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Review

Potentials for Utilization of Post-Fiber Extraction Waste from Tropical Fruit Production in Brazil – the Example of Banana Pseudo-Stem

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Abstract: This work presents an estimation of potential fiber recovery as well as non-fiber biomass generated from banana pseudo-stem, using Brazil as example. Characteristics and potential uses of non-fiber biomass are presented and explored, based on a literature review. The yearly generation of banana pseudo-stems in Brazil reaches 14 million tons. The potential fiber extraction from this waste was estimated to 1.11 million tons per year. Banana pseudo-stems have a high content of glucose and cellulose in the range of 52.2-74% and 42.2-63.9% of dry solids (DS) respectively, a nitrogen, phosphorus and potassium content around 0.3-2.8, 0.2-0.5 and 4.0-4.6% of DS respectively, according to previous findings. The carbon/nitrogen ratio was reported in levels of 21-66. Previous studies have shown potentials of energy recovery from banana stem waste in the order of 64-196 dm^3 CH_4/kg DS through anaerobic digestion and 1.87-2.65 kg ethanol/kg dry solid (1st generation) or 0.70-4.71 kg ethanol/kg dry solid (2nd generation). Potentials for energy recovery from ethanol stillage are also discussed, but banana stem generated stillage are poorly described in the literature and more studies are needed to improve estimations of potentials for energy recovery also from these fractions. The gross energy recovery from banana pseudo-stems generated yearly in Brazil can vary from 4625-10300 TJ with a recovery of N-tot of 9-18 thousand tons, depending on chosen treatment combinations. Thus, fiber extraction together with combinations of technologies for energy and nutrient recovery could be of large interest in countries with high generation of banana waste.

Keywords: banana pseudo-stem; agricultural waste; natural fiber production; bioenergy; ethanol; biomass; nutrient; recovery.

1. Introduction

Fruit production is a major industry in many tropical countries. Brazil had a production of banana equaling 6.8 million tons, papaya equaling 1.8 million tons and mango equaling 1.2 million tons in 2009 (IBGE, 2010). Waste produced within the fruit sector can be divided into pre- and post-consumption waste, where pre-consumption waste is generated in the production phase, i.e. non-fruit biomass such as leaves and stems, while post-consumption waste consists mainly of peels, seeds etc. i.e. non-edible parts of the fruits.

The present paper focuses on the species banana (*Musa spp.)* as Brazil is a major producer of banana (5th largest in the world according to IBGE (2010)). Characteristic for banana is also the short life cycle (around one year) and thus a low ratio between weight of fruit and non-fruit biomass, resulting in large amounts of biowaste. The current destination of pre-consumption residues in South-America is not well documented in the scientific literature. However, Li et al. (2010) report that in southern China, where banana plantation has a significant economic importance, pseudo-stems are normally cut and usually abandoned in the plantation to become organic waste and cause environmental pollution after harvesting of banana bunches. The same practice is reported to occur in India (Tock et al., 2010; Baigh et al., 2004). When decomposed, these wastes may produce gases such as hydrogen sulfide and ammonia that can pose serious environmental hazards (Ilori et al., 2007).

Potentials for fiber recovery from banana pseudo-stem have previously been reported in the scientific literature. According to Li et al. (2010), the high content of holocellulose and low content of lignin make the banana pseudo-stem bark, an ideal material for application in pulping and papermaking. This is also currently done in Kerala, India, where a craft type paper of good strength is made from crushed, washed and dried banana pseudo-stems mixed with betel nut husk (*Areca catechu* L.), yielding 48-51% unbleached pulp (Tock et al., 2010). Khalil et al. (2006) concluded that the high solubility in ethanol-benzene (10.6%) of banana pseudo-stem fibers makes them advantageous for decay resistance during fiber processing. However, Australian investigators hold that the yield of extracted banana fiber is too low to be economically viable. According to their results only 28-113 g can be obtained from 18-36 kg of green pseudo-stems; thus, 132 tons wet weight of pseudo-stems would be necessary for the production of 1 ton of paper (Tock et al., 2010). Previous studies have also shown that fibers from banana stem can be used for production of polymer composites and as substitute for glass-fibers in reinforced HDPE. Pacheco et al. (2011a) showed that an addition of 20 mass% of banana fibers to HDPE increases elastic modulus by more than 500% compared to pure HDPE, and gave the same value of elastic modulus as the addition of 10 mass% glass fibers. Also, stems from papaya and peach-palm have shown to be interesting materials for fiber extraction. Use of fibers from peach-palm has also become increasingly popular in recent years. Several producers of natural fiber based products currently use palm-fibers in production of parquet, panels and furniture (Fibradesign, 2012; Papyrus Australia, 2012). A summary of the results previously reported in scientific literature is presented in Table 1. As seen from Table 1, although biomass from banana pseudo-stems presents an interesting alternative for fiber production, for the major part of the residues, mainly consisting of non-fibrous pseudo-stem/stem, it is necessary to find other areas of use. In order to find potential uses for such materials, their characteristics as well as previous findings in relation to energy and nutrient recovery were investigated, based on data found in the scientific literature.

