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Characterization of Agro-Residues For Biogas Production and Nutrient Recovery In Kenya

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Abstract
The global drive towards meeting the sustainable development goals coupled with the persistent energy-intensive lifestyle presents an overwhelming need for exploring and exploiting new sources of energy that are both renewable and eco-friendly. Bioconversion of selected feedstock for energy production is a promising option for exploiting the huge potential offered by the underutilised residual waste streams. In Kenya, there exists an abundant supply of unexploited agricultural residues having substantial capacity to cater for the increasing energy demand. Indeed biogas technology offers a very attractive route to valorise various categories of biowaste and presents multiple benefits to the users and community besides meeting the energy needs, resource conservation and environmental protection. However sustainable application of biogas technology demands a sound understanding of the feedstock characteristics. The purpose of this research was therefore to contribute knowledge towards enhanced understanding of the characteristics and value of agro-residues in the context of biogas feedstock. The objective of this study was therefore to characterise different types of agricultural residues from maize, coffee, cotton, sugarcane and bananas so as to evaluate their suitability for biogas production and nutrient recovery in Kenya. The quality of the biogas produced as well as the mineral fertilizer replacement properties of the digestate are also evaluated following bio methane potential assay and spectrophotometric analysis. Results from the study demonstrate that maize, coffee, cotton, sugarcane and banana residues are quite suitable for biogas production whereas their digestate is very promising for nutrient recovery. While the focus of the research is Kenya, the implementation of the research findings has the potential impact of helping many energy deficient communities in world to significantly meet their needs for secure, affordable, reliable, clean and sustainable energy supply. Besides, exploitation of the potential presented by the agro-residues can spur an energy revolution hence resulting in a major economic impact in many countries.

Keywords: agro-residues, nutrient recovery, biomethanation, biogas, Kenya

INTRODUCTION

Agricultural production has continued to be the driver of economic development in many developing countries besides being the mainstay source of food and energy for a vast growing population. However, the abundant supply of the resultant readily available agro-residues has largely remained underutilized besides being perceived as waste for disposal. The most common route for the disposal of agricultural residues is burning in the fields, which present environmental problems besides depriving the soil of vital nutrients essential for enhanced productivity. In addition agricultural residues occasionally contribute to clogging of waterways. Conversely, there has been a steady decline in energy resources globally while the modern energy-demanding lifestyle continues to demand for increased exploration, exploitation and integration of new sources of energy while simultaneously utilising the available resources in a sustainable way.

The global drive towards meeting the sustainable development goalscoupled with the persistent energy-intensive lifestyle presents an overwhelming need for exploring and exploiting new sources of energy that are both renewable and eco-friendly (UN, 2015). Indeed in the wake of ever-diminishing energy resources, the modern energy-demanding lifestyle demands increased exploration, exploitation and integration of new sources of energy while simultaneously utilising the available resources in a sustainable way (Suberu, 2013; Nzila, 2012; Sebitosi, 2007). In the recent past a lot of research interest has emerged worldwide on the utilisation of biomass for generation of energy (Annabel, 2012; Deublein, 2008; Sims, 2004). Indeed, biomass in all its forms is researched to account for over 16 % (over 1097 million tonnes of oil equivalent (TOE) of the world's final energy consumption by 2020 (IEA, 2011). Biomass utilization is expected to increase as a strategy for carbon dioxide (CO_2) emission reduction since it is considered to be a CO_2 neutral fuel. The consideration of biomass as a green fuel is further attributed to its high degree of renewability,low contents of sulphur and ash. Furthermore bio fuel production from non-food crops (FAO, 2008) and agricultural residues (Nzila, 2010) has the potential of putting underutilized resources into optimal use and this can lead to national development as well as alleviation of poverty. In Kenya, typical to many developing countries, various agricultural residual biomasses that have a good potential to cater for the energy demand are available in plenty but largely remain underutilised. Bioconversion of selected residual waste streams for energy production through biogas production is a promising option for exploiting the huge potential offered by these largely underutilised residues.

