Asante *et al.*
Journal of Engineering and Applied Science (2024) 71:98
https://doi.org/10.1186/s44147-024-00431-9

Journal of Engineering and Applied Science

RESEARCH **Open Access**

Modeling and assessment of the techno-economic analysis of biogas and its potential for the generation of electricity from water hyacinth biomass

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Abstract

The study presents the economic feasibility assessment of converting the produced biogas from water hyacinth biomass into electricity. Approximately, 0.3793 m^3CH_4/kgVS was generated from the water hyacinth biomass. The research indicated that the available water hyacinth population on the Lower Volta River in the year 2020 could potentially generate a methane yield of $53.676 \times 10^6 m^3$. The volume of methane gas generated had the potential to produce an annual electricity output of 110.792 $\times 10^6$ kWh, which could be integrated into the national grid. The economic analysis indicated positive results with an initial total investment cost of $67,273,700. The project showed a positive net present value (NPV) of $8,923,769 and a levelized cost of 0.172 $/kWh. The simple payback and equity payback periods were determined to be 5.5 and 11.3 years, respectively. Furthermore, a sensitivity analysis conducted showed that the project's NPV remained positive when variations in input parameters such as initial cost, operations, and maintenance cost were less than 15% sensitive range. However, a 30% reduction in the feed-in tariff cost resulted in a negative NPV. In conclusion, biogas production from water hyacinth biomass in Ghana can make a significant contribution to the country's energy mix and help alleviate the energy shortfall in rural areas.

Keywords: Water hyacinth, Methane gas, Ret screen software, Simple payback, Equity payback, Sensitivity analysis

Introduction

Access to affordable and sustainable energy sources is essential for economic development particularly in a developing country like Ghana. The country has a growing population, an expanding economy, and increasing energy demands, which require new solutions for energy generation that are cost-effective, reliable, and environmentally friendly. Biogas production from water hyacinth biomass is one such solution that has the potential to address these challenges, while providing new opportunities for waste management and economic growth.

Reports have been made of invasive water hyacinth plant species in various water bodies across Africa including the Ologe Lagoon, Agbara, and Badagry creeks in Nigeria, the River Nile in Egypt, and the Zambezi River in Zambia [1]. In Ghana, there are reports of water hyacinth plants proliferating along parts of the Lower Volta River, as well as other aquatic habitats such as the River Tano and Abby-Tano [1]. For instance, water hyacinth has been found to constitute 36% of the total aquatic plant species and has an estimated biomass cover of 21.5 kg per unit area on the Lower Volta River in Ghana [2]. The presence of water hyacinth on fresh river bodies has had a severe impact on the economic well-being of the affected communities living along the riverbanks. The dense mats of water hyacinth block water pathways, hindering the transportation of goods and people and negatively affecting farming and fishing activities in the affected communities. The economic impact of the water hyacinth invasion has been estimated at around US $350 million per year due to losses in transportation and fisheries [3]. Additionally, the formation of dense mats by water hyacinth provides a favorable breeding ground for disease vectors such as mosquitoes and snail larvae, which negatively affect human health [4]. Several attempts have been made to control the spread of water hyacinth using biological, physical, and chemical means. However, these efforts have been found to be unsustainable due to the financial, environmental, and labor implications.

At the same time, the utilization of water hyacinth biomass for the production of biogas through the process of anaerobic digestion has been reported in literature [5–9]. It also contains a relatively high proportion of cellulose (20%) and hemicellulose (33%) with low lignin (10%) content per unit volume of dry matter, which makes it highly biodegradable [10]. Additionally, water hyacinth biomass is known for its high nitrogen content, essential nutrients, and fermentable matter [5]. Previous studies have reported maximum methane production of 387 ± 25 $NLCH_4$/kg VS when water hyacinth was digested with organic fraction municipal solid waste (OFMSW) as inoculum under thermophilic conditions for 50 days [11]. Methane production of 350 LCH_4/kg VS was observed when water hyacinth and digested sludge were used as inoculum and digested anaerobically under mesophilic conditions for 90 days [12]. Another investigation showed 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 [13]. To conclude, methane production in the range of 0.26—0.43 m^3/kgVS was reported during the anaerobic digestion of water hyacinth shoot and a mixture of high protein animal feed and Bermuda grass as seed inoculum under mesophilic conditions [14].

The results of technical feasibility studies on the conversion of water hyacinth into biogas indicate that the approach could be an efficient means of controlling its proliferation [15]. For instance, in Kenya, the anaerobic digestion of water hyacinth biomass harvested from Lake Victoria and cow dung were mixed in a volume ratio of 1:1 and fed to a $6m^3$ digester to generate biogas which had a methane content within the range of 43—49%. The generated gas was further upgraded through purification to 70—76% methane content and utilized as a fuel in an electricity generator and other direct heat applications [16].

However, literature on the technical and economic aspects of producing biogas from water hyacinth biomass through anaerobic digestion in Ghana, as well as its conversion to electricity and the related financial implications rarely exist. In order to perform the technical assessment, an estimation will be made regarding the quantity of water hyacinth biomass that will be available for harvest in 2020. Furthermore, an assessment will be conducted to determine the volume of methane that could be generated as well as the appropriate power capacity of the electricity generator set plant. The economic performance evaluation will be performed based on the net present value and payback time concepts.

Overall, the aim of the study is to conduct a technical and economic assessment involved in the generation of biogas from water hyacinth biomass and its subsequent utilization for electricity production in Ghana. The findings of the study could have important implications on the development and implementation of biogas production systems in the Volta Lake area and other regions facing similar environmental and economic challenges. By demonstrating the technical and economic feasibility of generating biogas from water hyacinth biomass, the study could help unlock new opportunities for sustainable energy generation and economic development in Ghana.

