

Energetic Balance of Biogas and Fertilizing Potential of Digestate from Anaerobic Digestion of *Manihot Utilissima*

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Abstract

Optimal scale production of biogas from the anaerobic digestion (AD) of organic wastes (OWs) as substrates has become one of stimulating environment-friendly procedures to foster the replacement of fossil energies by renewable ones. AD of OWs generated from households is desirable as an effective method to fight against environmental pollution effects of the latter in developing countries. Notably in Africa where each year there are more than 600,000 premature deaths following the use of solid biomass energy (especially charcoal). Yet, if assessing the potential of biogas production, that is, biochemical methane potential (BMP) has played a prominent role in the choice of substrates, in the other hand the evaluation of the optimal ratio between the quantity of variety OWs and the amount of energy to be produced has not received several attentions. The latter is valuable not only for energetic productivity but also for profitability. Thus, in this report, an energetic balance between the amount of leaves and stems of *Manihot Utilissima* (MU) annually produced as well as the energetic potential of their biogas were investigated. Cow manure (CM) was employed as inoculum, under mesophilic conditions of the collection sites: Ngaba and Ndjili in Kinshasa City Province (KCP), Congo DR, where the leaves and stems of MU are among the most generated wastes. Furthermore, we evaluated the fertilizing potential of digestates from the AD of the leaves and stems by their Carbon/Nitrogen (C/N) ratios.

The annual energetic potentials of biogas produced were estimated to be $1.362 \pm 0.028 \cdot 10^9$ kWh for the leaves and $0.337 \pm 0.006 \cdot 10^9$ kWh for the stems. These were associated to the energy needs for the KCP households corresponding to the use of charcoal. The latter was evaluated to be $166 \cdot 10^3$ tons for leaves and $41 \cdot 10^3$ tons for the stems of MU, respectively.

The fertilizing potential of digestates from the AD of the leaves and stems of MU assessed by their C/N ratios were determined to be 5 and 10, respectively; indicating that they are favorable for the cultivation of vegetables and fruit trees in KCP soils (C/N ~ 5) but also optimal for the organisms, soil conditioning and could improve the soils hydraulic conductivity (C/N ~ 10).

1. Introduction

Large cities in Sub-Saharan Africa, like KCP, Capital of Democratic Republic of Congo (DRC), are facing a dramatic population explosion (Khennas 2012; Hanif 2018; Mambanzulua et al. 2015a). This is the result of the increasing of rural-urban migration and the displacement of people from areas of armed conflicts such as the Eastern part of the DRC. Those displacements cause anarchic subdivisions in the peri-urban green spaces and increase crops and energy consumption in KCP (Hanif 2018; Mambanzulua et al. 2015a, b). Therefore, in KCP there is an increase in the production of improperly managed wastes, deforestation and decreasing areas of arable lands which are otherwise infertile (Hanif 2018; Mambanzulua et al. 2015a, 2015b; Barrios et al. 2006). In fact, the KCP produces annually about 3 million tons of wastes whose management is arduous. These wastes contain almost 55% of OWs, 94% of which are essentially vegetal sources (Mambanzulua et al. 2015a; Ministère Provincial d'Environnement 2019; Mulaji 2017).

Fortunately, from OWs, the AD or biomethanation produces biogas that essentially contains methane, and accordingly can solve the above mentioned multiple social-induced environmental issues. The AD of OWs with high energetic potential offers the possibility to recycle nutrients and inherently reduces greenhouse emissions (Mambanzulua et al. 2015b; Chandra et al. 2012; Surendra et al. 2014; Barakat et al. 2012; Chaaban 2001). AD has shown through its high performance to be an attractive and eco-friendly method for the treatment of the fermentable wastes, through which one can control the inherent pollution and cover energetic needs (Oumar et al. 2012; Malta-alvarez et al. 2000; Ward et al. 2018; Wyman and Goodman 1993). This energy is renewable and its net CO₂ contribution to the atmosphere is nil. Moreover, it could keep KCP away from deforestation by providing its households with a form of clean energy for cooking; given nearly 80% of the population of KCP rely on ligneous biomass (mainly charcoal) to satisfy their energy needs (Khennas 2012; Hanif 2018; Mambanzulua et al. 2015a, b). The biogas obtained by biomethanation of these wastes, is a second generation biofuel. The latter is more advantageous than the first or third generation biofuels (Hanif 2018; Mambanzulua et al. 2015b; Chandra et al. 2012). As an advantageous energy source, biogas is widely considered as a suitable fuel for heating facilities, power generation, and vehicles (Li et al. 2017; Galvagno et al. 2007; Shan et al. 2016). The residues or digestates that are generated from the AD are employed as an eco-friendly fertilizer; that could enable to avoid the non-environmental-friendly or traditional one that uses fire in agriculture, and consequently to protect the bio-diversity (Hanif 2018; Mambanzulua et al. 2015b; Koszel and Lorencowicz 2015).