Table 1. Potentials for fiber extraction from banana, papaya and peach-palm stem/pseudo stem

Species	% of wet biomass	Reference
Banana pseudo stem	8	Pacheco et al., 2011
Papaya stem	9	Pacheco et al., 2011
Peach palm stem	6	Pacheco et al., 2011
Banana pseudo stem	1.6-3.1	Tock et al., 2010
Banana pseudo stem	6.7	Aziz et al., 2011

2. Chemical Composition of Banana Stem/Pseudo-stem

Several studies have been performed on the chemical composition of banana pseudo-stem. They show that the composition in the outer bark of the pseudo-stem and the inner core of the stem differ largely. According to Li et al. (2010), the inner parts of the pseudo-stem contain no elementary fibers and fibers consist of pipes rather than fiber bundles, which is considered to have a positive effect on the transportation of water in the stem. This is in line with results from Pacheco et al. (2011b), showing that lignin content in fibers from the inner part of the banana stem equals only 50.9% of the content in fibers from the banana bark. According to Mophapaltra et al. (2010), the core of the banana pseudo-stem is rich in polysaccharides with traces of other elements, and has very low content of lignin. Results from previous analyses of the chemical composition in banana pseudo-stems are summarized in Table 2.

Table 2. Summary of data on the chemical characteristics of banana stems/pseudo-stems previously reported in the scientific literature

Type of biowaste	DS	VS	COD	Cellulose	Hemi-cellulose	Glucose	Holo-cellulose	Lignin	N-tot	P-tot	K	C/N-ratio	pH	Reference
	%	% of DS	g/L	% of DS	% of DS	% of DS	% of DS	% of DS	% of DS	% of DS	% of DS			
Banana pseudo stem	6.6	83.2											5.9	Velmurugan and Ramanujam, 2011
Dried banana steam	92	83						15						Kalia et al., 2000
Banana pseudo stem		98.5		63.9			65.2	18.6						Khalil et al., 2006
Banana pseudo stem	8.3	81		42.2				13.3	0.3	0.2	4.1			Velásquez Arredondo et al., 2009
Banana pseudo stem				44			16.5	8.1						Goncalvo Filho, 2011
Banana pseudo stem									2.8	0.4	4.2			Rahman, 2012
Banana pseudo stem	4	91.8		39.1		52.2	72.7	8.9						Li et al., 2010
Banana pseudo-stem		86		34-40		74	60-65	12						Mohapatra et al., 2010
Banana pseudo-stem		97.0		42.1	18.6			5.1						Aziz et al., 2011
Banana pseudo-stem		86.4					57.5	20.3						El-Zawawy et al., 2011
Banana pseudo-stem	5	90		52.3	9.9			11.2	0.6			66.0		Romero-Anaya et al., 2011
Banana pseudo-stem		84.6		55.5				22.3	1.4			27.5		Rosal et al., 2012
Banana pseudo-stem		85.4					65.2	12.7						Cordeiro et al., 2004
Average	7.5	87.9	48.9	47.0	13.0	63.1	55.4	13.4	1.5	0.4	4.3	38.2	6.0	
Banana stem and leaves			46.9						0.9	0.2	4.1	53		Formowitz et al., 2007
Banana pseudo-stem pith	13.6	21.6		10.8		11.7		3.3						Deivanai and Kasturi Bai, 1995
Banana pseudo-stem core		89.9		27.4		11.0		4.6						Aziz et al., 2011
Banana pseudo-stem juice	2.3-2.6	27-38	10.5-14.3										5.3-6.1	Calzada et al., 1988

Previous studies reported that the contents of mono-saccharides (glucose) and cellulose in banana pseudo-stem are high, while the content of lignin is commonly low. The content of glucose and cellulose was found to be in the ratio of 42.0-74.0 and 34.0-63.9% of DS, respectively, and lignin in the ratio of 5.1-22.3% of DS, in banana pseudo-stem, and 3.3-4.6% of DS, in the inner parts of the banana pseudo-stem. N-tot, P-tot and K-tot contents were found to be around 0.3-2.8, 0.2-0.5 and 4.0-4.6% of DS, respectively. C/N-ratios were reported in levels of 21-66. However, it should be remembered that these data also include fibrous parts of the banana pseudo stem, as the literature data contains very little information on the chemical composition of non-fiber biomass from banana pseudo-stem. The only published data found on such material (Deivanai and Kasturi Bai; 1995) suggest that both cellulose and lignin contents in such material are lower than the values presented for the pseudo-stem as a whole.