Biogas is produced through biomethanation process, which is a biological transformation through which organic matter is degraded through anaerobic digestion. The biomethanation process consists of a series of discrete reactions catalysed by a consortium of metabolic groups of different bacterial species through which organic matter is converted to the main products of methane, carbon dioxide and digestate (Ranali, 2007; Yadvika, 2004). Biomethanation can therefore be advantageously implemented as energy as well as fertilizer recovery and waste stabilization process in most agricultural production processes that otherwise release organic by-products and wastes (Keppler, 2006). In addition, the biogas energy from biomethanation could eventually contribute a significant portion of the lighting requirements especially in the rural areas. Besides, the fertilising characteristics of the digestate enable it to be used as green manure (Fenton 2012) for niche organic products thus providing multiple environmental and socio-economic benefits to the users and the community and hence contributing to poverty alleviation.

Biogas technology is therefore one of the widely employed bioconversion techniques that offers a very attractive route to utilize various categories of biowaste and offers multiple benefits besides meeting the energy needs, resource conservation and environmental protection. However sustainable application of biogas technology demands a sound understanding of the feedstock characteristics. Indeed biogas production is strongly influenced by feedstock restrictions such as substrate complexity, quality and quantity as well as year-round cost-effective availability. Consequently in a typical biogas value chain (BVC), biogas production depends for the most part on the biodegradability and hydrolysis rate of the substrate (Fernandes, 2009). Substrate availability and adequate digestibility is thus a principal requirement in biogas production systems. Nevertheless large quantities of potential biogas substrates remain underutilized due to prevalent knowledge gaps especially with respect to the suitability of these substrates for biogas production (Yu, 2008; Nzila, 2010). Indeed in many developing regions, the abundant supply of readily available biogas feedstock has largely remained underutilized while the needs for secure, affordable, reliable, clean and sustainable energy supply continues to escalate.

Hence it is imperative to screen and indeed map the substrates so as to evaluate their suitability for biogas energy production. The objective of this study was therefore to characterise different types of agricultural biowaste from maize, coffee, cotton, sugarcane and bananas so as to evaluate their suitability for biogas production and nutrient recovery in Kenya. The quality of the biogas produced as well as the mineral fertilizer replacement properties of the digestate are also discussed.

MATERIALS AND METHODS

The test substrates consisted of agricultural biowaste from maize stalks, coffee pulp residue, cotton waste, sugarcane leaves and banana stalks. All the agricultural biowaste samples were collected from different farms in Kenya. The samples were chopped and air- dried at ambient conditions to average equilibrium moisture content of 10% (±1.5). The variables analysed during the course of screening the different biowaste for energy production and nutrient recovery included dry matter (DM), ash content at 500°C, volatile solids (VS), total Chemical Oxygen Demand (COD), crude protein, crude fibre, volatile fatty acids (VFA), methane (CH_4), hydrogen sulphide (H_2S), total organic nitrogen (NH_4-N), total Phosphates (PO_4-P) and Potassium (K^+). The experimental set up for the BMP assay consisted of 20L mini laboratory digesters as previously reported in our earlier work(Nzila, 2008). The mini digesters were essentially airtight plastic barrels with rubber pipes for gas and liquid outlets. After placing the required amount of substrate and inoculum into the digesters, they then incubated at 30°C ± 2°C. The inoculum used was a sludge mixture consisting of active suspended digested cow dung and anaerobic granular sludge. The digested cow dung with 5.0 % DM and 67.0 % VS in DM was obtained from a local mesophilic cow dung-based biogas digester whereas the granular sludge with 16.2 % DM and 77.5 % VS in DM originated from the sediments of a mesophilic anaerobic lagoon treating paper mill effluents. The Substrate to Inoculum ratio (S/I ratio) on VS basis was kept at 0.6 to guarantee adequate presence of hydrolytic and methanogenic microbial populations.

