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From Sanitation to Clean Energy: Biogas Potential of Three Organic Wastes Collected in and Around Douala City (Cameroon)

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ABSTRACT

Waste management is a major concern in large cities under heavy demographic pressure. Landfill, the oldest form of solid waste management is gradually being replaced by new technics such as biomethanisation. With the purpose of contributing to the achievement of one of the Sustainable Development Goals, particularly SDG7 (affordable and clean energy), the aim of this study is to assess the fermentable fraction of organic wastes into biogas. This survey was carried out in and around Douala city. Biological material consisted of water hyacinth (WH), household wastes (HW), oil palm wastes (OPW) and a mixture of these three substrates (MS) was collected and introduced with cow dung used as inoculum in a biodigester. Some physico-chemical parameters of substrates were determined. Results have shown that substrates used have a pH around neutral. The C/N ratio has shown an excess of nitrogen in the WH, but a deficit in the OPW and MS. The household wastes have presented an ideal ratio for the biological stability of the anaerobic digestion system (21.153 ± 0.695). At the end of the experimentation, a large degradation of organic matter has been observed with COD decrease rates of 37.55 ± 0.12 % (WH), 45.46 ± 0.60% (HW), 48.27 ± 0.34% (OPW) and 46.71 ± 0.26% (MS). All air chambers were inflated and the combustion has shown a blue flame, proof of very high proportions of methane in the flammable biogas. A sanitation process has led to clean energy production.

Keywords: biodigester; methanisation; SDGs; waste management.

INTRODUCTION

Wastes have been defined as "abandoned matter, considered to be unusable and of no value, or even of negative value, by a society, in a given context and at a given period in its evolutionary process" [Lacour, 2012]. Since matter is itself a source of matter, the matter that makes up waste, composed of complex and organised molecules, represents a potentially recoverable resource. The ever-increasing and more diversified consumption observed throughout the world is leading to a production of wastes that is constantly increasing in quantity and quality. This is generating enormous risks for the environment [Afilal et al., 2007]. It is evident that the aforementioned situation is of greater concern in developing countries than in developed ones. This is due to the considerable technological backwardness that characterises them, which is a consequence of a lack of resources and the difficulty in adopting an appropriate approach to tackle this issue in a context-specific manner.

The rapid increase in waste production linked to economic growth, demographic pressure and anarchic urbanisation are weakening the waste management systems put in place by Governments, making the task more difficult and preventing them from ensuring effective and sustainable management [Ngambi, 2016]. To enhance the effectiveness of waste management policies, Cameroon Government has established a legal framework and institutional infrastructure to facilitate the implementation of defined strategies, with the objective of achieving a sanitation rate of 60% by the year 2035. This ambition necessitates also the incorporation of climate change considerations into sectorial strategies and policies, as well as the fight against pollutions and land degradation [MINEPAT, 2020].

Landfill is the most applied method of waste disposal in developing countries. This practice, which concerns almost 90% of urban waste of all categories, is justified, if not preferred to treatment by combustion, composting or methanisation, as an easy solution due to technological and financial constraints [Thonart et al., 2005]. The recovery of waste generally results in useful and often essential products for the local populations. The process of anaerobic digestion of waste results in both the production of organic fertilizers (compost) capable of increasing agricultural productivity and the transformation into biogas. The latter is a very important source of energy that makes life easier for populations, reduces dependence on fossil fuels and above all reduces deforestation and consequently participates in the fight against climate change [Afilal et al., 2014]. It shows that a well-organized sanitation process can help increase soil fertility (fight hunger) and provide clean and affordable energy.

Bio-methanisation is a technology for the treatment of the organic fraction of biomass generated. It has the potential to transform a waste problem into a source of wealth [Saidi and Abada, 2007]. In fact, it provides several opportunities following the recycling of organic waste. Indeed, anaerobic degradation of organic matter is increasingly recognised as a fundamental method of advanced technology for environmental protection and resource conservation [Satyanarayana et al., 2008; Karagiannidis and Perkoulidis, 2009]. The optimal functioning of this type of process is largely contingent upon the physico-chemical characteristics of the substrate utilized for fermentation, in addition to the effective control of the parameters of anaerobic digestion [Tcha-Thom, 2019].

Since a decade the Cameroon Government, through the Ministry in charge of Environment, has allocated an average of US$5 million per year to fight against water hyacinth and other invasive aquatic plants invading lakes and rivers. Despite this effort, water hyacinth remains a major challenge for aquatic ecosystems, due to its rapid growth and ability to rapidly invade new areas. In the study area, water hyacinth is considered as a major sanitation problem. In the other side, the study area possesses large farms of palm oil trees. A study by Nkongho et al. [2014] estimated that the annual production of waste from Oil palm farms (stalks, leaves, empty bunches, etc.) amounted to approximately 1.2 million tonnes in 2013 in this region. These large quantities of waste present a significant challenge in terms of environmental management, as a substantial portion of it is still disposed of in landfills or burned, resulting in adverse effects on the environment. The rapid growth of the urban population is leading to a growing imbalance between supply and demand for urban services and facilities, resulting in heavy pressure on existing infrastructure and increased waste production [Ngambi, 2016; Ngnikam et al., 2016; Sotamenou, 2018]. The city of Douala alone produces daily more than 2,000 tonnes of waste [Tchoupou and Ngnikam, 2017]. Many neighbourhoods in Douala still do not benefit from a regular waste collection service. The waste management system in place in Cameroonian cities, and by extension the city of Douala, is ineffective [Nguema et al., 2021].

Several SDGs are concerned by this research and the possible targets are plenty. With the purpose of contributing to the achievement of one of the Sustainable Development Goals, particularly SDG7 (affordable and clean energy), the aim of this study is to assess the fermentable fraction of organic wastes into biogas.

MATERIALS AND METHODS

Data collection

Water hyacinth was collected during campaigns to remove aquatic invasive plants from the banks of the Wouri River (Figure 1a). The household waste (HW) came from the restaurant of the University of Douala and from a small fruit juice production unit in the town (Figure 1b). Oil palm waste (OPW) was collected in a palm farm in a village called Londo-Bwapaki, about 40 km, NW of Douala. This oil palm waste consists mainly of the straw from sieving the palm nuts (Figure 1c). These wastes were chosen because of their availability in the study area.

