Biomass Conv. Bioref. (2017) 7:167–177
DOI 10.1007/s13399-016-0222-x

ORIGINAL ARTICLE

Comparative biochemical methane potential of some varieties of residual banana biomass and renewable energy potential

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Received: 9 May 2016 / Revised: 25 July 2016 / Accepted: 29 September 2016 / Published online: 9 October 2016

Abstract The biochemical methane potential (BMP) of peduncles, bulbs, and peels of three banana varieties (Grande Naine (GN; export dessert banana), Pelipita (PPTA; locally used plantain), and CRBP969 (phytopathogen resistant hybrid-plantain)) was investigated as an assessment of the bioconversion potential of these residues to renewable energy or biorefined chemicals. Biogas production was monitored manometrically for 132 days and its composition was analyzed using gas chromatography. The BMP ranged from 162 to 257 ml_CH4/g_DM for peduncles, from 228 to 304 ml_CH4/g_DM for bulbs, and from 208 to 303 ml_CH4/g_DM for green peels, with methane content of the biogas in the range 56 to 60 %. Bulbs and green peels showed bioconversion yields of 95 % of the chemical oxygen demand (COD). The GN variety was generally more biodigestible than PPTA, which appeared richer in lignocellulosic fibres. The peels biodigestibility reduced with maturation and was already limited to 56 % of the COD at the yellow stage. The energy resource available in the residues of banana production is very significant, increasing by 91 % the energy resource offered by banana crop, which is generally limited to the nutritional value of the fruit pulp. In the study case of the African leading producer of bananas and plantains (Cameroon), the amount of available residues from the sole export variety GN could feed about 4 % of the annual electricity consumed by the country, i.e., a supply of electricity to an additional 9×10^5 people. Such valorization of the residual banana biomass could help banana-producing countries to become less dependent on fossil fuels and less prone to energy shortages.

Keywords Biochemical methane potential · Varieties · Maturation · Peduncles · Peels · Bulbs

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Abbreviations

AD	Anaerobic digestion
BMP	Biochemical methane potential
CARBAP	African Research Centre on Bananas and Plantains
CHP	Combined heat and power plant
CRBP	Previous name of CARBAP
COD	Chemical oxygen demand
DM	Dry matter
FM	Fresh matter
GC	Gas chromatography
GN	Grande Naine
PHP	Plantations Haut Penja
PPTA	Pelipita
VS	Volatile solids

1 Introduction

Banana is an herbaceous tropical plant, grown intensively in many developing countries. This plant is stenothermic, cultivated in hot and wet regions, and bears fruits all the year around. There are approximately 1200 varieties of bananas all over the world [1]. Banana is a general term embracing a number of species or hybrids in the genus Musa of the Musaceae family. Almost all of the known edible-fruit cultivars arose from two diploid species, *Musa acuminata* (AA) and *Musa balbisiana* (BB). There are diploid, triploid, and tetraploid hybrids of subspecies of *M. acuminata* and subspecies between *M. acuminata* and *M. balbisiana* [2, 3]. The worldwide annual production of bananas and plantains is approximately 125 million t [4] which generates about 250 million t of fresh lignocellulosic biomass residues [5]. In Africa, the main producers are Uganda and Cameroon, and they are among the world's 20 leading producers of banana [4]. In Cameroon, the production of bananas and plantains represents the second agricultural economic resource of the country after wood [6]. The introduction of new varieties and improvement of farming techniques have contributed to increase the production [7]. For the year 2012, production reached 1.4 million t in Cameroon, resulting in residues corresponding to about 90,000 t dry matter [8]. These banana residues are non-food biomass resources and therefore do not compete with human food supply. They are mainly constituted of peels, bulbs, leaves, pseudo-stems, corms, and banana peduncles, representing about 80 % of the total fresh plant weight. They are discarded after fruit harvest and can be left to dry on field, where they are then burned in large fire fields that cause some environmental burdens. Banana residues are also often gathered as big roadside piles within which non-controlled fermentation leads to emission of volatile organic compounds and greenhouse gas and contributes to spread mosquitoes and pathogens, with the corresponding environmental and health burdens. There is a need to develop appropriate management practices to mitigate negative impact on the environment. Anaerobic digestion appears to be a convenient and suitable solution for organic waste management, fertilizer recycling for agriculture, and renewable energy supply such as heat, electricity, and fuel [9]. Also known as biomethanation, anaerobic digestion is a natural bioprocess by which organic material is microbiologically converted under anaerobic conditions to biogas [10, 11]. It proceeds through a series of parallel and sequential processes and consists of four main steps, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, led by microbial consortia [10, 11]. One of the main advantages of anaerobic digestion is that a wide variety of wet organic substrates can be used [12]. The produced biogas is mainly composed of methane and carbon dioxide. It can be locally converted into electricity, which could help to meet the local needs, and help some countries to become less dependent on fossil fuels and less prone to energy shortages. Very few studies on anaerobic digestion of banana residual biomass have been published. Some results have been reported for banana pseudo-stems [13], banana leaves [14], banana peels [15–20], and various morphological parts of plants from the "Dwarf Cavendish" variety [21]. However, the influence of variety and morphological parts of banana plants on anaerobic biodigestibility has not yet been explored in a single study to date. In the present investigation, the anaerobic biodigestibility of banana peduncles, bulbs, and peels is compared for three varieties namely Grande Naine (export dessert banana), Pelipita (locally used plantain), and CRBP969 (phytopathogen resistant hybrid-plantain). The influence of maturation stage on the biodigestibility of the fruit peels from green to yellow with a few brown spots is investigated as well. The obtained results are included in a more general approach to determine the renewable energy potential of banana crop whole residual biomass.

