\ mass\ compostion\ of\ nitrogen}{32.07}$$

Determination of experimental biomethane potential test

Biochemical methane potential (BMP) tests refers to the capacity of biodegradability of a substrate [29]. In the current study, the BMP test was defined as the volume of methane produced per gram mass of volatile matter present in the water hyacinth biomass. The biogas volume (ml) and methane concentration measured as (%v/v) of biogas produced were automatically recorded throughout the fermentation period. The contribution of errors in the *in-situ* measurement of the methane concentration due to the presence of air at the headspace volume of the fermenters was corrected according to procedure outlined by Scherer et al. [24]. Accordingly, the continuous displacement of air in the headspace volume was calculated to obtain the actual final methane percentage. The correction was made possible by first calculating at any given time (t) for the successive difference in biogas production (Eq. (11)), percentage of newly produced biogas at the headspace (Eq. (12)), the percentage volume of methane at the headspace (Eq. (13)), corrected methane percentage (Eq. (14)), corrected methane volume (Eq. (15)) and cumulated methane volume (Eq. (16)).

$$Difference\ in\ Biogas\ production\left(V_{Biogas.\ diff.}\right) = V_t - V_{t-1} \tag{11}$$

where V_t and V_{t-1} are any two successive biogas volumes

The % volume of newly produced biogas at the headspace section (F_t)

$$(F_t) = \frac{V_{Biogas.\ diff}}{V_{Headspace}} \times\ 100 \tag{12}$$

The proportion of biogas at the headspace section at any given time (β_t)

$$(\beta_t)\ = F_t + \beta_{t-1} - \left(\frac{\beta_{t-1} \times\ F_t}{100}\right) \tag{13}$$

where $\beta_{t-1} = 0$ and it represents the initial %volume of methane at the headspace section

The corrected % methane $(V_{methane\ percetage})$

$$\left(V_{mp}\right)\ = \frac{M_s}{\beta_t} \times\ 100 \tag{14}$$

where M_s is the % methane of reading from the methane sensor

$$The\ corrected\ methane\ volume\ (V_{methane}) = \frac{V_{mp}}{100} \times\ \left(V_{Biogas.\ diff.}\right) \tag{15}$$

$$Cumulated\ methane\ volume(V_{methane}) = \sum_{n=i}^{n=f} V_{methane} \tag{16}$$

where $n = i$ and $n = f$ are the intial and final corrected volumes of methane.

The final methane concentration (%v/v) produced at the end of the experiment was obtained from the ratio of the cumulated methane volume Eq. (16) to the cumulative volume of biogas production during the incubation period expressed as a percentage Eq. (17) .

$$CH_4\ concentration = \frac{\sum V_{Methane}}{\sum V_{Biogas}} \times\ 100 \tag{17}$$

The net methane concentration produced from the water hyacinth biomass only was obtained by subtracting the concentration of the methane produced by the control fermentation vessel (F1) from each of the test fermentation vessels (F2) and (F3) using Eq. (18).

$$\left(\frac{\sum V_{Methane\ \ Test\ \ fermenter,\ \ corrected}}{\sum V_{Biogas\ \ Test\ \ fermenter}} - \frac{\sum V_{Methane\ \ control\ \ fermenter,\ \ corrected}}{\sum V_{Biogas\ \ \ control}}\right) \times\ 100 \tag{18}$$

Biodegradability

Anaerobic biodegradability of a substrate is percentage of its volatile fraction that is converted to biomethane during anaerobic digestion process [30]. The presence of the lignin component in the cell wall of a plant biomass represents the main factor that limits the extent of the degradation of the cellulose portion. To a large extent, the proportion of the constituents of a plant cell wall (cellulose, hemicellulose and lignin) affects the biodegradability of a biomass substrate [31]. Factors ranging from the composition of the organic substrate, particle size, inoculum source, concentration and experimental conditions such as temperature, reactor volume and the method of gas measurement systems have been reported to affect the biodegradability of a substrate [32]. To enhance high degree of biodegradability in the present study, a particulate mean diameter size of 197 μm of the water hyacinth biomass was used. The mechanical pretreatment through the milling process was suitable to reduce the level of the lignin restriction and increase the surface area of the substrate for microbial degradation. A relatively short lag phase period in the current experiment could be expected due to the earlier utilization of the inoculum (FWS) for the breakdown of the fruit waste material which is lignocellulosic in nature. This makes the selected inoculum source suitable to enhance the biodegradability of the water hyacinth biomass. In addition, the flocculation process also enhanced the synergistic activities of the microbial population which resulted in the effective breakdown of the substrate. The biodegradability of the substrate was further enhanced by the addition of buffer system of 1 M sodium hydrogen carbonate to stabilize the pH of the system by neutralizing the volatile fatty acids associated with the acidogenic stage.

Modeling biogas production

Zweitering reparameterization of the Gompertz equation

The parameterized Gompertz model by Zweitering is known as the modified Gompertz model Eq. (19). The modified Gompertz model which describes the cumulative biogas production curve as a function of the bacterial growth was exploited to determine the maximum biogas production (P), the maximum production rate (K_z) and lag phase (λ) parameters for the design of biogas experiment. The bacterial growth curve shows an initial lag phase which is followed by an exponential phase and finally a decreasing growth rate down to zero resulting in a maximum value of the organisms.

$$Y = P \times exp\left\{ -exp\left[\frac{K_z \times e}{P}(\lambda - t) + 1\right]\right\} \tag{19}$$

Y = *Cumulative biogas production*(*Nml biogas per gram VS*)
P = *Maximum biogas potential* (*Nml biogas per gram VS per minute*)
R_m = *Maximum biogas production rate* (*Nml biogas per gram per VS per minute*

First order model

The First order kinetic model is normally considered during the modelling of the hydrolysis stage of anaerobic digestion process [33]. The model assumes the hydrolysis stage is the limiting step of the anaerobic digestion process.

As a result, the cumulative biogas production during the fermentation period is described by (Eq. (20)). It provides additional information about the hydrolysis rate constant of given substrate [34]. The model will be exploited to estimate the biogas production rate constant (K) and biogas potential (P) of the water hyacinth biomass used in this study.

$$Y = P(1 - exp(-K \times t)) \tag{20}$$

Y = *Cumulative biogas yield time* (*days*)
P = *Biogas potential of the substrate* (*ml per gram per VS add*)
K = *Hydrolysis rate constant*(*per day*)
t = *Time* (*day*)

Logistic function model

Similar to the modified Gompertz model, the logistic function model (Eq. (21)) relates the growth of the methanogenic bacteria to methane production during the anaerobic digestion process and considers the lag phase as an important factor for biogas production [35]. The logistic function model assumes that the rate of biogas production is proportional to the quantity of biogas already produced [34]. In other words, the model assumes the methane production is proportional to the maximum rate of methane production [36].

$$Y = \frac{P}{1 + exp\left\{\frac{4 \times R_m(\lambda - t)}{P} + 2\right\}} \tag{21}$$

Y = *Cumulative biogas yield time* (*day*)
P = *Biogas potential of the substrate* (*ml per gram per VS add*)
R_m = *Maximum biogas production rate* (*ml biogas per gram per VS per day*

t = *Time* (*day*)
λ = *Lag phase time* (*day*)

The validity of the models will be evaluated using the correlation coefficient (R^2) and Root Mean Square Error (RMSE) where, R^2 measures the goodness of fit and RMSE is the standard deviation of the predicted and the experiment measured values.

Transference function model

The transference function model (Eq. (22)) also known as the reaction-curve model was derived from the first-order kinetic model where the hydrolysis constant is replaced by the ratio of between the methane potential and the methane velocity. The model assumes an anaerobic digestion process could be considered as an input and output system [36]. The model was exploited to predict the potential, maximum rate of production and lag phase associated with methane and biogas production from the biomass.

$$Y = P\left(1 - exp\left(-R_m\frac{(t-\lambda)}{P}\right)\right) \tag{22}$$

Y = *Cumulative biogas yield time* (*day*)
P = *Biogas potential of the substrate* (*ml per gram per VS add*)
R_m = *Maximum biogas production rate* (*ml biogas per gram per VS per day*
t = *Time* (*day*)
λ = *Lag phase time* (*day*)

Results and discussion

Structural and chemical composition of water hyacinth

The structural composition of a biomass may differ based on its geographical location, the procedure developed for the analysis (gravimetric, chromatography and spectroscopy) and the parts of plant (root, stem, leave) used for the analysis [37]. In this study, the direct method reported by Auma et al. [3] was slightly modified by drying at a temperature of 60 °C prior to the determination of the lignin fraction. The results revealed that, the water hyacinth used contained 49.98 % cellulose, 28.99 % hemicellulose and 9.50 % lignin. The relatively high amount of cellulose and hemicellulose determined from the water hyacinth biomass used in the study indicated the presence of biodegradable components which could to be used for biogas production. As shown in Table 3, varying structural compositions of water hyacinth have previously been reported in literature. To begin with, a structural composition of 43.01 % cellulose, 29.13 % hemicellulose and 6.9 % lignin in water hyacinth has been reported [38]. Another study proposed 24 % cellulose, 30 % hemicellulose and 16 % lignin for water hyacinth biomass [39]. A review publication by [40] indicated 20 % cellulose, 33 % hemicellulose and 10 % lignin compositions for water hyacinth biomass. The variation in the results of the structural composition of the water hyacinth in literature could be attributed to the environmental and geographical location of the plant.

The results from the ultimate analysis of the water hyacinth biomass together with the results of other published works are presented in Table 4. The results from the current experiment were used in the Boyles equation (Eq. (10)) to estimate the theoretical biomethane potential of the water hyacinth biomass.

Characterization of inoculum

The results on the assessment of the Fruit waste sludge inoculum for pH, total solids, volatile solids and alkalinity are presented in Table 5. After the flocculation process, there was an increase in the total solids and the volatile solids contents of the sludge. The total solid content was increased from 2.46 to 5.20 representing about 111 % increment. The volatile solid content also increased from 81.75 to 84.85 % which showed about 3.8 % increment. The flocculation process transforms the watery sludge into a more semi solid form. This reduces the interspatial distance between the bacteria cells and enhance biogas production as reported by Scherer et al. [24].

The results on the presence of elemental traces in the sludge revealed an amount of 0.021 mg/l of Iron with limited amount of nickel and cobalt. The presence of the iron could enhance anaerobic digestion processes because, it is utilized in the transport system of the methanogenic bacteria for the conversion of CO_2 to CH_4, and functions both as an electron acceptor and donor [43].

Table 3
Structural composition of water hyacinth biomass.

	Structural composition of water hyacinth biomass		
Research	Cellulose	Hemicellulose	Lignin
Current study	**49.98**	**28.99**	**9.5**
[38]	43.01	29.13	6.9
[39]	24	30	16
[40]	20	33	10
[1]	24.5	34.1	8.6

Table 4
Elemental composition of water hyacinth biomass.

Elemental percentage composition of water hyacinth biomass					
Research	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur
Current study	**23.3**	**3.15**	**22.1**	**2.08**	**0.18**
[39]	38.4	5.85	28.1	2.9	0.47
[41]	29.7	4.52	64.6	0.97	0.21
[42]	49.33	5.96	43.46	1.09	0.17
[14]	20.4	4.53	–	0.74	0.21

Table 5
Characterization of fruit waste sludge.

Parameter	Units	Raw sludge	Flocculated sludge
pH		7.34	7.33
Total solids (TS)	%	2.46	5.20
Volatile solids (VS)	% TS	81.75	84.85
VS/TS ratio		33.23	16.32
Alkalinity	mg $CaCO_3$	2960	4602
Iron	mg/l	0.021	–
Nickel	mg/l	0.0001	–
Cobalt	mg/l	0.00011	–

Particle size analysis

As shown in Fig. 2A, a semi log graph of retained mass of particles against the particle geometric mean diameter was plotted. Besides, another semi-log graph of the percentage of cumulative passing against the nominal sieve opening was also drawn as shown in Fig. 2B. The geometric mean diameter D_{50} was determined graphically to be 197 μm. This was obtained after fitting the data to a Logistic model Eq. (23) which was developed by Orthogonal Distance Regression iteration in Origin Pro 8 software where P_s is the cumulative passing and D is the particle size diameter. As an illustration, for cumulative undersize of 10 % where $P_s = 10$, the geometric mean diameter of milled particles was determined to be 104 um. Accordingly, the particle sizes of D_{30} *and* $D_{60,}$ were determined to be 144 μm and 202 μm, respectively, as shown in Table 6.

The coefficient of uniformity (Cu) and the coefficient of gradation (Cc) of the particle size distribution were determined to be 1.94 and 0.99 ≈ 1.0 respectively. The value of the coefficient of uniformity obtained was less than 4 which indicated the particle size of the milled water hyacinth biomass was uniform and had the same size [44].