Cow dung was used as the inoculum, although anaerobically digested sewage sludge is one of the most effective inocula for biomethanisation [Lübken et al., 2010]. Ruminant manure, particularly cow manure, is also an excellent inoculum due to its high concentration of methanogenic microorganisms [M'sadak and Baraket, 2014]. The availability of the inoculum and its cost have been identified as key factors influencing the choice of cow manure as an inoculum [Angelidaki and Ellegaard, 2003]. Cow dung was collected from the municipal slaughterhouse, then preserved in sterilised polystyrene bags and transported to the Plant Biology and Physiology Laboratory at the University of Douala on the day the methane fermentation process commenced. The substrates were manually cleaned of all inorganic waste by selective sorting, dried at a natural temperature, and then crushed by an artisanal grinder.

Substrate characterisation

Prior to any anaerobic digestion operation, it is of the utmost importance to conduct a physico-chemical characterisation of the samples to assess the methanogenic potential of the substrates, optimise the anaerobic digestion conditions, identify potential inhibitors, and ensure effective management of the organic waste [Mata-Alvarez et al., 2000; Angelidaki and Sanders, 2004; Zhang and Banks, 2008]. To achieve this goal, different parameters were measured including dry matter, volatile matter, carbon, nitrogen, and mineral elements.

Dry matter content (%)

The dry matter (DM) content was determined according to standard (ISO 11465). Twenty grams of gross mass (GM) were taken from each sample and placed in an oven at 105 ± 2 °C for 24 hours. The corresponding DM values were obtained by successively weighing the samples before and after oven drying. The dry matter content was determined using the formula

$$DM(\%) = \frac{M2}{M1} \times 100 \quad (1)$$

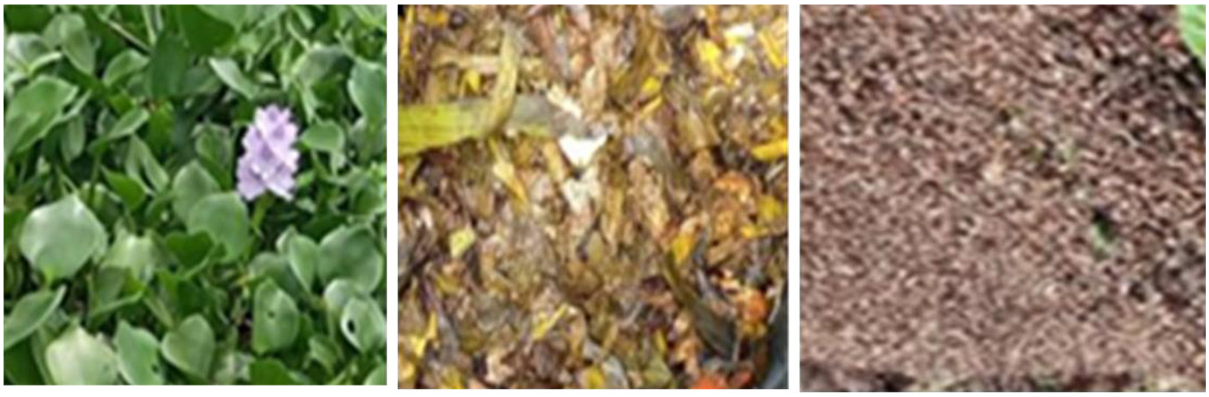
where: $M1$ – fresh mass of the sample; $M2$ – mass after removal from the oven.

Volatile dry matter rate

The volatile organic pool was evaluated using the NFU 44160 procedure. Previously desiccated samples were calcined in a muffle furnace at 550 °C for 4 hours. The loss of mass, in relation to the quantity of dry matter, corresponds to the volatile dry matter (VDM) rate. The calculation is performed using the formula VDM (%), which is defined as:

$$VDM(\%) = \frac{M2-M3}{M2} \times 100 \quad (2)$$

where: $M2$ – mass after removal from the oven, $M3$ – mass at the oven outlet.



(a) (b) (c)

Figure 1. Substrates used: a) water hyacinth; b) household waste; c) oil palm waste

Total ash

Total ash was determined according to standard (NF ISO 21656). It was carried out by placing the dry sample in a crucible in a muffle furnace at 600 °C for 5 hours until a light grey or whitish colour was obtained. The contents were expressed as percentages on a dry basis. The percentage of ash is therefore

$$A(\%) = \frac{M4}{M2} \times 100 \quad (3)$$

where: *M*2 – dry mass of the sample; *M*4 – mass leaving the furnace.

Total organic carbon

Total organic carbon (TOC) was determined by titration. A solution of potassium dichromate was added to 20 g of the sample in the presence of sulphuric acid. After the reaction, the TOC concentration was determined by measuring the amount of dichromate that did not react with the sample [Koirala and Khadgi, 2017]. Total carbon is calculated using the Formula

$$TOC = \frac{(A-B)\cdot 10 \cdot 0.004}{P\cdot A} \quad (4)$$

where: *TOC* ($gC\cdot kg^{-1}MS$) – organic carbon concentration; *A* – volume of potassium dichromate used for the control (ml); *B* – volume of dichromate used for the sample (ml); 0.0004 – number of grams of C per ml of dichromate; *P* – sample mass.

Total nitrogen (NTK)

The technique used is the Kjeldahl method [Bremner, 1966]. This method consists of a titration analysis in 3 successive steps. Firstly, mineralisation: the organic nitrogen in the sample is mineralised by boiling sulphuric acid at 400 °C in the presence of a selenium and potassium sulphate catalyst to produce ammonium, followed by distillation: The ammonium is distilled in the presence of excess sodium hydroxide to give ammonia, which is recovered by condensation; finally, the condensed ammonia is titrated by dissolution in boric acid. The resulting solution was titrated with hydrochloric acid. The total nitrogen was calculated using the Formula:

$$NTK = \frac{(v0-v2)\cdot c1 \cdot M}{m} \quad (5)$$

where: *NTK* ($gNTK\cdot kg^{-1}MS$); *V*0 – volume in ml of the sodium hydroxide solution required for the blank; *V*1 – volume in ml of the sodium hydroxide solution required for the determination of the sample; *C*1 – concentration in moles per litre of the sodium hydroxide solution; *M* – molecular weight of nitrogen (*M* = 14 g/mol).