2 Material and methods

2.1 Sample preparation

The banana peduncles, banana peels, and bulbs for the varieties Grande Naine (GN; dessert banana), CRBP969 (previous name of CARBAP; hybrid-plantain), and Pelipita (PPTA; cooking banana) were obtained from the *African Research Centre on Bananas and Plantains* (CARBAP) and *Plantations Haut Penja* (PHP; only for the variety Grande Naine) in Cameroon. The varieties selected for this study are described in Table 1 [22, 23]. The bulbs and peduncles were collected after the mature fruits had been harvested. The soil residues were removed with water rinsing, and the harvested biomass was cut into pieces with size of approximately

Table 1 Botanical accession of the studied varieties

Variety	Analysis Code	Specie/genetic group	Subgroup	Origin	Fruit type
Grande Naine	GN	AAA	Cavendish	Asia (China/Vietnam)	Dessert
Pelipita	PPTA	ABB	Pelipita	Philippines	Cooking banana
CRBP969	CRBP969	AAAB	(Hybrid-plantain)	CARBAP (Cameroon)	Hybrid-plantain

50 mm. The samples were stored either fresh frozen at −20 °C or air dried at 55 °C for 48 h. The air-dried samples were ground with a rotary knife cutter into powder with particle size of less than approximately 1 mm and stored in polypropylene bags until use. The frozen samples were thawed and ground with a rotary knife cutter into particles with diameters of maximum 10 mm just before use.

Banana peels were collected at three different stages of ripeness: stage 1 (green), stage 5 (more yellow than green), and stage 7 (yellow/a few brown spots). These stages of ripening are the most used in industrial transformations and traditional culinary preparations. The peels were collected from the first two hands of bunches harvested in the field. Stages of maturation of the fruits were followed in the laboratory at temperatures between 20 and 25 °C. The fruits were washed and separated into pulp and peel. The obtained peels were dried at 60 °C for 24 h, then ground into powder with particle size of less than 1 mm, and stored in polypropylene plastic bags at room temperature until use. Only air-dried (60 °C) banana peels were used in this study.

2.2 Chemical analysis

The dry matter (DM) content of the samples was determined gravimetrically after drying at 105 °C for at least 24 h. The dry residue was subsequently burned in a furnace at 550 °C until constant weight was achieved (usually 24 h). The loss of mass was defined as the volatile solids (VS). The chemical oxygen demand (COD) content was determined according to Standard Methods [24]. The COD of inoculum was measured with the COD Cell Test method (Spectroquant® Kits 1.14541.0001 and 1.14555.0001, Spectroquant® ThermoReactor 620, Photometer SQ200, Merck Germany) according to the provider's instructions.

2.3 Anaerobic digestibility assay (BMP)

The biochemical methane potential (BMP) assay was performed according to the method described by Wang et al. [25]. The anaerobic inoculum was amplified by incubating for 10 days at 35 °C under anaerobic conditions, a methanogenic primary inoculum maintained in the laboratory fed with freshly collected activated sludge as a substrate, in a ratio of 0.3 $g_{COD\_activated\_sludge\_substrate}/g_{COD\_methanogenic\_primary\_inoculum}$. The activated sludge was collected at the Chastre municipal wastewater treatment plant (Mont-Saint-Guibert, Belgium). Upon arrival in the laboratory, the sludge was left to settle in the dark at 4 °C for 24 h. The clear supernatant was removed to concentrate the sludge to 15–20 $g_{\_COD}$/l prior to use.

Bioreactors consisted of 1-l Schott Duran GL 45 bottle, with a glass tube at the top side (Fig. 1). A two-way Luer polycarbonate valve (Fisher Scientific) was connected at the extremity of this glass tube. The bioreactor bottle was capped with a PBT screw cap, containing a PTFE-coated silicone seal.

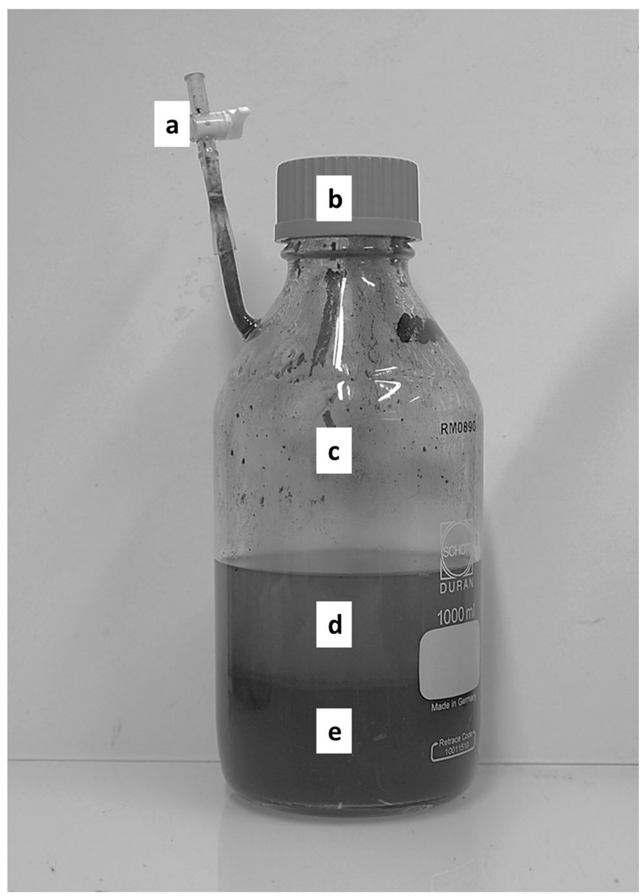

Fig. 1 Bioreactor used for the anaerobic digestion test (picture by Awedem [22]). *a* Two-way Luer polycarbonate valve, *b* sealing cap, *c* headspace, *d* supernatant, and *e* inoculum + substrate

Each bioreactor was checked to be airtight and resistant to internal pressure before each use.