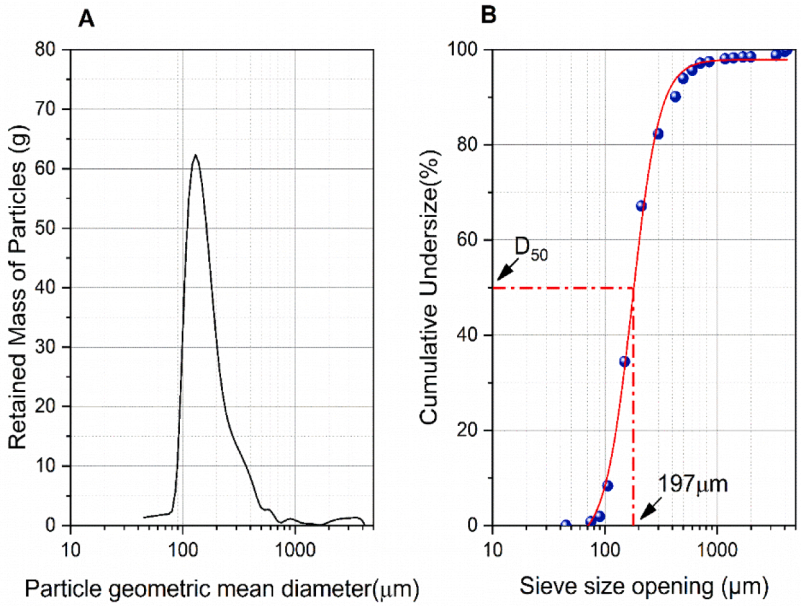

Fig. 2. A. The retained mass of milled water hyacinth particles on each sieve. B. The cumulative percentage undersize mass of water hyacinth particles on sieves size (4000–25 μm).

Table 6
Particle size of cumulative percentages water hyacinth substrate.

Cumulative passing (%)	Particle size (μm)
$D_{10}(P=10)$	104
$D_{30}(P=30)$	144
$D_{60}(P=60)$	202
$D_{50}(P=50)$	197

$$P_s = 97.94 + \frac{-3.95 - 97.94}{1 + \left(\frac{D}{175.17}\right)^{3.55}} \tag{23}$$

$$C_u = \frac{D_{60}}{D_{10}} = \frac{202}{104} = 1.94$$

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} = \frac{144^2}{104 \times 202} = 0.99 \approx 1.00$$

Elsewhere, the study on the effect of different particle size (0.088 mm, 0.4 mm, 1.0 mm, 6.0 mm, and 30.0 mm) of agricultural and forest residues on biogas production were performed in batch reactors at 37 °C. The maximum quantity of methane (362 l/kg TS) was produced by the 0.088 mm particles [45].The effect of varying particles of water hyacinth on biogas production was investigated using cow dung mixed with blood as the inoculum source. The particle size of feedstock used were 0.001 mm, 0.05 mm, 1.0 mm and 2.5 mm. The highest volume of biogas (0.39 L) was produced by the digester which contained 0.00l mm particles. This was followed by the 0.05 mm particle size digester which produced 0.34 L. The digester bearing the 2.5 mm particle size of feedstock had the least volume of biogas production [46]. Moreover, a study to investigate the effect of different size particles (1.6 mm, 6.4 mm and 12.7 mm) of water hyacinth feedstock, nitrogen and inoculum volumes on biogas production revealed that, the cumulative biogas production was on the 15th day of incubation where the 6.4 particle size digester produced the maximum volume of biogas. Regardless, the total biogas (0.2–0.28 g/l VS) which was produced on the 60th day were similar irrespective the particle size [47]. This also affirms the position that, smaller particles only contribute to the kinetics of biogas production rather than the bulk biogas production at the end of the incubation period [48]. The results indicate the rate of biomethanation mostly increases with smaller particle size because, greater amount of degradable organic matter is usually produced which tends to favor methanogenesis [49]. However, relatively large size particles tend to have small surface area which reduces the microbial-substrate interaction leading to lower volume of biogas production. In this study, particle size of 0.197 mm digested for 61 days under mesophilic conditions of 29 ± 3 °C yielded methane volume of 402.62 ml/gVS and 356.03 ml/gVS in Fermenters F2 and F3, respectively. Even though the same quantity and size of particles size were introduced into Fermenters F2 and F3, the difference in the volume methane production could not be explained explicitly. However, different dynamics of microbial behavior with respect to access and breakdown of the water hyacinth biomass in the two different fermenters may have accounted for the current observation.

Estimation of theoretical biomethane potential

The theoretical methane potential signifies the maximum quantity of methane that can be generated from a given substrate during anaerobic digestion. The theoretical BMP of the water hyacinth was estimated based on the elemental chemical composition (C, H, N, O, S). Clearly, the location and nutrient availability of the aquatic environment of the source of the water hyacinth may have variable effect on the available fractional composition of these elements. As a result, different values of theoretical biomethane potential values of water hyacinth may be estimated. In a similar manner, the theoretical methane potential values of 383.4, 331.8, 351.3 and 352.6 ml CH_4/g VS were determined using the Boyles equation for water hyacinth biomass, which was collected from Goyal para pond river, Mula-Mutha river, Pavana river all located in India and Lake Victoria in Uganda, respectively [50]. The results of the theoretical BMP varied because the molar fractions of C, H, N, O, S, in the water hyacinth samples were specific to the different aquatic sources.

The chemical formula $C_{1.94}H_{3.15}O_{1.38}N_{0.15}S_{0.01}$ was determined for water hyacinth according to the outlined procedure in Section "Estimation of theoretical biomethane potential". The chemical formula was used in the Boyles equation (Eq. (24)) to determine the theoretical biomethane potential.

$$BMP_{Th} = \frac{\left[\left(\frac{a}{2}\right) + \left(\frac{b}{8}\right) - \left(\frac{c}{4}\right) - \left(\frac{3d}{8}\right) - \left(\frac{e}{4}\right)\right] \times 22400}{12a + b + 16c + 14d + 32e} \left[\frac{mL}{gVS}\right] \tag{24}$$

$$= \frac{\left[\left(\frac{1.94}{2}\right) + \left(\frac{3.15}{8}\right) - \left(\frac{1.38}{4}\right) - \left(\frac{3 \times 0.15}{8}\right) - \left(\frac{0.01}{4}\right)\right] \times 22400}{(12 \times 1.94) + 3.15 + (16 \times 1.38) + (14 \times 0.15) + (32 \times 0.01)}$$

$$= 422.23 \left[\frac{mL}{gVS}\right]$$

Estimation of experimental biomethane potential

Following the procedure outlined in Section "Determination of experimental biomethane potential test", the experimental BMP of water hyacinth was determined from fermenters F2 and F3 at the end of the incubation period. The trend of cumulative net methane production from each of the two fermenters is presented in Fig. 3. Methane production started immediately at the beginning of the fermentation period in both fermenters, F2 produced a volume methane of 442.43 ml and F3 registered a volume of 408.80 ml at the end of the first day. The methane volume production curve in F2 increased sharply till the 55th day with a recorded volume of 5530 ml which slowly increased to a total cumulative volume of 5576 ml at the end of the fermentation period. Similarly, the asymptotic stage of methane production in F3 was also reached on the 55th day with a volume of 4926 ml.

At this point, methane production was mostly constant till the end of the experiment where a volume 4931 ml was noted. Though Fermenters F2 and F3 were both served with the same Inoculum to substrate ratio (I:S =10), difference in methane volumes within the range of (0–11.5 %) were observed till the end of the incubation period. The observation could be attributed to the variation in microbial adaptation to the water hyacinth substrate and substrate accessibility in test fermenters.

The specific methane production was determined as 402.62 ml CH4 /g VS and 356.03 ml CH4 /g VS for the F2 and F3 fermenters, respectively. The net percentage of methane for (F2) and (F3) were also determined to be 46.4 % and 43.3 %, respectively. Mathematically, the cumulative net methane volume for a test fermenter (F2) was obtained by taking the difference in the total cumulated corrected methane volumes between the Test fermenter (F2) and the Control fermenter (F1).

$$\textbf{Net methane volume} = \sum V_{Methane\ \ Test\ \ fermenter,\ \ corrected} - \sum V_{Methane\ \ control\ \ fermenter,\ \ corrected}$$

$$\textbf{Net}\ \text{methane volume (F2)} = 10583.61499 - 5007.31424 = 5576.300\ \text{ml}$$

$$\textbf{specific net methane yield} = \frac{Net\ methane\ vol.\ fermenter\ (F2)}{Mass\ of\ water\ hyacinth\ per\ gram\ volatile\ solids}$$

$$\text{Specific net } \textbf{methane}\ \text{yield (F2)} = \frac{5576.300\ ml}{13.85\ /gVS} = 402.62\ \text{Nml/gVS}$$

$$\textbf{\textit{Net}}\ \textbf{methane}\ \textbf{\textit{content}} = \frac{Net\ Methane\ volume}{Net\ Biogas\ volume} \times\ 100$$

$$Net\ \textbf{Methane}\ Volume = cumulated\ Methane\ vol.(F2) - cumulated\ Methane\ vol.(Control\ fermenter)$$

$$\textbf{\textit{Net Methane vol}}. = 10583.61499 - 5007.31424 = 5576.300$$

$$Net\ Biogas\ volume = cumulated\ biogas\ vol.(F2) - cumulated\ biogas\ vol.(Control\ fermenter$$

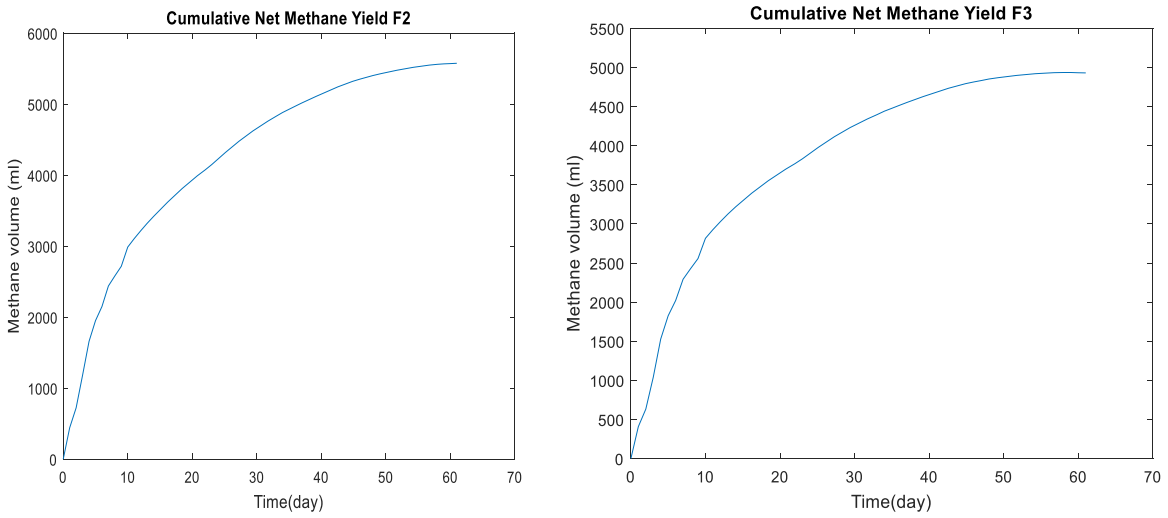

Fig. 3. Cumulative net methane yield for fermenters F2 and F3.

Net biogas vol. = 19798.789 − 7784.29688 = 12014.492

$$Net\ methane\ content = \frac{5576.3}{12014.492} \times\ 100 = 46.41\%$$

In Table 7, the maximum methane production of 387±25 NL_{CH4}/kg VS was reported during the fermentation of water hyacinth with Organic Fraction Municipal Solid Waste (OFMSW) as an inoculum source at an S:I ratio 1:1 under thermophilic conditions for 50 days [51]. Similarly, ultimate methane production of 350 L_{CH4}/kg VS was reached when water hyacinth and digested sludge as the source of inoculum at an I:S ratio of 3:1 were digested anaerobically under mesophilic conditions for 90 days [52]. Further, the anaerobic digestion of water hyacinth inoculated with at 25 % volume of cattle dung for 120 days under mesophilic conditions resulted in the methane production of 244 L_{CH4}/kg VS [53]. Methane production of 196 and 213 L_{CH4}/kg VS, respectively, for high and low lignin content water hyacinth was recorded for a biomethanation test where sewage sludge was employed as the source of inoculum at an I:S ratio of 2:1 under mesophilic condition. Another investigation revealed a cumulated methane volume of 237.37 LCH_4/kg VS when the squeezed-out-water from water hyacinth biomass inoculated at a mixing ratio of 1:1 by volume was digested anaerobically for 60 days [54]. To conclude, methane production of range of 0.26–0.43 $m^3\ kg^{-1}$VS was generated when water hyacinth shoot and a mixture of high protein animal feed and Bermuda grass as seed inoculum was digested under mesophilic condition [55]. The volumes of specific methane production observed in the current experiment fell within the reported literature range [51,55].