The parameters analysed prior to the commencement of the Bio Methane Potential (BMP) assay included DM, VS, ash content, crude protein and crude fibre content. The parameters monitored during the course of the BMP assay included gas volume and composition, pH and VFA concentration. The gas volume in each reactor was measured daily through downward displacement of a water column while the pH, VFA and composition in terms of CH_4, CO_2 content were measured weekly. The characterisation of the substrates in terms of DM, ash, VS and total COD analysis were performed according to standard methods (Nzila, 2010). The crude dietary fibre was analysed by means of a combination of enzymatic and gravimetric methods according to (Prosky, 1992). Nitrogen analysis was performed according to modified Kjeldahl method in which the sample is digested using H_2SO_4 and $H_2O_2$with $CuSO_4$ as catalyst. All nitrogen is converted to $(NH_4)_2SO_4$, which is later determined by adding an excess of NaOH and by distilling the liberated NH_3. This free NH_3 is collected in H_3BO_3 solution and titrated with HCl solution. The crude protein content was calculated by multiplying the nitrogen content estimated via the Kjeldahl method by 6.25 g protein per g N. The analysis of nutrient parameters in terms of NH_4^-N, PO_4^-P and K^+ was performed using a digital spectrophotometer *NANOCOLOR* 500D according to the Macherey-Nagel spectrophotometer manual (Macherey-Nagel,2011). The determination of NH_4-N was based on the reaction basis whereby at a pH value of about 12.6, ammonium ions react with hypochlorite and salicylate in the presence of sodium nitroprussiate as catalyst to form a blue indophenol from which the concentration of NH_4-N (mg/l) is obtained photometrically. Similarly, the determination of PO_4-P was based on the reaction basis whereby ortho-phosphate ions react with molybdate/vanadate to form a yellow phosphate-molybdate-vanadate complex from which the concentration of PO_4-P (mg/l) is obtained photometrically. Determination of potassium on the other hand was based on the reaction basis whereby potassium reacts with sodium tetraphenylburate to form an insoluble compound that can be photometrically measured as turbidity.

RESULTS AND DISCUSSIONS

Physico-chemical characterisation of complementary biogas feedstock flows in Kenya

The physico-chemical characterisation of the different biowaste is presented by means of proximate analysis (**Table 1**) in terms of DM, VS, ash, crude protein and crude fibre. The solid biowaste had a relatively high ash content ranging from 4.63% (coffee pulp residues) to 33.77% (banana stalks). In comparison to woody biomass ash (<1% for softwoods and 1–3% for hardwoods) these ash contents are extremely high, but they are not uncharacteristic for agro-industrial residues since ash contents in the range from 5 to 22 % by weight for wheat straw, corn stover and cotton gin waste have been reported (Agblevor, Mingle et al. 2006).

Nevertheless, the high ash content values can be attributed to the incorporation of inorganic materials in the residues. The VS content ranged from 66% (for banana stalks) to as high as 94% (coffee pulp residues). Volatile solids are generally one of the common indicators for biogas production potential hence in this aspect coffee pulp residues would be expected to yield the highest amount of biogas whereas banana stalks would be expected to yield the lowest amount of biogas. Of course this proposition presupposes long term conditions (over three months) since in the short term (around 30 days) the anaerobic digestibility of the residue and the absence of toxic intermediates is much more important (Ranalli 2007).The crude protein and fibre content of the residues were generally comparable. However sugarcane leaves and banana stalks were an exception with significantly low crude protein content of 1.41% and 0.08%. On the other hand the crude fibre content for all the solid residues was quite comparable apart from coffee pulp residues that had a significantly lower crude fibre content of 21%. The crude protein and fibre content of coffee pulp residues, cotton residues and maize stover also render them suitable for use as animal feed, however the hard crusty appearance of coffee pulp residue coupled with bitter taste make it unattractive to animals. Similarly, the low protein content of sugarcane leaves and banana stalks render them unsuitable for use as animal feed. Moreover since the crude protein content of most plant-based substrates has a strong influence on the biogas potential (Lubken, Gronauer et al. 2007) then it can be postulated that the biogas yield from both sugarcane leaves and banana stalks would be probably lower as compared to the other residues.

Table 1: Proximate analysis of the biowaste (Standard dev, n=2, in brackets)

Substrate	%DM	% ASH *	%VS *	Crude Protein *	Crude Fibre *
Coffee pulp residues	92 *(4)*	5 *(1)*	94 *(2)*	12.21 *(1.12)*	21.09 *(1.96)*
Sugarcane leaves	20 *(0)*	29 *(4)*	71 *(4)*	1.41 *(0.10)*	80.26 *(1.28)*
Sugarcane bagasse	94 *(1)*	4 *(1)*	90 *(1)*	1.17 *(0.20)*	94.49 *(0.76)*
Cotton residues	91 *(1)*	4 *(0)*	88 *(1)*	15.56 *(3.94)*	63.41 *(4.02)*
Maize stover	93 *(1)*	5 *(0)*	95 *(0)*	10.86 *(0.31)*	80.84 *(0.75)*
Banana stalks	10 *(0)*	34 *(1)*	66 *(1)*	0.08 *(0.00)*	85.13 *(2.98)*

*Expressed in terms of %DM; values for DM, ASH and VS have been rounded off.