Three identical experiments were performed, one for each substrate, i.e., peduncles, bulbs, and peels, with all varieties tested simultaneously. Each experiment was performed in triplicate, with negative control consisting of water in the place of sample in order to determine the biogas produced by the inoculum alone. Each bioreactor was filled with the inoculum (7.5 $g_{\_COD}$) and incubated at 35 °C for at least 2 h in order to allow the rebalancing of CO_2 between the liquid phase and the gas phase. A known mass of substrate at 35 °C was added in order to reach a COD ratio of 0.2 $g_{COD\_substrate}/g_{COD\_inoculum}$. Demineralized H_2O was added to complete the volume to 580 mL. Each bioreactor headspace was flushed for 2 min with a constant flow of nitrogen gas in order to ensure the absence of oxygen in the bioreactors prior to hermetic closure. The batch bioreactors were incubated at 35 °C in the dark under anaerobic conditions for 132 days. The end of anaerobic digestion was determined when the biogas production rate of the bioreactor with substrate plus inoculum did not exceed any more the biogas production rate of the bioreactor with only the inoculum.

The biogas production was monitored using a UNIK type manometer (5000 PTX5072-TA-A3-CA-H0-PA, GE Measurement & Control Solutions) connected to the bioreactor through a two-way valve. The manometer was equipped with a display (DMS-40LCD-4/20S, Datel Inc. Mansfield, MA, USA) calibrated for absolute pressure ranging from 900 to 1300 mbar with accuracy of 0.1 mbar. The pressure was converted to gas production using the ideal gas law ($T = 0$ °C and $p = 1013.25$ mbar) with the headspace volume of each bioreactor determined independently. The gas pressures were monitored at regular intervals to ensure that the pressure was maintained below 1150 mbar. Using a polypropylene syringe closed with a two-way Luer polycarbonate valve (Fisher Scientific), gas samples were collected and analyzed every day during the first 2 weeks, every 2 days during the next 3 weeks and when the pressure in the collection bottles was high enough to deliver enough gas for analysis.

Gas composition was determined using a two-channel gas chromatography (Compact GC, Global Analyser Solutions™, Interscience, Belgium) equipped with a thermal conductivity detector on each channel: the first channel equipped with a RI-QBond column (10 m × 0.32 mm) allowed to separate and analyze CO_2. The elution was performed under isotherm conditions at 60 °C with helium as carrier gas at 20 mL/min. The second channel had a RI-QBond column (2 m × 0.32 mm) followed by a Molsieve 5A column (7 m × 0.32 mm). The elution was performed under isotherm conditions at 70 °C with argon as carrier gas at 10 mL/min. The columns placed in series permitted successively to separate CO_2 from the other gases as in the first channel (first column), then the H_2, O_2, N_2, and CH_4 gases were separated in the second column while the CO_2 was back flushed in the first column. The detectors were heated at 90 °C and the filaments at 170 °C. Argon and helium, and calibrated mixtures of H_2, N_2, CO_2, CH_4, and air were used to calibrate the instrument for determining the proportions of CH_4, H_2, and CO_2 in the biogas. The biogas and methane productions of the inoculum were subtracted from the productions of each bioreactor to determine the net substrate production.

2.4 Statistical analysis

All the analyses were performed in triplicate and the data obtained were statistically analyzed with IBM SPSS software 20.0 for Windows. The Tukey honestly significant difference (HSD) test, also known as a *t* test, and one-way analysis of variance (ANOVA) test were used for bth othe compositional comparison and the BMP of the three varieties. Statistical differences were measured at 95 % confidence level ($p < 0.05$), and the results were expressed as means ± standard deviation (SD).

3 Results and discussion

3.1 Proximate composition of banana residual biomass

The characteristics of the banana peduncles, banana bulbs, and banana peels samples are given in Tables 2, 3, and 4, respectively, for the three tested varieties. The GN variety was shown to have the highest ash content (low VS in Tables 2–4) among the three varieties, especially for the banana peduncles. PPTA variety had the highest dry matter content for fresh residues. Significant statistical difference was observed between the three varieties for dry matter, volatile solids, and chemical oxygen demand, and this was regardless of the fact that the sample was fresh or dried ($p < 0.05$). The ash content obtained for the dry banana peduncles samples were in general higher than those observed with fresh samples (Table 2). That difference in ash content between fresh and dry residues might be related to the time required for drying, which may not have excluded some degradations of the sample organic matter. However, the ash contents observed for the three banana residues were in accordance with Oliveira et al. [26] and Mohapatra et al. [27] who reported that all morphologic parts of banana plant contained considerable amounts of ashes (from 11.6 to 26.8 %). The COD values obtained were within the expected range for polysaccharides (banana peduncles, banana bulbs; Tables 2 and 3). For banana peels, the COD increased with peel maturity (Table 4) to higher values, indicating the increasing proportion of more reduced (electron rich) carbon, like in proteins or lipids.

