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The potentials of production of biogas from constructed wetland macrophytes

Adelere E. Adeniran* and Uduoghene B. Onothoja

Civil and Environmental Engineering Department, University of Lagos, Lagos State, Nigeria.

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This study investigated the potential of biogas production from three (3) constructed wetland macrophytes: Water hyacinth (WH), cattail (CT) and *Cyperus papyrus* (CP). The digesters used had capacity of 0.22 cm^3 each. They were operated under anaerobic conditions with organic loading rate (ORL) of 0.2 kg VS/m^3.day and hydraulic retention time (HRT) of 5 days. Observations were made for a period of 128 days. The results show that the three macrophytes produced methane (CH_4) and carbon dioxide (CO_2) in reasonable quantities. The other gases such as H_2S and CO were present in minute quantities only. The results show mean biogas production flows of 38.52±13.05, 75.63±14.34 and 38.52±13.05 mL/kg VS for WH, CT and CP respectively. The mean percentage CH_4 production for WH, CT and CP were 54.45±6.86, 42.02±11.10 and 38.52±13.05%, respectively. The corresponding mean percentage CO_2 productions were 42.71±3.0, 39.73±4.48 and 43.24±2.96%. The energy potentials in terms of calorific value were 9.22, 7.02 and 6.13 W/kg of biomass for WH, CT and CP respectively. It was concluded that from water hyacinth alone, a conservative off-grid renewable energy of about 11,825 MW/year is possible as addition to reduce the Nigerian energy demand gap.

Key words: Renewable energy, biogas, macrophytes, constructed wetland, Nigeria.

INTRODUCTION

In the face of dwindling global fossil fuel, the need to reduce greenhouse gases and provide cheap and sustainable sources of energy especially in the developing world, it has become necessary to explore alternative sources of energy from different kinds of biomasses. The necessity for sustainable development, dwindling global fossil fuel resources and modern advances in technologies for waste treatment and disposal has placed green technology and biogas as alternative of energy on the front burner of research (Ackom et al., 2013). Renewable energy sources developed from plants, animals and microbial biomass such as organic residues and waste from all human activities are often accorded priority in efforts to mitigate the greenhouse effect and eventually achieve a completely sustainable energy supply (Mschandete, 2009; Jeng et al., 2012). Biogas, a major by-product of anaerobic digestion, is a typical example of renewable energy. It is combustible with CH_4 and CO_2 as its major constituent while gases such as H_2S, CO are present in very minute quantities (Sudhakar

*Corresponding author. E-mail: eadeniran@unilag.edu.ng, engrea@yahoo.com.

et al., 2013).

Certain wetland macrophytes have over the years been known for their beneficial uses as well as their detrimental effects on the environment. Apart from their efficiency for use as wastewater treatment in constructed wetlands (Adeniran, 2015), water hyacinth is known for its fecund growth and persistent aquatic problem leading to ecological and economic difficulty ranging from navigation impediments, irrigation system clogging and eutrophication (Ezeri, 2002; Malik, 2007; Mathur, 2013). On the coast of Nigeria, water hyacinth (WH) is known to be a menace. In addition to being detrimental biologically to the aquatic environment, it physically blocks the waterways thereby impeding transportation and human activities. Their masses when adrift dislodge fishing nets in water resulting in huge financial losses to artisanal fisher-folk. WH also provides a hiding for snakes and other dangerous aquatic organisms (Ezeri, 2002). On the other hand, cattail and *Cyprus papyrus* which are ubiquitous in their distribution and exhibit rapid growth rate have the potential to eliminate other native plant species in their domain and obstruct water ways (Alvinge, 2010).

Some works are available in literature on the biogas production from the anaerobic digestion of macrophytes from natural wetlands. Dipu et al. (2011) investigated the potential of wetland macrophytes like *Typha* sp. (cattail), *Eichhornia* sp. (water hyacinth), *Salvinia* sp., *Lemna* sp., *Azo* Kurniawan *lla* sp. and *Pistia* sp. for biogas production in India. Other works carried out were on macrophytes from natural wetland and water ways (Njoku et al., 2016; Njogu et al., 2015, Kurniawan et al., 2014, Sheeraz et al., 2013). In addition, the work of Kurniawan et al (2014) was conducted by mixing natural wetland macrophyte with buffalo dung. Sugumaran et al. (2014), used water hyacinth blended with cow dung, while Tian et al., 2016) investigated the efficiency of biogas slurry by earthworm-constructed wetland. In this study the potential of biogas production by three macrophytes (water hyacinth, cat tail and *Cyprus papyrus*) harvested from a constructed wetland for the treatment of domestic sewage without the use of inoculants (cow dung, buffalo dung etc.) was investigated to accelerate the production of biogas. The objective of this current work was to find alternative, effective and productive use for the macro-phytes that have to be harvested on a regular basis to ensure the efficient performance of the constructed wetland treatment facilities. The viability of the use of the constructed wetland harvested macrophytes as alternative sources sustainable and renewable energy sources of sustainable and renewable energy.