MU is widely cultivated in the world (Han et al. 2011; Bell et al. 2000) and 11% of the global crops is owned by DRC, which is the second African producer after Nigeria (Bell et al. 2000). The MU is very cultivated in the world because it contains abundant nutrients and in DRC it rapidly grows in marginal land like the KCP soils (Mambanzulua et al. 2015a, 2015b; Han et al. 2011; Bell et al. 2000). The increase in MU plantation is highly beneficial for economic development (Han et al. 2011; Bell et al. 2000).

The leaves and stems of MU are one of the most abundant among the vegetable wastes produced in the KCP (Mambanzulua et al. 2015a, 2015b; Ministère Provincial d'Environnement 2019; Mulaji 2017). Mambanzulua et al. (2015b) previously investigated the energetic potential of the biogas from the leaves of MU. In his report, the AD was achieved by heating the reactor at 30 °C (the ambient temperature in tropical areas like KCP) and using an anaerobic sludge as inoculum. The latter was taken from an anaerobic digester treating agro-food organic wastes. It was inoculated before with a sludge collected from a full-scale anaerobic digester treating an activated sludge from a municipal waste water treatment plant. The reported results showed that leaves of MU were favorable for the AD under mesophilic conditions.

Indeed, the leaves of MU are often accompanied with their stems in the garbage dumps of KCP. However, the AD of stems of the MU at ambient temperature is still not carried out and has remained uninvestigated. The energetic balance of the leaves and stems of MU produced were not evaluated. Furthermore, the characterization of the fertilizing potential of their digestates and the arable land surfaces to be fertilized by these fertilizers were not experimentally assessed.

Thus, the main goal of the present investigation was to assess energetic potential of the biogas from the AD of leaves and stems of MU as well as the energetic balance between the biogas and the quantities these wastes annually produced in KCP. The substrates were sampled in two municipalities of the KCP: Ngaba (Rond point Ngaba Market) and Ndjili (Quarter 9), which are the most densely populated. After determining the BMP of these two substrates owing to their AD, the energetic potentials of these wastes were thereafter evaluated. And knowing the possible annual quantity of these wastes produced in the KCP, we finally had to determine the energetic balance of the biogas from the wastes.

Furthermore, we evaluated the fertilizing potential of the digestates generated and the necessary arable land surface breadths to be fertilized by the latter. Since the nature of the inoculum also has a significant influence on biogas production for a given biomass (Mambanzulua et al. 2015b; Chynoweth et al. 1993; Rodriguez-Chiang and Dahl 2015; Lawal et al. 2016), the CM was used as inoculum under mesophilic conditions of the KCP. Moreover, in the KCP the CM is easily accessible; it is the most active inoculum in the KCP and more active than activated sludge (Oumar et al. 2012; Hussain and Dubey 2017; Ashekuzzaman and Poulsen 2011; Shin et al 2001). More importantly, this process is economically beneficial to implement in the developing countries of Sub-Saharan Africa like the DRC.

We have empirically demonstrated the broad spectrum of energy needs of the KCP households in charcoal that can be covered by the biomethanization of the stems and leaves of MU and the potential fertilizer of their digestates.

2. Materials And Methods

2.1. Substrates and Inoculum Sampling

Stems and leaves of MU were sampled in two municipalities of the KCP, in Ngaba: blue in the map (Rond point Ngaba Market) and in Ndjili: red in the map (Quarter 9) in DRC (Fig. 1A). The choice of these two areas is due to the fact that they are the most densely populated where there are major generation of wastes of MU. The stems and leaves (Fig. 1B-1C) were identified by the Herbarium at the Department of Biology, University of Kinshasa. These samples were washed, dried at the ambient temperature, ground and stored in plastic bags and used for analyses and further tests.

The CM (Fig. 1D) was collected from Slaughterhouse of Masina in Kinshasa. The collected CM was kept at ambient temperature in sealed plastic bags.