Methods

General description of the methodology

The methodology used in this study was aligned to the following steps: assessment of the quantity of the water hyacinth biomass that was available for harvest from the lower portion of the Volta River for the year 2020, followed by its characterization for (total solids, volatile solids, pH, ash, carbon, hydrogen, nitrogen, oxygen, and sulfur). Likewise, the fruit waste sludge used as the seed inoculum was equally characterized. The water hyacinth biomass and inoculum were mixed on the basis of the available volatile solid content and fed to the BlueVis anaerobic digester setup. At the end of the anaerobic digestion period, the value of the experimental biomethane potential of the water hyacinth biomass was used as a basis for estimating the potential volume of methane that could be generated from the overall water hyacinth population on the Lower Volta River. The subsequent steps involved the determination of the electrical energy potential and finally conducting an economic feasibility study using the RETScreen software.

Due to the rapid spread and uneven distribution of water hyacinth on the Lower Volta River in Ghana, obtaining accurate estimates of its quantities could be challenging. However, the lower section of the Volta River had been assessed to determine both the overall extent of aquatic weed coverage and the proportion of that coverage specifically occupied by water hyacinth in 2020 [2]. The amount of water hyacinth biomass that existed in the study area as of the year 2020 was assessed using the reported growth rate of fresh water hyacinth biomass at 72.2 g/m^2 per day (equivalent to 263.5 t/ha per year) [17]. The annual methane potential was derived from the specific mean methane volume at the end of the anaerobic digestion process. Finally, the annual electrical energy potential (Ep) and the capacity of the generator plant (Pc) were calculated with the assumption that the generated methane volume would serve as the fuel source. The values of the electrical energy potential (Ep) and generator plant capacity (Pc) were subsequently utilized as vital input parameters in the economic feasibility studies.

Analytical methods

The pH values were measured using a Hanna Combo pH/EC/TDS and temperature tester (model 198,129 low range). To determine the total solid (TS) content, each of the water hyacinth (WH) and fruit waste sludge (FWS) samples was dried at 105℃ for 8 h in a Fisher Isotemp Senior model size oven, following the standard method [18]. The volatile solid (VS) content of the WH and FWS samples were determined using the standard method [19] which involves heating to a constant mass at 550℃ for 2 h in a Thermo Scientific Thermolyne benchtop muffle furnace. The determination of the structural composition of the water hyacinth biomass was performed at the physiology laboratory of the Cocoa Research Institute of Ghana (CRIG) using the modified direct method procedure as described by [20]. The alkalinity tests were performed according to the standards proposed by [21]. The atomic absorption spectroscopy (AAS) method, as explained by [22], was used to detect and quantitatively determine the elemental traces (C, H, N, O, S, Mg, Mn, Ni, Fe) present in the water hyacinth and fruit waste sludge samples.

Characterization of water hyacinth biomass

The water hyacinth biomass was harvested from the Lower Volta River at Kpong in the Eastern region of Ghana, which is located within the borders described by [2]. Samples of the entire plant, including the root, stem, and leaves, were cleaned and cut into smaller sizes for ease of handling. The smaller size particles of the water hyacinth biomass were subsequently analyzed for moisture content, total solids, volatile solids, and ash contents using the same analytical method procedures as mentioned by [9]. A substantial amount of the harvested water hyacinth was dried and milled in batches for 15 min to achieve a particle size of 197 µm using a CЍTRONIC high-speed bleeder machine (model no. CTC-17135). This processed material was utilized for the biomethane potential (BMP) test.

Characterization of the inoculum

The fruit waste sludge (FWS) served as the inoculum source for the biomethane potential test. The FWS was obtained from a mesophilic biodigester plant located at the fresh and dry fruit processing company premises at Adeiso, Eastern Region, Ghana. The plant operates under ambient temperature conditions and a hydraulic retention time of 18 days, with a temperature range of 28—35℃. In order to expel as much available carbon (IV) oxide as present, the raw FWS was subjected to a hunger phase of 15 days at room temperatures between 26 and 29℃. Afterwards, flocculation procedure was performed using Synthofloc 5840 VS flocculating agent according to the method outlined by [23] to increase the total solid content of the raw FWS. The flocculation process also reduced the interspatial distance and encouraged synergistic activities among microorganisms to enhance biogas production. The flocculated FWS was characterized for parameters such as total solids, volatile solids, alkalinity, pH, and total organic carbon. Moreover, the buffering capacity of the flocculated FWS was improved by the addition of 20 ml of 1 M sodium hydrogen carbonate before it was fed into the fermenter bottles.

Experimental setup

The experimental biomethane potential (BMP) of water hyacinth was conducted using a modern BlueVis BMP equipment setup. The setup consisted of three 5.0 L capacity biodigester bottles, each fitted with a stirrer handle and BCP-CH_4 methane sensor (BlueSens, Germany). The first digester bottle served as the control while the remaining two bottles were used as the test fermenters. To measure biogas production, the biodigester bottles were connected to a digital flow meter and a data logger. The data logger was used to record and store biogas measurement data, while a desktop computer installed with 4.2 bioprocess software was used for data analysis and display. The software was used to analyze and display the BMP test results in a user-friendly format for further analysis. The data logger and computer software ensured that the data collected was analyzed efficiently and accurately.