MATERIALS AND METHODS

Study area

This study was carried out on the Constructed Wetland site at the Service Area of the Works and Physical Planning Department of the University of Lagos (Figure 1). University of Lagos is located in the Mainland of Lagos, the commercial capital of Nigeria. Lagos, the biggest and most important city in Nigeria has been classified as a mega city with a population of over 10 million. It is located on 06°25'N 03°27'E on the West African Coast with an average temperature of 32°C and an annual mean rainfall of 1532 mm. The University of Lagos has a day population of about 55,000 (Kadri and Associates, 2016).

Biomass preparation

This research was carried out from September 2015 to January 2016 at the University of Lagos constructed wetland sewage treatment plant. Three macrophytes (i) Water hyacinth (Figure 2), (ii) cattail (Figure 3) and (iii) *C. papyrus* (Figure 4) were harvested from the constructed wetland wastewater treatment plant and investigated for their biogas potential under anaerobic conditions using experimental batched biogas digesters. The macrophytes were harvested separately and cleaned to remove soil. The samples were then chopped into tiny pieces (2-5cm length) for ease of decomposition (Hendriks and Zeeman, 2009). Forty (40) kg of each of the chopped macrophytes was weighted and mixed with water in the ratio of 2:3. The substrates were fed into the three well labeled bio-digesters through the feeding inlet. After feeding, all digesters were tightly closed and observations were made for a period of 128 days.

Biogas digesters

The three (3) typical anaerobic batch digesters were constructed from locally available 220 L plastic containers at the constructed wetland site of the University of Lagos, Nigeria. Each of the digesters was fixed with digital thermometer, pressure gauge and an outlet to measure the percentage of each of the gases of the biogas (Figure 5). The schematic diagram and the picture of the experimental digester are shown in Figure 6. The digesters had a capacity of 0.22 cm^3 and were operated under anaerobic conditions with organic loading rate (ORL) of 0.2 kg VS/m^3.day and hydraulic retention time (HRT) of 5 days.

Sampling and data collection

A digital weighing machine was used to accurately measure 40 kg of each of the macrophyte biomasses. A gas analyzer (GFM 406 series) was used to determine the production percentage (%) of the four gases of the biogas produced. The temperature and pressure in the bio-digesters were read in triplicates at about 1:00 pm daily from thermometers and pressure gauges, respectively. The percentage of the gases present (CH_4, CO_2, H_2S and CO) were also measured with the GFM 406 series gas analyzer at the same time for the 128 days. The data recorded for each parameter was an average of three readings.

Energy calculations

Calorific values

The potential energy for each of the macrophytes was calculated from the result obtained. The equation proposed by Klaus (1988), which has been widely used, was adopted in the calculation of potential energy of the biogas obtained from the macrophytes. Methane (CH_4) is the most important component from where biogas energy or fuel is derived; the other components do not contribute to the calorific ("heating") value and are often "washed out" in