2.2. Characterization of the substrates and inoculum

2.2.1. Physical and chemical analysis of the substrates and the inoculum

The substrates and inoculum, that is, leaves and stems of MU, and CM, respectively, were characterized by determining the following parameters: dry matter or dry weight (DW), the ash content and the organic matter or volatile solid (VS) (SI1A-SI1C). The contents of dry matter, ash and organic matter were evaluated according to the standard methods, based on weight loss of heating/or sintering of sample-desiccator, and were operated in the Memmert oven (SI1A-SI1C) (Mambanzulua et al. 2015b; APHA 1992; Liu 2019). Prior, the values of dry weight and the ash weight were determined and then followed by the content of organic matter or volatile solid. The DW were determined by drying the samples (substrates and inoculum) at 105 °C in oven (Memmert) and monitoring the weight until the latter became constant (SI1A). Then, the ash content were determined by sintering the dried samples in furnace (Nabertherm) at 600 °C until the weights were constant (SI1B). The content of organic matter or volatile solid were obtained as the difference between the values of dry weight and the ash weight (SI1C). The contents in P and K were determined by the atomic absorption spectrophotometry (SI1D) (spectrophotometer, Perkin Elmer Analyst 200), while the Total Kjeldahl N (TKN) were determined by titrimetry (Mambanzulua et al. 2015b) (SI1E) and content in total organic carbon (TOC) were determined according to the method of Walkey and Black (Black and Evan 1965; De Vos et al. 2007) (SI1F).

2.2.2. Chemical analysis and bioactive substances in leaves and stems of MU

Except saponins, all the active chemical groups in the aqueous extracts of leaves and stems were identified by qualitative colorimetry as describe in literature (Mambanzulua et al. 2015b; Wagner and Bladt 1966) (SI2).

The saponins were determined by a semi quantitative method based on the formation of persistent foam of at least 1 cm height during 15 minutes when vigorously agitating 5 mL of aqueous extracts in a test tube (Mambanzulua et al. 2015b) (SI2).

2.3. Biochemical Methane Potential (BMP) and Energetic Balance

The Biogas and methane yields assays of stems and leaves of MU were determined by following the procedure described by Rodriguez et al. (2005) and Wang et al. (1994) (SI3). The tests were carried out in triplicate in 600 mL bottles filled with 500 mL of a mixture. The mixture consisted of 500 mL of phosphate buffer solution (with the pH adjusted to 7.5 with NaOH 3 N), 1250 mg dry weight (DW) of CM as inoculum and 6670 mg DW milled leaves or stems.

As positive control, we utilized 800 mg of cane sugar (CS, saccharose), 500 mL of buffer solution and 1250 mg DW of CM. The negative control sample consisted of 500 mL of buffer solution and 1250 mg DW of anaerobic sludge inoculum. No energetic substrate was added to the blank samples. Each test was performed in triplicate.

When the sample bottles were filled, they were capped tightly with rubber septa (Mambanzulua et al. 2015b; Amon et al. 2006). The bottles were then incubated at 25 °C, and the composition and volume of biogas produced were periodically measured during 128 days, in accordance to the method of CO₂ absorption by KOH (Mambanzulua et al. 2015b; Hiligsmann et al. 2011) (Fig. SI1).

Biogas or methane yield was calculated by dividing the biogas or methane volume (m³) by the weight (kg) of sample VS added to each bottle (Mambanzulua et al. 2015b; Wang et al. 1994; Banks and Heaven 2013). The balance between the amount of stems or leaves produced annually in the KCP and the annual energetic potential of the biogas resulting from their AD was calculated from their BMP and the Lower Heating Value (LHV) of methane (Li et al. 2017; Borja and Rincón 2017; Chen et al. 2008; Abbasi et al. 2012) (SI3).

2.4. Analysis of digestates

After 128 days of AD, the digestates were separated in liquid and solid residues by centrifugation and filtration on 0.2 µm cellulose acetate membrane for TOC, TKN, P and K analyses (Mambanzulua et al. 2015b) (SI1D-SI1F). The TOC and TKN were expressed relatively to the quantity of the digestates resulting from the inoculum, or from the total digestates (inoculum and substrates), or from the substrates alone by considering that the inoculum DW did not change after the digestion.

3. Results And Discussion

3.1. Biogas and methane production

The evolution of the biogas production was monitored in different digesters in order to assess the AD of stems and leaves of MU. Figure 2 shows the total cumulative volumes of biogas (Fig. 2A) produced and that of methane (Fig. 2B) obtained after purification of the biogas by the absorption of CO₂ by the KOH (Fig. SI1) versus time. Obviously, it is shown that no biogas production was detected for the blank samples or negative control (T-). After 128 days of AD, the total cumulative volume of biogas produced was observed to be 501.5 ± 8.5 mL for the positive control (T+), with a total volume of methane of 421.0 ± 13.0 mL. This corresponded to 84.0% of the biogas produced. The detection/or non-detection of biogas for (T+)/or (T-), respectively, enabled us to highlight the methanogenic activity of inoculum as well as the methanogenic potential of substrate. More importantly the fact that the biogas was not detected in (T-) make us sure and confident that all the biogas were produced from the AD of substrates. The total cumulative volume of biogas produced were evaluated to be 1144.5 ± 40.0 mL and 921.0 ± 31.0 mL for stems and leaves of MU, respectively. The cumulative amount of methane was 946.0 ± 18.0 mL for the stems of MU. That represented about 83.0% of methane in biogas. By contrast the amount of methane was 770.0 ± 16.0 mL for leaves of MU, representing about 84.0% of methane in the biogas.