Experimental biomethane potential test

An inoculum to substrate ratio (ISR) of 10 was used in the experimental BMP test based on the available volatile solid content in the water hyacinth biomass and inoculum. Proximate analysis was conducted to determine the total solids and volatile solids present in both the inoculum and water hyacinth. The analysis showed that 138.52 gVS of the inoculum and 13.85 gVS of the water hyacinth biomass would be required to establish the chosen value of ISR. In order to meet the required amount of volatile solid contents, 2880 g of inoculum and 39.82 g of water hyacinth biomass (milled to a particle size of 197 μm) were carefully weighed using a mass balance and added to each of the test fermenters as demonstrated by [9]. The control fermenter contained only the measured mass of the inoculum. All three fermenter bottles were sealed and allowed to undergo anaerobic digestion for 61 days, maintaining a mesophilic temperature range of 29 ± 3℃. The biogas volume and methane content were measured and recorded daily using the BlueSens flowmeter and BCP-CH_4 methane sensor throughout the fermentation period.

Correction of in situ *methane volume measurement*

During the anaerobic digestion period, the biogas volume in milliliters (ml) and the methane concentration, measured as percentage by volume (%v/v), were automatically recorded. However, errors in the in situ measurement of methane concentration were corrected due to the presence of air in the headspace volume of the fermenters. To rectify this error, a specific procedure outlined in reference [9, 23] was followed. The procedure involved the calculation of the continuous displacement of air in the headspace volume to obtain the actual final methane percentage using equations (Eqs. 1—7).

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

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)

$$(F_t) = \frac{V_{Biogas.diff}}{V_{Headspace}} \times 100 \tag{2}$$

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

$$(\beta_t) = F_t + \beta_{t-1} - \left(\frac{\beta_{t-1} \times F_t}{100}\right) \tag{3}$$

β_{t-1} = Proportion of biogas in the headspace at time, $t-1$.

F_t = Percentage volume of newly produced biogas in the headspace.

At the beginning of the experiment ($t = 1$), there would be no biogas in the headspace before the first biogas is produced. $\beta_{1-1} = 0$ consequently, substituting $t = 1$ into Eq. 3, and Eq. 3 simplifies to $\beta_1 = F_1$. This implies that the biogas concentration becomes equal to the percentage volume of the biogas in the headspace at the start of the experiment.

The corrected % methane (V_{mp})

$$\left(V_{mp}\right) = \frac{M_s}{\beta_t} \times 100 \tag{4}$$

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

The corrected methane volume ($V_{methane}$)

$$(V_{methane}) = \frac{V_{mp}}{100} \times \left(V_{Biogas.diff.}\right) \tag{5}$$

$$Cumulated\ methane\ volume\ (V_{methane}) = \sum_{n=i}^{n=f} V_{methane} \tag{6}$$

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

$$\left(\frac{\sum V_{Methane_{Test\ fermenter,\ corrected}}}{\sum V_{Biogas_{Test\ fermenter}}} - \frac{\sum V_{Methane_{control\ fermenter,\ corrected}}}{\sum V_{Biogas_{control}}}\right) \times 100 \tag{7}$$

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. 7. To calculate the net methane volume for fermenters F2 and F3, the methane volume produced by the control fermenter F1 was first corrected. This corrected methane volume was then subtracted from the corrected methane volumes produced by the test fermenters F2 and F3. The average of the resulting net methane volumes from the two fermenters was determined and used in the estimation of the annual methane potential volumes from the available water hyacinth biomass.

Assessment of water hyacinth population and electrical energy potential

Quantification of the water hyacinth mass on the Volta river

The quantification of water hyacinth biomass on the Lower Volta River in Ghana was determined using available data in literature. A study [2] conducted in the year 2020 indicated that the total area occupied by the aquatic weeds on the Lower Volta River had reduced to 4095 ha. The water hyacinth biomass alone accounted for 36% of the infested area which translated to 1474.2 ha. Using the reported growth rate of water hyacinth biomass at 72.2 g/m2 per day which is equivalent to 263.5 t/ha per year [17], the fresh mass of water hyacinth biomass which existed on the Lower Volta River in the year 2020 was estimated to be $388,451.7\ tonnes$ equivalent to $388.4517 \times 10^6 kg$ as shown below.

$$1474.20ha \times 263.5^{tons}/_{ha.year} = 388,451.7^{tons}/_{year}$$

Assessment of the volatile solid content and biomethane potential of water hyacinth reserves

The amount of volatile solid content in a feedstock determines its suitability for biogas production. The viability of the water hyacinth biomass for biogas production was measured by its volatile solid content, which was estimated based on the results of a proximate analysis test. The test revealed that the water hyacinth biomass had a total solid (TS) content of 64.73% and a volatile solids (VS) content of 53.73%. The total volatile solid content available in the freshwater hyacinth population for the year 2020 was estimated to be $135.101 \times 10^6 kgVS$ as shown from steps (1) to (2) :

(1) $Mass\ of\ TS = \frac{64.73}{100} \times 388.4517 \times 10^6 kg = 251.444 \times 10^6 kg$
(2) $Mass\ of\ VS = \frac{53.73}{100} \times 251.444 \times 10^6 kg = 135.101 \times 10^6 kgVS$

In order to assess the biomethane potential of the water hyacinth reserve at the study area, the average of the results from the experimental BMP tests conducted was used. According to the results, fermenters F2 and F3 produced specific net methane volumes of 402.62 mlCH$_4$/gVS and 356.03 mlCH$_4$/gVS, respectively, as reported in [9]. This resulted in a mean value of 379.3 ml CH$_4$/gVS (equivalent to 0.3793 m^3 CH$_4$/kgVS). Consequently, the total methane volume expected to be generated from the total volatile solids content in the available fresh biomass for the year 2020 was estimated to be $53.676 \times 10^6 m^3$ as shown below.

$$Potential\ methane\ volume = total\ volatile\ solid\ content \times mean\ methane\ vol./kgVS$$

$$135.101 \times 10^6 kgVS \times \frac{0.3973m^3}{kgVS} = 53.676 \times 10^6 m^3$$