3. Potential Uses of Non-fibrous Biomass from Pseudo-stems

Based on data displayed in Table 2, potentials for use of these biomass fractions for energy and nutrient recovery purposes were explored based on previous findings reported in the scientific literature.

3.1. Nutrient Recovery through Aerobic Degradation

Composting is an aerobic degradation process in which parts of the organic material is transformed into CO_2 and water, while the remaining part is stabilized to a humic and nutrient rich substance. The process is carried out by microorganisms such as bacteria, fungi and worms. The humic substance will to a large extent contain lignin, which is not extensively mineralized during composting. The mineralization occurring is most importantly carried out by thermophilic fungi with an optimal working temperature around 45 ˚C. At these temperatures, degradation of lignin can reach more than 20% (Toumela, 2002).

The optimal water content in composting material is around 60%. Smaller size of particles in the substrate increases the degradation rate. The pH will change during the degradation process, and an initial pH around 7 is considered preferable. Aerobic digestion is an exothermic process, resulting in release of thermal energy. The temperature will vary over the degradation process and can reach temperatures as high as 90 ˚C. However, temperatures over 70 ˚C can char the compost and result in spontaneous ignition. The surrounding temperature will to some extent affect the gained temperature. Thus, higher temperatures can be expected in tropical regions (Brunt et al., 1985).

The C/N ratio can be of large importance for the degradation rate of hemicellulose and cellulose as well as lignin in composted materials. A decreased C/N-ratio has been responsible, according to previous studies, for a significant increase in the degradation ratio of cellulose and hemicellulose, from 10-20% with a C/N ratio of 50-54 to 40-80% with a C/N ratio of 11-35. Higher initial nitrogen content will increase the degradation ratio of more easily degradable carbon, while it might be inhibiting degradation of lignin, through alterations in the microorganism community, inhibition of the production of ligninolytic enzymes or formation of toxic and/or inhibitory compounds (Eiland et al., 2001). The optimum C/N ratio in composting material is around 30:1 (Brunt et al., 1985).

Several previous experiences on composting of banana waste have been reported in the scientific literature. However, few of them were related to the composting of pseudo-stems. Formowitz et al. (2007) showed that a high degradation of organic matter can be achieved in banana waste composting (chopped fruits and stalks), using un-covered heaps with a substrate/structure material (sawdust) ratio of 12:1. 76% of the wet weight and 78% of the dry weight were lost over a 35 day-long composting experiment. The same study showed that the C/N-ratio in banana waste (leaves and stem) can be high, in this case as high as 56. Chun Yan et al. (2011) studied co-composting of banana pseudo-stem with chicken manure and optimized the process in relation to N-tot losses in a study performed in southern China. It was seen that the lowest losses were found in composts with 65% humidity and a C/N ratio of 25 and a procedure of turning the compost every second day.

3.2. Energy Recovery through Thermal Processes

Pseudo-stems from banana plants can be used for bioenergy production through direct combustion. The calorific energy content (as higher heating value, HHV) in banana pseudo-stem was determined as 17.75 MJ/kg DS (LHV = 14.25) (Rosal et al., 2012). Banana pseudo-stem has, according to both Rosal et al. (2012) and Romero-Anaya et al. (2011), a low sulfur content (0-0.05% of DS). This can be compared to the palm stem HHV determined to 17.38 MJ/kg DS by Wilson et al. (2011). The same study also presents data on chlorine and sulfur contents in palm stem (0.18 and 0.13% of dry mass respectively) with the conclusion that this biomass makes it a less adequate material for direct incineration, as chlorine and sulfur are the major contributing factor to ash formation as they facilitate the mobility of inorganic compounds from the fuel to surfaces where they form the corrosive compounds (Wilson et al., 2011). Potential energy recovery can be calculated to be around 2.85 MJ/ton DS based on an assumed electricity recovery of 20% in the incineration process. However, in many tropical countries where these plants are grown, the infrastructure for controlled incineration with energy recovery is un-common. Direct combustion can therefore result in emission of environmentally hazardous compounds and little chance for energy recovery. Also, as seen above, the water content in this biomass is commonly high and will make combustion difficult (Tock et al., 2010). Another alternative is gasification with supercritical water (SCWG). Successful SCWG of biomass with low DS (5% in the case of water hyacinth) has been reported (Matsumura, 2002). Produced gas was seen to have an energy content of 20.6 MJ/Nm^3. However, the technology is expensive and more research is needed before it can be considered commercially viable (Tock et al., 2010).