The delay observed before the biogas production starts could be attributed to the concentration of organic matter in the substrates (VS). Indeed, the biogas production in the digester containing higher concentration of organic matter like the stems rapidly produced (10 days) the biogas after inoculation,

whereas the digester with lower content of organic matter lately produced (20–30 days) the biogas after incubation (Fig. 2A, B; Table 1). Although the pH conditions were suitable in the different digesters, that is, between 6.5 and 7.2 (Appels et al. 2008; Turovskiy and Mathai 2006; Zhang et al. 2013; Peng et al. 2014).

Table 1
Physical and chemical characterization of the substrates and the inoculum

Components	Substrates		Inoculum
	MU Leaves	MU Stems	CM
Dry weight (%)	80.8 ± 0.0	17.1 ± 0.4	21.6 ± 0.2
Organic matter (% DW)	85.2 ± 0.3	91.0 ± 0.2	16.1 ± 0.4
TOC (mg/g DW)	357.5 ± 14.3	530.5 ± 15.4	486.4
TKN (mg/g DW)	50.5 ± 0.8	23.8 ± 0.3	26.1
P (mg/g DW)	2.2	180.2	27.6
K (mg/g DW)	21.5	142.3	10.5
C/N	7	22	19
C/N/P	163/23/1	227/10/75	180/9/10

The physical and chemical analysis of the substrates (Table 1) showed that the MU stems contained lower amount of nitrogen, and high contents of carbon and mineral elements (K and P) compared to MU leaves. Moreover, the C/N ratio was in the optimal range (C/N: 20–30) for a good AD (Banks and Heaven 2013; Borja and Rincón 2017; Yen and Brune 2007; Akunna 2015). Biogas production containing 84% from cane sugar, which is free of nitrogen revealed that the inoculum contained nutrients capable to trigger the methanization.

Although the C/N ratio of the substrate has high influence on the AD process (Banks and Heaven 2013; Borja and Rincón 2017; Yen and Brune 2007; Akunna 2015), we also noticed that the proportion of methane in the biogas depended not only on the C/N ratio of the substrates, but also on that of the total composition in the digester. This was proved by the fact that the methane yield recorded by cane sugar (0.526 m³ of CH₄/ kg.VS) was around that theoretically expected (0.692 m³ of CH₄/kg.VS) (SI3). This methane yield was achieved after 50 days of AD and stayed nearly steady after 128 days like that of the MU leaves (Fig. 2).

The range of concentration of K required for its stimulating effect of the AD under mesophilic conditions is 200–400 mg/L (Appels et al. 2008; Turovskiy and Mathai 2006). The methanization of leaves of MU could be stimulated by the K because its concentration was determined to be 287 mg/L. The half maximal inhibitory concentration of K of the AD is IC₅₀ ~ 2900 mg/L (Appels et al. 2008; Turovskiy and Mathai 2006). However, with a K content of about 1900 mg/L for the stems of MU, which is by far lower

than the IC_{50} , the methanation of this substrate was not affected by the concentration this mineral. The same effect was observed for phosphorus.

The C/N or C/N/P ratio in the leaves of MU alone and in the overall composition of digester before AD were not in the range recommended (C/N: 20–30; C/P/N: 150/4/1) (Banks and Heaven 2013; Borja and Rincón 2017; Yen and Brune 2007; Solarte-Toro et al. 2018). For the stems of MU, only the C/N ratio was in the range commonly recommended but not their C/N/P (Table 1, 2).

Due to their difficulty to solubilize induced by their composition rich in cellulosic fiber (Han et al. 2011; Reed et al. 1982; Klinpratoom et al. 2015), the production of methane of the stems of MU continued to increase after 128 days of AD (Fig. 2). This is justified that the TOC concentration of 10.9 mg/g for stems in their liquid residues compared to 73.3 mg/g for leaves (Table 2).

The conversion rate of the CS in biogas was about 70%, but those of two substrates were approximatively 19% for the leaves and 16% for the stems according Table 2.