Estimation of the energy potential of water hyacinth biomass using a generator set

Equation 11 was used to calculate the electrical energy potential (Ep) in kilowatt-hours (kWh) that could be generated by the combustion of the generated biomethane in a generator set. The formula was derived by initially multiplying the specific volume of methane (m^3) by the low heating value (LHV) in MJ/m^3 as represented in Eq. 8. The resulting energy potential in MJ was then converted to kWh by dividing by 3.6, as shown in Eq. 9. The efficiency (eff) of the generator set, which typically ranges from 25 to 36%, and the capacity factor (CF) for typical bioenergy plants ranging from 85 to 95% as proposed by [24] were then taken into account to derive (Eq. 11). Eventually, the electricity potential was estimated using the value of the parameters as shown in Table 1. The capacity factor of the generator set represents the ratio of the electrical energy that would be produced

Table 1 Parameters for estimating the annual electricity potential

Parameter	*CH_4*	*LHV_{CH4}***(MJ/m^3)**	*Efficiency*	*CF*
Value	$53.676 \times 10^6 m^3$	37.2	0.25	0.85

to the electrical energy that would have been produced if the plant operated at maximum capacity.

$$E_p(\text{MJ}) = \text{CH}_4 \times \text{LHV}_{\text{CH4}} \tag{8}$$

Using the conversion factor $1\text{kWh} = 3.6\text{MJ}$

$$E_p(\text{kwh}) = \frac{\text{CH}_4 \times \text{LHV}_{\text{CH4}}}{3.6} \tag{9}$$

Introducing the efficiency (eff) of the generator set variable

$$E_p(\text{kwh}) = \frac{\text{CH}_4 \times \text{LHV}_{\text{CH4}} \times \text{eff}}{3.6} \tag{10}$$

Introducing the capacity factor (CF) for bioenergy plants

$$E_p(\text{kWh}) = \frac{\text{CH}_4 \times \text{LHV}_{\text{CH4}} \times \text{eff} \times \text{CF}}{3.6} \tag{11}$$

Estimation of plant capacity

The installed capacity of the plant was determined with the assumption that it operated throughout the year (8760 h) by using (Eq. 12).

$$P_c = \frac{\boldsymbol{E_p}(\textbf{kWh})}{8760\text{h}} \tag{12}$$

Evaluation of economic viability

Economic analysis is frequently used to determine the economic viability of a potential project by conducting a comprehensive cost–benefit analysis. The RETScreen software, which is primarily designed for the purpose of project planning, analysis, and implementation of energy projects, was used to assess the economic feasibility of the biogas production system. The study utilized the net present value (NPV), simple, and equity payback periods to assess the project's economic feasibility. These financial indicators were employed to determine whether the project would generate a positive or negative return on the investment over a specified time frame. Table 2 shows the underlying presumptions and factors that were considered for the economic assessment of the project.

The revenue for the project was determined by selling 100% of the electric energy produced by the biogas generator to the grid at a feed-in tariff (FiT) rate of 0.175\$/kWh [25], which is the prevailing rate for biomass electricity generation in Ghana. The total investment cost for a biogas power plant covers the costs of planning, engineering, building expenses, fuel handling, preparation machinery, and other equipment costs. The total estimated cost for the construction of the biodigester and the purchase of the generator

Table 2 Economic inputs adopted for analysis

Parameter	Units	Value	Reference
Feed-in tariff	\$/kWh	0.175	[25]
Total cost of biogas digester and generator	\$/kW	5000	[24]
Fixed O&M cost	%	6	[24]
Variable O&M cost (nonfuel)	\$/kWh	0.020	[26]
Variable O&M cost (fuel)	\$/kWh	0.014	[26]
Annual power plant availability	%	94	[27]
Annual inflation rate	%	2	[28]
Discount rate	%	6	[29]
External financing	%	100	Author's Assumption
Debt term	Years	8	Author's Assumption
Capital interest rate	%	16.5	[30]
Project life	Years	15	[26]

was estimated at \$5000/kW [31]. The operation and maintenance cost (O&M) (fixed) is a yearly cash expenditure that is expressed as a fixed cost of 1 kW of installed capacity per annum while the variable O&M cost is expressed kWh annually.

The project capital was assumed to be entirely funded by external debt with an interest rate of 16%, which is the average interest rate in Ghana for a 20-year period [30]. A sensitivity analysis was conducted to evaluate how alterations in key parameters, including the initial investment cost, operating and maintenance expenses, and feed-in tariffs could influence the project's financial performance. The analysis helped to identify the most critical factors that affected project economics and develop strategies to mitigate risks and improve financial performance.

The net present value (NPV)

The difference between the current value of cash inflows and outflows over time is the NPV. Equation 13 can be used to compute the net present value (NPV), which is used to assess a project's profitability [32].

$$\mathrm{NPV} = \sum\nolimits_{n=1}^{N} \frac{X_n}{(1+R)^i} \tag{13}$$

where X_n represents net cash flow, N represents the calculation time, and R represents the actual annual discount rate.

Simple payback period (SBP)

One of the variables to consider when starting a project is the payback period (PBP). The number of years at which a project's cost becomes profitable is calculated by working out Eq. 14 as reported by [32].

$$\mathrm{SPB} = \frac{\mathrm{PJ}_{\mathrm{rev}-}\mathrm{AD}_{0\&\mathrm{M}}}{\mathrm{AD}_{\mathrm{Inv}}} \tag{14}$$

where $\mathrm{PJ}_{\mathrm{rev}}$ is the annual revenue generated, $\mathrm{AD}_{\mathrm{O\&M}}$ is the annual operation and maintenance cost, and $\mathrm{AD}_{\mathrm{inv}}$ is the total investment cost of the project.