Mineral elements

The EDX-7000 series energy dispersive X-ray fluorescence spectrometer was used to determine all the minerals of the substrates qualitatively and quantitatively between 11 (Na) and 92 (U) in the periodic table [Shimadzu, 2013]. It is used for non-destructive elemental analysis of solid, powder and liquid samples. When a sample is irradiated with X-rays from an X-ray tube, the atoms in the sample produce individual X-rays that are emitted from the sample. These X-rays are known as 'fluorescent X-rays' and have a unique wavelength and energy characteristic of each element that produces them. Qualitative analysis can therefore be carried out by studying the wavelengths of the X-rays, the intensity of the fluorescent X-rays being a function of the concentration. Quantitative analysis is also possible by measuring the quantity of X-rays at the wavelength specific to each element. It measures the energy (kev) and intensity of the fluorescent X-rays produced to determine the nature and content of the elements in a sample.

Biogas potential of substrates

Experimental design

Tests were carried out in batch-type biodigesters adapted from the model of Doerr and Lehmkuh [2008]. These biodigesters consisted of three blocks: a fermenter with a capacity of 250 l, an air chamber for biogas storage, and a burner (Figure 2). The three units were connected by pipes with floodgates. Batch digesters are characterised by a single loading operation of substrate, inoculum and, in some cases, a chemical additive (usually alkaline). Once filled, the digester is sealed until fermentation is complete. The process is carried out over a period of 90 days.

Preparation of the raw material

The pre-treated substrates (WH, HW, OPW and MS) were introduced into the corresponding digester at 15 kg DM each, together with 20 litres of methanogenic bacterial slurry (seeding) obtained from bovine rumen residues. Subsequently, 132 litres of tap water were added to fill the digester to 2/3, resulting in a water dilution of 90% [Afilal et al., 2013]. The system was installed outdoors at room temperature.

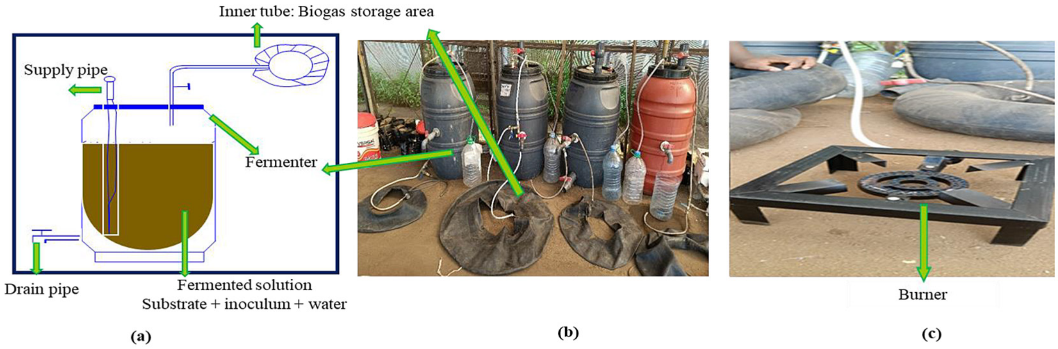


Figure 2. Batch-feed digester: a) Schematic illustration; b) Field experiment and c) Burner

Progression of few biodigestion parameters

- Hydrogen potential (pH) – hydrogen potential is a very interesting indicator of the stabilisation and smooth running of anaerobic digestion, providing information on the acidity or alkalinity of the fermentation medium. The pH was measured weekly using a precision multi-parameter from Hanna Instruments model number HI98127.
- Chemical oxygen demand – the organic pollutant load is usually determined by chemical oxygen demand (COD). This is a measure of the amount of oxygen required to oxidise the organic and oxidisable inorganic matter in a sample. It can also be used to assess the organic loading and biodegradability of a substrate [Tcha-Thom, 2019]. The Hanna Instruments test kit, based on the potassium dichromate photometric method, was used [Li et al., 2018].

Characterisation of the biogas produced

The biogas produced was determined using two tests. The "quantitative test", which is an estimation of the biogas produced, is carried out firstly by observing the swelling of the air chamber with the naked eye [Nelson and Cox, 2017]. Secondly, by weighing the mass (kg) of biogas every two weeks using a sensitive balance. This was done by measuring the empty mass of the air chamber and subtracting it from the mass of the entire air chamber. The "qualitative test" has concerned the composition of the biogas. This was analysed using a biogas detector (H_2S, O_2, CH_4 and CO_2), an infrared absorption analyser, model number IRCD4. This allows the different components of a gas sample to be separated based on their steric configuration and polarity. Gaseous samples are introduced by aspiration using a pump at a pressure of less than 1500 mbar. The actual presence of a combustible gas was confirmed by *in situ* combustion every two weeks [Nelson and Cox, 2017].

Statistical analysis

Data were introduced to Excel 2013 software for descriptive analysis and graphical representation. The data obtained were also subjected to other analysis using the SPSS software, version 26.1 IF006. The Duncan's parametric test was employed for the purpose of comparing the mean methane production between substrates.

RESULTS

Physico-chemical characteristics of substrates

The physico-chemical parameters of the substrates were evaluated in terms of pH, DM, VDM, C/N ratio and mineral elements. This highlighted the primary characteristics of the substrates to be digested and identified alternatives that could guide the subsequent phase of the substrate study. The results of these overall parameters are shown in Table 1.

All the substrates sampled had a hydrogen potential around neutral, with values of 7.3 ± 0.8 for (WH), 7.50 ± 0.10 for (OPW), 7.7 ± 0.5 for (MS) and 7.80 ± 0.02 for (HW). The dry matter content of the waste exhibited a considerable range, from 7.6 ± 1.5% (for WH) to 58.9 ± 1.4% (for OPW). The volatile dry matter (VDM) content demonstrated a similarly broad spectrum of values, from 30.52 ± 7.58% (OPW) to 63.17 ± 4.57% (HW).