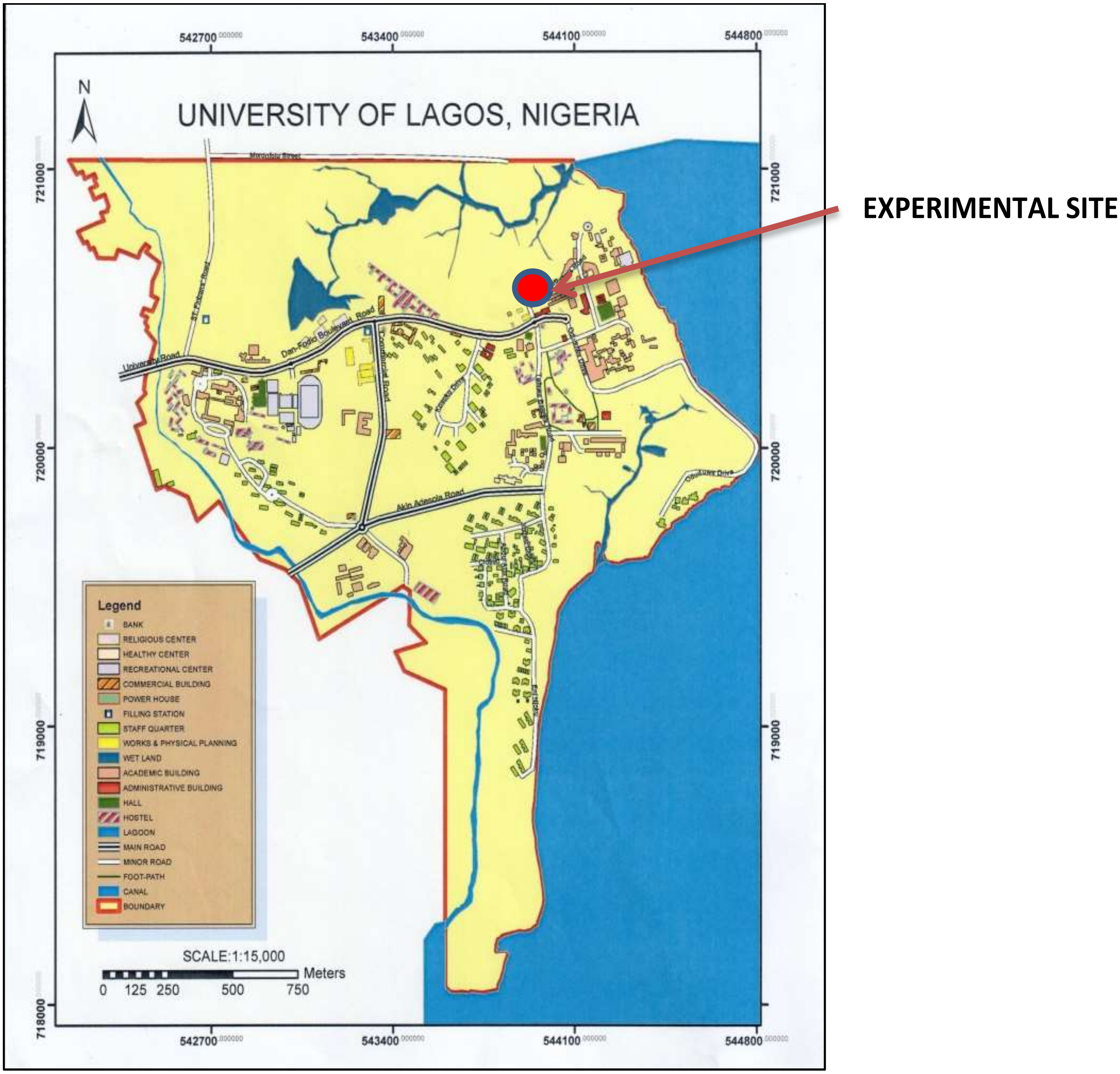

Figure 1. Study site at the University of Lagos.

purification plants in order to obtain a gas with almost 100% CH_4 (Klaus, 1988). Therefore the calorific value of CH_4 (which depends on its percentage, temperature and pressure) is the component used in the analysis and calculation of the calorific value of biogasof the macrophytes. The thermodynamic parameters for CH_4 at standard temperature and pressure are (i) Molar mass M (16.04 kg/kmol), (ii) Density ρ (0.72 kg/m^3), (iii) Gas constant R = 0.518 kJ/kg K and (iv) Lower calorific value, H_u (50,000 kJ/kg).

Equation 3 derived from Equations 1 and 2 by Klaus (1988) were used in the calculation of the calorific values (potential energies) for each of the constructed wetland harvested macrophytes.

$$\rho CH_{4(act)} = \rho CH_4(std) * \frac{P(act)}{P(std)} * \frac{T(std)}{T(act)} \quad (1)$$

$$H_{u,\ act} = \frac{V(CH4)}{V(Total)} * \rho CH4_{(act)} * H_{u,std} \quad (2)$$

Substituting (1) in (2) gives:

$$H_{u,\ act} = \frac{V(CH4)}{V(Total)} * \rho CH_4(std) * \frac{P(act)}{P(std)} * \frac{T(std)}{T(act)} * H_{u,std} \quad (3)$$

Figure 2. Water Hyacinth**.**

Figure 3. Cattail.