Table 2 Composition of banana peduncles as fresh frozen (F) or as oven dried (D) samples

	Fresh (F)/dry (D)	GN_PHP	GN_CARBAP	PPTA	CRBP969
Dry matter (g_DM/100g_FM)	F	6.869 ± 0.005b	5.073 ± 0.004c	8.553 ± 0.003a	5.874 ± 0.007bc
	D	70.585 ± 0.006d	90.170 ± 0.001a	85.154 ± 0.003c	87.887 ± 0.005b
Volatile solids (g_VS/100g_DM)	F	76.625 ± 0.005c	77.35 ± 0.01c	83.410 ± 0.005b	86.36 ± 0.01a
	D	64.27 ± 0.02c	71.20 ± 0.01b	82.178 ± 0.004a	83.062 ± 0.009a
COD (g_COD/g_VS)	F	1.105 ± 0.004c	1.08 ± 0.01c	1.223 ± 0.005b	1.33 ± 0.01a
	D	1.34 ± 0.03a	1.224 ± 0.009c	1.263 ± 0.007b	1.22 ± 0.01c

Means with different letters on the same row are statistically different ($p < 0.05$)

DM dry matter, *FM* fresh matter, *VS* volatile solids, *COD* chemical oxygen demand, *PHP* Plantations Haut Penja, *CARBAP* African Research Centre on Bananas and Plantains

3.2 Biochemical methane potential

The biochemical methane potential of fresh and dry banana peduncle (FBP and DBP), fresh and dry bulbs (FB and DB), and dry banana peel (DPL) is given in Figs. 2, 3, and 4, respectively. All three types of residues show bioconversion yields to biomethane ranging between 87 and 95 % COD_CH4/COD_substrate. After 132 days, the digestion of the GN peduncles was not yet totally completed. Banana bulb residue had the highest BMP with a bioconversion yield of 95 % (Fig. 3). PPTA variety had generally the lowest BMP among all the varieties. Green banana peels (maturation stage one) were more digestible than more mature peels. Dried substrates had a generally slightly faster methane production kinetic, as compared to fresh substrates, while they had similar final production. Dried substrates were finely ground, thus possibly more accessible to enzymatic and microbial degradation. However, reducing the particle size had no more advantageous effect after 25 days of digestion time. Similar results on the effect of particle size on anaerobic digestion have also been observed with various agro-industrial residues [15, 28, 29]. The methane content (%CH_4) in the biogas ranged from 56 to 60 % *v*/*v* for all the residues, and GN variety had the highest methane percentage in the biogas (60 % *v*/*v*). Dried residues had in general the lower %CH_4 in biogas (56–58 % *v*/*v*). This observation could be explained by the loss of some substances by sample degradation during the drying.

3.3 Renewable energy potential

3.3.1 BMP comparison with previous studies

The BMP obtained in the present study are compared in Table 5 with those reported in previous studies on the renewable energy potential from anaerobic digestion of banana residues. The BMP of the present study was found to be the highest for all banana residual biomass samples tested. That difference in biodigestibility might be related to difference in biomass composition (VS, COD, lignin, crystalline cellulose) [11]. Biomass composition depends on cropping environment (soil, climate, etc.) and storage conditions. Indeed, reported data on banana residues from Cameroon [22, 23, 30, 31, and the present study] and Nigeria [32, 33] show in general higher dry matter, volatile solids, fibers, ash, and total carbohydrate contents than those obtained from India [27] or Portugal [26, 34]. The higher VS/DM observed could probably explain the

Table 3 Composition of banana bulbs as fresh frozen (F) or as oven dried (D) samples

	Fresh (F)/dry (D)	GN_PHP	GN_CARBAP	PPTA	CRBP969
Dry matter (g_DM/100g_FM)	F	13.781 ± 0.008b	12.69 ± 0.01b	20.030 ± 0.003a	19.786 ± 0.007a
	D	84.026 ± 0.004c	91.721 ± 0.001a	90.017 ± 0.007b	89.331 ± 0.004b
Volatile solids (g_VS/100g_DM)	F	86.67 ± 0.01b	91.359 ± 0.006a	93.407 ± 0.002a	92.37 ± 0.01a
	D	88.561 ± 0.006ab	89.460 ± 0.001a	89.214 ± 0.007a	83.50 ± 0.04b
COD (g_COD/g_VS)	F	1.17 ± 0.01b	1.165 ± 0.006b	1.186 ± 0.002a	1.21 ± 0.01a
	D	1.158 ± 0.008a	1.172 ± 0.003a	1.15 ± 0.01b	1.14 ± 0.04b

Means with different letters on the same row are statistically different ($p < 0.05$)

DM dry matter, *FM* fresh matter, *VS* volatile solids, *COD* chemical oxygen demand, *PHP* Plantations Haut Penja, *CARBAP* African Research Centre on Bananas and Plantains

Table 4 Composition of banana peels

	Stage of Maturation	GN_CARBAP	PPTA	CRBP969
Dry matter (g_DM/100g_FM)	1	82.70 ± 0.01a	85.879 ± 0.002a	86.406 ± 0.002a
	5	81.911 ± 0.008a	83.374 ± 0.005b	85.155 ± 0.002b
	7	80.32 ± 0.01a	80.792 ± 0.008c	80.356 ± 0.002c
Volatile solids (g_VS/100g_DM)	1	87.72 ± 0.01a	87.306 ± 0.008a	88.52 ± 0.01a
	5	83.34 ± 0.01b	85.206 ± 0.007b	85.74 ± 0.03b
	7	83.26 ± 0.01b	87.818 ± 0.004a	87.839 ± 0.006a
COD (g_COD/g_VS)	1	1.08 ± 0.01c	1.122 ± 0.008b	1.13 ± 0.01b
	5	1.45 ± 0.05b	1.47 ± 0.01a	1.49 ± 0.04a
	7	1.55 ± 0.02a	1.45 ± 0.01a	1.54 ± 0.01a