3.3. Energy Recovery through Ethanol Production

Brazil has a strong tradition on the manufacturing of ethanol from sugar cane and sugar cane molasses. In this 1st generation ethanol production, glucose readily available in the biomass is converted to ethanol through fermentation. Ethanol can also be generated from corn, wheat, rye, barley, sorghum and other starch-rich biomass after an initial hydrolysis where starch is converted to glucose. The 2nd generation ethanol is produced from lignocellulosic biomass. Several different conversion technologies for cellulose and hemicellulose have been developed, such as acid (diluted/concentrated), alkaline or enzymatic hydrolysis. The conversion also commonly results in generation of substances which could inhibit the subsequent fermentation process, such as furfural, cinnamaldehyde, syringaldehyde etc. Alkali treatments with calcium hydroxide or ammonia can be used to remove such compounds before fermentation (Niga, 2009). As seen in Table 2, both glucose and cellulose are present in banana pseudo-stem. Thus, both 1st and 2nd generation ethanol is possible alternatives for energy conversion.

Several studies have been carried out using banana fruit and banana waste as feedstock for ethanol production. Experiences are presented below and summarized in Table 3. Goncalves Filho (2011) showed potentials for use of banana pseudo-stem for production of second generation ethanol. A conversion factor of 74.1% of cellulose to glucose was achieved, using enzymatic hydrolysis with NaOH pretreatment. Acid hydrolysis reached a conversion factor of 49%. A conversion factor of 0.31 was achieved when the total stem was used (including bark) and 0.37 using only the pressed-juice from the same. This is 72 and 86% respectively of the conversion factor gained when using sugar-cane as substrate, and banana pseudo stem was therefore seen as a potentially interesting substrate for further development and diversification of Brazilian ethanol production (Goncalves Filho, 2011). El-Zawawy et al. (2011) compare alkaline pulping, microwave alkaline treatment, water hydrolysis and steam explosion as pretreatments for banana pseudo-stem. The authors conclude that water hydrolysis generate the largest cellulose to glucose conversion, followed by steam explosion. However, the highest ethanol yields were achieved by using alkaline pulping when acid hydrolysis has been used and steam explosion in the case of enzymatic hydrolysis use, as these procedures result in a lower degree of crystallinity which enhances the enzymatic hydrolysis. Previous studies have also shown successful cellulose to sugar conversion of banana stem through use of aerobic fungi (Medeiros et al., 2000).

Veláquez Arredondo et al. (2009) obtained ethanol from banana pulp, fruit, stalks and peels in the ratios of 7.9, 5.7, 0.6 and 0.7% per ton of wet biomass input through acid hydrolysis (pulp and fruit) and enzymatic hydrolysis (stalk and peels). At the same time, residues in the form of stillage, residual biomass and lignin amounting to 136.9, 108.4, 31.0 and 56.2% of input substrate of pulp, fruit, stalks and peels respectively were generated. It was also seen that the energy input was higher than the output.

An alternative to the processes for conversion of cellulose to glucose suggested by Goncalves Filho, (2011) is an integrated process of first generation ethanol production of glucose with subsequent acid and enzymatic hydrolysis of generated stillage for conversion of hemicellulose and non-hemicellulose to sugars. Such conversion of hemicellulose to xylose and arabinose can be performed with a recovery factor of 80%, while the conversion to glucose from other cellulose compounds was as low as 22%, and the use of enzymes was high. High levels of inhibitory substances (mainly furfural) were also produced in the process. Also, due to the low pH in stillage, pH control using lime was needed before fermentation could be performed.

Enzymatic hydrolysis often provides higher yields of cellulose rich substrates, but can be expensive. Baigh et al. (2004) used a wild strain of *Trichoderma lignorum,* a fungi isolated from fields where banana was cultivated. This cellulosic enzyme complex is naturally abundant in banana cultivations where it plays an important role in the aerobic degradation process. Products generated from the culture were used as enzyme source in the saccharification of substrates. Thus, this enzyme provides an interesting alternative as a native and low cost alternative to commercial enzymes.

Table 3. Summary of results of ethanol production from banana waste

Substrate	Ethanol (kg/ton DM)	Ethanol(MJ/ ton DM)	Process	Reference
Banana stem	129.5	3469	2nd gen. enzymatic hydrolysis	Goncalvo Filho, 2011
Banana stem	85.6	2294	2nd gen. acid hydrolysis	
Banana pulp	305.4	8184	Acid hydrolysis	Veláquez Arredondo et al., 2009
Banana fruit	2715.6	72779	Acid hydrolysis	
Banana stalks	96.9	2596	Enzymatic hydrolysis	
Banana peels	67.9	1819	Enzymatic hydrolysis	
Banana stem	186.6	5002	1st gen.	Li et al., 2010
Banana stem	470.7	12615	2nd gen. Acid hydrolysis 20% H_2SO_4	Khan et al., 2002
Banana stem	70.3	1184	2nd gen. Acid hydrolysis 10% H_2SO_4	
Banana stem	265	7094	1st gen.	Mohapaltra et al., 2010

Note: DM = dry matter.