Where: $\rho_{CH4(act)}$ = Actual density of CH4 (kg/m^3); $\rho_{CH4\,(std)}$ = CH_4 at standard temperature and pressure (0.72 kg/m^3); $P_{(act)}$ = Actual pressure (°K); $P_{(std)}$ = Pressure at standard temperature and pressure (°K); $H_{u,\,act}$ = Actual calorific value (kJ/m^3); $H_{u,\,std}$ = Calorific value at standard temperature and pressure = 50,000 kJ/kg; $V_{(CH4)}$ = Mean % CH_4 as measured, and $V_{(Total)}$ = 100% biogas.

Potential energy calculation

The potential energy can be calculated from:

Figure 4. *Cyprus papyrus.*

Figure 5. Picture of the biodigester.

$$P_e = (\frac{C_v * G_v}{\Delta T})/B_w \quad (4)$$

Where: Pe = Potential energy; Cv =Calorific value MJ/m^3; Gv = Available digester biogas volume (m^3); B_w = Biomass weight (Kg) and ΔT = Interval of time (s) = 1 day = 86,400s.

RESULTS AND DISCUSSION

Characteristics of substrates of the macrophytes

Several researchers, over time, have established that pH, conductivity, total dissolved solids (TDS), dissolved

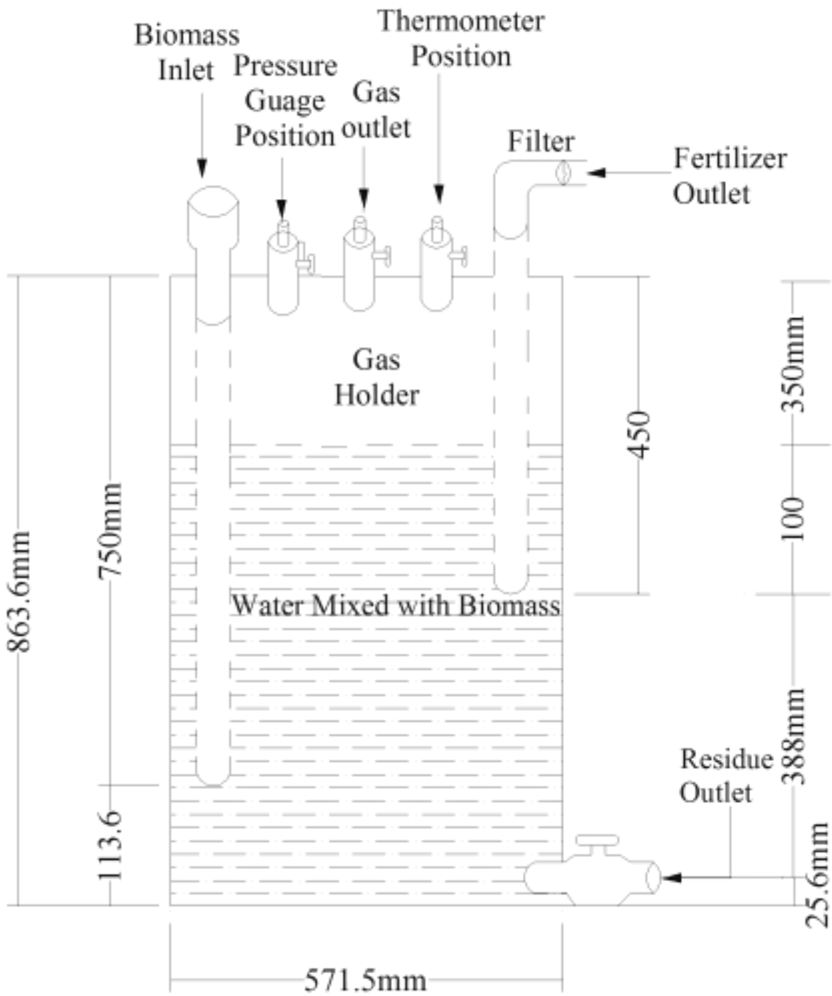

Figure 6. Schematic diagram of biodigesters.

Table 1. Characteristics of prepared slurry of the macrophytes.