Means with different letters on the same column are statistically different ($p < 0.05$)

DM dry matter, *FM* fresh matter, *VS* volatile solids, *COD* chemical oxygen demand, *CARBAP* African Research Centre on Bananas and Plantains

higher BMP obtained [39]. For peels, the varietal difference and maturation stage can possibly explain the difference in BMP, as maturation stages and varieties have been not specified by the cited literature. Moreover, Awedem et al. [22], Tiappi et al. [23], and Happi Emaga et al. [30] had shown that there were differences in biochemical composition of banana residues of the same genotype and confirmed the varietal difference within the same genomic group, which would explain the differences in BMP. Apparent differences in biodigestibility can also be induced by differences in experimental conditions. Our long incubation time (132 days) for the BMP assay could explain the higher BMP, as compared to those presented in Table 5. For peduncles and bulbs, the difference in BMP might be due to the experimental conditions, as the authors cited for the BMP comparison of these two morphological parts used to open their bioreactors in order to adjust pH with KOH, while we kept our bioreactors closed during anaerobic digestion process.

3.3.2 Energy resource: food vs waste

The amount of residual banana biomass generated by fruit production is 1 $kg_{residues\ FM}/kg_{fruit\ FM}$ [4, 5, 35], corresponding to 0.22 $kg_{residues\ DM}/kg_{fruit\ FM}$ (Table 6). The dry matter distribution and BMP of the residual fractions are summarized in Table 6 (data lines 4 and 6). When converted to methane by anaerobic digestion, the energy potential is 0.059 $m^3_{CH4\ from\ residues}/kg_{fruit\ FM}$, corresponding to 2.1 $MJ_{CH4\ from\ residues}/kg_{fruit\ FM}$. On the other hand, the nutritional value of the edible part of the fruit is 15 $MJ_{metabolic\ energy}/kg_{pulp\ DM}$ [37] corresponding to 2.3 $MJ_{metabolic\ energy}/kg_{fruit\ FM}$. When converted to methane, the residual biomass represents an energy resource of more than 91 % of the metabolic energy that can be recovered from the fruit pulp that is used as food (2.1 $MJ_{CH4\ energy}/kg_{fruit\ FM}$ as compared to 2.3 $MJ_{metabolic\ energy}/kg_{fruit\ FM}$). Valorizing the residual biomass would thus significantly increase the energy supplied to human activities by banana cropping.

3.3.3 Renewable energy contribution of banana residual biomass to energy requirement: study case of Cameroon

Table 6 presents an assessment of the energy that could be generated as methane and derived electricity from banana residual biomass in Cameroon. The biomethane produced can be converted by several pathways to biofuels, heat, and electricity; the conversion pathways depend on the specific local needs and available resources. The assessment below was restricted to the biomass of the GN variety, which is the most

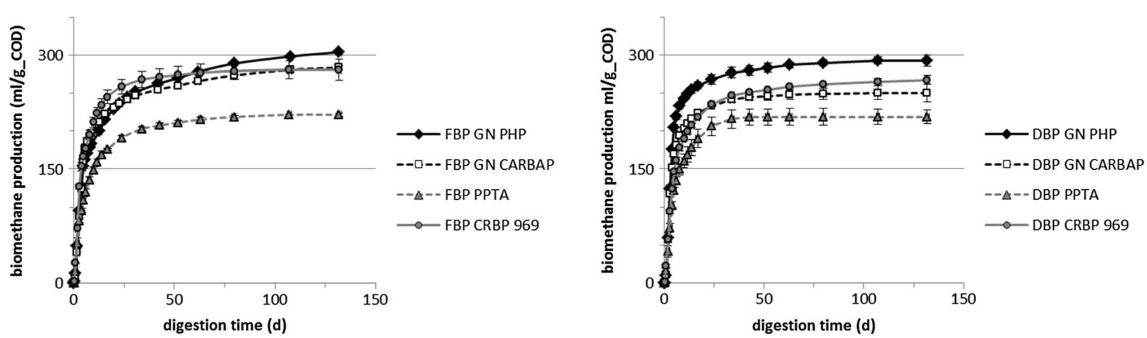

Fig. 2 Cumulated methane produced by fresh (F; *left*) and dry (D; *right*) banana peduncles (BP). *Vertical lines* correspond to the standard deviations of triplicates

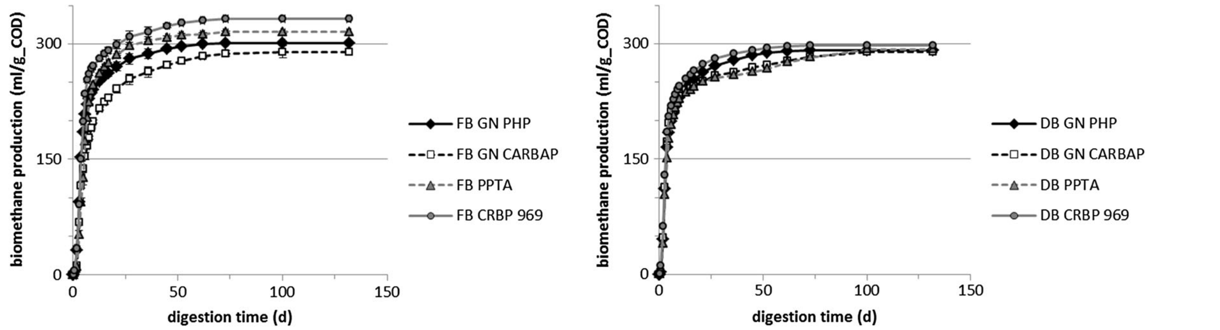

Fig. 3 Cumulated methane produced by fresh (F; *left*) and dry (D; *right*) bulbs (B). *Vertical lines* correspond to the standard deviations of triplicates