3.4. Energy Recovery through Anaerobic Digestion

Anaerobic digestion is another waste-to-energy alternative for biomass with higher water content. In wet processes, a DS below 20% is required, while substrates with DS > 20% can be treated in dry processes. C/N-ratios within the range of 15-25 have previously been presented as optimal for anaerobic digestion (Liu et al, 2008; Handeerichung, 2004; Nyuns 1986; Speece, 1984). The process is sensitive to low pH and the optimum pH lies between 6.5 and 7.5 (Liu et al., 2008). Thus, the degree of alkalinity is of importance and a range of 2000-4000 mg $CaCo_3$/liter has previously been suggested for stable digestion (Sharma et al., 1999). The theoretical potential of methane production from banana pseudo-stem can be determined based on the content of proteins, carbohydrates and fat reported by Aziz et al. (2011). The calculation of the potential was based on data from Christensen et al., (2003) (Table 4). Gained values can be compared to the theoretical potential in other organic wastes, such as food waste from households selectively collected in paper bags (Davidsson et al., 2007), 267-500 Ndm^3/kg DS.

Table 4. Content of proteins, carbohydrates and fat in full-scale samples in relation to literature values

Fraction	Banana pseudo-stem	Banana pseudo stem (core)	CH_4 potential (Ndm^3/kg DS)
Fat (% of DS)	0.24	1.18	1014
Proteins[1] (% of DS)	0.89	3.52	496
Carbohydrates (% of DS)	87.5	76.4	415
Ash (% of DS)	0.24	1.18	0
Theoretical CH_4 potential (Ndm^3/kg DS)	370	344	

Note: [1] As Kjeldahl nitrogen.

Several previous studies have also reported empirical data from anaerobic degradation of banana pseudo-stem and other types of banana waste fractions. These are presented below and summarized in Table 5.

Velmurugan and Ramanujam (2011) studied the performance of banana pseudo-stem material in a single stage fed-batch anaerobic reactor for biogas production. The material was grinded prior to trials. Results show risks for a rapid acidification and instability of the reactor due to high volatile fatty acids (VFA) concentrations in the process. In order to decrease the risk for VFA accumulation, the organic loading rate (OLR) was kept low. This resulted in a constant high alkalinity (>4750 mg $CaCO_3$/L). Also the VFA/alkalinity ratio remained under 0.4, previously suggested as an indication for stable processes (Callaghan et al., 2002). Zainol et al. (2008) investigated the biogas production from banana pseudo-stem in 10 liter anaerobic sequencing batch bioreactors under various temperatures (26-40 ˚C), organic loading rates (OLR) (0.4-2.0 g TS/L/d) and hydrolytic retention time (HRT) (3-20 days). It was found that for maximum biogas yield the levels of the variables are as follows: temperature = 35.8 ˚C, OLR = 1.42 g TS/L/d and HRT = 11.7 days. Experiments conducted with these optimized levels of variables gave an average biogas yield of 1.95 L CH_4/g COD. Calzada et al., (1988) investigated the characteristics and methane production potential of juice from crushed banana stem. The juice was kept frozen prior to the trials. In the mesophilic batch tests, an inoculum/substrate ratio of 10/90 was used. Volatile solids reductions (at HRT of 3 and 2 days) ranged from 38 to 46%, while the COD reductions ranged from 39 to 63%. The gain in biogas production from the batch test was nevertheless low. Also the methane concentration in produced biogas was found to be low, 30-46%. Suggested explanations include an initial low concentration of volatile solids and the presence of inhibiting polyphenols in the banana juice.

Table 5. Summary of results reported in the literature for anaerobic degradation of banana waste

Substrate	**CH_4 (L/kg TS)**	**CH_4 (% in gas)**	**Process**	**Reference**
Banana pseudo-stem	64		Continuous feeding (2.5 gVS/d), 35 ˚C	Stewert at al., 1984
Sundried banana stem	267-271	68-78%	Batch tests, HRT= 57 d, 35 ˚C	Kalia et al., 2000
Sundried banana stem	212-229	68-78%	Batch tests, HRT = 24 d, 55 ˚C	Kalia et al., 2000
Juice from crushed banana pseudo-stem	1.49 v/v day	29-46%	Continuous feeding (3.5 svm^3/d), HRT = 3 d	Calzada et al., 1988
Banana trash	9	72%	Batch test	Deivanai and Kasturi Bai, 1995
Banana peels	291	51-53%	Not stated	Prema et al., 1992
Fresh banana leaves	189	55%	Two phase digestion	Chanakya et al., 1993
Dried banana leaves	162	55%	Two phase digestion	Chanakya et al., 1993
Banana pseudo-stem	1.95 L/g COD	n.s.	Continuous feeding (ORL = 1.42 gTS/L/d) HRT = 11.7 d, 35.8 ˚C	Zainol et al., 2008

Note: VS = volatile solids, HRT = hydrolytic retention time, d = days.