Gross biogas production

The gross biogas production referred to the total biogas generated from the contribution of the water hyacinth biomass and the Fruit waste sludge inoculum during the fermentation process. The final volumes of biogas produced by F2 and F3 fermenters were directly read from the BlueViscount flowmeter as shown in Fig. 4. There was a consistent rise in biogas production to the end of the fermentation period where a total cumulative volume of 19,798.8 ml (0.129 L/gVS) and 19,168.6 ml (0.125 L/gVS) was recorded for F2 and F3, respectively, and a difference of 630.2 ml of biogas representing 3.2 % was noted. The difference in gross biogas production could be attributed to more sluggish anaerobic bacterial response to the conversion of the available organic matter to biogas in F3. A total biogas volume of 44.9 L/kg water hyacinth was reported after 40 days of fermentation period using cow dung as the inoculum source [56]. In addition, the anaerobic digestion of water hyacinth and sheep waste for 60 days reported a maximum biogas yield of 0.36 L/gVS under mesophilic conditions [16].

$$\text{Gross Biogas Volume } \Big/ \text{Production (F2)} = \sum V_{Biogas\ \ Test\ \ fermenter} = 19798.8\ \text{ml}$$

Gross methane production

The gross methane production is the bulk volume of methane obtained from the water hyacinth biomass and the fruit waste sludge (inoculum) at the end of the fermentation period. There was a sharp rise in gross methane volume in each of fermenters F2 and F3 from the beginning of the experiment till the 61st day where a total of 10,583.6 ml and 9938.3 ml were recorded, respectively, as shown in Fig. 5. A total of methane volume difference of 645.3 ml observed between F2 and F3 which supposedly implied that a higher conversion rate of the substrate occurred in F2 than in F3.

$$\text{Gross methane Volume } \Big/ \text{Production (F2)} = \sum V_{Methane\ \ Test\ \ fermenter,\ \ corrected} = 10583.615\ \text{ml}$$

Daily gross biogas production

The total volume of biogas generated on daily basis from the water hyacinth biomass and Fruit waste sludge (inoculum) throughout the fermentation period was estimated. The trend of daily gross biogas production within the fermentation period is shown in Fig. 6. Daily gross biogas production in fermenter F2 showed an initial biogas volume of 654.5 ml, 868.1 ml and 845.9 ml on the 1st, 4th and

Table 7
Summary of previous studies on Anaerobic digestion of water hyacinth.

Research	Substrate	Inoculum	Mixing ratio ISR	Hydraulic retention time (days)	Temperature	Methane yield (LCH_4/kg VS)
Current work	WH	FWS	**10**	**61**	Mesophilic	**356–402**
[51]	WH	OFMSW	0.1	50	Thermophilic	387±25
[52]	WH	DS	3	90	Mesophilic	350
[53]	WH	CD	–	120	Mesophilic	244
[54]	SWWH	M		60	Mesophilic	237.37
[55]	WHS	HPAF+BG+DM	–	–	Mesophilic	260–430

WH: Water hyacinth; FWS: Fruit waste sludge; OFMSW: Organic fraction municipal solid waste; DS: Digested sludge; CD: Cattle dung; SWWH: Squeezed-out-water as water hyacinth juice; M: Microorganism; WHS: Water hyacinth shoot; HPAF: High Protein Animal Feed; BG: Bermuda Grass; DM: Define medium.

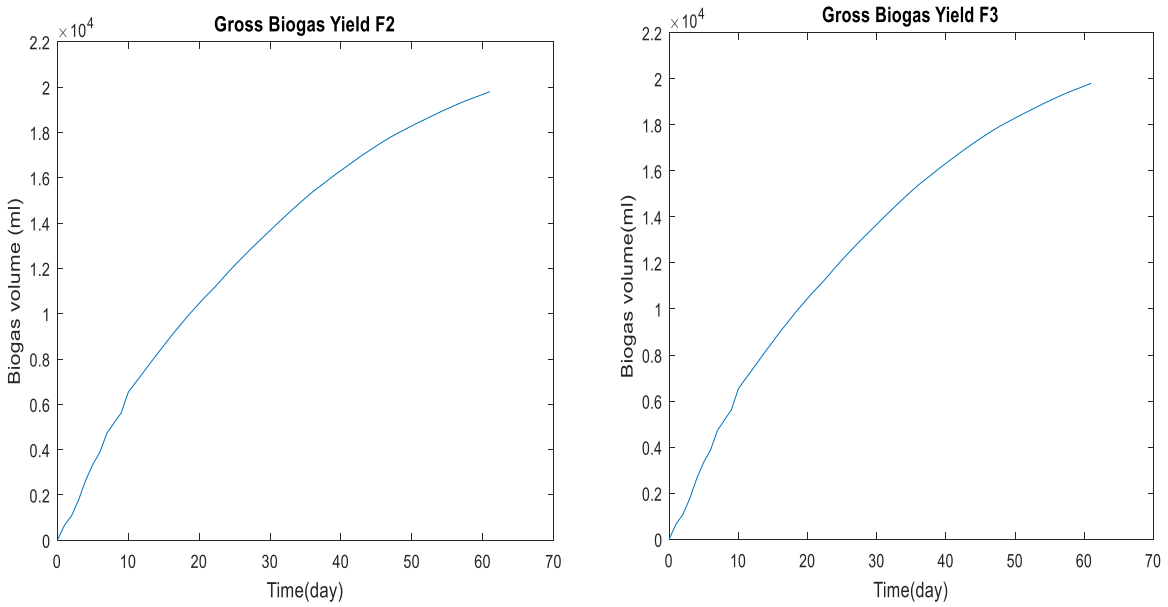

Fig. 4. Gross biogas yield from fermenters F2 and F3.

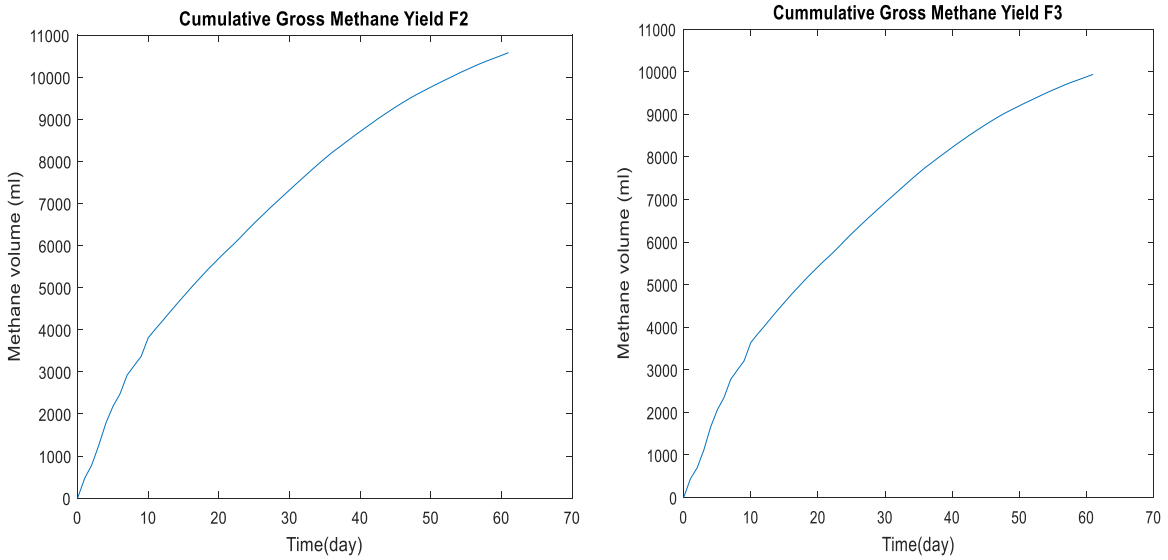

Fig. 5. Cumulative gross methane yield for fermenters F2 and F3.

7th days, respectively, amidst intermittent fluctuations on 2nd, 6th and 9th days of fermentation. This notwithstanding, the highest volume of biogas production was observed on the 10th day at a volume of 909.6 ml. Afterwards, a gradual decline in production was observed till a volume of 119.5 ml at the end of the fermentation period. The trend daily gross biogas production in F3 showed a similar pattern as F2 except that a peak volume of 925 ml was observed earlier on the 4th day of fermentation. The observed volume exceeded the maximum daily volume recorded in F2 by 1.79 %. In addition, another spike in volume production for F3 was observed on the 10th day with a biogas volume of 913 ml. Subsequently, there was decline in biogas production till a volume of 111.7 ml at end of the fermentation period. The spikes and fluctuations of daily gross production as depicted by Fig. 6. occurred based on the degradable organic matter accessible to the anaerobic bacteria responsible for biogas production. Access limitation to degradable organic matter by the anaerobic bacteria could prolong the time for the maximum biogas production. A peak volume of 1474 cm^3 of biogas production occurred at the end of the fifth week (35th day) of fermentation when water hyacinth and cow dung were anaerobically digested for 9 weeks (63 days) [57]. High peaks indicated high biogas production volumes which could be explained from the point of view that, relatively large amount of degradable organic matter was accessible and consequently degraded for the purpose of biogas production. However, the intermittent fluctuation in biogas production observed indicated the period of relatively small available degradable

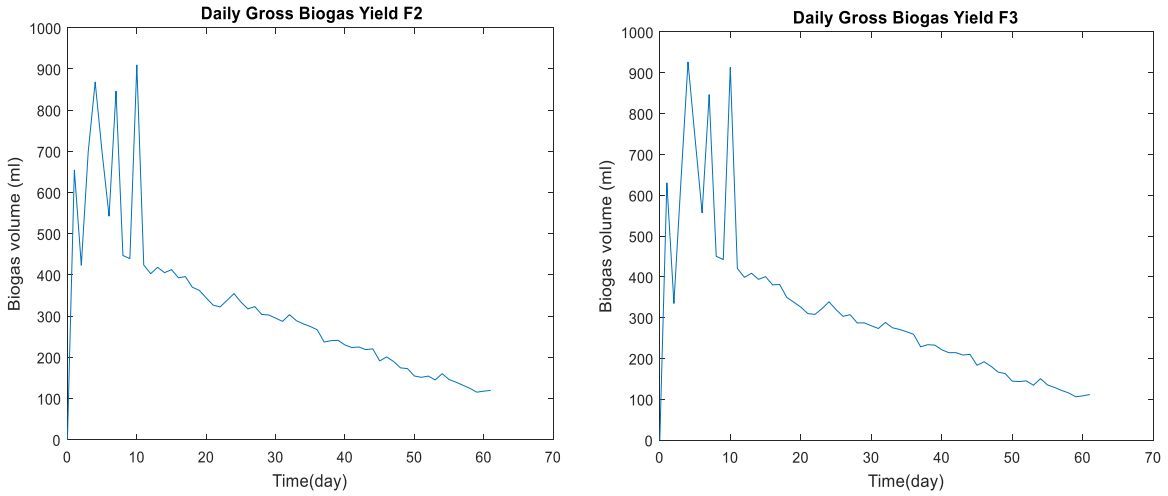

Fig. 6. Daily gross biogas yield for fermenters F2 and F3.

organic matter for biogas production. The consistent decline in daily biogas production also corresponded to the decline in the available degradable organic matter to the anaerobic bacteria.

Daily gross methane production

The daily gross methane production refers to the total volume methane generated from the water hyacinth biomass and the fruit waste sludge (inoculum) on daily basis. The trend of daily gross methane production within period of digestion is shown in Fig. 7. Interestingly, fermenters F2 and F3 produced the highest gross methane volume on the 4th day of the fermentation period with a recorded volume of 522.6 ml and 535.8 ml, respectively, which corresponded to difference of 2.5 %. In addition, identical peaks were also observed on the 7th and 10th day of fermentation in each of fermenters F2 and F3 which clearly indicated an insignificant difference in gross methane production in the test fermenters. Specifically, on the 7th and 10th day of fermentation, 442.7 ml and 441.3 ml of gross methane was observed in F2 whiles 425.9 ml and 430 ml were found in F3. On the last day of the fermentation period, 65.4 ml of gross methane volume was recorded in F2 whiles 58.9 ml was observed in F3. The slight difference in maximum daily gross methane production (2.5 %) between F2 and F3 showed a similar respond to the breakdown of cellulose and hemicellulose portions of the substrate for methane production. Likewise, high peak volumes of methane implied the availability of relatively high amount of degradable organic matter for methanation processes.

Net biogas production

The net biogas production is the total biogas generated from the water hyacinth biomass without the contribution of the biogas

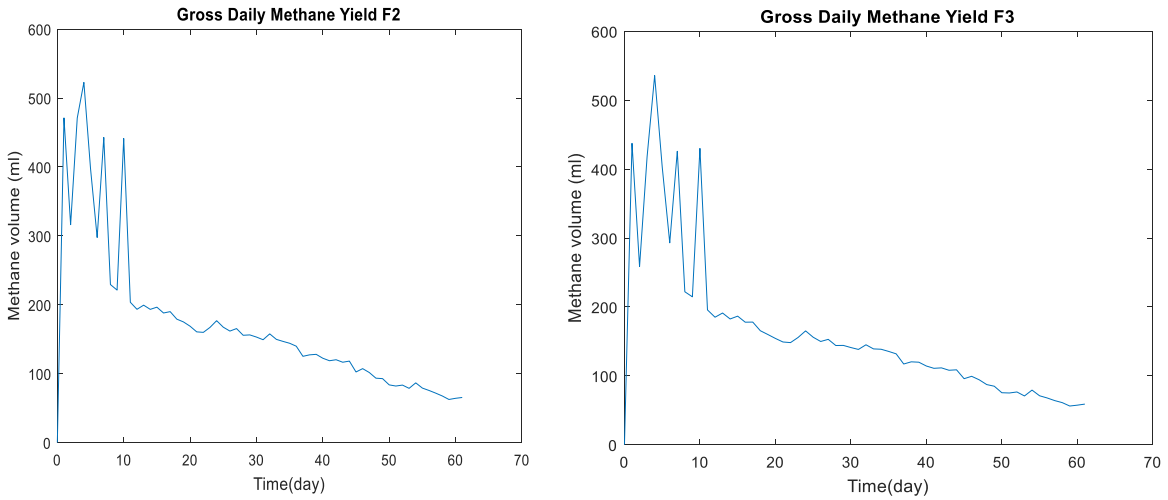

Fig. 7. Daily gross methane yield for fermenters F2 and F3.

generated from the fruit waste sludge during the fermentation period. The test fermenters F2 and F3 showed steady rise in biogas production from the start of the experiment and assumed asymptotic stage on the 50th day of fermentation with recorded values of 11,693.9 ml and 11,158.6 ml, respectively. Biogas production from F2 and F3 was stable throughout the remaining days of fermentation until a final volume of 12,014.4 ml (867 ml/gVS) and 11,384.2 ml (821 ml/gVS) on 61st day. Fermenter F2 produced 5.5 % more biogas volume than F3. This showed a relatively more active response of the anaerobic bacteria in F2 towards the breakdown of the degradable solids for biogas production. The anaerobic digestion of water hyacinth using digested sludge as inoculum source for 120 days yielded 337 NL/kg VS under mesophilic condition [53]. A cumulative net biogas yield of 25,780 ml was reported after 30 days of anaerobic digestion of water hyacinth using animal waste inoculum from a biogas plant under mesophilic conditions [58]. Moreover, cumulative biogas yield of 458.44 L was reported during the fermentation of squeezed water from water hyacinth and microorganisms under mesophilic conditions for 60 days [59]. Another research revealed a total biogas production volume of 406 NL/kg VS under mesophilic condition during the anaerobic digestion of water hyacinth and cow dung for 30 days [60]. In addition, a total specific volume of biogas of 552 NL/kg VS was reported following the anaerobic degradation of water hyacinth and cow dung for 60 days under mesophilic conditions [61].