About the C/N ratio, the WH substrates exhibited a C/N ratio between 10 and 20, with a mean value of 18.50 ± 2.78. In contrast, the OPW and MS substrates exhibited a C/N ratio > 40, with a mean value of 289.08 ± 1.88 and 1589.12 ± 738.41, respectively. HW substrates have a C/N ratio of 21.153 ± 0.695

Table 1. Physico-chemical parameters of substrates

Parameter	WH	HW	OPW	MS
Global analysis				
pH	7.3 ± 0.8	7.8 ± 0.02	7.5 ± 0.1	7.7 ± 0.5
DM (% MB)	7.6 ± 1.5	19.8 ± 1.0	58.9 ± 1.4	28.3 ± 0.9
VDM (% MS)	36.3 ± 3.5	63.2 ± 4.6	30.5 ± 7.6	37.8 ± 5.6
TOC (g.kg-1MS)	212.9 ± 38.1	258.0 ±15.6	184.7 ± 22.7	254.0± 1.8
NTK (g.kg-1MS)	11.5 ± 0.3	12.2 ± 0.3	0.64 ± 0.1	0.2 ± 0.1
C/N	18.5 ± 2.8	21.2 ± 0.7	289.1 ± 1.9	1589.1 ± 738.4
Ash (% MS)	23.9 ± 2.4	15.5 ± 1.1	42.5 ± 0.04	16.3 ± 1.3
Analysis of mineral elements				
K (% MS)	39.9 ± 1	69.8 ± 0.1	9.9 ± 0.04	34.4 ± 0.1
Ca (% MS)	22.32 ± 0.05	16 ± 0.04	11.1 ± 0.03	22 ± 0.1
Fe (% MS)	15.8 ± 0.02	6.6 ± 0.02	32.3 ± 0.04	25.2 ± 0.04
Si (% MS)	1.9 ± 0.1	3.4 ± 0.04	28 ± 0.2	8.9 ± 0.1
Cl (% MS)	14.7 ± 0.06	/	/	/
Mn (% MS)	3.2 ± 0.01	0.5 ± 0.01	0.5 ± 0.01	1.9 ± 0.01
Ti (% MS)	0.8 ± 0.009	1.6 ± 0.02	9.5 ± 0.04	5.02 ± 0.03
S (% MS)	0.6 ± 0.01	0.7 ± 0.01	1.6 ± 0.02	1.1 ± 0.01
Cu (% MS)	0.1 ± 0.004	0.2 ± 0.008	0.2 ± 0.008	0.2 ± 0.007
P (% MS)	0.1 ± 0.02	0.2 ± 0.02	0.4 ± 0.04	0.2 ± 0.03
Sr (% MS)	0.2 ± 0.002	0.1 ± 0.004	0.1 ± 0.004	0.2 ± 0.004
Al (% MS)	/	Traces	5.177 ± 0.321	/
Br (% MS)	0.1 ± 0.003	0.1 ± 0.005	/	0.1 ± 0.004
Nb (% MS)	/	/	0.2 ± 0.004	/
Ar (% MS)	Traces	/	/	Traces
Cr (% MS)	/	/	0.1 ± 0.008	/
Rb (% MS)	0.1 ± 0.002	0.3 ± 0.005	0.1 ± 0.005	0.1 ± 0.004
Rh (% MS)	Traces	Traces	Traces	Traces
Te (% MS)	/	Traces	/	/
Eu (% MS)	Traces	/	/	/
V (% MS)	0.1 ± 0.008	/	/	0.2 ± 0.013
Zn (% MS)	0.2 ± 0.004	0.1 ± 0.006	0.2 ± 0.007	0.2 ± 0.006
Zr (% MS)	0.01 ± 0.002	/	0.7 ± 0.006	0.4 ± 0.004

which is within the optimal range for methanisation (situated between 20 and 30). A mineral analysis of different substrates revealed a high diversity of mineral elements. A total of 23 elements were reported.

Determining the biogas potential of substrates

Progression of a few biodigestion parameters

- Variation in hydrogen potential – the hydrogen potential is a crucial parameter in the anaerobic digestion process, as methanogenic organisms are highly susceptible to pH fluctuations. Figure 3 illustrates the pH evolution in the four reactors WH, HW, OPW and MS. During the fermentation process, there is a slight decrease in pH during the initial seven-day period, followed by an increase in pH and its gradual stabilisation around neutrality for the remainder of the fermentation period.
- Variations in COD – the variations in COD for the four reactors as a function of time are shown in Figure 4. These variations in chemical oxygen demand began with the following values: 2401.00 ± 7.55 g O_2/l; 1300.67 ± 4.04 g O_2/l; 1494.33 ± 6.03 g O_2/l; 1498.67 ± 9.07 g O_2/l for (WH), (HW), (OPW) and (MS) respectively.