Parameter	Units	Macrophyte		
		Water hyacinth (WH)	Cattail (CT)	*C. papyrus* (CP)
pH		7.68	7.52	7.47
Electric conductivity	µS/cm	1.17	1.26	1.31
Total dissolved solids	mg/l	636	522	438
BOD_5 (20°C)	mg/l	67.8	63.2	57.2
Sulphate	mg/l	64.78	61.71	58.43
Manganese	mg/l	7.42	6.78	6.59
Dissolved oxygen	mg/l	4.52	3.21	3.19
Iron	mg/l	1.98	1.74	1.63
Nitrate	mg/l	24.3	19.6	17.5
C/N ratio	-	18.96	10.84	9.46

oxygen (DO), and biochemical oxygen demand (BOD, when moderate) create suitable conditions for the production of biogas (Adeniran et al., 2016; Bodhke, 2009; Ismail et al., 2012; Ademoroti, 1996). As shown in Table 1, the parameters of the substrates of the three macrophytes used in this work are observed to be

Table 2. Statistical analysis of data obtained for three macrophytes studied (n = 128 days).

Parameter	Macrophyte		
	Water hyacinth	Cattail	*C. papyrus*
CH_4 (%)	54.45±6.86	42.02±11.10	38.52±13.05
CO_2 (%)	42.71±3.0	39.73±4.48	43.24±2.96
H_2S (%)	0.03±0.03	0.03±0.03	0.01±0.01
CO (%)	0.02±0.02	0.14±0.15	0.01±0.01
Total biogas flow (mL/kg VS)	6.969.90	5,378.90	4.930.90
Mean biogas flow(mL/kg VS)	38.52±13.05	75.63±14.34	38.52±13.05
Temperature (°C)	30.34±3.12	29.18±4.58	30.51±2.07
Pressure (mbar)	39.38±12.44	17.58±10.52	7.15±2.67
Calorific value (MJ/m^3)	17.21±2.1	13.09±3.60	11.78±3.98
Potential energy (W/kg)	9.22	7.02	6.31

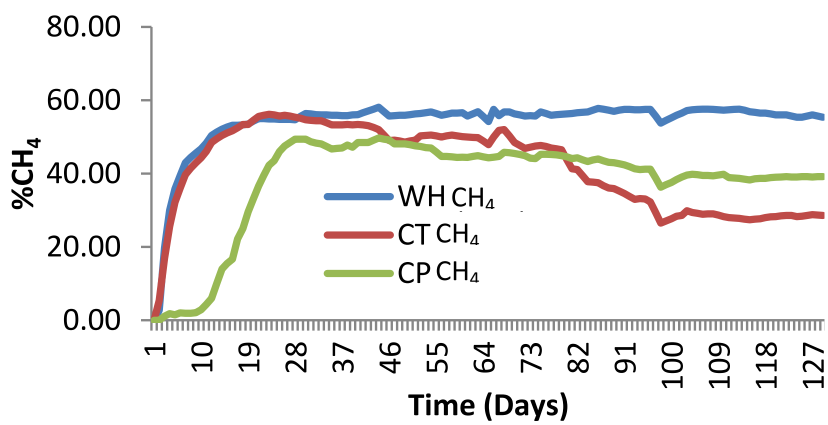

Figure 7. Observed $\%CH_4$ production rate of WH, CT and CP.

moderate.

The results obtained were analyzed statistically using MS Excel for means and standard deviations. The calorific value (potential energies) was also calculated using Equations 3. The summary of the results obtained for the three (3) macrophytes are as shown in Table 2.

Biogas production

Methane (CH_4) is the energy component of the biogas. The energy potential of the biogas is a factor of the percentage methane obtainable from a sample of biogas. The comparative trend of the production of methane (CH_4) for the three macrophytes is as shown in Figure 7. It was observed that WH produced the highest percentage of CH_4 with a mean CH_4 of 54.45±6.86%, a maximum of 58.10% and minimum of 0.0% (on day 1). The percentage production of CH_4 rose steadily from 0.0% on day 1, reached 55% on the 20th day and 58.10% on the 45th day; it remained consistent oscillating between 55.0 and 57.5% for the rest of the observation period. The average methane production of cattail was 42.02±11.10% during the period of observation. The production rate of CH_4 in CT increased at the same rate with water hyacinth till the 22nd day and then began to drop till it reached 28.6% on the 128th day. *C. papyrus* had the lowest percentage of methane with an overall average of 38.52±13.05%. This may be due to the hard texture of CP making it complex for biodegradation or a higher lignin content when compared with WH and CT with softer textures (Figure 7). The available surface area has however been defined as important as it determines how well the hydrolytic enzymes can get into the material and the cellulose. One important factor linked to this is the crystallinity of the cellulose more amorphous cellulose increases the surface area and makes it easier to degrade. The pore size of the substrate in relation to the enzyme size is also important and decides how far the enzymes can penetrate into the material itself (Hendriks and Zeeman, 2009). It is noted that WH has the largest leave surface area, followed by CT and then by CP. Carbon dioxide (CO_2) (Figure 8) was also produced in relatively high percentages during the observation period.