Net daily biogas production

The net daily biogas production is the total biogas generated from the water hyacinth biomass on daily basis. The contribution of the inoculum in terms of biogas production is not considered. The net daily biogas production for fermenters F2 and F3 is graphically presented in Fig. 4. 6. The test fermenters F2 and F3 produced the maximum biogas volume on the 5th day of the fermentation where F2 and F3 reached 787.3 ml (56.8 ml/gVS) and 845 ml (62.6 ml/gVS), respectively. Relatively low peak volumes were subsequently observed on the 8th and 11th with intermittent fluctuation volumes between the period for fermenters F2 and F3. Further decline in the net daily biogas production occurred in the remaining days until minimum volumes of 18.2 ml and 10.43 ml at end of the fermentation period. In a similar experiment, a maximum daily biogas production of 9.23 L/kg VS was obtained on the 22nd day of fermentation when the squeezed out water from water hyacinth was digested with microorganism under mesophilic conditions for 60 days [59]. Probably, variable period of adaptation and access to the substrate by the anaerobic bacteria for biogas produced may account for the difference in the observed peak volumes (Figs. 8 and 9).

Net daily methane production

The net daily methane production is the total volume of methane generated from the water hyacinth biomass only during each day of the fermentation period. According to Fig. 10, maximum net daily methane volumes of 475.3 ml and 488.6 ml were noted on the 5th day of fermentation for F2 and F3, respectively. The F3 fermenter produced 13.3 ml (2.8 %) higher methane volume than in F2. The current situation suggests that microbial activities with respect to bioconversion of the substrate to methane were similar in both fermenters. In each of F2 and F3, lower peaks of methane production were observed on the 8th and 11th day which was like the trend of net daily biogas production. Further, methane production declined in the subsequent days where a volume 4.4 ml and 1.97 ml was recorded at end of the fermentation period. Elsewhere, peak volume of 2120 ml of methane was reached on the 12th day of fermentation when urea pretreated water hyacinth was anaerobically digested under mesophilic conditions using combined municipal waste (20 %) and animal manure (80 %) as the inoculum source [59].

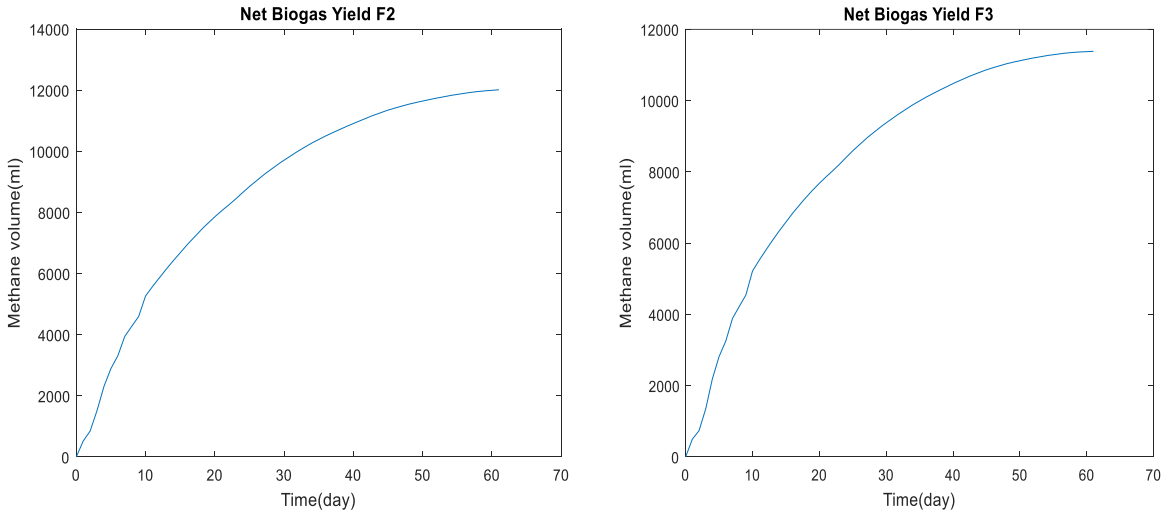

Fig. 8. Net biogas yield for fermenters F2 and F3.

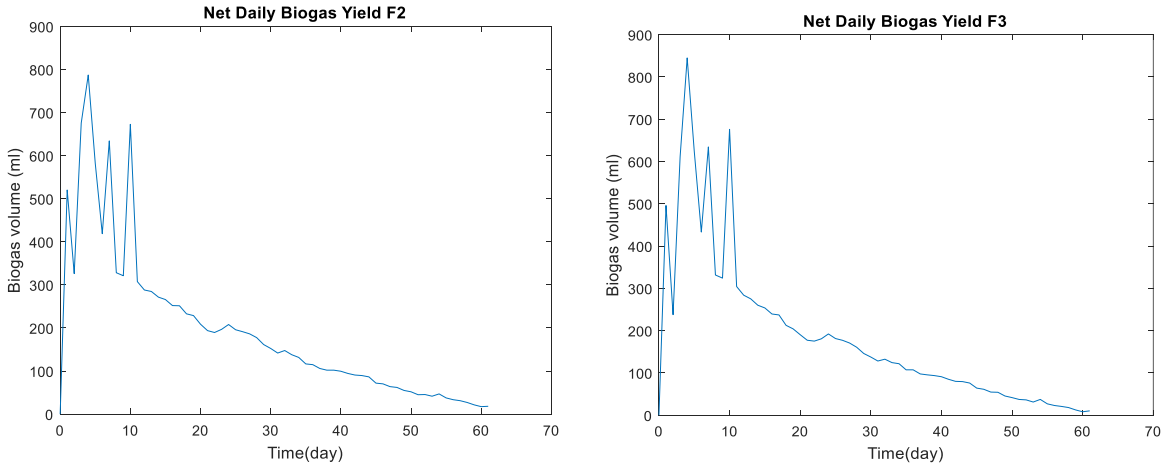

Fig. 9. Net daily biogas yield for fermenters F2 and F3.

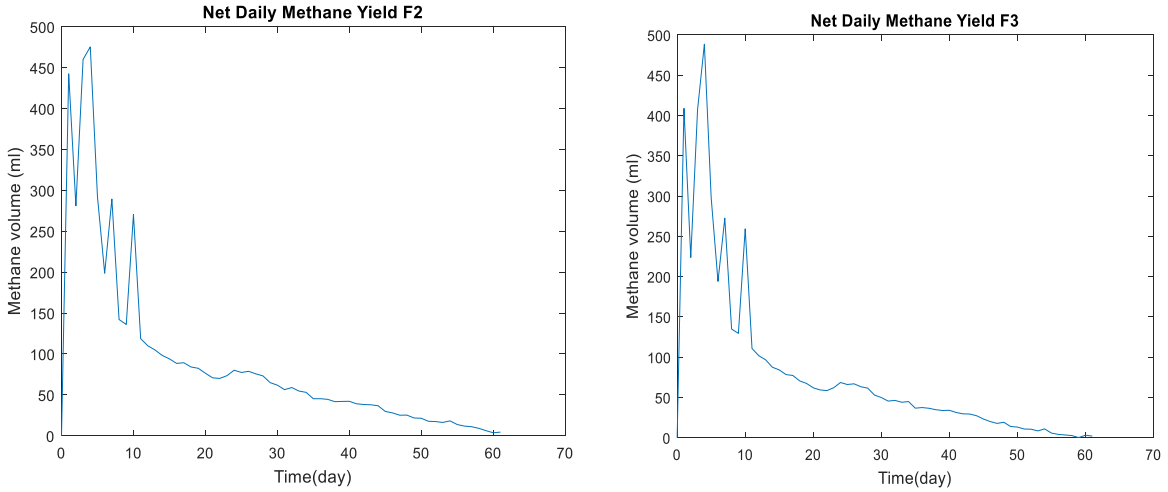

Fig. 10. Net daily methane yield for fermenters F2 and F3.

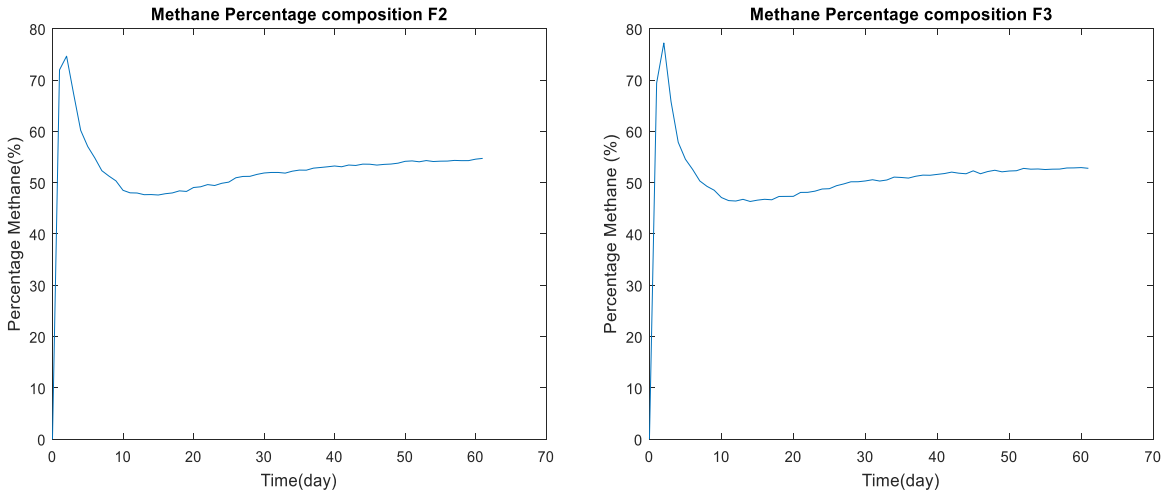

Fig. 11. Methane percentage composition for fermenters F2 and F3.

Corrected methane composition

The error associated with the *in-situ* methane volume measurement which mainly results from the presence of air at the headspace volume of the fermenter bottles and the connecting tubes was corrected. Due to the initial presence of air at the headspace section of the fermentation bottles, the percentage composition of methane measured initially by the methane sensor do not reflect the true methane percentage generated from the anaerobic digestion process. Hence, it was corrected according to the steps mentioned previously by Scherer et al. [24]. The corrected percentage of methane for the F2 and F3 during the fermentation period is graphically shown in Fig. 11. The fermenters F2 and F3 showed a similar trend in methane composition. The maximum percentage composition for F2 and F3 was reached on the 2nd day of fermentation at 74.65 % and 77.22 %, respectively. Subsequently, there was a reduction to 48.5 % on the 10th for F2 and 46.5 % on the 11th day for F3. Thereafter, there was a steady methane composition for F2 and F3 fermenters until final compositions of 54.7 % and 52.8 % was achieved at the end of fermentations, respectively. As an illustration the *in-situ* methane measurement for Fermenter F2 on the 61st day of fermentation was determined as follows:

1. Find the *difference in Biogas production*

$$\left(V_{Biogas.\ diff.}\right) = V_t - V_{t-1}$$

where V_t *and* V_{t-1} *are any two successive biogas volumes*

$$\left(V_{Biogas.\ diff.}\right) = 19798.79 - 19679.27 = 119.51 \text{ ml}$$

1. Find *the % volume of newly produced biogas at the headspace section* (F_t)

$$(F_t) = \frac{V_{Biogas.\ diff}}{V_{Headspace}} \times 100 = \frac{119.51}{2000} \times 100 = 5.975\ \%$$

2. Find *the % volume of methane at the headspace section* (β_t)

$$(\beta_t) = F_t + \beta_{t-1} - \left(\frac{\beta_{t-1} \times F_t}{100}\right) = (99.99 + 5.975) - \frac{99.99 * 5.975}{100} = 99.99\%$$

3. Find the *corrected % methane* $(V_{methane\ percetage})$

$$\left(V_{mp}\right) = \frac{M_s}{\beta_t} \times 100 = \frac{54.73}{99.99} \times 100 = 54.74\ \%$$

where M_s *is the % methane of reading from the methane senso*

Biodegradability

Anaerobic biodegradability was evaluated from the ratio of the experimental determined BMP value to the theoretical BMP value expressed as a percentage. It indicates the proportion of the total water hyacinth biomass that was converted to methane during the anaerobic conditions. The experimental BMP values fermenter F2 and F3 at end of the fermentation period were 402.62 and 356.03 ml/gVS. The theoretical methane potential for the water hyacinth biomass was estimated to be 422.23 ml/gVS. As a result,

Table 8
Results on the first order kinetics studies on biogas production.