Kalia et al. (2000) concluded that banana stem, due to its fibrous nature, is not suitable for methanogenesis process, and acid and alkali pre-treatments can be employed to breakdown its fibrous texture. The total methane yield decreased with increasing TS in substrate. The methane yields under thermophilic conditions were 13-16% less than those under mesophilic conditions. However, the incubation periods were only 24 days in thermophilic conditions, as compared to 57 days for maximum biodegradation in mesophilic degradation. The methane concentration was slightly higher in thermophilic conditions (72-78%) compared to mesophilic (68-71%). Also leaves from banana production have been analyzed as biogas substrate, using solid phase digestion with leachate recirculation. Results showed a potential production of 189 and 162 L CH_4/kg TS for fresh and dry leaves respectively (Chanakya et al., 1993). However, in order to produce biogas from leaves, a pretreatment is needed, which can be both labor and energy consuming (Chanakya et al., 1993).

4. Discussion

As seen in Table 2, substantial work has been done in relation to the properties and chemical composition of different types of banana pre- and post-consumption waste. However, the literature does not always specify clearly the parts of the banana plant biomass investigated, making comparisons of results difficult.

4.1. Lignin Content

Lignin is not converted into sugars either through acid/enzymatic hydrolysis or through anaerobic digestion. The lignin-content in banana pseudo-stem can according to results presented here differ largely. This could be explained by characteristics variations among the different species. Although data describing the chemical composition in the inner parts of the banana pseudo-stem are scars, they indicate a lignin-content below 5% of DS. This makes the combination of fiber extraction, using mainly the outer parts of the pseudo-stem, and ethanol production or, alternatively biogas production, from non-fibrous fractions, an interesting area for further research.

4.2. Water Content and C/N-ratio

High water content (>60%) in composted material increases the risk for creation of anaerobic conditions and either higher or lower water contents result in a decreased degradation rate. Thus, non-fiber biomass from banana pseudo-stems is not seen as adequate for composting, unless rather large amounts of structure material are used. However, addition of structure material could increase the C/N-ratio, which, according to previous studies already can be high in these substrates in relation to process optimum (Romero-Anaya et al., 2011; Formowitz et al., 2007). Thus, in relation to the composition data presented in Table 2, aerobic degradation is not seen as an interesting alternative for these waste fractions, mainly to the high humidity in this material. If this treatment alternative is chosen, large amounts of structure materials should be applied. As seen in Table 2, reported C/N-ratio in banana pseudo-stem differs largely for different sources. According to Prema et al. (1992) and Rosal et al. (2012) the ratio is within the range of 15-30 previously presented as optimal for anaerobic digestion (Liu et al., 2008). The C/N-ratio can be controlled, for example through addition of cattle manure. This will decrease the ratio and can also increase the buffer capacity and hence decrease the risk for acidification (Velmurugan and Ramanujam, 2011). In order to have a steady regrowth of microorganisms in anaerobic processes, not only nitrogen but also several other nutrients are needed. Optimum levels of Ca, Mg, Na and K have previously been determined to 100-200, 75-150, 100-200 and 200-400 mg/L respectively (Alkan-Ozkaynak and Karthikeyan, 2011). Thus, depending on the used substrate, nutrient addition might be needed.

4.3. pH

The commonly low pH (3.5-6.1 in different types of banana residues, Table 3) found in these wastes, thus resulting in risks of rapid acidification and large production of volatile fatty acids (VFA), can reduce the methanogenic activity and thus biogas production from anaerobic degradation of this waste (Bouallagui et al., 2004). Thus, the rate limiting step in the biogas production process is likely to be the methanogenesis rather than hydrolysis. In order to minimize risks for acidification, the organic load rate must be kept low. However, this will decrease the efficiency of the process. As seen above, stillage from ethanol production normally has a pH around 4-5.5 and pH adjustment is needed prior to anaerobic digestion. Alkan-Ozkaynak and Karthikeyan (2011) showed that pretreatment of corn ethanol thin stillage with lime does not only raise pH, but also eliminates some potentially inhibitory parts of the stillage content such as oleic acid through precipitation by Ca. In the case of composting processes the sensitivity to low pH is much less severe and pH adjustment through liming should be avoided, as this (especially in combination with elevated temperatures) can increase losses of ammonia (Diaz et al., 2007).