Table 2
C/N/P ratio and K quantity of different samples in the digester before and after AD

Substrates and inoculum	Before AD		After AD	
	C/N/P	K(mg)	C/N/P	K(mg)
Inoculum alone	186/10/11	13	186/10/11	13
Positive control	293/10/10	13	218/10/10	13
MU leaves	600/75/10	156	517/75/10	156
MU stems	216/10/65	962	187/10/65	962

The analysis of secondary bioactive metabolites or bioactive substances in the leaves and stems of MU showed the presence of saponins and catechic tannins (Table 3). However, their presences did not affect the methanization of the leaves and stems. Indeed, it is known that some plants or their extracts with high concentrations of secondary bioactive metabolites such as saponins, tannins, essential oil, organosulphur compounds, flavonoids and many other metabolites have potential to inhibit methane production (Mambanzulua et al. 2015b; Patra and Saxena 2010; Mambanzulua et al. 2015c, Beauchemin et al. 2008). The methonogenesis is inhibited at concentrations of secondary bioactive metabolites above 0.3 g/L (Mambanzulua et al. 2015b, c). This behavior indicated that that concentrations of saponins and catechic tannins in the leaves and stems would be less than 0.3 g/L.

Table 3
Bioactive substances in leaves and stems of MU

Components	leaves	stems
Saponins	+	+
Flavonoids	-	-
Alkaloids	-	-
Anthraquinones (bound quinones)	-	-
Catechic tannins	+	+
Gallic tannins	-	-
Anthocyanins	-	-
Leuco-anthocyanins	-	-
+ : sustrate contains the component - : sustrate do not contain the component		

The methane yields of our two substrates were therefore $0.156 \pm 0.003 \text{ m}^3 \text{ CH}_4/\text{kg VS}$ and $0.136 \pm 0.003 \text{ m}^3 \text{ CH}_4/\text{kg VS}$ for stems and leaves of MU respectively (SI3). These methane yields are in the range of those found by Amon Thomas et al. (2006) and stipulated by Gunaseelam (2004) for the vegetable wastes, whose the range is between 0.12 to 0.43 m^3 of $\text{CH}_4/\text{kg VS}$ depending in the chemical composition of the substrate.

This difference of the biogas or methane yields for the stems and leaves could be due to the difference between their organic matter and C/N ratio.

The yields of the methane obtained par Mambanzulua et al. (2015b) after 100 days of AD of the leaves at the concentration of 13 g/L was $0.023 \text{ m}^3 \text{ CH}_4/\text{g VS}$ at $30 \text{ }^\circ\text{C}$. In this study, after 100 days of AD, the methane yield obtained in the same concentration leaves at $25 \text{ }^\circ\text{C}$ was about 6-fold higher. That could be explained by the fact that methanogenic activity of CM used in this work is approximately 6-fold superior than that of the anaerobic sludge which came from in origin activated sludge. It is reported in the literature that the CM is more active than activated sludge which is inoculum from anaerobic reactor. The methanogenic activity of the CM is $3\text{--}13 \text{ mg CDO-CH}_4/\text{g VS}$ by contrast that of the activated sludge is not exactly known. However, the latter is classified in the range of $1\text{--}2 \text{ mg CDO-CH}_4/\text{g VS}$ and it depends on the features of the granular sludge, type of the substrate, environmental conditions, and the test procedure (Hussain and Dubey 2017; Ashekuzzaman and Poulsen 2011; Shin et al 2001).

3.2. Energetic potentials of biogas

The calorific value of biogas is proportional to its methane content. This can be determined thanks to Lower Heating value (LHV) and the proportion of methane in the biogas produced (Borja and Rincón 2017; Chen et al. 2008; Abbasi et al. 2012). The proportions of methane in the biogas produced from the

stems and leaves of MU were 83% and 84%, respectively. These correspond to the calorific values evaluated at 7.820 kWh/m³ and 7.914 kWh/m³, respectively. These energy values found are within the range of the biogas calorific value reported in the literature (4.726 kWh/m³ – 9.452 kWh/m³) (Li et al. 2017; Borja and Rincón 2017; Chen et al. 2008; Abbasi et al. 2012).