First order kinetics studies on biogas production			
Parameter	Units	Fermenter F2	Fermenter F3
Hydrolysis rate constant (K)	Day^{-1}	0.049	0.053
Predicted Biogas Yield (P)	ml	12,668	11,918
Measured Biogas Yield (P)	ml	12,014	11,384
Difference between Predicted and Measured Biogas yield	%	5.44	4.48
Coefficient of determination (R^2)		0.999	0.998
Adjusted (R^2)		0.999	0.988
RMSE		111	127
P- value		2.52E-116	7.87E-112

biodegradability of 95.36 % and 84.32 % were achieved at the end of the fermentation period which implied a large portion of the biomass was converted to methane gas.

$$Biodegradability = \frac{Experimental\ BMP}{Theoretical\ BMP} \times\ 100 = \frac{402.62}{422.23} \times\ 100 = 95.36\%$$

Kinetic modeling

First order kinetics for biogas production

The predicted and measured values for biogas production based on the First order kinetic model for the fermenters F2 and F3 is presented in Table 8. The difference in error percentage between the predicted and measured biogas yield was evaluated to be 5.44 % and 4.48 % in F2 and F3, respectively. According to Ref. [62] deviations which is equal, or less than 10 % between the theoretical and the measured values indicates an accurate prediction of the proposed model. This implied that, the first order kinetic model could accurately predict the behavior of biogas yield production in both F2 and F3. The relatively low percentage difference between the predicted and measured values in F3 showed that, the kinetic model fitted better with the biogas yield from F3 than in F2 fermenter. The values of the first order disintegration or hydrolysis constant were evaluated as 0.049 $day^{-1}$and 0.053 day^{-1} for F2 and F3, respectively, with an average value of 0.051^{-1} day. Clearly the rate of breakdown of the water hyacinth biomass was higher (8.16 %) in F3 than in F2. The relatively high disintegration constant value estimated for F3 might have contributed to the higher observed biogas volume (845 ml) during the peak day (5th day) of fermentation. It implied that, more hydrolyzed organic compounds were present in F3 for subsequent conversion to biogas production. Though fermenters F2 and F3 were served from a common bulk substrate source, the slight difference in hydrolysis rate constants could be expected because of possible varying microbial adaptation behavior. The presence of the relatively high lignin content (10 %) in the water hyacinth biomass exploited in the current experimental work might have inhibited the rate of breakdown of the degradable organic matter by the hydrolytic anaerobic bacteria. Hydrolysis rate constants between 0.05 and 0.09 day^{-1} have been reported for high content lignocellulosic materials [63,64]. To evaluate the fitness the first order kinetic model, the predicted values of biogas yield were evaluated and plotted using MATLAB R2016b edition against the measured biogas yield values as shown in Fig. 12. The coefficient of determination (R^2) values of 0.999 and 0.998 were estimated for F2 and F3, respectively.

First order kinetics for methane production

Table 9 presents the predicted and measured values of methane production for fermenters F2 and F3 according to the first order kinetic model. The deviation between the predicted and measured methane volume for F2 and F3 were observed to be 0.361 and 0.364 %, respectively. The relatively low deviation less 10 % indicated the first order kinetic model exhibited a high prediction accuracy for methane production in the present study. The disintegration or hydrolysis constant for methane production was estimated to be 0.067 and 0.074 day^{-1} for F2 and F3, respectively with an average value of 0.071 day^{-1}. The estimated disintegration constant values are in reasonable agreement with the previously reported values for lignocellulosic materials [63]. Again, F3 showed a higher disintegration constant value than F2 and this was evident by the higher volume of recorded methane (488.6 ml) in F3 where more degradable organic substrates were converted to methane on the peak period (5th day). Similarly, the predicted values of methane yield were also evaluated and plotted using MATLAB R2016b edition against the measured methane yield values as shown in Fig. 13. The coefficient of determination (R^2) values of 0.988 and 0.989 were estimated for F2 and F3, respectively.

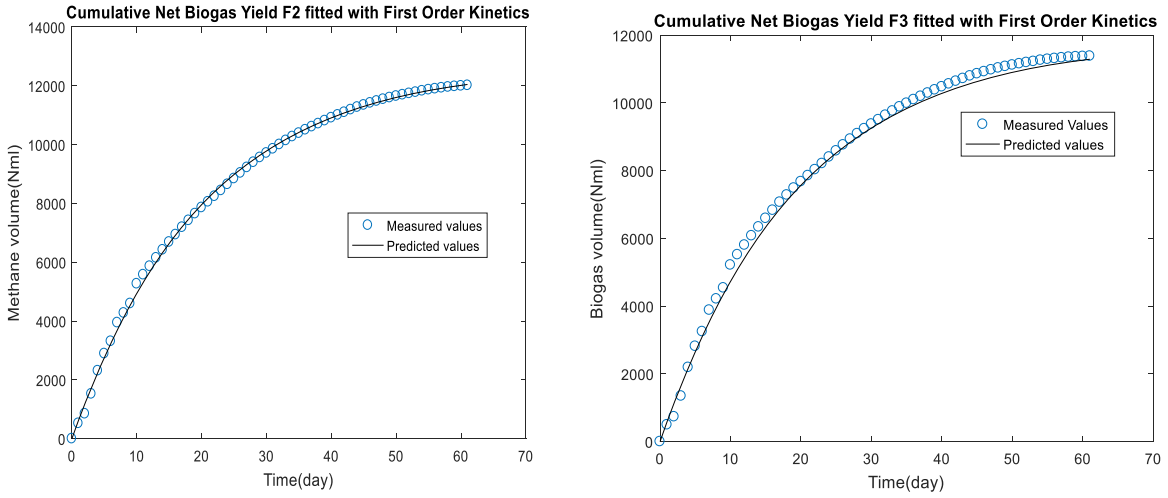

Fig. 12. Comparison between measured and predicted first order kinetics model data on biogas yield for fermenters F2 and F3.

Table 9
Results on the first order kinetics studies on methane production.

First order kinetics studies on methane production			
Parameter	Units	Fermenter F2	Fermenter F3
Hydrolysis rate constant (K)	Day^{-1}	0.067	0.074
Predicted methane yield (P)	ml	5556.2	4913.1
Measured methane yield (P)	ml	5576.3	4931.0
Difference between predicted and measured methane yield	%	0.361	0.364
Coefficient of determination (R^2)		0.988	0.989
Adjusted (R^2)		0.988	0.989
RMSE		157	130
P- value		3.4E-88	1.35E-90

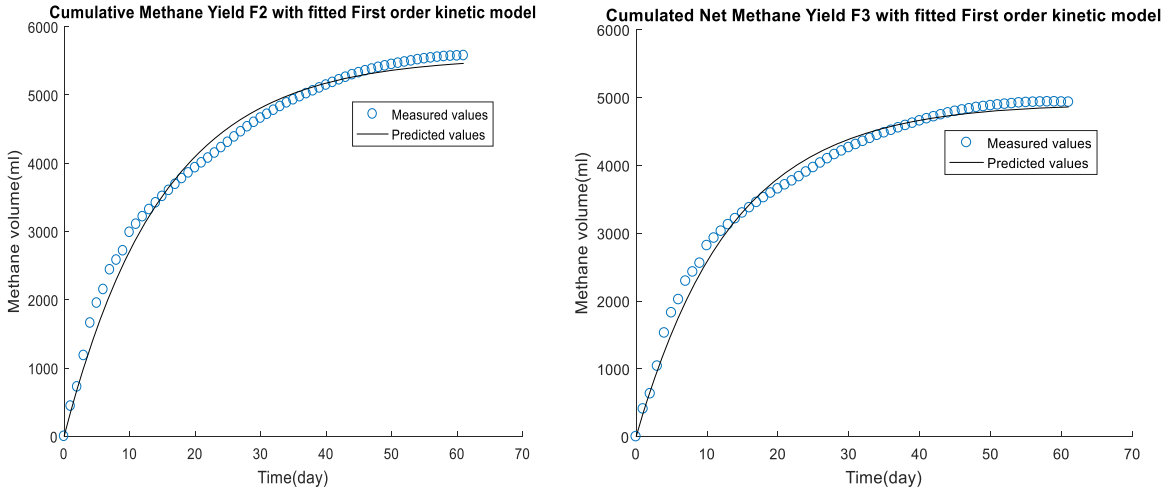

Fig. 13. Comparison between measured and predicted first order kinetics model data on methane yield for fermenters F2 and F3.

Gompertz kinetics on biogas production

The proposed re-parameterized Gompertz model by Zweitering and colleagues also known as the modified Gompertz model [65] was exploited to determine biogas potential of the water hyacinth biomass. As seen in Table 10, the predicted biogas potential, the maximum rate of biogas production as well as the lag phase of the fermentation process for F2 and F3 is presented. The difference between the predicted and measured biogas potential of the substrate was determined as 0.847 and 1.101 % for fermenters F2 and F3, respectively. Undoubtedly, the percentage deviation between the predicted and the measured biogas potential was less 10 % which implied the modified Gompertz model exhibited a high prediction accuracy for biogas production in the present work. Moreover, the model predicted a maximum biogas production rate of 0.43 % difference between fermenters F2 and F3. This showed a similar microbial activity with respect to the rate of the substrate conversion to biogas formation in the two fermenters. The lag phase which represents the period of adaptation and initiation for bacterial multiplication prior to biogas production in fermenters F2 and F3 were predicted to be negative time values for both F2 and F3. The failure of the Gompertz model to adequately describe the starting point as well as making sense of the lag phase value in biogas production simulation has already been reported [66]. This is because, the lag

Table 10
Results on the Gompertz model kinetics studies on biogas production.

Gompertz model kinetics studies on biogas production			
Parameter	Units	Fermenter F2	Fermenter F3
Predicted biogas potential	ml/gVS	11,913	11,260
Specific rate of biogas production	ml/gVS.day	370.68	372.29
Measured biogas yield (P)	ml/gVS	12,014	11,384
Lag phase period	day	−2.38	−2.15
Difference between predicted and measured methane yield	%	0.847	1.101
Coefficient of determination (R^2)		0.988	0.987
Adjusted (R^2)		0.988	0.987
RMSE		367	368
P- value		3.12E-83	3.87E-82

time fitted from experimental data for bio-product formation using the modified Gompertz model could be negative [67]. This normally occurs under circumstances where bioproducts are formed almost immediately after the start of the fermentation process. The Fruit Waste Sludge (FWS) inoculum was collected from an operational biogas facility. Hence, it was most probable to produce biogas immediately from the active inoculum source at the beginning of the fermentation period without a defined lag phase period. Though the modified Gompertz model was able to predict the biogas potential and the rate of biogas production from the water hyacinth biomass adequately, it could not determine the exact duration of the lag phase prior to biogas production. Lastly, the fitness of the model to the experimental data was conducted and plotted using MATLAB R2016b edition as shown in Fig. 14 where the coefficient of determination (R^2) values of 0.988 and 0.987 were estimated for F2 and F3, respectively.

Gompertz kinetics on methane production

The kinetic studies on methane production from anaerobic digestion process was performed using the modified Gompertz model. The outcome of the kinetics studies in terms of methane production, maximum methane production rate and the lag phase of the anaerobic digestion process is shown in Table 11. Again, the difference between the predicted and measured methane production potential were found to be 1.66 and 0.96 % for fermenter F2 and F3, respectively. This implied the modified Gompertz kinetic model exhibited a high prediction accuracy for methane production [62] even though a higher fitness was observed in F3 than in F2. The maximum methane production rate for the fermenters were found to be equal which clearly indicated a similar microbial activity with respect to the substrate conversion rate to methane production. However, a negative time value of lag phase duration was predicted by the model equation which indicated there was practically no lag phase period during the fermentation period. The active inoculum (FWS) used coupled with the inherent availability of biodegradable components might have initiated methane production immediately at the start of the fermentation process. In a study to compare the batch anaerobic digestion and biomethane potential of five different livestock manure using different statistical models, the modified Gompertz model predicted a zero lag phase period which was attributed to the use active inoculum and the presence of the soluble degradable material in each of the livestock manures [68]. Because the modified Gompertz model was formulated to describe biological and bacterial growth rather than their product formation, the use of the model for the simulation of bioproduct formation cannot be appropriate without correction [67]. This notwithstanding, the fitness of the model to the measured data was conducted and plotted using MATLAB R2016b edition as shown in Fig. 15 where the coefficient of determination (R^2) values of 0.975 and 0.974 were estimated for F2 and F3, respectively.