4.4. Energy Recovery

In Table 6, some of the key parameters for energy recovery through anaerobic digestion, ethanol production and direct combustion in banana pseudo-stems are displayed and compared with literature data from other plants. It is seen that both the cellulose and holocellulose content in banana pseudo-stem are comparable with the levels found in aspen and straw, while the lignin content is lower in general. Both the heating value and ethanol production from banana pseudo-stem are high compared to data found for sugar cane bagasse, which currently is used for both direct combustion and production of 2nd generation ethanol. However, the difference in dry matter substance in banana pseudo-stem (8.3%) and bagasse (50%) would make energy recovery through direct combustion much more difficult in the first case. However, data presented in Table 3 also shows that the potential energy recovery through anaerobic digestion and ethanol production of banana pseudo-stem vary largely, based on results from previous studies. Thus, more work is needed in order to establish well documented optimization of such processes, as well as to investigate the potentials for anaerobic digestion and ethanol production of the non-fibrous biomass from this waste. In relation to bagasse from sugar cane, the content of lignin and hemi-cellulose in banana pseudo-stem and principally stem core is low. The biogas potential is lower compared to sugar beet and corn sillage. However, it should be remembered that these crops are currently produced as energy crops with the aim of producing biogas in countries such as Germany, while the banana pseudo-stem is a waste product.

Table 6. Comparison of banana pseudo-stem with other biomass in relation to potential energy recovery

Plant	**Reference**	**Cellulose**	**Glucose**	**Holo-cellulose**	**Hemi-cellulose**	**Lignin**	**Ash**	**LHV**	**CH_4**	**Ethanol**
				(% of DS)				MJ/kg DS	L/kg DS	kg/kg DS
Aspen	Gong, 2007	45		77.6-79.2	77.6-79.2	24.6	0.52-1.03			
Straw	Liu et al., 2003	36.2		63.1	63.1	15.45	12.87		270	
Corn	Špalková et al.,2009; Weiland et al., 2010								310-420	
Sugar beet	Gunaseelan, 1997; Weiland et al., 2010								340-360	
Sugar cane bagasse	Rosal et al., 2012; Dawson and Boopathy, 2008	30			23	22		13.79		7-19.9
Palm stem	Rosal et al., 2012							13.85		
Banana pseudo-stem	Gonzalvez-Filho, 2011	34-55.5	52.2-74	57.5-72.7	9.9-18.6	5.1-22.3	1.5-19	14.25	64-271	1st gen: 187-265; 2nd gen: 70-471

Note: DS = dry substance, LHV = lower heating value.

Energy recovery through ethanol production results in large amounts of residues – mainly in the form of stillage with low DS concentration. The stillage generation varies largely for different substrates (0.22 L/kg beets; 3.8 L/kg cane molasses; 6.29 L/kg corn (Wilkie et al., 2000)). Previous studies of anaerobic digestion of stillage from beet molasses ethanol production have shown potentials for energy recovery in the order of 1100 MJ/L (Wilkie et al., 2000). Thus, anaerobic digestion of stillage generated in ethanol production of non-fibrous parts of banana pseudo-stem is an important area for further research. It should also be remembered that both ethanol production and anaerobic digestion allow nutrient recovery.

4.5. Estimation of Potential Energy and Nutrient Recovery – the Case of Banana Pseudo-stem in Brazil

The total potential for energy and nutrient from banana pseudo-stem waste generated yearly in Brazil was estimated based on a combination of data presented in Tables 1- 4 & 7. However, a number of assumptions have been made. Previous studies have presented the maximum theoretical conversion of cellulose to 1.11 g glucose/1 g cellulose (Finguerut, 2006) and the maximum theoretical conversion of 1 g glucose to 0.511 g ethanol (Dias, 2008). Thus, the theoretical maximum ethanol production from banana pseudo-stem could be calculated based on the average content of glucose and cellulose shown in Table 2. For an estimation of an actual cellulose/glucose conversion, average data from Gonçalvo Filho (2011) were used (combining conversion through enzymatic hydrolysis (0.822 g/g) and acid hydrolysis (0.544 g/g)). For the conversion of glucose to ethanol, a factor of 0.7 was used (Gonçalvo Filho, 2011). In the case of methane generation, estimated energy recovery was based on average production reported in previous studies presented in the literature. No data was found in relation to the volume of stillage generated in ethanol production neither based on glucose nor cellulose banana pseudo-stem. Hence, averages from production based on conventional and cellulose substrates based on Wilkie et al. (2000) were used in the calculation. Also in the case of COD concentration in stillage from banana pseudo-stem, averages from production based on conventional and cellulose substrates were used (Table 7). Used factors for energy and nutrient recovery and used average composition data are displayed in Table 8.