Table 3 Structural composition of water hyacinth

Research	Structural composition of water hyacinth Biomass		
	Cellulose	Hemicellulose	Lignin
Current study	**49.98**	**28.99**	**9.5**
[34]	43.01	29.13	6.9
[35]	24	30	16
[36]	20	33	10
[37]	24.5	34.1	8.6

Table 4 Proximate analysis results on water hyacinth biomass

Proximate analysis	
Moisture	35.27%
Total solid	64.73%
Volatile solid	53.73%
Ash	11%

Internal rate of return (IRR)

The IRR is determined as the discount rate, that makes the NPV equal to zero, by computing the formula in Eq. 15 according to [33].

$$\mathrm{NPV} = \sum_{i=1}^{N} \frac{\mathrm{TC}_i}{(1+\mathrm{IRR})^i} = 0 \tag{15}$$

where TC_i is the cash flow in year i, and N is the lifetime of the project.

Results and discussion

Characterization of water hyacinth biomass

The direct method for determining the structural composition of water hyacinth biomass was modified by drying the biomass at a temperature of 60℃. The results showed that the biomass was composed of 49.98% cellulose, 28.99% hemicellulose, and 9.50% lignin. This implied the water hyacinth biomass had a significant amount of cellulose and hemicellulose, which are important components for the production of biogas. Usually, it is possible to overcome the lignin component that restricts the ease of biodegradation through pretreatment methods such as mechanical or chemical methods based on availability and the financial implications involved. Various factors can impact the composition of the biomass, such as the age of the plant during the time of harvest, the growth conditions, and environmental factors like temperature and humidity. Nutrient availability is another significant factor that may impact the structural composition of the biomass. Consequently, different structural compositions of water hyacinth biomass have been reported in literature as shown in Table 3. These results could be used to inform decisions about the potential uses and applications of water hyacinth biomass.

Results on the proximate analysis of the water hyacinth biomass on a dry basis as shown in Table 4 indicated 35.27% moisture, 64.73% total solids, 53.73% volatile solids, and 11% ash contents. The proximate analysis results suggest that water hyacinth biomass has the potential to be used as a feedstock for energy production, particularly for biogas production. However, the relatively high moisture content of the biomass would require additional energy for drying, which would impact the overall energy efficiency of the process.

In the case of the ultimate analysis test of the water hyacinth biomass, it was found that the biomass contains 23.3% carbon, 3.15% hydrogen, 22.1% oxygen, 2.08% nitrogen, and 0.18% sulphur.

Characterization of fruit waste inoculum

The properties of an inoculum are critical for successful biogas production, and its characterization is essential for process optimization. In this study, the physical and chemical properties of the inoculum used were investigated as shown in Table 5. The results showed that the inoculum had a pH of 7.33, indicating that it was slightly basic. The total solid content was determined to be 5.2%, and the volatile solids content was 84.85% of the total solids, which suggested a high proportion of organic matter that could be converted into biogas. The VS/TS ratio of 16.32 indicated that the inoculum had undergone a fair amount of degradation. The alkalinity of the inoculum was 4602 mg $CaCO_3$, indicating a high buffering capacity that could help maintain a stable pH in the system. Although the concentration of trace elements was relatively low, it did not significantly impact microbial activity. The results suggested that the inoculum has excellent potential for biogas production and provides useful information for the optimization of the biogas production process.

In situ methane content correction with experimental biomethane potential test

At the end of the mesophilic fermentation at 29 ± 3℃ for a period of 61 days, a significant amount of biogas and methane volumes were observed. The production of biogas was steady, resulting in a final gross biogas accumulation of 19,798.79 ml and 19,168.55 ml for test fermenters F2 and F3, respectively, as shown in Fig. 1. The control fermenter, F1, produced a total biogas volume of 7784.30 ml.

To measure the methane volume, the percentage of methane composition was measured in situ using a methane sensor. To ensure accuracy, the initial presence of air in the headspace volume of the fermenter bottles and connecting tubes was taken into account

Table 5 Characterization of fruit waste sludge

Parameter	Units	Flocculated sludge
pH		7.33
Total solids (TS)	%	5.20
Volatile solids (VS)	% TS	84.85
VS/TS ratio		16.32
Alkalinity	mg $Caco_3$	4602
Iron	mg/l	0.021
Nickel	mg/l	0.0001
Cobalt	mg/l	0.00011

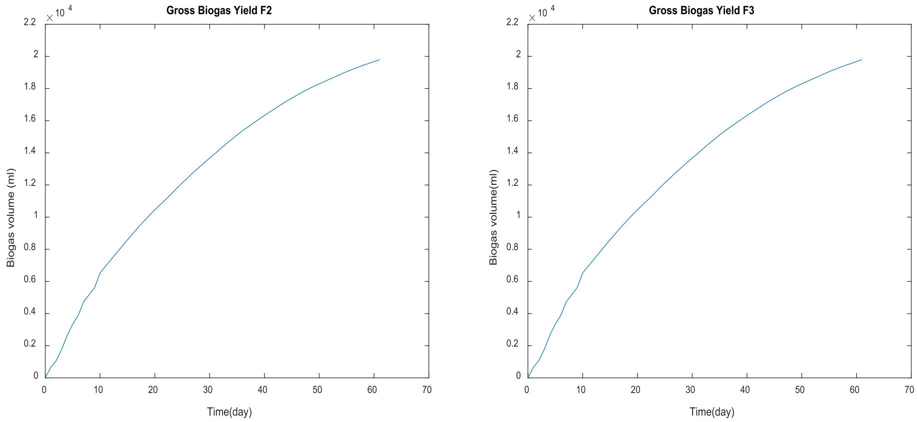


Fig. 1 Gross biogas yield from fermenters F2 and F3

Table 6 Methane composition correction

Fermenter	Methane composition percentage (%)		
	In situ values	Corrected values	Error change
F1	59.10906	60.18078	1.81
F2	54.72950	54.73023	0.001
F3	52.79628	52.79729	0.002