Logistic model on biogas production

The results on the kinetic studies performed by fitting the experiment data on cumulative biogas production into the Logistic model equation is presented in Table 12. The Logistic model provides information on potential biogas potential of a substrate, the maximum rate of biogas production and the lag phase. The difference between the measured experimental and predicted biogas production was determined to 3.11 and 3.08 % for the fermenters F2 and F3, respectively. Though a higher fitness was observed for fermenter F3 and F2, the Logistic model predicted well since the percentage error between the experimental and the predicted values was less than 10 % [62]. The maximum biogas production rate was attained at 343.57 and 342.87 ml/gVS.day for the fermenter F2 and F3.

This indicates a slightly higher microbial activity in fermenter F2 than in F3. A negative value of lag phase duration time was predicted for the two fermenters. The presence of biodegradable component in the active FWS inoculum effected biogas production immediately at the start of the fermentation process. The fitness of the model to the experimental data was conducted and plotted using MATLAB R2016b edition as shown in Fig. 16 where the coefficient of determination (R^2) values of 0.976 and 0.974 were estimated for F2 and F3, respectively.

Logistic model on methane production

The Logistic model was again used to simulate the kinetic parameters of methane production from fermenters F2 and F3. The results of the kinetic parameters predicted by the model are shown in Table 13. The error percentage of deviation between the experimental and predicted values on methane potential production was determined to be 3.14 and 2.97 % for fermenter F2 and F3, respectively. The Logistic model was found to be appropriate for the prediction of the behavior of methane production pattern from the two fermenters because of the relatively low value of percentage of deviation [62]. Besides, a similar microbial conversion activity could be inferred as the maximum methane production rate predicted by the model was 156 and 155 ml/gvs.day for fermenter F2 and F3, respectively. Lag phase period was virtually absent as negative time was predicted by the model. The fitness of the model to the experimental data was conducted and plotted using MATLAB R2016b edition as shown in Fig. 17 where the coefficient of determination (R^2) values of 0.961 and 0.958 were estimated for F2 and F3, respectively.

Transference function model on biogas production

The Transference function module was employed to simulate the production of biogas generated from the anaerobic digestion process. The results of the kinetic parameters such as the biogas potential, the maximum production rate and the duration of the lag phase period is shown in Table 14. The percentage error of deviation between the measured values and predicted values from the model was determined to be 5.52 and 4.44 % for fermenter F2 and F3, respectively. Consequently, the model was deemed appropriate for the prediction of biogas production behavior of the two fermenters as the percentage error deviation was less than 10 % [62]. A

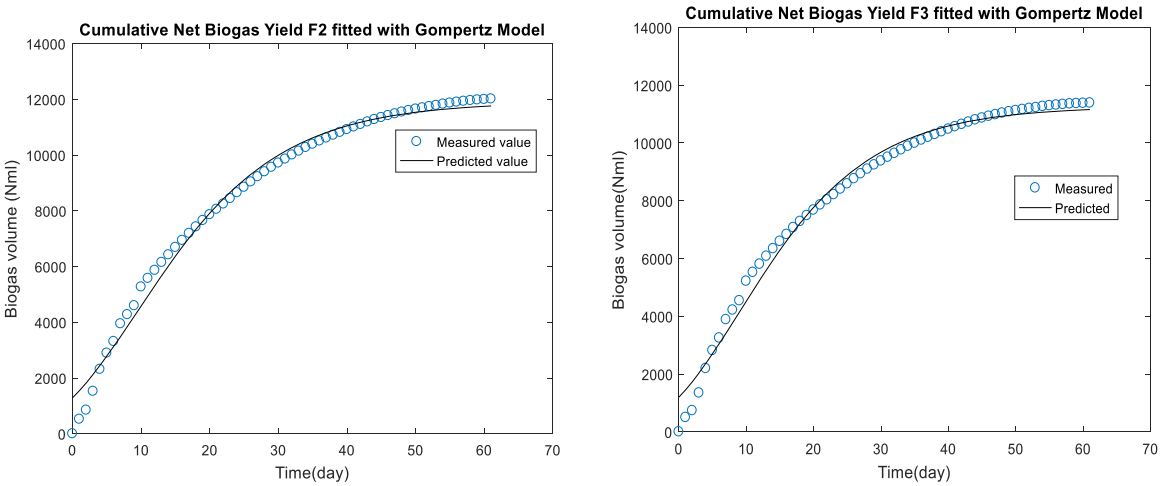

Fig. 14. Comparison between measured and predicted Gompertz model data on biogas yield for fermenters F2 and F3.

Table 11
Results on the Gompertz model kinetics studies on methane production.

Gompertz model kinetics studies on methane production			
Parameter	Units	Fermenter F2	Fermenter F3
Predicted methane potential	ml/gVS	5485	4884
Specific rate of methane production	ml/gVS.day	177.45	177.7
Measured methane yield (P)	ml/gVS	5576	4931
Lag phase period	day	−4.73	−3.99
Difference between predicted and measured methane yield	%	1.66	0.96
Coefficient of determination (R^2)		0.975	0.974
Adjusted (R^2)		0.974	0.973
RMSE		226	205
P- value		6.44E-77	7.18E-77

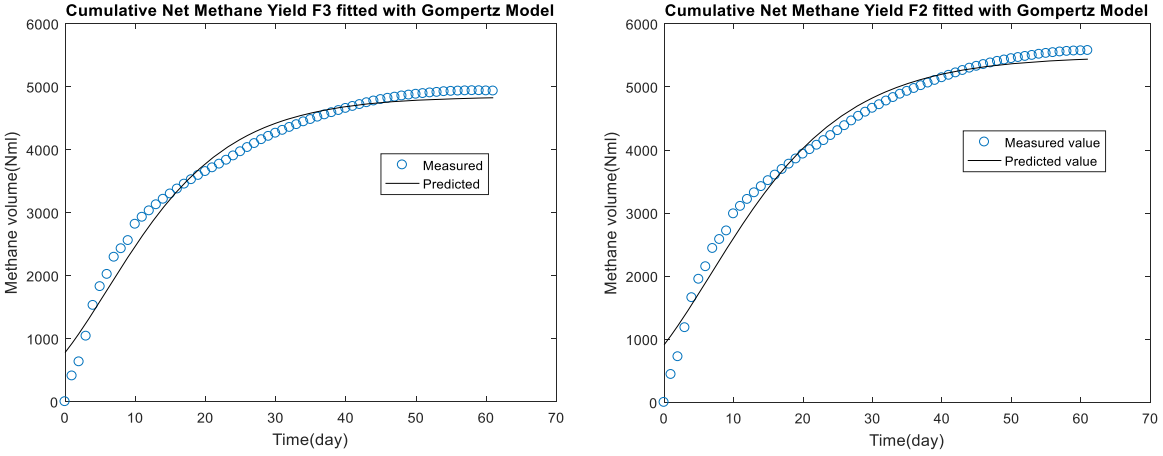

Fig. 15. Comparison between measured and predicted Gompertz model data on methane yield from fermenters F2 and F3.

relatively higher value of maximum biogas production rate was observed in fermenter F3 than in F2. This could infer a higher substrate conversion rate in F3 by the microbes present in the FWS inoculum. The model further predicted lag phase period predicted −0.03 and 0.11 days for fermenters F2 and F3, respectively. The predicted lag phase values indicate the absent of lag phase period since the values were less than one and the production of biogas began at the start of the fermentation process due to the present of biodegradable components in the inoculum which were easily converted by the microbes [69] The fitness of the model to the experimental data was conducted and plotted using MATLAB R2016b edition as shown in Fig. 18 where the coefficient of determination (R^2) values of 0.99

Table 12
The results on the logistic model kinetics studies on biogas production.

Logistic kinetics studies on biogas production			
Parameter	Units	Fermenter F2	Fermenter F3
Predicted biogas potential	ml/gVS	11,652	11,044
Maximum rate of biogas production	ml/gVS.day	343.57	342.87
Measured biogas yield (*P*)	ml/gVS	12,014	11,384
Lag phase period	day	−2.93	−2.75
Difference between predicted and measured biogas yield	%	3.11	3.08
Coefficient of determination (R^2)		0.976	0.974
Adjusted (R^2)		0.976	0.974
RMSE		524	521
P- value		4.14E-74	3.02E-73

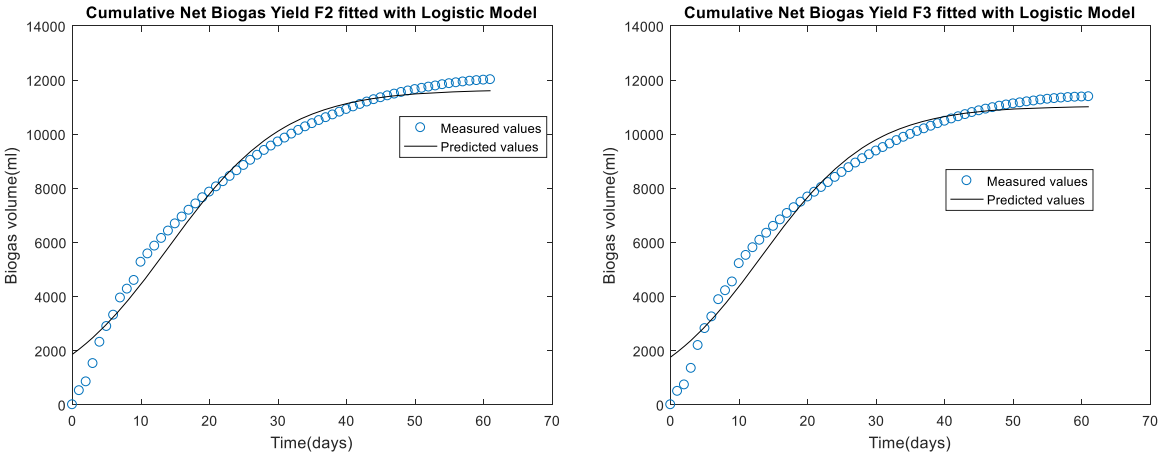

Fig. 16. Comparison between measured and predicted logistic model data for biogas yield from fermenters F2 and F3.

Table 13
Results on the logistic model kinetics studies on methane production.

Logistic kinetics studies on methane production			
Parameter	Units	Fermenter F2	Fermenter F3
Predicted methane potential	ml/gVS	5406	4789
Maximum rate of methane production	ml/gVS.day	156	155
Measured methane yield (*P*)	ml/gVS	5576	4931
Lag phase period	day	−6.22	−5.41
Difference between predicted and measured biogas yield	%	3.14	2.97
Coefficient of determination (R^2)		0.961	0.958
Adjusted (R^2)		0.96	0.957
RMSE		284	260
P- value		5.04E-71	8.18E-71

and 0.998 were estimated for F2 and F3, respectively.

Transference function model on methane production

The results of the kinetic parameters obtained from the simulation of methane production using the Transference function is shown in Table 15. The percentage error of deviation between the predicted and measured methane volume for F2 and F3 were observed to be 1.65 and 0.87 %, respectively. The relatively low values of percentage error deviation less 10 % showed the Transference function was appropriate to predict the methane production pattern from the two fermenters. The Transference model predicted a maximum methane production rate of 333.43 and 337.32 ml/gVS.day for the fermenters F2 and F3, respectively. This implied a higher rate of 1.17 % of substrate conversion in fermenter F3 than in F2. The values of lag phase period predicted by the model were negatives and implied a condition of no period of adaptation since methane production started at the onset of the fermentation process. The fitness of the model to the experimental data was conducted and plotted using MATLAB R2016b edition as shown in Fig. 19 where the coefficient of determination (R^2) values of 0.992 and 0.991 were estimated for F2 and F3, respectively.

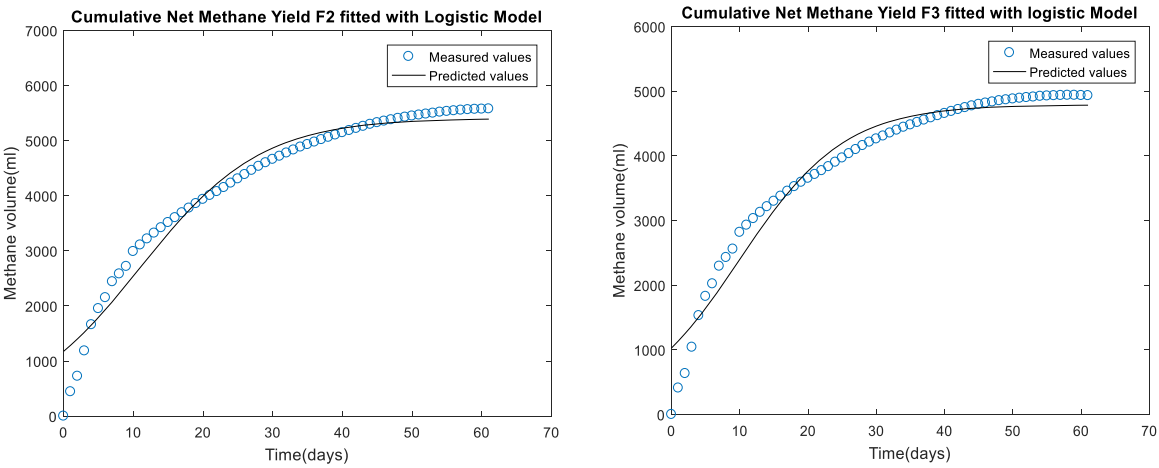

Fig. 17. Comparison between measured and predicted logistic model data on methane yield from fermenters F2 and F3.