Table 7. Values used for estimation of energy and nutrient recovery based on literature data

Process	Value	Comment	Reference
Dry substance (DS)	7.5%	Empiric, banana pseudo stem	Average based on Table 2
Glucose → Ethanol	0.511 g/g DS	Theoretical	Finguerut, 2006
Cellulose → Glucose	1.11 g/g DS	Theoretical	Dias, 2008
Cellulose → Glucose	0.683 g/g DS	Average	Goncalvo Filho, 2011
Glucose → Ethanol	0.358 g/g DS	Enzymatic hydrolysis and acid hydrolysis	Goncalvo Filho, 2011
DS → Methane	0.114 L/g DS	Empiric, banana pseudo stem	Average based on Table 2
COD → Methane	0.35 CH_4/g COD	Theoretical	Spinosa and Vesilind, 2001
COD in stillage	68.8 g/L stillage	Glucose based (1st gen.)	Wilkie et al., 2000
COD in stillage	15 g/L stillage	Cellulose based (2nd gen.)	Wilkie et al., 2000
Stillage production	13.9 L/L ethanol	Glucose based (1st gen.)	Wilkie et al., 2000
Stillage production	4.0 L/L ethanol	Cellulose based (2nd gen.)	Wilkie et al., 2000
N-tot	1.8% of DS	Empiric, banana pseudo stem	Average based on Table 2
P-tot	0.4% of DS	Empiric, banana pseudo stem	Average based on Table 2
K-tot	4.2% of DS	Empiric, banana pseudo stem	Average based on Table 2
Compost, N-tot loss	50% of N-tot	Empiric, municipal solid waste	Boldrin et al., 2009

The combination of data from Table 1 with results displayed in Table 5 shows that the gross energy recovery from banana pseudo-stems generated yearly in Brazil can vary from 4625 to 10300 TJ, with a recovery of N-tot in the order of 9-18 thousand tons, depending on chosen treatment alternative combinations.

Table 8. Potential energy and nutrient recovery from banana pseudo-stem per ton dry biomass

Energy/nutrient recovery process	**Energy recovery alternatives (MJ/ton DS)**				**Nutrient recovery (kg/ton DS)**		
	Ethanol	Biogas (stillage)	Biogas (pseudo stem)	Total	N-tot	P-tot	K-tot
Ethanol (1st generation)	4 513			4 513			
Ethanol (1st generation) + biogas (stillage)	4 513	1 296		6 081			
Ethanol (1st + 2nd generation)	6 511			6 511			
Ethanol (1st + 2nd generation) + biogas (stillage)	6 511	2 436		8 947			
Biogas (pseudo-stem)			4 022	4 022	18	4	42
Compost					9	4	42

5. Conclusions

The generation of banana pseudo-stem in Brazil reaches around 14 million tons per year. This biomass is currently often left in the field, for uncontrolled degradation, or eliminated through uncontrolled combustion, resulting in a sub-optimization in the reutilization of nutrients and emissions of different types of environmentally hazardous compounds. This review presents previously published data on the chemical composition of this biomass. Based on the review it was seen that the amount of usable fibers potentially extractable from this biomass reaches around 1.11 tons per year. Non-fiber biomass has a low dry matter content (6.6-13.6%) and high content of volatile solids (81-86% of dry matter content). N-tot, P-tot and K-tot contents around 0.3-2.8, 0.2-0.5 and 4.0-4.6% of dry matter content, respectively, have been reported. The high content of glucose and cellulose (37.7-74% and 37.0-63.9% of dry matter, respectively) makes the banana pseudo-stem an interesting alternative for first and second generation ethanol, with a potential production of 187-265 (1st generation) and 70-470 (2nd generation) kg ethanol/ton dry biomass based on previous experiences. Previous experiences also show a methane generation through anaerobic digestion of 64-271 L CH_4/kg dry matter. However, due to the low pH in banana pseudo-stem (5.3-6.1) pH adjustment prior to anaerobic digestion is required.

The review shows that the gross energy recovery from banana pseudo-stems generated yearly in Brazil can vary from 4625 to 10300 TJ with a recovery of N-tot in the order of 9-18 thousand tons, depending on chosen treatment alternative combinations. Based on the above, it could be concluded that fiber extraction and recovery for material production purposes, together with combinations of technologies for energy and nutrient recovery, could be of large interest in countries with high generation of the types of biowaste investigated in the present study. However, to refine knowledge on potentials related to such a biorefinery concept, more research needs to be done, principally in the following areas: (1) optimization of biogas production from non-fiber pseudo-stem/stem biomass, (2) optimization of glucose and cellulose based ethanol from non-fiber pseudo-stem/stem biomass, (3) potentials for anaerobic digestion of glucose and cellulose from non-fiber pseudo-stem/stem biomass ethanol stillage, (4) potentials for nutrient recovery, and (5) net energy recovery factors.

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