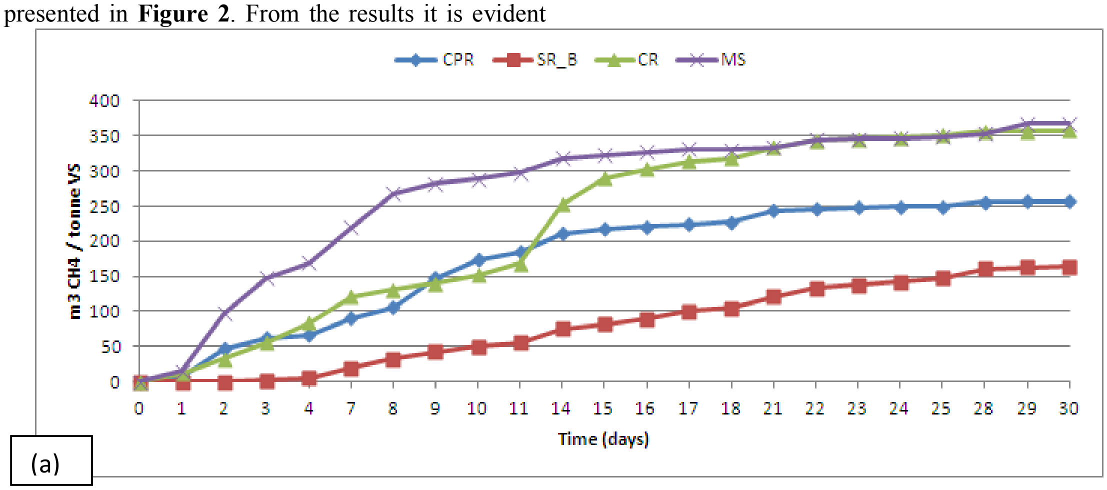
Bio-Methane Characterisation of Complementary Biogas Feedstock Flows in Kenya

The bio-methane characterisation of the different complementary biogas feedstock flows in terms of methane yield per tonne VS is presented in **Figure1**. The net results (after correction for blanks) show that the complementary biogas feedstock flows have a range of methane production from as low as 91 m^3*CH_4/tonne VS* (sugarcane leaves) to as high as 368 m^3*CH_4/tonne VS* (maize stover). The methane yield from coffee pulp residue, cotton residue and maize stover was above 70% of the respective final yield within two weeks of digester operation while the yield from the two sugarcane residues and banana stalks was less than 45% of the respective final yield over the same period. Generally the methane yield from both sugarcane leaves and banana stalks (**Figures 1a** and**1b**) are significantly lower as compared to the yield from the other feedstock.This occurrence implies that the anaerobic digestion and hence mineralisation of both sugarcane leaves and banana stalks is quite different from that of coffee, sugarcane bagasse, cotton residue and maize stover. There is possibly a wide array of physical, chemical and biological factors behind such an occurrence. Nevertheless, from **Table 1** it is apparent that the relatively lower VS content coupled with significantly higher ash content in both sugarcane leaves and banana stalks possibly has a direct bearing on the low biogas yield from the two residues. These findings are in agreement with previous studies showing that anaerobic mineralisation of some COD does not necessarily end up with more biogas (Ranali 2007; Nzila et al 2008).

From the foregoing, it is apparent that coffee pulp residue, cotton residue and maize stover are better complementary biogas feedstock and necessitate a shorter residence time in the digester as compared to the sugarcane residues and banana stalks. The bio-methane potential in terms of m^3 CH_4/ton substrate is presented in **Figure 2**. From the results it is evident that the methane production from the different complementary biogas feedstock lies in the range of between 13 to 344 m^3 CH_4/ton substrate. The results further demonstrate the suitability of coffee pulp residue, cotton residue and maize stover as complementary biogas feedstock.