Table 14
Results on the transference function kinetics studies on biogas production.

Transference function kinetics on biogas production			
Parameter	Units	Fermenter F2	Fermenter F3
Predicted biogas potential	ml/gVS	12,677	11,889
Maximum rate of biogas production	ml/gVS.day	112	127
Measured biogas yield (P)	ml/gVS	12,014	11,384
Lag phase period	day	−0.03	0.114
Difference between predicted and measured biogas yield	%	5.52	4.44
Coefficient of determination (R^2)		0.999	0.998
Adjusted (R^2)		0.999	0.998
RMSE		112	127
P- value		1.24E-113	1.81E-109

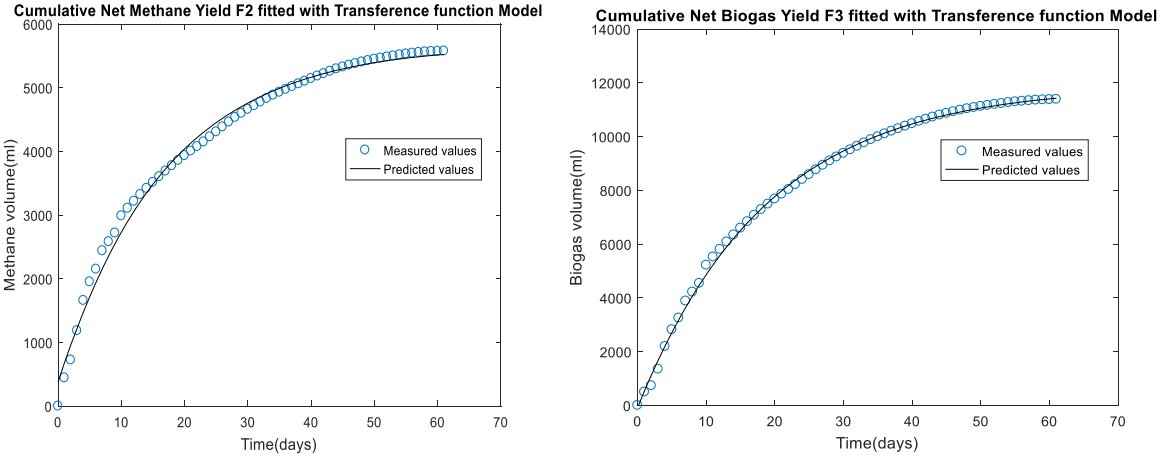

Fig. 18. Comparison between measured and predicted transference function model data on biogas yield from fermenters F2 and F3.

Conclusion

The study has focused on the assessment of biogas and methane potential of water hyacinth biomass collected from the Volta River basin in Ghana. For the same value of Inoculum to substrate ratio (ISR=10), different volumes of biogas and methane yields were recorded for the two test fermenters F2 and F3. The cumulative volume of biogas production was measured to be 12,014 ml and 11,384 ml for Fermenters F2 and F3, respectively. For a total volatile solid mass of 13.85 g substrate, an experimental biogas potential of 867.47 ml/gVS and 821.97 ml/gVS were determined for F2 and F3, respectively. For methane production, a total cumulated volume

Table 15
Results on the transference function kinetics studies on methane production.

Transference function kinetics on methane production			
Parameter	Units	Fermenter F2	Fermenter F3
Predicted methane potential	ml/gVS	5668	4974
Maximum rate of methane production	ml/gVS.day	333.43	337.32
Measured methane yield (*P*)	ml/gVS	5576	4931
Lag phase period	day	−1.17	−0.82
Difference between predicted and measured methane yield	%	1.65	0.87
Coefficient of determination (R^2)		0.992	0.992
Adjusted (R^2)		0.992	0.991
RMSE		129	115
P- value		3.07E-91	1.81E-109

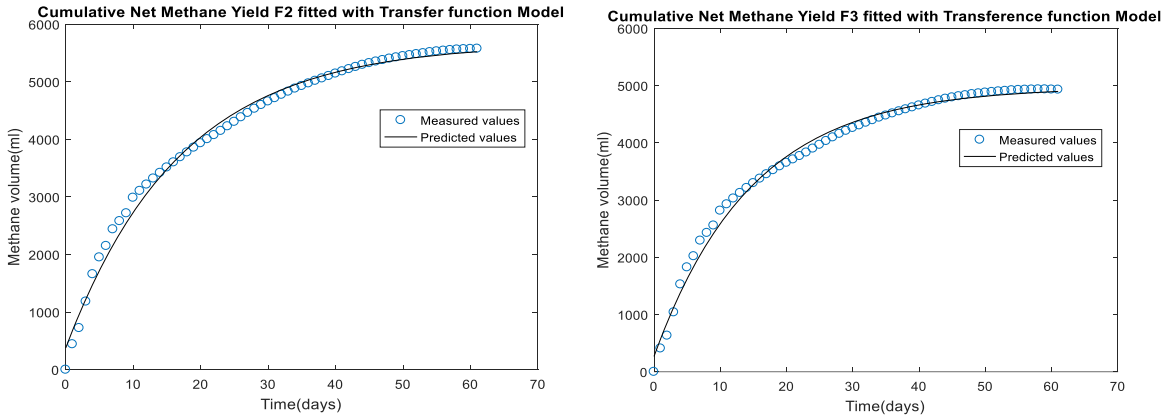

Fig. 19. Comparison between measured data and predicted transference function model data on methane yield from fermenters F2 and F3.

of 5576.30 ml and 4931.02 ml which translate to experimental biochemical methane potential value of 402.62 ml/gVS and 356.03 ml/gVS were realized for fermenters F2 and F3, respectively. The theoretical methane potential of the water hyacinth biomass was determined as 422.23 ml/gVS. Accordingly, the biodegradability was estimated to be 95.3 and 84.3 %, respectively, for fermenter F2 and F3, respectively. This implied the Fruit waste sludge inoculum had the potential to adequately breakdown the water hyacinth biomass. Four kinetic models were employed for the simulation of the biogas and methane volumes generated from each of fermenters F2 and F3. Based on the results of the statistical curve fitting, the first order kinetic and the Transference function models were found to be the best to appropriately describe the cumulative biogas production with very high goodness of fit ($R^2 = 0.999$ and 0.998) for F2 and F3, respectively. This was followed by the Modified Gompertz model which exhibited a goodness of fit ($R^2 = 0.988$ and 0.987) for F2 and F3, respectively. Lastly, the logistic model showed a coefficient of determination value of ($R^2 = 0.976$ and 0.974) for F2 and F3 fermenter bottles. Moreover, all the test models showed percentage error deviation within the range of (0.887–5.44 %) between the theoretical and measured biogas volumes. This implied the proposed models predicted the biogas production behavior of the reactors very accurately. For methane production, the First order kinetic model exhibited the highest goodness of fit values $R^2 = 0.998$ and 0.989 for F2 and F3, respectively. This was followed by the Transference model which showed an R^2 value of 0.992 for each of the fermenters F2 and F3. The Modified Gompertz model was next with an $R^2 = 0.975$ and 0.974 for F2 and F3. The Logistic model showed an $R^2 = 0.961$ and 0.958. Again, the percentage error of deviation between the theoretical and the predicted volumes were between 0.87 and 3.14 %. The outcome of the study shows that, the production of biogas from water hyacinth biomass harvested the Volta River basin of Ghana could offer sustainable control solutions to its invasion on water bodies whiles providing a cheap and reliable means of biofuel to the riparian communities.

Declaration statement

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Availability of data

The datasets generated during and analyzed are available from the corresponding author on reasonable request.

Consent for publication

All authors have shown concern for the publication of the manuscript.

CRediT authorship contribution statement

Enoch Asante: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Richard Arthur:** Methodology. **Emmanuel Okoh Agyemang:** Formal analysis, Investigation, Writing – review & editing. **Martina Francisca Baidoo:** Writing – review & editing. **Nana Yaw Asiedu:** Conceptualization, Formal analysis, Investigation, Supervision.

Declaration of Competing Interest

The authors declare that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Acknowledgment

We would like to acknowledge Prof. Dr. Dieter Bryniok, formerly of Hamm-Lippstadt University of Applied Sciences Germany, for the acquisition of the modern BlueSens Anaerobic digestion Set up equipment for the implementation of the WHy@Volta Project at Koforidua Technical University. Again, the financial support from the KNUST Engineering Education Project (KEEP) is well appreciated. We are also indebted to Shadrack Ofori and Abdul Rasack of Fresh and Dry Fruit Processing Company for the provision of the Fruit Waste Sludge. Lastly, we value the contributions of Samuel Asamoah and Emmanuel Tei Mensah of Koforidua Technical University.

Funding

Authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

References

[1] T. Ruan, R. Zeng, X.Y. Yin, S.X. Zhang, Z.H. Yang, Water hyacinth (Eichhornia crassipes) biomass as a biofuel feedstock by enzymatic hydrolysis, Bioresources 11 (1) (2016) 2372–2380, https://doi.org/10.15376/BIORES.11.1.2372-2380.
[2] A. Bhattacharya, P. Kumar, Water hyacinth as a potential biofuel crop, Electron. J. Environ. Agric. Food Chem. 9 (1) (2010) 112–122.
[3] E. Auma, O. Peter, K. Ndiba, P. Gikuma, Characterization of water hyacinth (E . crassipes) from Lake Victoria and ruminal slaughterhouse waste as co - substrates in biogas production, SN Appl. Sci. (2019), https://doi.org/10.1007/s42452-019-0871-z. July.
[4] P. Njogu, R. Kinyua, P. Muthoni, Y. Nemoto, Biogas production using water hyacinth (Eicchornia crassipes) for electricity generation in Kenya, Energy Power Eng. 7 (2015) 209–216, https://doi.org/10.4236/epe.2015.75021.
[5] K.A. Degraft-Johnson and F.J. Akpabey, "Aquatic plant management in Ghana", 2015.
[6] E. Honlah, D.O. Appiah, A.Y. Segbefia, M. Mensah, The utility of water hyacinth in communities along River Tano and Abby-Tano Lagoon, Ghana, Am. J. Soc. Sci. Res. 5 (1) (2019) 1–9.
[7] N.M. Mitan, Water hyacinth: potential and Threat, Mater. Today Proc. 19 (2019) 1408–1412, https://doi.org/10.1016/j.matpr.2019.11.160.
[8] S. Patel, Threats, management and envisaged utilizations of aquatic weed Eichhornia crassipes: an overview, Rev. Environ. Sci. Biotechnol. 11 (2012) 249–259, https://doi.org/10.1007/s11157-012-9289-4.
[9] J.H. Patil, M.A. Raj, P.L. Muralidhara, S.M. Desai, G.K.M. Raju, A.S. Collection, Kinetics of anaerobic digestion of water hyacinth using poultry litter as inoculum, Int. J. Environ 3 (2) (2012) 3–7.
[10] W. Li, et al., Methane production through anaerobic digestion: participation and digestion characteristics of cellulose, hemicellulose and lignin, Appl. Energy 226 (2018) 1219–1228, https://doi.org/10.1016/j.apenergy.2018.05.055. May.
[11] M. Khalil, M.A. Berawi, R. Heryanto, A. Rizalie, Waste to energy technology: the potential of sustainable biogas production from animal waste in Indonesia, Renew. Sustain. Energy Rev. 105 (2019) 323–331, https://doi.org/10.1016/j.rser.2019.02.011. February.
[12] K. Meena, V. Kumar, V.K. Vijay, Anaerobic technology harnessed fully by using different techniques: review, in: Proceedings of the 2011 IEEE 1st Conference on Clean Energy and Technology (CET 2011), 2011, pp. 78–82, https://doi.org/10.1109/CET.2011.6041440.
[13] J.H. Patil, P.H. Sanil, D Chaitra, Study on biomethanation of water hyacinth using primary sludge as inoculum study on biomethanation of water hyacinth using primary sludge as inoculum, J. Chem. Pharm. Res. 4 (18) (2012.) 2255–2260.
[14] M. Hernández-Shek, L. Cadavid-Rodríguez, I. Bolaños, A. Agudelo-Henao, Recovering biomethane and nutrients from anaerobic digestion of water hyacinth (Eichhornia crassipes) and its co-digestion with fruit and vegetable waste, Water Sci. Technol. 73 (2) (2016), https://doi.org/10.2166/wst.2015.501.
[15] O.F. Oke, A. Campus, A. Thelma, O. Campus, Anaerobic co-digestion of water hyacinth and cow dung for biogas production, Technol. Sci. (2015) 41–44.
[16] J.H. Patil, M.A.L. Antonyraj, S. Bb, M. Kumar, Anaerobic co-digestion of water hyacinth and sheep waste, Energy Procedia 52 (2014) 572–578, https://doi.org/10.1016/j.egypro.2014.07.112.
[17] O. Access, "Biogas production from water hyacinth (*Eichhornia Crassipes*): the effect of F /M ratio biogas production from water hyacinth (*Eichhornia Crassipes*): the effect of F / M ratio", 2018.
[18] DIN/EN12879, Characterization of Sludges- Determination of the Loss on Ignition of Dry Mass, 2001.
[19] DIN/EN12280, Characterization of Sludges - Determination of Dry Residue and Water Content, 2001.
[20] APHA, Standard Methods for the Examination of Water & Wastewater, 17th ed., American Public Health Association, 1989. Washington.
[21] Perkin Elmer Coorporation, Analytical methods for atomic absorption spectroscopy, Anal. Methods (1996) 216.
[22] C. Nyamekye, et al., Evaluating the spatial and temporal variations of aquatic weeds (Biomass) on Lower Volta River using multi-sensor Landsat Images and machine learning, Heliyon 7 (5) (2021), https://doi.org/10.1016/j.heliyon.2021.e07080.
[23] A. Jillavenkatesa, S. Dapkunas, L.S. Lum, Particle Size Characterization, Material science and Engineering Laboratory (2001) 32–33.