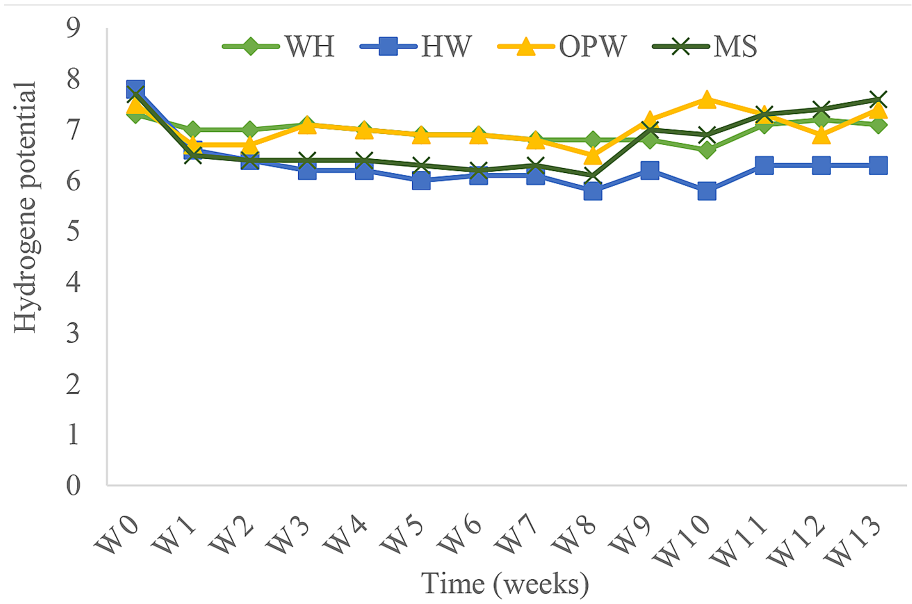


Figure 3. Changes in pH during the fermentation process

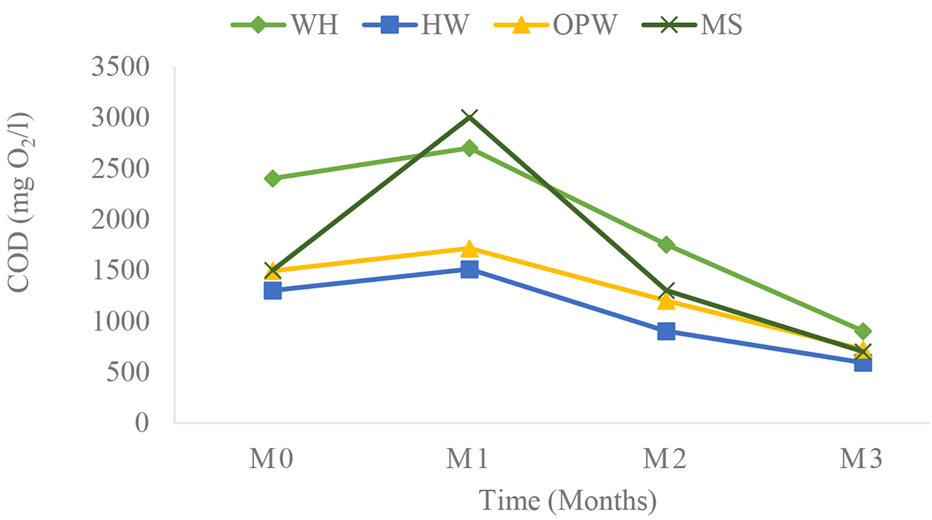


Figure 4. Changes in COD as a function of time

During the first month of fermentation, an increase in COD was observed, reaching a maximum at time (M1): 2699.67 ± 9.50 g O_2/l (WH); 1510.00 ± 10.00 g O_2/l (HW); 1714.67 ± 13.05 g O_2/l (OPW) and 3000.67 ± 9.02 g O_2/l (MS). Thereafter, a continuous decrease in COD values was observed until the third month, with a minimum of 591.33 ± 7.77 g O_2/l, obtained in the reactor containing the HW.

- The rate of reduction of organic matter – the degradation of organic matter led to abatement rates of the order of 37.55 ± 0.12%; 45.46 ± 0.60%; 48.27 ± 0.34% and 46.71 ± 0.26% respectively for WH; HW; OPW and MS (Figure 5).

Characterisation of the biogas produced

- Quantitative test – the biogas production did not start quickly, with the first data recorded after two weeks of fermentation. During the 12 weeks of digestion, the largest quantities of biogas production were all recorded between weeks 4 and 8 (Figure 6). The maximum production values were recorded in the 6th week: (0.65; 0.44; 0.15 and 0.11 kg) respectively for (WH, HW, OPW and MS)

Figure 7 shows the cumulative biogas production from the four types of substrates. These biogas production kinetics are divided into three main phases:

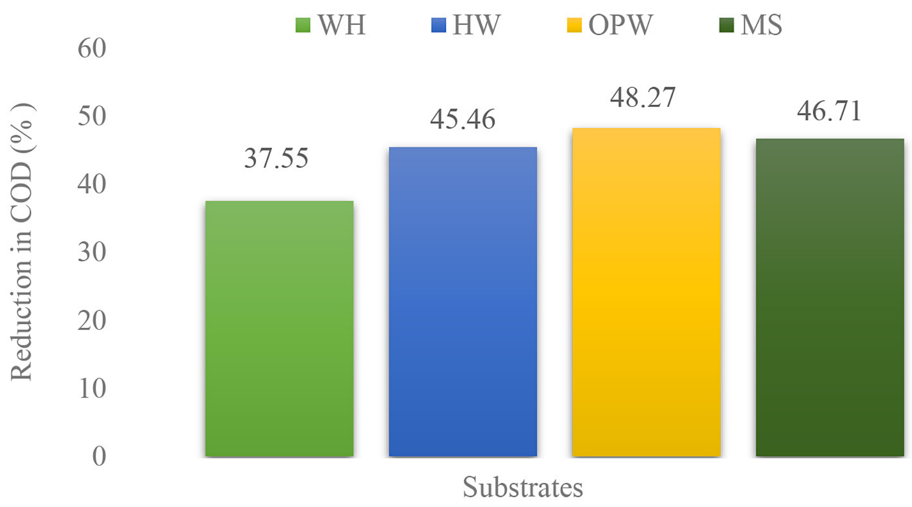


Figure 5. COD abatement rate

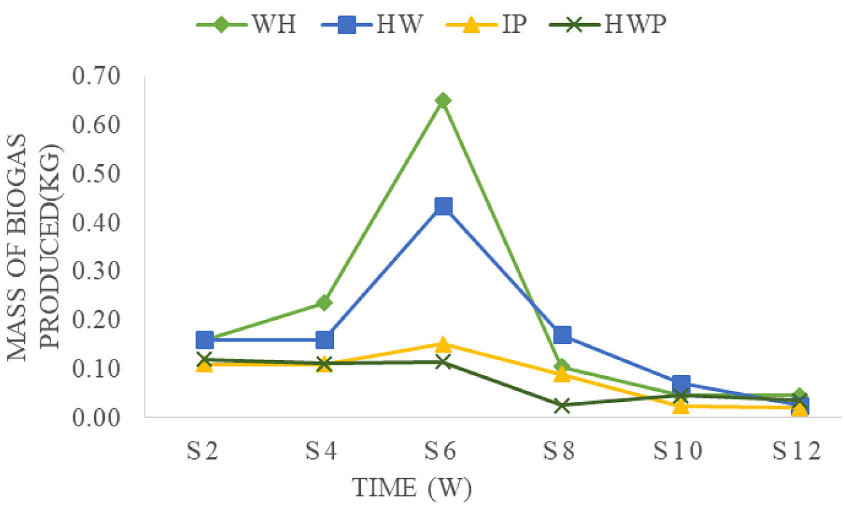


Figure 6. Biogas production as a function of time

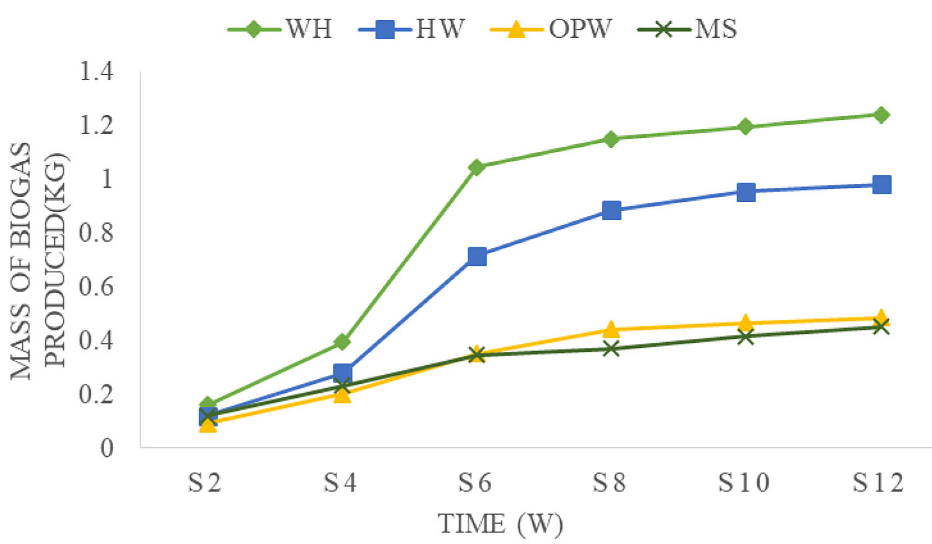


Figure 7. Biogas accumulation as a function of time

the first corresponds to the latent phase, which lasted for a very short time (less than two weeks); the second is the optimal production phase, which lasted from the fourth to the eighth week; and finally, the third phase, which is the stationary phase. This phase was reached after eight weeks of fermentation. The final biogas production for the WH, HW, OPW and MS substrates is 1.24 kg, 0.98 kg, 0.45 kg and 0.485 kg respectively. The substrates studied are favourable for biogas production (Figure 8).

- Qualitative testing of the biogas produced – the primary interest in anaerobic digestion lies in the biogas produced, which is assessed essentially by its methane content Figure 9. As with cumulative biogas production, this phase also reveals three main phases. Firstly, the latency phase, from the start of fermentation to the fourth week of fermentation. This is followed by the exponential production phase, when methane production is at its peak, from the 4th to the 8th week. Finally, there is the plateau phase, when stability is reached after eight weeks of fermentation.

The CH_4 compositions of the biogas samples were 86% WH), 78% (HW), 99% (OPW) and 87.7% (MS) Figure 10. Duncan's parametric test showed a significant difference between (HW) and (OPW). However, no significant difference was observed between (WH) and (MS) at P = 0.05. The results of the combustibility test obtained during this experimental study show that biogas produced from different types of substrates is combustible with blue-coloured flames Figure 11b.

DISCUSSION

The results of the physico-chemical characterisation of the different substrates show that the hydrogen potential of all the substrates is neutral, which means that all these substrates are easily digestible. This result could be explained by the presence of certain minerals in the substrates, such as silica and alumina, which have a low affinity for H^+ and OH^- ions, giving them the ability to maintain a neutral pH when in contact with water [Nelson and Cox, 2017]. These results are like those obtained by Tcha-Thom [2019] on unstored slaughterhouse substrates and stored slaughterhouse substrates with pH values of 7.7 ± 0.5 and 7.7 ± 0.6, respectively.

The dry matter content shows that the water hyacinth substrate has a very high-water content (DM = 7.6 ± 1.5%), certainly due to its living environment (aquatic plant). This result is like that reported by Lacour [2012] for cabbage (9.3%).

The evaluation of the volatile dry matter content is a very practical data in the implementation of methane fermentation, which was between 30.52 ± 7.58% (OPW) and 63.17 ± 4.57% (HW). These levels are relatively low compared to those reported by Ukondalemba et al. [2016].

The C/N ratio showed that the water hyacinth substrates contained an excess of nitrogen, while those of oil palm waste and the mixture (MS) have had deficient. These values are higher than those reported by Kra et al. [2018], who also had a nitrogen deficiency of 198.23 and 180.29