Gas Quality

The biogas H_2S content (ppmv) for all the substrates (**Figure 3**) ranged from as low as 105 (for maize stover) to 1,100 (sugarcane leaves) whereas the CH_4 content varied from 40 % (sugar cane leaves) to 62 % (cotton residue). Generally, one of the major contaminants of biogas is H_2S commonly ranging from 2,000 – 20,000 ppmv depending on the pH value and sulphate concentration of the substrate (Schieder, Quicker et al. 2003). The presence of H_2S in the biogas renders it "sour" that is malodorous and corrosive besides causing SO_2 emissions during combustion. Consequently for domestic applications such as in lighting and combustion in burners and boilers, the H_2S content is required not to be more than 0.1% or 1,000 ppmv (Ranalli 2007; Amrit, Jagan et al. 2009). Removal of H_2S (desulphurisation) from the biogas, normally by means of caustic scrubbing or iron sponge beds, is required so as to render the gas suitable as a fuel (Jensen and Webb 1995). In this regard, the biogas from coffee pulp residue, sugarcane bagasse, maize stover, cotton residue and banana stalks can be regarded to be suitable for direct domestic application since it is within the required limit for H_2S content. On the other hand the biogas from sugarcane leaves is deemed to be about 10% above the allowable limit for domestic applications and hence might require desulphurisation prior to any combustion.



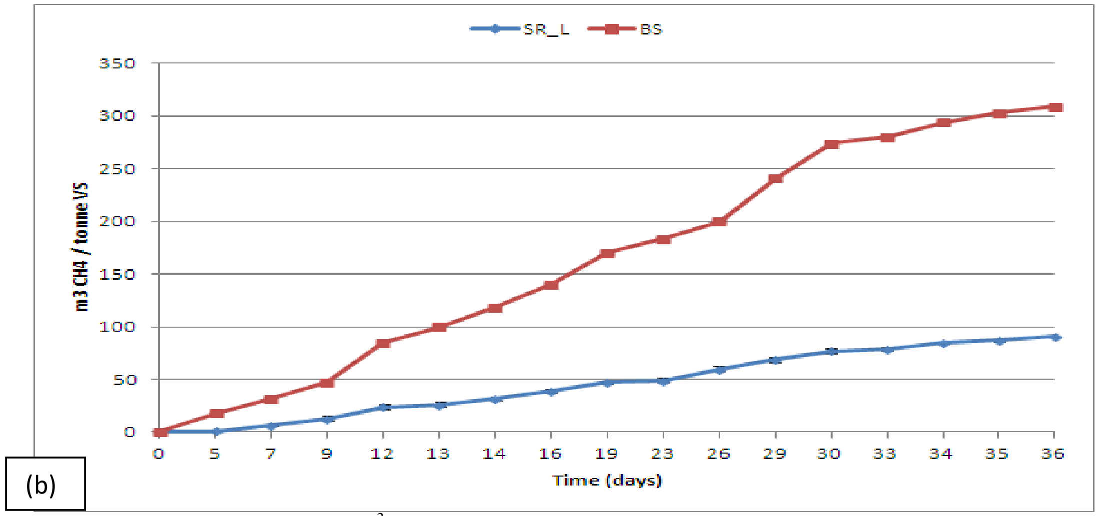


Figure 1: Bio methane potential (m^3 CH_4/ton VS) of (a) coffee pulp residue (CPR), sugarcane bagasse (SR_B) cotton residue (CR) and maize stover (MS) and (b) sugarcane leaves (SR_L) and banana stalks (BS)