However, in KCP, the MU is the first most consumed vegetable and the second most planted (Mambanzulua et al. 2015a, 2015b; Mulaji 2017; Bell et al. 2000). KCP produces annually about 3 million tons of wastes. These wastes contain 1.65 million of organic wastes, which represents 55% (Ministère Provincial d'Environnement 2019). Previous research has shown that these organic wastes are essentially composed (94%) of vegetable wastes of which the majority is leaves (Mambanzulua et al. 2015a, 2015b; Mulaji 2017). Considering that the latter consisted mainly of leaves or stems, the annual energetic potential of vegetable wastes produced in the KCP will therefore be estimated at $1.362 \pm 0.028 \cdot 10^9$ kWh for leaves (SI4A) and $0.337 \pm 0.006 \cdot 10^9$ kWh for the stems (SI4B). Knowing that the LHV of charcoal is about 8.229 kWh/kg (Solarte-Toro et al. 2018; Jenkins 2015; Gary 2010), the annual energetic potential obtained would cover the energy needs for the KCP households corresponding to the use of charcoal, evaluated with $166 \cdot 10^3$ tons for the leaves, and with $41 \cdot 10^3$ tons of charcoal for the stems (SI4). The substitution of the use of charcoal by biogas in KCP households, will allow them to spare from the problems of air pollution which causes 4 million premature deaths each year in the world, with more than 600 000 in African countries following the use of solid biomass energy (Ifegbesan et al. 2016; WHO 2018). The Table 4 reports the energy amounts in the resulting biogas production from the AD of leaves and stems of MU during 100 and 128 days.

Table 4

Energy amounts in the resulting biogas production from the anaerobic digestion of leaves and stems of MU during 100 and 128 days.

Samples concentrations	Methane yields for 100 days (L/g VS)	Methane yields for 128 days (L/g VS)	Energies for 100 days (kWh/g VS)	Energies for 128 days (kWh/g VS)
1.6 g CS/L	0.519 ± 0.020	0.526 ± 0.016	$4.888 \pm 0.188 \cdot 10^{-3}$	$4.958 \pm 0.153 \cdot 10^{-3}$
13.3 g leaves MU/L	0.136 ± 0.003	0.136 ± 0.003	$1.277 \pm 0.027 \cdot 10^{-3}$	$1.277 \pm 0.027 \cdot 10^{-3}$
13.3 g stems MU/L	0.148 ± 0.002	0.156 ± 0.003	$1.399 \pm 0.023 \cdot 10^{-3}$	$1.468 \pm 0.028 \cdot 10^{-3}$

3.3. Fertilizing potential of the digestates

The fertilizing potential of the digestates of leaves and stems of MU is primarily due to the availability of the mineral elements (N, P, K) previously retained in the complex structures of these wastes, owing to their mineralization through AD. The N, P and K concentrations in the liquid digestate for the stems were

determined to be 2.1, 85.0 and 117.3 mg/L respectively. By contrast, the N, P and K concentrations in the liquid digestate for leaves were 13.7, 4.4 and 110.0 mg/L respectively.

We evaluated the fertilizing potential of the digestates utilizing their C/N ratio. We noticed that the C/N ratio of Leaves digestates has fallen to 5. The digestate with a C/N ratio of 5 is recognized to be favorable for vegetable crops and fruit trees soils (Mambanzulua et al. 2015b; Mulaji 2017; Hawke and Summers 2003; Glowacka et al. 2020). The C/N ratio of the digestats resulting from the AD of stems was 10. A C/N ratio of 10 is considered optimal for the organisms, soil conditioning and could improve the soils hydraulic conductivity (Mambanzulua et al. 2015b; Hawke and Summers 2003; Wrap 2016; Lessard and Bihan 2003; Sparling et al. 1999).

It has been shown that one can spread until 30 tons of dry matters of digestate by hectare per year on an acidic poor soil (Mambanzulua et al. 2015a; Glowacka et al. 2020; Wrap 2016; Sparling et al. 1999). Therefore, with the $222 \cdot 10^3$ and $1.039 \cdot 10^6$ tons of digestates that we can produce from methanization of $1.55 \cdot 10^6$ tons of stems and leaves of MU, respectively, produced in Kinshasa per year, one could fertilize 7,400 hectares for stems and 39,966 hectares for leaves (SI5A, SI5B).

4. Conclusion

In summary the present report investigated the energetic balance between the amount of leaves and stems of Manihot Utilissima (MU) annually produced in the KCP as well as the energetic potential of their biogas, by utilizing the CM as inoculum. This work was carried out at the ambient temperature of 25 °C (under mesophilic conditions) favorable to tropical regions such as KCP, where leaves and stems of MU are among the most generated vegetable wastes.