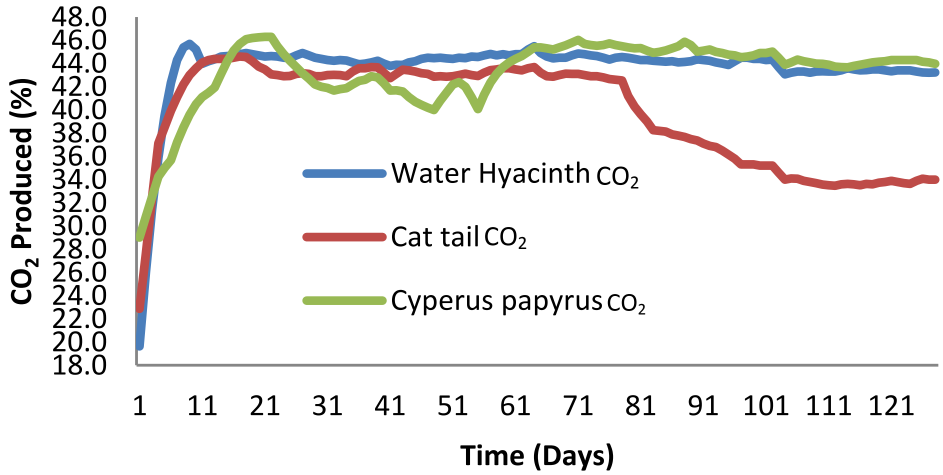

Figure 8. Observed $\%CO_2$ production rate of WH, CT and CP.

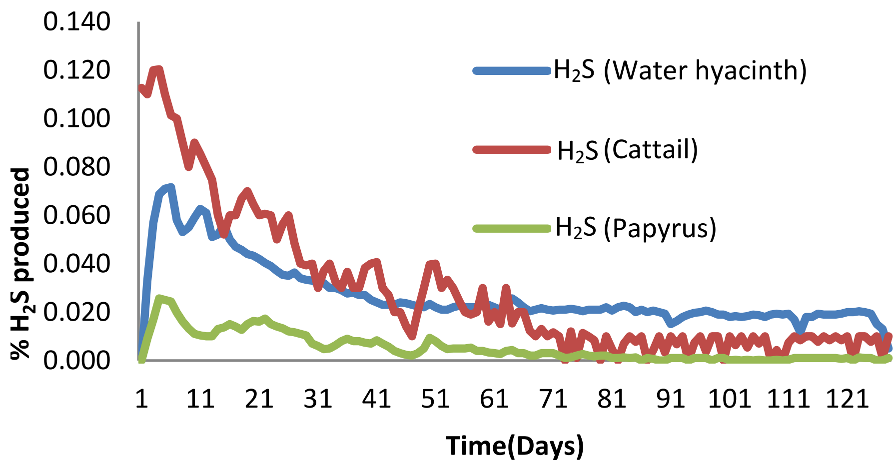

Figure 9. Observed $\%H_2S$ production rate of WH, CT and CP.

For the WH, the maximum value of CO_2 was 46% and steady production between 45 and 43% was observed from about the 10th day to the 128^{th} day. Also for CP, the $\%CO_2$ rises from 0% from day zero to about 47% on day 21, then it drops for about 40 days to a level of 40.5% and rose to become consistent around 43% until the 128^{th} day when the observation was concluded. This high content of CO_2 in biogas (if not purified) makes it suitable for domestic cooking because under this condition, it is not explosive. Hydrogen sulphide (H_2S) and carbon monoxide CO from the macrophytes are presented in Figures 9 and 10. It was observed that they were available at the initial stage of the experiment in minute quantities. However, as the stages of acidolysis and methanogenesis are reached in the biological remediation process, H_2S and the CO are converted to H_2SO_4 and H_2CO_3 hence H_2S and CO_2 are no longer traceable. These are depicted in Figures 9 and 10.