Table 7 Water hyacinth fermentation results in the gross and net parameters

Gross parameter values					Net parameter values	
Parameter	Units	F1	F2	F3	F2	F3
Methane content	V/V%	64.33	53.46	51.85	46.41	43.31
Methane volume	ml	5007.31	10,583.61	9938.34	5576.30	4931.02
Biogas volume	ml	7784.30	19,798.79	19,168.55	12,014.49	11,384.25
Sp. biogas volume	ml/gVS	-	**129.94**	**125.80**	**867.47**	**821.97**
Specific methane volume	ml CH_4/gVS	-	**69.46**	**65.23**	**402.62**	**356.03**

Water hyacinth (gVS) = 13.85, fruit waste sludge inoculum (gVS) = 138.52, total volatile solids (gVS)

and corrected. Table 6 shows the in situ measurement of methane composition for the control and test fermenters. The procedure adopted a correction error of 1.81% in the control fermenter (F1), but the errors corrected in the case of test fermenters F1 and F2 were negligible.

The gross cumulated methane volume and corrected compositions were 10,583.61 ml (60.18%) and 9938.34 ml (54.73%) for F2 and F3, respectively. The volume ratio of gross methane production to gross biogas production, expressed as a percentage, yielded 53.46% and 51.85% for F2 and F3, respectively.

To obtain the net biogas production for F2 and F3, the difference in biogas volumes between the test fermenters and control fermenters was determined. This resulted in a net biogas production of 12,014.49 ml and 11,384.25 ml for F2 and F3, respectively, as shown in Table 7. Similarly, the difference in methane volumes between the test fermenters and control was taken to obtain the net methane volumes of 5576.30 ml and 4931.02 ml for F2 and F3, respectively, as shown in Fig. 2.

To determine the net-specific biogas and methane production solely from the water hyacinth biomass, the net biogas and methane volumes were divided by the volatile solid content (13.85gVS) of the biomass that was mixed with the inoculum. In the case of the net-specific biogas production of water hyacinth, F2 and F3 yielded 867.47 ml /gVS and 821.97 ml/gVS, respectively. In addition, the net-specific methane volume of the water hyacinth biomass was determined to be 402.62 ml CH_4/gVS and 356.03 ml CH_4/gVS for F2 and F3, respectively. The current results were found to be in the range of experimental biomethane production values reported by previous studies [12, 14].

Annual electricity generation potential and power capacity

Substituting the values of the parameters presented in Table 1 into Eq. 11 found under Sect. 2.8.3, the annual electrical energy potential that could be produced from the generator set was determined to be 117.864×10^6 kWh as shown below. Nevertheless, due to regular maintenance shutdowns, the annual plant availability was assumed to be 94% [27] which decreased the electrical potential to 110.792×10^6 kWh. Additionally, the annual power capacity (kW) was also determined to be $13,454.74kW$.

$$E_p(\text{kWh}) = \frac{\text{CH}_4 \times \text{LHV}_{\text{CH4}} \times \text{eff} \times \text{CF}}{3.6}$$

$$E_p(\text{kWh}) = \frac{53.676 \times 10^6\text{m}^3 \times 37.2 \times 0.25 \times 0.85}{3.6} = 117.864 \times 10^6\text{kWh}$$

$$E_p(\text{kWh}) = 0.94 \times 117.864 \times 10^6\text{kWh} = 110.792 \times 10^6\text{kWh}$$

Economic assessment

The financial strategy employed for this project involved securing a loan that would cover the entire cost of the project. To determine the viability of the project, the annual cost of the loan, the loan duration, interest rate, and operational and maintenance costs,

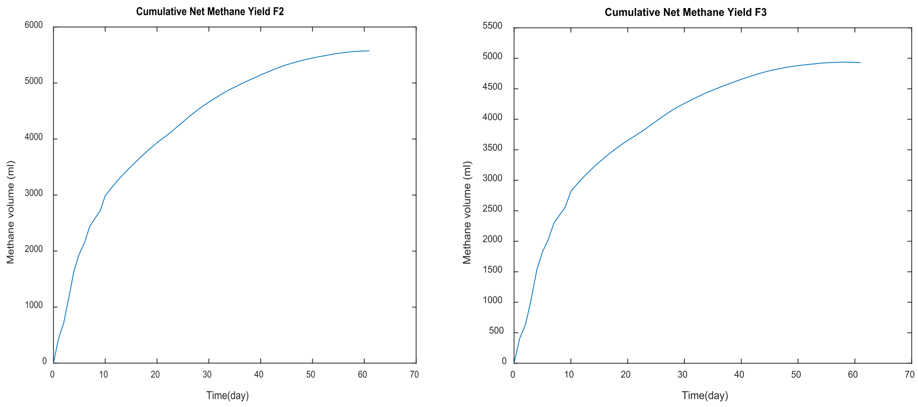
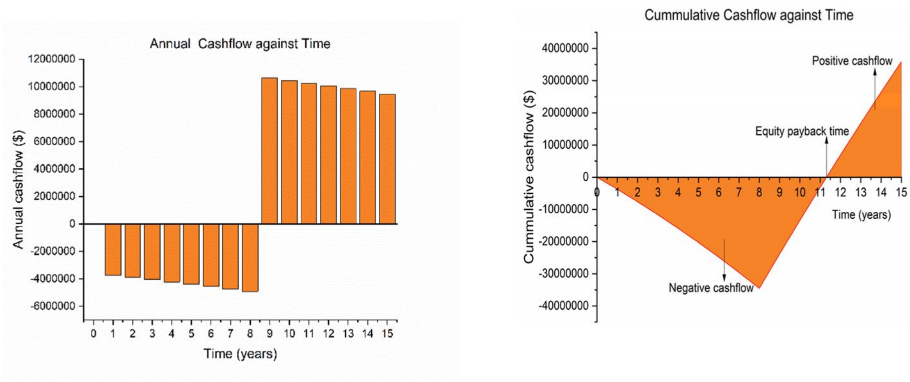