produced and commercially used in Cameroon. About half of GN fruits are exported [40], and their peels are not available locally. The corresponding exported peels have been excluded from the assessment. Only maturation stage 1 was considered for banana peels. The locally largely used plantain has not been considered due to lack of data on available biomass. With respect to the methane production kinetics (Figs. 2, 3, and 4) and data from Kalia et al. [13] and Chanakya and Sreesha [14], a digestion time of 40 days would be a practical optimum. When considering a digestion time of 40 days, the energy potential is 613 GWh_{CH4}/year, with biomethane potential of 223, 297, 292, 215, and 210 m^3/t_DM for peduncles, bulbs, peels, stems, and leaves, respectively.

However, transportation of substrates from the fields to the anaerobic digestion plant and of digestate back to the fields would require transportation fuel. The energy as fuel required for transportation of banana residues and digestate (transported using a 180 KW tractor with trailer) was calculated and adapted from other agricultural transportation operations (Achilles et al. [41], Gerin et al. [42], and Nguyen et al. [43]). It is about 12.9 MJ t_{FM}^{-1} km^{-1}. The tractor with trailer has the advantage of driving on all roads, especially in rural areas. If we consider a mean distance of 10 km from the field to biogas plant and an amount of 1.4 million t_{FM} residual substrates in Cameroon

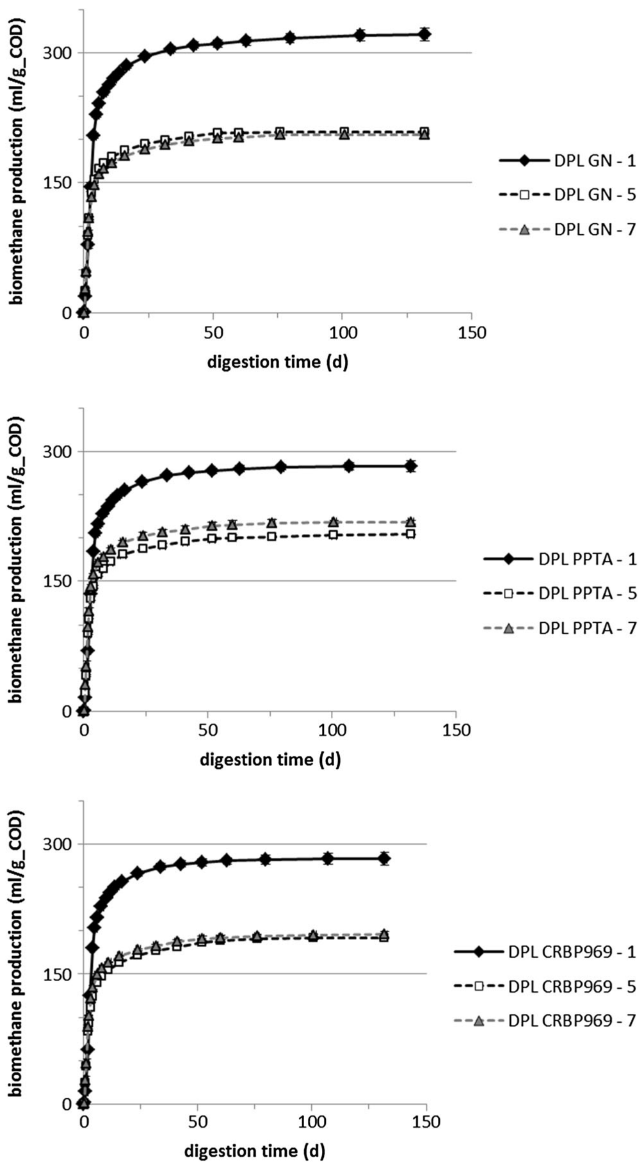

Fig. 4 Cumulated methane produced by dry banana peel (DPL) at different stages of maturation (1-5-7, respectively). *Vertical lines* correspond to the standard deviations of triplicates

Table 5 BMP comparison with reported previous studies on banana residues

Banana residues	Methane yield ml_CH_4/g_DM	Reference
Banana peduncle[a]	162	[21]
Banana peduncle[b]	257	This study
Banana bulb[a]	144	[21]
Banana bulb[c]	304	This study
Banana peel[d]	231	[15]
Banana peel[d]	251	[14]
Banana peel[d]	266	[16]
Banana peel[b]	303	This study

[a] Williams' variety

[b] GN variety and maturation stage one

[c] CRBP969 variety

[d] Maturation stages and varieties have been not specified

Table 6 Estimation of the energy that could be generated from the biomethane annually in Cameroon from banana residual biomass