The annual energetic potential of biogas produced from vegetable wastes of MU from the KCP would cover the energy needs for the KCP households corresponding to the use of charcoal. This energy is renewable and its net CO₂ contribution to the atmosphere is nil. Moreover, it could keep KCP away from deforestation by providing its households with a form of clean energy for cooking. The substitution of the use of charcoal by biogas in KCP households, will allow them to spare from the problems of air pollution which causes 4 million premature deaths each year in the world, with more than 600 000 in African countries following the use of solid biomass energy. In addition the fertilizing potential of digestates resulting from the anaerobic digestion of leaves and stems of MU were evaluated by their C/N ratios. The characteristics of this fertilizer show that not only they are favorable for the cultivation of vegetables and fruit trees on the KCP soils but also optimal for the organisms and the conditioning of the soil.

Abbreviations

AD: Anaerobic digestion; OWs: Organic wastes; BMP: Biochemical methane potential; MU: Manihot Utilissima; CM: Cow manure; KCP: Kinshasa City Province; Congo DR: Democratic Republic of Congo; C/N: Carbon/Nitrogen ratio; kWh: Kilowatt-hour; DW: Dry weight; VS: Volatile solid; TKN: Total Kjeldahl

Nitrogen; TOC: Total organic carbon; CS: Cane sugar; LHV: Lower Heating Value; T-: Negative control and T+: Positive control.

Declarations

Availability of data and material

Data will be made available upon request

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing Interest

The authors declare no competing interest

Funding

Not applicable

Authors' contributions

BM Nsimba and PN Mambanzulua designed the study and wrote the protocol. BM Nsimba managed the analyses of the study. BM Nsimba and PN Mambanzulua wrote the first draft of the manuscript and managed the study. NL Basosila and VA Korangi performed the statistical analysis. M Saidi and YE managed the literature searches.

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Supplementary Information

Supplementary information on physical and chemical characterization of stems, leaves of MU and Cow Manure (Supplementary information SI1), Determination of bioactive substances in leaves and stem of MU (Supplementary information SI2), Determination of Biogas and methane yields (Supplementary information SI3), Determination of energetic potential of biogas produced (Supplementary information SI4), and evaluation of the area of KCP land to be fertilized (Supplementary information SI5).