Potential energy

The mean calorific values of the three biomasses were also determined using Equations 3. Water hyacinth was discovered to have the highest energy value of 17.21±2.1 $MJ/m^3/day$ followed by cattail 13.09±3.60 $MJ/m^3/day$; *C. papyrus* had the least energy value (11.78±3.98 $MJ/m^3/day$). From Equation 4, the estimated potential energy were 9.22 W/kg (WH), 7.02 W/kg (CT) and 6.31 W/kg (CP).

Conclusion

The scale of renewable-energy potential is much larger than the public or policymakers realise. Recent studies have estimated concentrated solar thermal power potential in Nigeria at over 427,000 MW (Newsom, 2012;

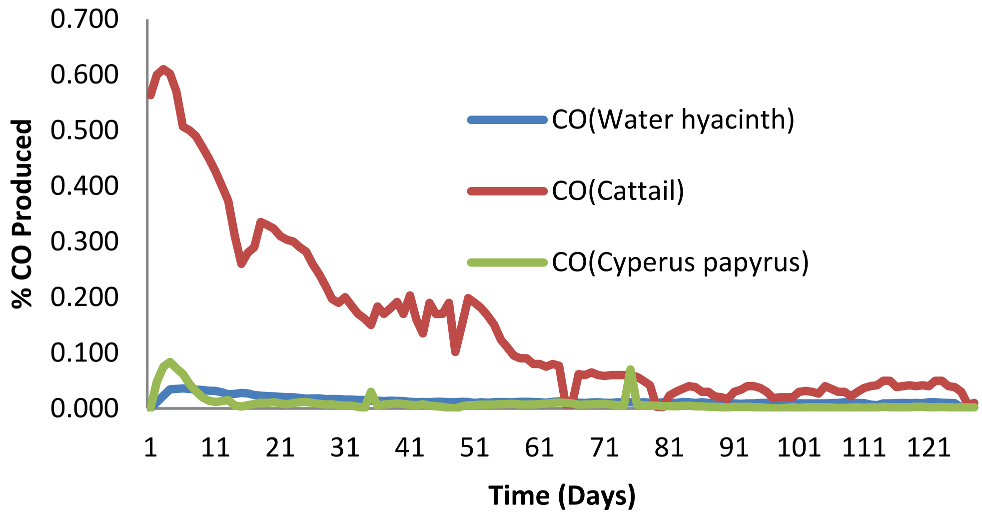

Figure 10. Observed % CO production rate of WH, CT and CP.

Ofoefule et al., 2010). Present levels of power generation of around 5000 MW/day meet only a fraction of demand, and renewable energy could play an escalating role. Large-scale renewable power generation could prove transformational, but small consumer- and household-level systems could offer energy independence for the majority with presently limited or zero access to reliable electricity (Newsom, 2012). The huge potential for renewable energy in the country is mostly untapped. Barriers to the development of renewables include: The large oil and gas production in the South together with government fuel subsidies, the lack of clarity/market information on private sector opportunities, and a general knowledge gap concerning financial support mechanisms available within the country (https://www.africa-eu-renewables.org). Ofoefule et al. (2010) stated that biogas has globally remained a renewable energy source derived from plants that uses solar energy during the process of photosynthesis.

The biomass resources of Nigeria are mainly crops, forage grasses, shrubs, animal wastes and waste arising from forestry, agriculture and municipal and industrial activities. Crops such as sweet sorghum, maize, and sugarcane are the most promising feedstock for biofuel production. According to estimates, the daily production of animal waste in Nigeria is about 227,500 tons, which could lead to about 6.8 million m^3 of biogas. Though the technology itself is not yet established in the country, a variety of research covering different aspects of biogas production in Nigeria, such as technical feasibility or policy recommendations, are ongoing (https://www.africa-eu-renewables.org).

This study, which is part of the ongoing research to establish and educate the policy makers on the huge potential of renewable energy in Nigeria, has shown that water hyacinth, cattail and *C. papyrus* are good sources of renewable energy generation. In particular, it has been shown that water hyacinth which of all three biomasses has a greater potential for negative impact on man and his environment is a better source of renewable energy. Currently, annual average yield of water hyacinth in the Nigerian Delta area (South-South, Nigeria) alone has been estimated to be 3,225,000 tons/year (Elenwo and Akankali, 2016). With a conservative reuse of 40% for renewable energy, an estimated 11,825 MW/year can be added to the off-grid energy demand of Nigeria.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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