	Banana peduncles	Banana bulbs	Banana peels	Banana stems	Banana leaves	Total
Annual production of fruits (t_FM/year)[a]						1.4×10^6
Annual fresh biomass production (t_FM/year)[b]						2.8×10^6
Annual dry biomass production (t_DM/year)[b]						313,600
Distribution of morphological fractions in banana residual biomass (%_DM)[c]	7	11	40	18	24	100
Annual biomass production by biomass fraction (t_DM/year)	21,952	34,496	62,720[h]	56,448	75,264	250,880
Biomethane potential (m^3/t_DM_fraction)	257[i]	304[i]	303[i]	215[j]	210[k]	262
Energy in biomethane derived from banana residues (GWh_CH4/year)[d]	56	105	190	121	158	630
Electric energy derived from biomethane conversion (GWh_electricity/year)[d,e]	20	37	67	43	56	223
Net electric energy available when considering CH_4 production with 40 days retention, transportation and plant self-consumption (GWh_electricity/year)[g]	/	/	/	/	/	193
Heat energy derived from biomethane conversion (GWh_heat/year)[d,e]	28	52	95	61	79	315
Net heat energy available when considering CH_4 production with 40 days retention, transportation, and plant self-consumption (GWh_heat/year)[g]	/	/	/	/	/	274
Electricity consumption in Cameroon (GWh/year)[f]						5267
Total population of Cameroon in 2014 (inhabitants)[f]						23,130,708
Population equivalents that could be supplied with banana derived net electricity available (inhabitants)[g]						905,660

[a] Obtained from the annual production of bananas in Cameroon [8]

[b] Estimated with 11.2 % DM of annual production [4, 5, 35]

[c] Obtained from Tchobanoglous et al. (1993) cited by Happi Emaga et al. [30]; Lassoudière [35]; FAO [7]; FAO [4]; Kamdem et al. [5]; and Kamdem et al. [21]

[d] Calculated from the lower heating value (LHV) of 1 m^3 of CH_4 (9.94 kWh/m^3) [5]

[e] Calculated from electricity production by co-generation (0.35 kWh_electricity/kWh_CH_4 and 0.50 kWh_heat/kWh_CH_4) [5]

[f] Obtained from the annual electricity consumption per inhabitant [36]

[g] See text

[h] Only from peels locally available (half of fruits produced) [40]

[i] Figs. 2, 3 and 4

[j] [13]

[k] [14]

(Table 6), the energy for transportation will be about 50 GWh_{fuel}/year. Considering that the additional fossil fuel needed for transportation would be made available by the fuel substituted by methane in the electricity production, the net renewable energy made available by anaerobic digestion of banana residues is 613−50 = 563 GWh_{CH4}/year. Conversion of this methane by a combined heat and power plant (with yield of 0.35 MJ_electricity/MJ_CH_4) [5] would produce 197 $GWh_{electricity}$/year.

The self-consumption of the anaerobic digestion process (energy demand of stirrer, pumps or heating systems) of vegetal substrate is about 5 % of the total energy output of the plant (i.e., 2 % of electric energy and 3 % of heat energy) [42, 43]. In most cases, the heat and electricity required by the digester will be consumed from those produced by the combined heat and power (CHP) plant from the biogas. The net electricity made available on the grid would then be about 197 × (1−0.02) = 193 $GWh_{electricity}$/year. Cameroon has a national electrical consumption of about 5×10^3 $GWh_{electricity}$/year [36]. As a leading African producer of bananas and plantains, the banana residual biomass could cover about 4 % of the annual electricity consumed in Cameroon or 30 % of the annual electricity needs of the economic capital Douala, which is the most populated city and the largest consumer of electricity in Cameroon [36].

Cameroon has a population of more than 23 million inhabitants. If we consider that every Cameroonian is supplied with electricity, the mean electricity consumption is about 229 kWh/(capita year). A banana contribution of 4 % of the electricity requirement of Cameroon may seem small, but this corresponds to about 905,660 Cameroonian people who could be supplied with electric energy, although CH_4 productivity could be improved. Then, it becomes obvious that this banana biomass contribution is quite important. Moreover, if we take into account the other banana varieties cropped in Cameroon for local needs, this renewable energy contribution could be doubled [38]. Banana-producing countries could then become less dependent on fossil fuels and less prone to energy shortages by producing biomethane from banana lignocellulosic wastes, which would also lead to benefits in terms of environmental protection and sustainable development. These banana residues are non-food biomass resources and therefore do not compete with human food supply.

Conversion of the net renewable energy by a combined heat and power plant (with yield of 0.50 MJ_heat/MJ_CH_4) [5] would produce 282 GWh_{heat}/year. Heat consumed by the process is about 3 % [42, 43]. The net heat available for industrial processes or household heating would then be about 274 GWh_{heat}/year. Heating can be useful in the west and southwest regions of the country where banana is also cropped and where the weather can be quite cold, especially in the rainy season.

In order to digest the banana residues, anaerobic digesters are needed. The amount of 1.4×10^6 $t_{residues\ FM}$/year with hydraulic retention time of 40 days would require a digestion capacity of 1.5×10^5 m^3. If we consider digesters of 1000 m^3 capacity, this would correspond to 1500 biogas plants over the banana producing area. For the sake of comparison, more than 8726 biogas plants, with each a total installed electric output in megawatt, were present in Germany in 2014 [44].

The simplified assessment above does not take into account all the practical constraints of the implementation of a biogas production plant. It allows, however, to set the orders of magnitude of the renewable energy potential. In order to make the process sustainable and profitable, the anaerobic digestion plant should be operated where the fresh banana residues are directly available, i.e., in plantations for stems, leaves, peduncles, and bulbs, and close to the banana processing industry for fruit peels. This will avoid the costs of collection and transportation of residues. The energy derived from methane could contribute to an environmentally and economically sustainable development of the country, and the digestate produced at the end of the process could also generate additional important savings for the farmers, since the process leads to a stabilized final product, which can be used to improve and maintain soil quality and fertility.