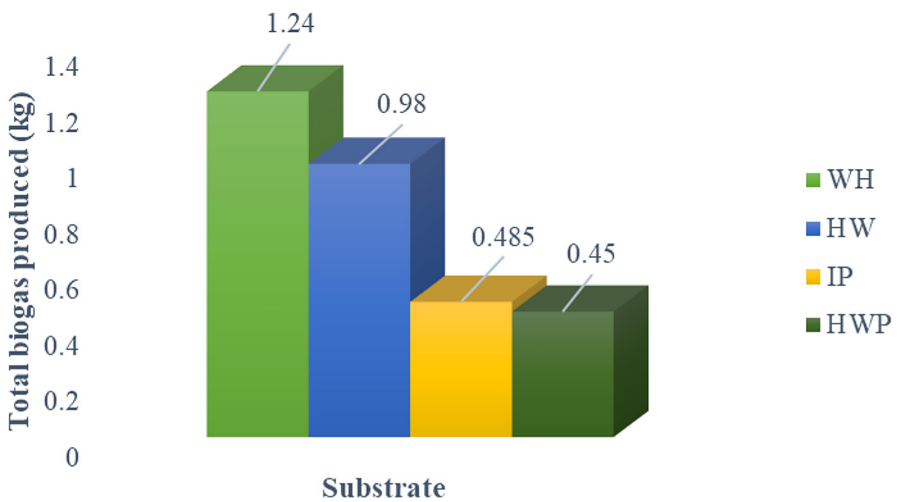


Figure 8. Final biogas production from substrates

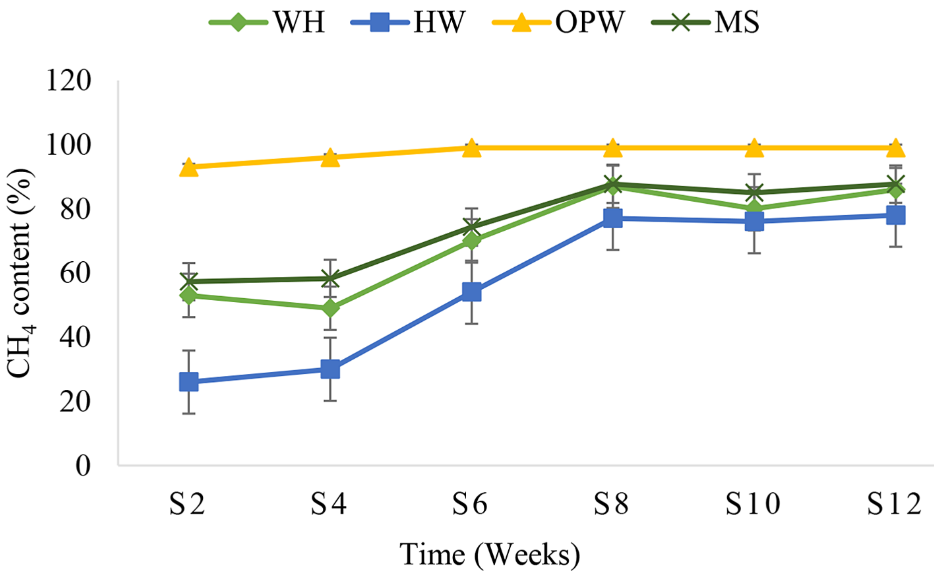


Figure 9. Trends in methane content of biogas from different reactors

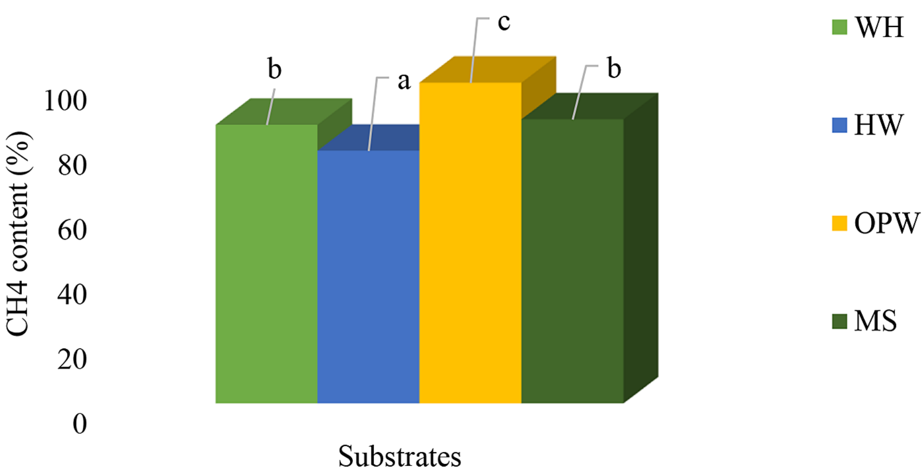


Figure 10. Methane content of biogas from different substrates

Figure 11. Final illustrations of the experimentation: a) air chambers filled with biogas; b) flames showing the combustion of biogas produced

for cassava juice and cassava peels, respectively. Only household waste had an optimal C/N ratio for anaerobic digestion, falling within the range of 20 to 30. This is because these extreme values ensure the biological stability of the system [Gunaseelan, 2004]. A high C/N ratio indicates that methanogenic bacteria will consume nitrogen rapidly to satisfy their protein requirements. Consequently, the carbon will not be degraded, which, according to Chandra et al. [2012], will result in a low biogas production rate.

Conversely, if the C/N ratio is very low, nitrogen will be released and accumulate in the form of ammonium (NH_4^+). Excessive NH_4^+ formation leads to an increase in the pH of the medium through the formation of the NH3 form. Above a pH of 8.5, toxic effects on methanogenic bacteria appear [Chandra et al., 2012; Akindele and Sartaj, 2017]. Only the DM substrate has a suitable C/N ratio for anaerobic digestion. The characterisation of the solid matrix of substrates enables the constraints of the biomethanisation process to be anticipated [Jabeen et al., 2015].

The high mineral diversity plays an essential role in methane fermentation, as evidenced by the findings of Angelidaki and Sanders [2004], who have demonstrated that these minerals are essential for the optimal functioning of the microorganisms involved in fermentation. This phenomenon is exemplified by the case of potassium, which was the most prevalent element in all the substrates, except for oil palm waste. This element plays a major role in several crucial stages of the methanisation process. Yu et al. [2017] highlight the role of potassium in the activation of enzymes, maintenance of ionic balance, stimulation of microbial growth and reduction of methanogenesis inhibitors. Phosphorus is an important element in the production of adenosine triphosphate (ATP), the main source of energy used by methanogenic microorganisms. Batstone et al. [2002] indicate that the growth of methanogenic bacteria is enhanced by the provision of phosphorus, which has a knock-on effect on methane production. Considering the aforementioned results, it is evident that the various substrates were complex, essentially organic materials, each exhibiting its own biomethanogenic potential.