[24] P.A. Scherer, R. Arthur, S. Antonczyk, Accelerated Biomethane Potential assay for straw with artificially flocculated sludge and defined 'synthetic manure, Bioresour. Technol. Rep. 15 (2021), 100787, https://doi.org/10.1016/j.biteb.2021.100787. May.
[25] R.J. Teodorita Al Seadi, D. Rutz, H. Prassl, M. Kottner, T. Finsterwalder, S. Volk, Downloaded from http://lemvigbiogas.com/. 2008.
[26] M. Lesteur, et al., Alternative methods for determining anaerobic biodegradability: a review, Process Biochem. 45 (4) (2010) 431–440, https://doi.org/10.1016/j.procbio.2009.11.018.
[27] J. Mbugua, D. Mbui, J. Mwaniki, F. Mwaura, Biochemical Methane Potential (BMP) of market wastes from Nairobi inoculated with Dagoretti slaughterhouse waste, Int. J. Sci. Res. Sci. Eng. Technol. 4099 (2020) 81–90, https://doi.org/10.32628/ijsrset207418.
[28] I. Angelidaki, W. Sanders, Assessment of the anaerobic biodegradability of macropollutants, Rev. Environ. Sci. Biotechnol. 3 (2) (2004) 117–129, https://doi.org/10.1007/s11157-004-2502-3.
[29] M. Quintero, L. Castro, C. Ortiz, C. Guzmán, H. Escalante, Enhancement of starting up anaerobic digestion of lignocellulosic substrate: fique 's bagasse as an example, Bioresour. Technol. 108 (2012) 8–13, https://doi.org/10.1016/j.biortech.2011.12.052.
[30] H. Kaur, R.R. Kommalapati, Optimizing anaerobic co-digestion of goat manure and cotton gin trash using biochemical methane potential (BMP) test and mathematical modeling, SN Appl. Sci. 3 (8) (2021), https://doi.org/10.1007/s42452-021-04706-1.
[31] J. A. Chandler and W. J. Jewell, "Predicting Methane Fermentation Biodegradability," 1980, pp. 39–40.
[32] F. Raposo, M.A. De Rubia, R. Borja, Biochemical methane potential (BMP) of solid organic substrates : evaluation of anaerobic biodegradability using data from an international interlaboratory study anaerobic digestion of solid organic substrates in batch mode : an overview relating to met, Renew. Sustain. Energy Rev. 16 (1) (2018) 861–877, https://doi.org/10.1016/j.rser.2011.09.008.
[33] C.P.C. Bong, L.Y. Lim, C.T. Lee, W.S. Ho, J.J. Klemeš, The kinetics for mathematical modelling on the anaerobic digestion of organic waste - A review, Chem. Eng. Trans. 61 (2017) 1669–1674, https://doi.org/10.3303/CET1761276.
[34] S.K. Pramanik, F.B. Suja, M. Porhemmat, B.K. Pramanik, Performance and kinetic model of a single-stage anaerobic digestion system operated at different successive operating stages for the treatment of food waste, Processes 7 (9) (2019), https://doi.org/10.3390/pr7090600.
[35] Q. Zhang, X. Xi, Kinetics analysis of anaerobic digestion of wheat straw pretreated by freezing-thawing, Chem. Eng. Trans. 81 (no. 2019) (2020) 637–642, https://doi.org/10.3303/CET2081107.
[36] J.P. Blasius, R.C. Contrera, S.I. Maintinguer, M.C.A. Alves de Castro, Effects of temperature, proportion and organic loading rate on the performance of anaerobic digestion of food waste, Biotechnol. Rep. 27 (2020) e00503, https://doi.org/10.1016/j.btre.2020.e00503.
[37] A.O. Ayeni, O.A. Adeeyo, O.M. Oresegun, T.E. Oladimeji, Compositional analysis of lignocellulosic materials: evaluation of an economically viable method suitable for woody and non-woody biomass, Am. J. Eng. Res. (44) (2015) 2320–2847 [Online]. Available, www.ajer.org.
[38] M. Asrofi, et al., Isolation of nanocellulose from water hyacinth fiber (WHF) produced *via* digester-sonication and its characterization, Fibers Polym. 19 (8) (2018) 1618–1625, https://doi.org/10.1007/s12221-018-7953-1.
[39] V.P. Rathod, et al., Biogas production from water hyacinth in the batch type anaerobic sciencedirect biogas production from water hyacinth in the batch type anaerobic digester, Mater. Today Proc. 5 (11) (2018) 23346–23350, https://doi.org/10.1016/j.matpr.2018.11.072.
[40] S. Pandey, N. Singh, A.K. Nirala, A. Giri, Dynamics of water weed *Eichhornia crassipes*: a review, Int. J. Res. Appl. Sci. Eng. Technol. 3 (10) (2015) 137–140 [Online]. Available: www.ijraset.com.
[41] T. Kunatsa, A. Mufundirwa, Biogas production from water hyacinth case of lake Chivero - Zimbabwe. A review, Int. J. Recent Technol. Eng. 2 (2) (2013) 138–142.
[42] Y Unpaprom, T Pimpimol, K Whangchai, R Ramaraj, Sustainability assessment of water hyacinth with swine dung for biogas production, methane enhancement, and biofertilizer, Biomass Convers. Biorefinery 2 (2020) [Online]. Available, https://doi.org/10.1007/s13399-020-00850-7.
[43] S. Myszograj, A. Stadnik, E. Płuciennik-Koropczuk, The influence of trace elements on anaerobic digestion process, Civ. Environ. Eng. Rep. 28 (4) (2019) 105–115, https://doi.org/10.2478/ceer-2018-0054.
[44] M. Budhu, Soil Mechanics And Foundations, John Wiley& Sons, Inc, 2000, 3rd Editio.
[45] S.K. Sharma, I.M. Mishra, M.P. Sharma, J.S. Saini, Effect of particle size on biogas generation from biomass residues, Biomass 17 (4) (1988) 251–263, https://doi.org/10.1016/0144-4565(88)90107-2.
[46] Y. Nalinga, I. Legonda, The effect of particles size on biogas production, Int. J. Innov. Res. Technol. Sci. 4 (2) (2016) 9–13 [Online]. Available, http://repository.udom.ac.tzhttp//hdl.handle.net/20.500.12661/2133.
[47] K.K. Moorheada, R.A. Nordstedt, Batch anaerobic digestion of water hyacinth : effects of partilce size, plant nitrogen content and inoculum volume, Bioresour. Technol. 44 (1993) 71–76.
[48] I. Angelidaki, et al., Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays, Water Sci. Technol. 59 (5) (2009) 927–934, https://doi.org/10.2166/wst.2009.040.
[49] R.A. Dar, U.G. Phutela, Optimization of biogas production from water hyacinth (*Eichhornia crassipes*, J. Appl. Nat. Sci. 9 (4) (2017) 2062–2067, https://doi.org/10.31018/jans.v9i4.1489.
[50] J Quintana-Najera, A.J. Blacker, L.A. Fletcher, D.G. Bray, A.B. Ross, The Influence of Biochar Augmentation and Digestion Conditions on the Anaerobic Digestion of Water Hyacinth, Energies 15 (2022) 2524, https://doi.org/10.3390/en15072524 [Online]. Available.
[51] L.A. Romero De León, et al., Biochemical methane potential of water hyacinth and the organic fraction of municipal solid waste using leachate from Mexico City's Bordo Poniente composting plant as inoculum, Fuel 285 (2020) 2021, https://doi.org/10.1016/j.fuel.2020.119132. September.
[52] N. Paepatung, A. Nopharatana, W. Songkasiri, Bio-methane potential of biological solid materials and agricultural wastes, Asian J. Energy Environ. 10 (01) (2009) 19–27.
[53] M.M. El-Shinnawi, M.N.A. El-Din, S.A. El-Shimi, M.A. Badawi, Biogas production from crop residues and aquatic weeds, Resour. Conserv. Recycl. 3 (1) (1989) 33–45, https://doi.org/10.1016/0921-3449(89)90012-8.
[54] T. Hudakorn, N. Sritrakul, Biogas and biomass pellet production from water hyacinth, Energy Rep. 6 (2020) 532–538, https://doi.org/10.1016/j.egyr.2019.11.115.
[55] A. Shiralipour, P.H. Smith, Conversion of biomass into methane gas, Biomass 6 (1–2) (1984) 85–92, https://doi.org/10.1016/0144-4565(84)90011-8.
[56] R. Rozy, R.A. Dar, U.G. Phutela, Optimization of biogas production from water hyacinth (Eichhornia crassipes, J. Appl. Nat. Sci. 9 (4) (2017) 2062–2067, https://doi.org/10.31018/jans.v9i4.1489.
[57] M.K.C. Sridhar, A.O. Coker, H.B. Taiwo, O. Abiodun, Experiments on co-digestion of cow dung and water hyacinth (*EichhorniaCrassipes*) for biogas yield, Int. J. Sci. Basic Appl. Res. 15 (1) (2014) 16–24, https://doi.org/10.13140/RG.2.1.4935.3689.
[58] F. Shah, Q. Mahmood, A. Pervez, N. Rashid, M. Shah, A. Iqbal, Effect of Pretreatment and Substrate Ratios in Biorefinery Employing Co-digestion of Plant Biomass and Poultry Waste, Front. Energy Res. 6 (143) (2019) 1–14, https://doi.org/10.3389/fenrg.2018.00143.
[59] D.D. Keche, Z.M. Fetanu, W.Z. Babiso, A.C. Wachemo, Anaerobic digestion of urea pretreated water hyacinth removed from Lake Abaya; bio-methane potential, system stability, and substance conversion, RSC Adv. 12 (14) (2022) 8548–8558, https://doi.org/10.1039/d2ra00303a.
[60] I. Bhui, A. Kuruvilla, S. Chaudhury, S. Balachandran, Influence of volatile fatty acids in different inoculum to substrate ratio and enhancement of biogas production using water hyacinth and salvinia, Bioresour. Technol. 270 (2018) 409–415, https://doi.org/10.1016/j.biortech.2018.09.055.
[61] K.A. Mathew, et al., Biogas production from locally available aquatic weeds of Santiniketan through anaerobic digestion, Clean Technol. Env. Policy (2014), https://doi.org/10.1007/s10098-014-0877-6.
[62] F. Raposo, R. Borja, M.A. Martín, A. Martín, M.A. de la Rubia, B. Rincón, Influence of inoculum-substrate ratio on the anaerobic digestion of sunflower oil cake in batch mode: process stability and kinetic evaluation, Chem. Eng. J. 149 (1–3) (2009) 70–77, https://doi.org/10.1016/j.cej.2008.10.001.
[63] N.H. Garcia, A. Mattioli, A. Gil, N. Frison, F. Battista, D. Bolzonella, Evaluation of the methane potential of different agricultural and food processing substrates for improved biogas production in rural areas, Renew. Sustain. Energy Rev. 112 (2019) 1–10, https://doi.org/10.1016/j.rser.2019.05.040. May.
[64] D.P. Chynoweth, C.E. Turick, J.M. Owens, D.E. Jerger, M.W. Peck, Biochemical methane potential of biomass and waste feedstocks, Biomass Bioenergy 5 (1) (1993) 95–111, https://doi.org/10.1016/0961-9534(93)90010-2.

[65] K.M.C. Tjørve, E. Tjørve, The use of Gompertz models in growth analyses, and new Gompertz-model approach: an addition to the Unified-Richards family, PLOS One 12 (6) (2017) 1–17, https://doi.org/10.1371/journal.pone.0178691.
[66] D.P Van, G. Hoang Minh, S.T. Pham Phu, T. Fujiwara, A new kinetic model for biogas production from co-digestion by batch mode, Glob. J. Environ. Sci. Manag. 4 (3) (2018) 251–262, https://doi.org/10.22034/GJESM.2018.03.001.
[67] J. Zhu, Development of general Gompertz models and their simplified two-parameter forms based on specific microbial growth rate for microbial growth, bio-products and substrate consumption, Adv. Biotechnol. Microbiol. 4 (3) (2017), https://doi.org/10.19080/aibm.2017.04.555640.
[68] G.K. Kafle, L. Chen, Comparison on batch anaerobic digestion of five different livestock manures and prediction of biochemical methane potential (BMP) using different statistical models, Waste Manag. 48 (2016) 492–502, https://doi.org/10.1016/j.wasman.2015.10.021.
[69] H.E. Gulsen Akbay, N. Dizge, H. Kumbur, Enhancing biogas production of anaerobic co-digestion of industrial waste and municipal sewage sludge with mechanical, chemical, thermal, and hybrid pretreatment, Bioresour. Technol. 340 (2021), 125688, https://doi.org/10.1016/j.biortech.2021.125688. July.