Fig. 2 Net methane yield from fermenters F2 and F3

Table 8 Economic indicators of water hyacinth for electricity production

Parameter	Units	Value
Plant capacity	kW	13,454.74
Annual electricity production	kWh/year	110,791,711
Initial total investment	$	67,273,700
Total annual cost	$	4,862,203
Levelized cost of energy	$/kWh	0.172
Pre-tax IRR (equity)	%	10.3
NPV	$	8,923,769
Total annual savings and revenue	$	19,963,905
Simple payback	Years	5.5
Equity payback	Years	11.3
Annual GHG emission reduction	tCO_2	57,536
Annual GHG emission income	$	575,356



A **B**

Fig. 3 Annual cashflow and cumulative cashflow with debt leverage

as well as the expected system lifetime were considered. By taking these factors into account, a sound financial plan that would ensure the project's success was established.

According to Table 8, the use of anaerobic digestion (AD) to generate electricity from water hyacinth in Ghana is financially feasible, with a positive net present value (NPV) of $8,923,769 and a simple payback period of 5.5 years and an equity payback period of 11.3 years when debt leverage is factored. This assessment is consistent with the results of other studies associated with the estimation of electricity generation from biogas production conducted in Ghana [38–40]. The AD plant has the potential to produce 117.864 × 10^6kWh of electricity per year, resulting in annual cash flow savings of $19,963,905. The findings suggest that using water hyacinth to generate electricity through AD could be a profitable and sustainable source of energy in Ghana.

The yearly and cumulative cash flow analysis conducted using the RETscreen software is presented in Fig. 3. In Fig. 3A, the pre-tax yearly cash flows are presented, taking into account the debt leverage. In addition, the model calculates the cumulative cash flows as shown in Fig. 3B, representing the net pre-tax flows accumulated from year 0 onwards. These cash flows reflect the estimated net cash inflows and outflows each year throughout the project's lifespan. Debt payments begin in year 1, as they occur after year 0. The graph reflects the difference between total annual costs and the total annual savings or revenue over the project's lifetime. Based on the graph, the break-even point considering debt leverage payments was determined to be 11.3 years as shown in Fig. 3B.

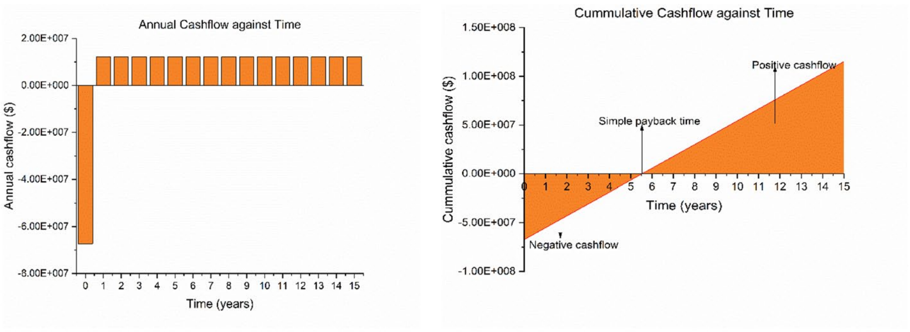
On the other hand, Fig. 4A and B portray the annual and the cumulative pre-tax cash flows over the project life, respectively, excluding the consideration of debt leverage. In this situation, it is presumed that the sole financial obligation at the beginning of year 0 is the initial investment cost, and any annual net cash inflows are received at the end of year 0. Notably, the analysis reveals a break-even point of 5.5 years as shown in Fig. 4B indicating the time it takes for the project to reach a point of financial equilibrium without debt interest payments.

In summary, the analysis indicates that the presence of debt leverage extends the break-even point to 11.3 years, resulting in negative net yearly cash flows during the debt term of the project. However, if debt leverage is not considered, the project reaches a financial equilibrium much earlier, at 5.5 years.

Climate impact assessment

Anaerobic digestion is a process that involves using a digester to handle fermentable materials. One of the advantages of using biogas is that it produces very few greenhouse gases such as carbon dioxide during combustion. However, effective cleaning techniques should be used to prevent any emissions that may occur. In Ghana, the greenhouse gas emission factor for power projects excluding solar and wind is 0.53 tCO_2/MWh, according to the Ghana Energy Commission [41].

To determine the GHG income for the project, a GHG cost of \$10/tCO_2 was used [42] and a GHG credit transaction fee of 2% of the total revenue was estimated. The total GHG reduction potential for the project is shown in Table 8. It was found that the potential power project could result in a GHG emission reduction of 57,536 tons of CO_2. As a result, encouraging power generation from anaerobic biogas systems is one of the best strategies for reducing greenhouse gas emissions and aiding the country in contributing to its sustainable development goal.



A **B**

Fig. 4 Annual cashflow and cumulative cashflow without debt leverage

Sensitivity analysis

The purpose of the sensitivity analysis was to investigate how changes in key input variables would affect the NPV (net present value) of the project. The analysis was conducted using three different scenarios, and the selected input variables were the project's initial cost, operations and maintenance (O&M) cost, and the feed-in tariff (FiT). The analysis was performed using a sensitivity range of ± 30%, which implied that the values of the input variables were varied within a range of plus or minus 30% of their original values. The NPV of the project was then calculated for each scenario to determine the effect of varying the selected input variable on the project's overall financial performance.