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Figures

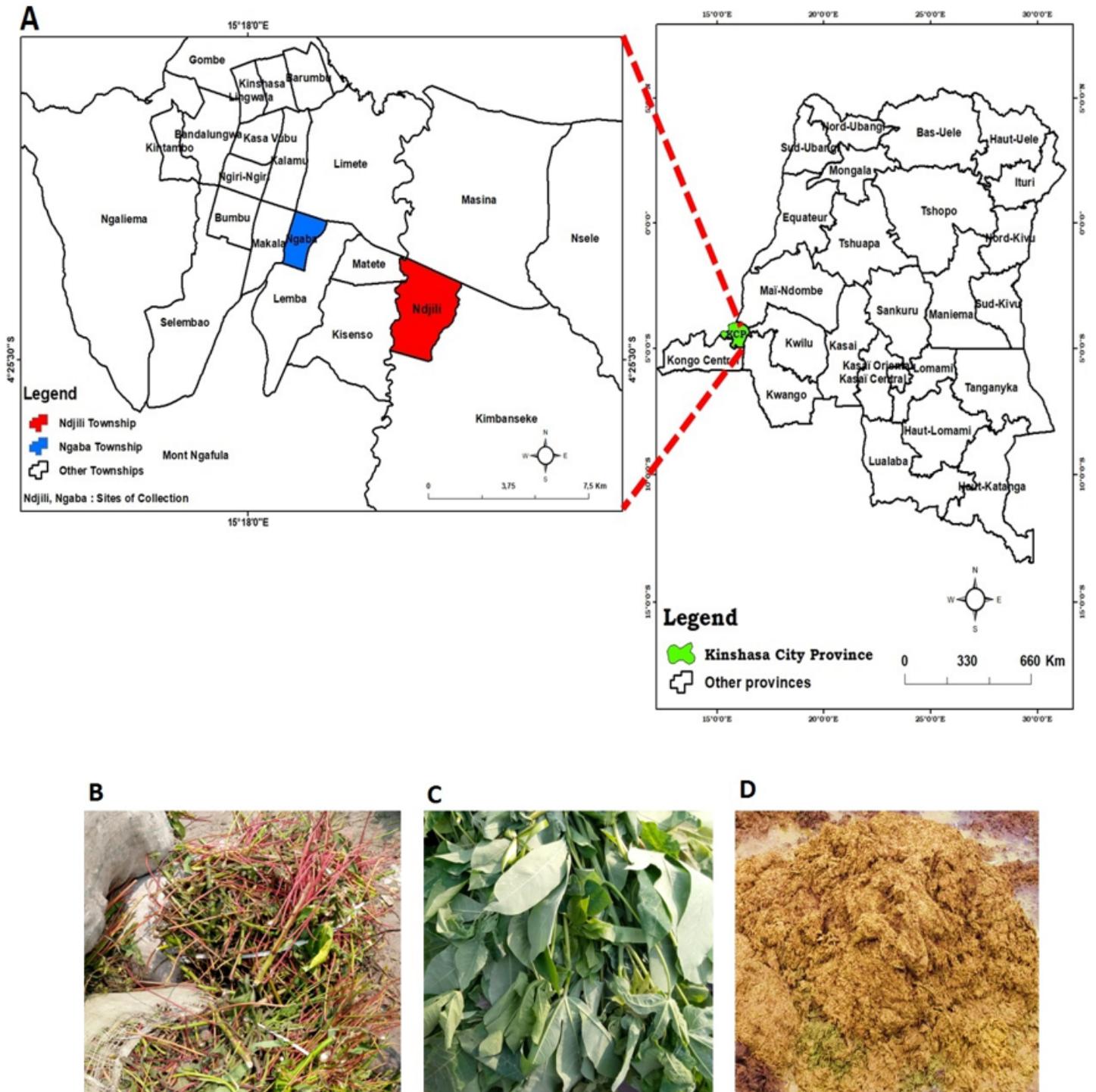


Figure 1

Cartography of DR Congo, location of the KCP (in green) and the sites of collection (Ngaba: in blue, Ndjili: in red) (A), Stems of MU (B), Leaves of MU (C) and inoculum: Cow manure (D).

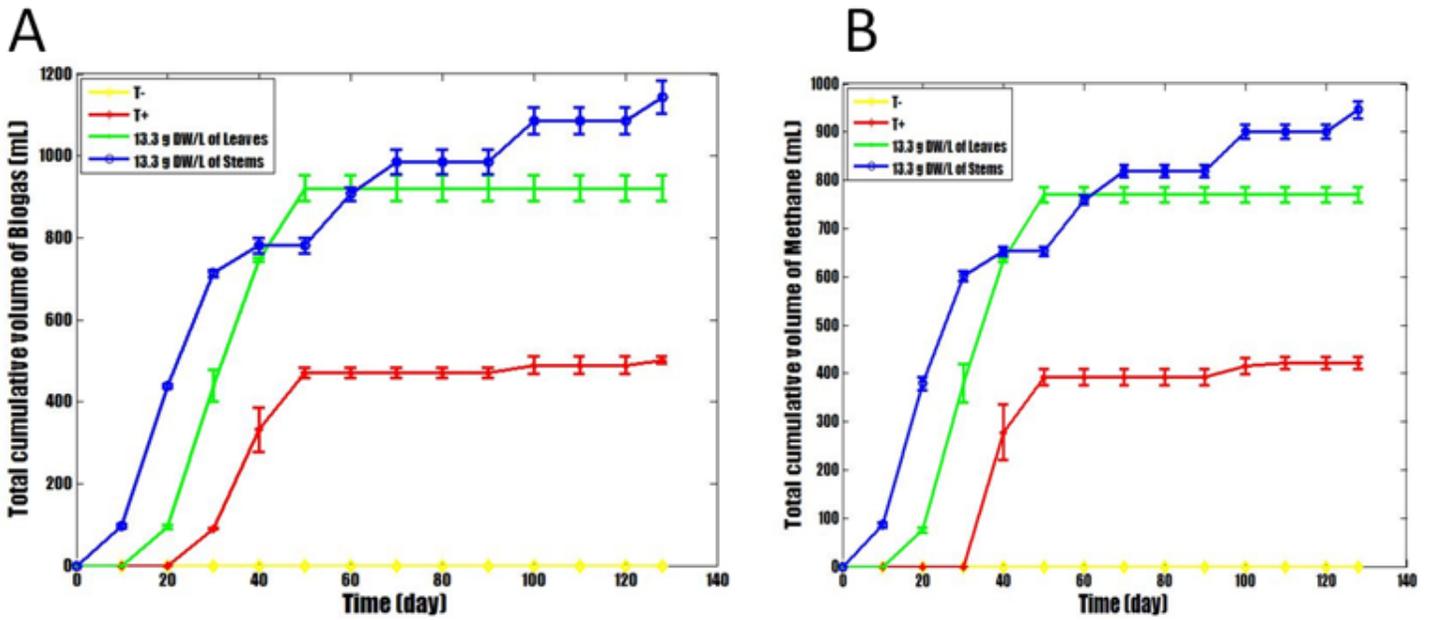


Figure 2

Total cumulative volumes of biogas and methane produced from the AD of the leaves and stems of MU for different reactors versus time. (A) Produced biogas, and (B) Produced methane

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