The reduction in pH observed during the first week can be attributed to the decomposition of organic matter, which results in the formation of volatile fatty acids and an increased release of CO_2 within the reaction chamber, this indicates the commencement of the hydrolysis and acidogenic phases. Its stabilisation to a neutral level is justified by the fact that the methanogenic bacteria consume VFA to produce biogas [Budiyono et al., 2013]. It is important to note that anaerobic digestion processes are strongly influenced by pH. Anaerobic digestion is most optimal when occurring in a neutral pH environment, with values between 6.5 and 8.5 [Almansour, 2011]. Significant fluctuations in the pH of the reaction medium have been shown to inhibit microbial activity, consequently reducing biogas production.

The observed increase in chemical oxygen demand during the first month of the process is indicative of the exponential growth of the microorganisms involved in the first two phases of biomethanisation (hydrolysis and acidification). This growth is particularly evident in the acidogenic microorganisms. The growth rate is particularly rapid during the initial 48 days of the process, which is consistent with the findings of Hess [Hess, 2007] who posits that microorganisms are responsible for the organic overload. The gradual reduction in the organic load until the organic matter is exhausted is indicative of biogas production. The results demonstrate an abatement rate of approximately 37.55 ± 0.12% for water hyacinth and 48.27 ± 0.34% for oil palm waste. These values indicate that anaerobic digestion is an effective method for controlling organic pollution. Tahri et al. [2016] reported lower values for trials conducted on potato waste. In contrast, Zerrouki et al. [2017] observed an organic load removal rate of approximately 60% in the case of anaerobic digestion of orange juice.

Regarding the characteristics of this biomethanisation phenomenon, it is evident that the cow's purse, which has been inoculated with the substrates, exhibits a high diversity of microorganisms. This diversity ensures the production of biogas under a wide range of environmental conditions.

Microbial communities play a pivotal role in the biomethanisation process, with their composition, dynamics, adaptation, and interactions exerting a profound influence on the observed performance and results. A diverse microbial community is conducive to more efficient degradation of organic matter and enhanced methane production [Güllert et al., 2016]. The relative abundance of different microbial groups (bacteria, methanogenic archaea, etc.) can influence the stages of the methanisation process and biogas production [Astals et al., 2015]. As with any biological process, the presence of water is a fundamental requirement. A humidity level of 60–70% is considered the minimum requirement. It is necessary that the waste be sufficiently moist for hydrolysis to occur in a normal manner. Conversely, if the substrate is deficient in moisture, acidification will occur at an accelerated rate, which is detrimental to methanogenesis. Therefore, the optimal substrate concentration is 85 to 90% water with 10 to 15% dry matter [Almansour, 2011].

The expansion of the air chambers is indicative of microbial activity. The production of biogas, resulting from methanogenic fermentation, was observed for all the substrates tested. The highest values for biogas production were recorded between weeks 4 and 8, which corresponds perfectly with the kinetic trends observed for chemical oxygen demand. The decline in COD values observed after the fourth week was accompanied by an increase in biogas production, with peaks recorded in the sixth week for all substrates. The pronounced fluctuations in biogas production observed between the different substrates can be attributed to the physico-chemical characteristics of the substrates. These results align with the findings of numerous authors who have demonstrated the energy potential of biomass [Sakouvogui et al., 2021; Almoustapha et al., 2008; Sawadogo et al., 2023]. Sakouvogui et al. [2021] have demonstrated the efficacy of biogas production from pig slurry and cow dung in mono- and co-digestion. Almoustapha et al. [2008] have demonstrated the potential for biogas and compost production from water hyacinth, while Sawadogo et al. [2023] have investigated the anaerobic co-digestion of cashew nut agro-industrial waste with organic waste.

The kinetics of methane production reveal three phases. The first, known as the latency phase, with little growth observed, is due to the action of microorganisms of the hydrolytic and acidogenic family. However, Mosey [1983] points out that these microorganisms can be facultative anaerobes as well as strict anaerobes, and produce carbon dioxide during these reactions. This phase is followed by an increase in methane production, which can be attributed to the proliferation of methane-producing bacteria. Finally, a plateau phase ensues during which the biomass is exhausted. The quality of biogas is primarily assessed based on its methane content. According to Akrout [1992], biogas is of superior quality when its methane percentage is high. In this study, the proportions of biogas obtained for the WH, HW, OPW and MS substrates were 86%, 78%, 99% and 87.7% respectively. The observed outcomes can be attributed to the fact that the samples underwent a preliminary purification process to eliminate impurities, in addition to their elevated VDM content.

The results obtained are comparable to those reported by Konaté et al. [2013], who observed an 80.5% efficiency under Sahelian conditions for the treatment of domestic wastewater, and Picot et al. [2003], who reported an 83% methane yield under Mediterranean conditions for the treatment of urban wastewater. Biogas is a combustible gas mixture if the methane content is greater than or equal to 50%. The combustion of biogas is characterised by the release of a yellow or blue flame, depending on the methane content. The combustion of the biogas produced by the four substrates results in a continuous blue flame. These results are consistent with those of Bong et al. [2017], who state that a persistent blue flame confirms the presence of a significant proportion of methane, i.e. 50% or more. These findings are also consistent with those of Luboya et al. [2020], who similarly demonstrate that for this proportion of methane, biogas is flammable.

CONCLUSIONS

Biomethanisation is a technology for the treatment of the organic fraction of biomass used for environmental protection and resource conservation. In this process, organic matter is converted by the action of microorganisms into energy. The objective of this study was to assess the fermentable fraction of organic wastes into biogas to contribute to the production of clean and affordable energy. The results have shown the relevance of bio-digestion and the potential availability of biogas in different substrates. Upon completion of the fermentation process, a pronounced degradation of organic matter was observed. The four air chambers were filled with flammable biogas, with methane contents over 78%. The biomethanisation of organic waste represents a promising technology to produce biogas, which can be utilised as a source of renewable energy. The data obtained in this study could be used to launch large-scale pilot initiatives, given that the inputs selected here are abundantly available in the study area and produce high-quality biogas with a methane content of approximately 80%. From a concept to solve a sanitation problem, this survey has led to produce clean and renewable energy, contributing thereby modestly to several SDGs targets.

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