The findings revealed that the net present value (NPV) remained positive for both the initial cost and the O&M (operations and maintenance) cost variables, as long as an increment within 15% was not exceeded. However, when the FiT rate was reduced by 30%, the NPV became negative, indicating that the project's profitability was significantly impacted by these changes. Table 9 provides more detailed information on the sensitivity analysis, such as the values of the input variables used, the calculated NPV for each scenario, and the corresponding impact on the project's financial performance.

Conclusions

The study examined the viability of utilizing water hyacinth biomass for generating methane gas and subsequently converting it into electricity in Ghana. After a 60-day anaerobic digestion process, the biomethane potential test resulted in the production of $0.3793 m^3 CH_4/kgVS$ of methane gas. It was estimated that approximately 388.4517×10^6kg of fresh water hyacinth biomass, containing a volatile solid content of 135.101×10^6kgVS was estimated to be available for biogas production for the year 2020. This could yield an annual methane gas volume of approximately $53.676 \times 10^6 m^3$. The study projected that a plant capacity of 13,454.74 kW could be used to convert this methane gas into electricity, resulting in an annual electrical potential of 117.864×10^6kWh. However, after considering the 94% factor for operations and maintenance, the revised annual electrical potential was 110.792×10^6kWh. Moreover, the research highlighted that utilizing this method could lead to a significant reduction of 57,536 tCO_2 in greenhouse gas emissions. From the financial perspective, the results showed a positive net present value of $8,923,769 with simple payback and equity payback periods of 5.5 and 11.3 years, respectively. To assess its

Table 9 Sensitivity of the NPV to key input parameters

	Initial cost				
Percentage	−30%	−15%	0%	15%	30%
Value	47,091,590	57,182,645	67,273,700	77,364,755	87,455,810
NPV	38,243,435	23,583,602	8,923,769	−5,736,064	−20,395,897
	Operations and maintenance cost (O&M cost)				
Value	1,128,166	1,369,916 1	7,803,350	8,973,853	10,144,355
NPV	35,095,297	22,009,533	8,923,769	−4,161,995	−17,247,759
	Feed-in tariffs (FiT)				
Value	122.5	148.75	175.10	201.25	227.5
NPV	−47,568,157	−19,322,194	8,923,769	37,169,732	65,415,695

robustness, the study conducted a sensitivity analysis, modifying input variables such as the initial cost, operations and maintenance cost, and feed-in tariff by ± 30%. The results on the variation of the initial and operations and maintenance cost parameters resulted in a positive net present value except for a 15% increment and beyond. However, a 30% reduction in the feed-in tariff cost resulted in a negative net present value.

The research findings suggest that utilizing water hyacinth biomass for methane gas production to generate electricity in Ghana is both technically and financially feasible. However, it is crucial to consider external factors such as technological advancements, market competition, and changes in government policies, which can significantly influence the long-term sustainability and success of this conversion process. Technological advancements can enhance the efficiency and cost-effectiveness of harvesting, processing, and conversion of the water hyacinth biomass into biogas, thereby improving overall scalability. Market competition, particularly from alternative renewable energy sources like solar can also impact the economic viability of biogas production by affecting demand and investment decisions. Additionally, changes in government policies regarding renewable energy, including subsidies play a key role in fostering investment and creating a favorable regulatory environment for biogas projects. Conversely, policy changes that reduce support for renewable energy may impede the growth of the biogas industry. Therefore, stakeholders must carefully consider and adapt to these external factors to ensure the continued growth and viability of biogas as a renewable energy source.

It is important to note that challenges such as the inconsistent availability and supply of the water hyacinth biomass can impede the successful implementation of the project due to its susceptibility to weather variations. Additionally, difficulties involved in securing external funding for both the construction and operation of the biogas plant may pose a significant barrier to the project implementation. Furthermore, the absence of a readily accessible market for the electricity generated from the biogas plant, coupled with competition for electrical energy demand from alternative renewable sources like solar and hydro could hinder the project's smooth implementation and sustainability.

Consequently, it is advisable to conduct further research and testing to assess the project's long-term sustainability.

Acknowledgements
The authors would like to express gratitude to Shadrack Ofori and Abdul Razack of Fresh and Dry Fruit Processing Company at Adeiso, Ghana, for providing the fruit waste sludge that was used as the inoculum source for the BMP test. We would also want to extend special thanks to Prince Owusu of the Ecological Laboratory (Ecolab) at the University of Ghana, Legon, for offering valuable feedback on the characterization of the water hyacinth biomass and fruit waste sludge. Moreover, the authors acknowledge the valuable contribution of Rafiatu Kotei of the Physiology Laboratory at the Cocoa Research Institute of Ghana (CRIG) station at Akim Tafo, who assisted in determining the structural composition of the water hyacinth biomass.

Authors' contributions
EA and NYA: Methodology, investigation, formal analysis, visualization, and writing—original draft. NYA and AA: Conceptualization and writing—review and editing. EA, SS, EOA, and AN: Resources, methodology, formal analysis, and writing—review and editing. EOA, IA, and AN: Resources and validation. NYA, AAA, and IA: Validation and writing—review and editing. EA and SS: Writing—original draft. NYA, AA, and AAA: Supervision and writing—review and editing. All authors have read and approved the final manuscript.

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

Availability of data and materials
The datasets generated for this manuscript will be made available by the corresponding author upon request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 27 December 2023 Accepted: 13 April 2024

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