While the present assessment does not take into account the energy potential from the biomass of locally used plantain (lack of data on available biomass), which could increase significantly the energy output as CH_4 of the whole banana biomass, the total output energy obtained represents more than 85 % of the energy potential available in optimal conditions (Table 6). The results of this assessment clearly indicate that AD of banana residues is a technology that can increase energy security in banana producing regions. However, the fossil energy involved in production, storage, construction and maintenance of machines, digester plant, and buildings should be taken into consideration for a more general energetic and economic assessment.

3.4 Influence of variety on anaerobic digestibility

For banana peduncles and green peels, the GN variety produced significantly ($p < 0.05$) more methane than PPTA variety among the three varieties (Figs. 2 and 4). The higher total methane production of GN variety, as compared to PPTA, was probably due to its chemical composition. As visually observed, the PPTA tissues contained higher number of thicker lignocellulosic fibers, possibly explaining its highest DM content and lowest mineral content, respectively. These lignocellulosic fibers would limit the biodigestibility of the material and explain then the lowest methane potential. For GN, as compared to PPTA, the lower content in DM and fibers, the higher mineral content (Tables 2–4), the cellulose that is more easily hydrolyzed by cellulase [23], and the lower content in guaiacyl units of the lignin fraction [23] suggest the presence of tissues with less lignocellulosic fibers, but more metabolically active cells, with cell walls that contain less crystalline cellulose and are better swollen by water, which can explain a better access of hydrolytic enzyme to digest the GN tissues and the higher total methane production of GN variety. This is also consistent with other lignocellulosic substrates that have lower VS/FM that tend to have slightly higher anaerobic digestibility and higher methane content in the biogas [39]. In summary, the anaerobic digestibility was affected in consistent manner by the composition of the variety and GN was shown to be a better feedstock for anaerobic digestion.

3.5 Influence of maturation stage on the anaerobic digestibility of banana peels

Figure 4 shows that in all varieties, the maturation stage one (green) had the highest total methane production, with bioconversion yields ranging from 81 to 92 $\%_{COD}$, as compared to maturation stages five and seven whose yields were in the range 25 to 31 $\%_{COD}$. The methane content in the biogas evolved from 55 to 60 % with increasing maturation stage. The carbon in the peel material was more reduced (electron rich) with increasing maturity, as evidenced by the COD/VS ratio (Table 4). These results suggest changes in the biochemical composition of the fruit peels that result in lower biodigestibility of the organic matter. Happi Emaga et al. [30] investigated the influence of maturity on the banana peel composition. Their mass balance that included protein, fat, insoluble and soluble dietary fibers, starch, sugars, and ash was close to 100 % for the more mature stages, indicating that no major component was missed. The only quantitatively significant change was the conversion of starch to sugars with maturity. Such a change cannot explain the decrease in anaerobic digestibility or the increase of COD. The very slight absolute increases of proteins, fat, and fibers are not sufficient to explain the observed increase in COD or decrease of biodigestibility. Unfortunately, the dietary fiber method used by Happi Emaga et al. [30] that is based on selective fractions solubilization may possibly not detect some changes in the biochemical composition of the peel material that would explain the change in COD or digestibility. Peel color evolution from stage one to five is due to the degradation of chlorophyll and unmasking of carotenoids [27]. This change is not expected to result in significant reduction of the peel digestibility. Brown spots that appear in the peel with maturity are known to be largely due to polyphenol oxidation or condensation [30]. However, polyphenol oxidation is not expected to increase the COD to the range observed in Table 3. While being minor components in the mass balance, polyphenols and derived complexes responsible for the darkening can have protected the organic matter from enzymatic hydrolysis and explain some reductions of anaerobic digestibility with maturity. The general darkening of the peels observed during the drying process can possibly explain the reduced anaerobic digestibility.

4 Conclusion

The BMP of banana peduncles, banana bulbs, and banana peels ranged from 194 to 304 ml_CH4/g_DM. The methane content in the biogas ranged from 55 to 60 %. The GN variety was generally more biodigestible than PPTA variety. The low biodigestibility of PPTA variety was related to its fiber content, but further investigation should be done to characterize the lignin fraction. Maturation had a negative effect on the peels, whose biodigestibility decreased from $92\%_{COD}$ (green peels) to $56\ \%_{COD}$ (yellow peels with a few brown spots). The renewable energy potential as CH_4 that can be recovered from banana residual biomass corresponds to 91 % of the metabolic energy that is present in the edible pulp. When considering the residual biomass resulting from the GN cropped in Cameroon, the energy potential is 563 GWh_methane/year. The 193 GWh_net_electricity/year that can be derived from the methane corresponds to 4 % of the annual electricity consumed in Cameroon. This bioenergy could supply the electric energy requirements of about 9×10^5 people, i.e., more than half of total population of Douala, the most populated town in Cameroon. Nevertheless, the results showed that valorizing cropping banana residues could help to supply the energy requirements of human activities and contribute to an environmentally and economically sustainable development, especially in tropical banana-producing countries.

Acknowledgments Financial support and scholarship for this study (Project "Programme Interuniversitaire Cible: Valorization of banana residues and contribution to local sustainable development") were provided by the Commission Universitaire pour le Développement (CUD) and Wallonie-Bruxelles International (WBI) from Belgium. The authors are also grateful to the research staff from the Bioengineering Unit (UCL, Belgium), to the post-harvest technology laboratory, CARBAP-Cameroon, and to the laboratory for Food Science and Metabolism, LabSAM-Cameroon. A great acknowledgment to Thomas Nicolay, Florian Tiappi, Achu Mercy Bih, and Raphaël Tchokouassom for their technical support and assistance.

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