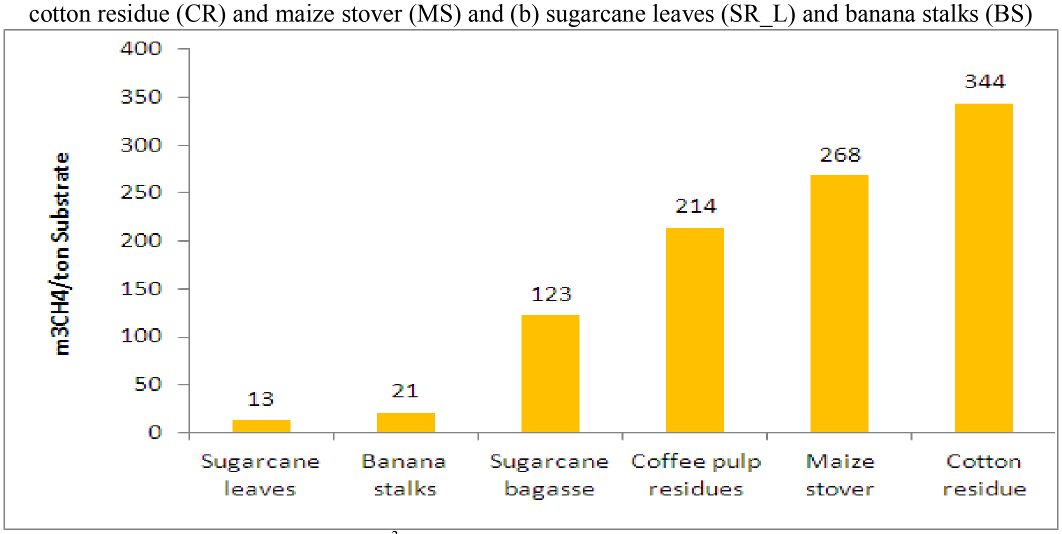


Figure 2: Bio-methane characterisation (m^3 CH_4/ton substrate) of complementary biogas feedstock flows in Kenya

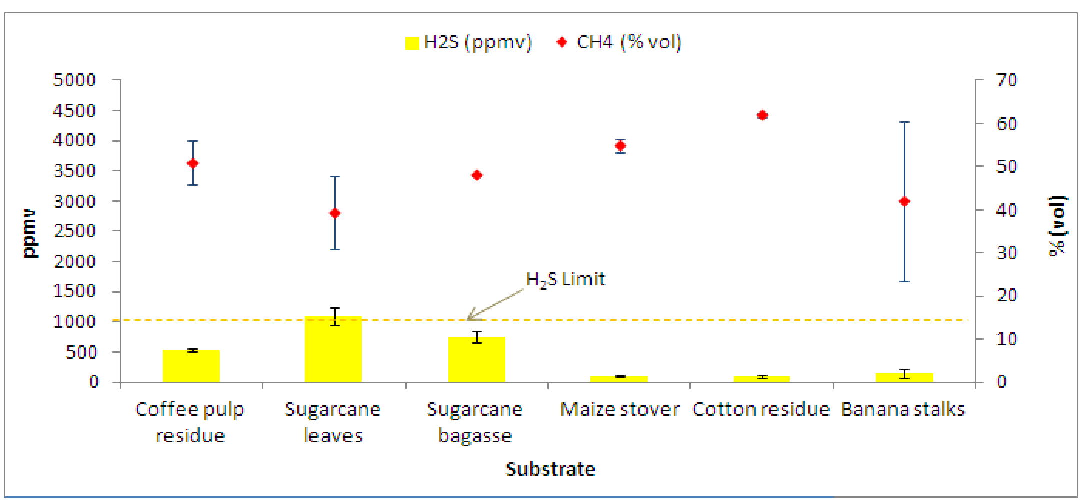


Figure 3: Biogas CH_4 content (%, vol.) and H_2S content (ppmv) from the different substrates showing the range of substrates whose biogas falls within the allowable H_2S limit of 1000 ppmv. (Error bars are included with standard deviation, n=7)

Nutrient Recovery Properties of the Digestate

Anaerobic digestion generally favours mineralisation hence the availability of nutrients such as NPK, which are regarded as the three most important elements in plant nutrition. The digestate slurry thus presents a potential source of NPK nutrients thus knowledge of the fertilizing properties is essential for any meaningful integrated crop sustenance scheme. The results (**Figure 4**) show that the digestate slurry from all the substrates contains appreciable quantities of the NH_4^+-N, K^+ and PO_4^{3-}-P nutrients. On average the nitrogen and phosphate content were generally comparable for all the different digestate however the potassium content was about two to five times more than respective the nitrogen content. Nonetheless, most soils in Kenya are rich in potassium hence it is not of primary importance in the country as a source of soil nutrient (Mathenge 2009). The relatively large nutrient content in sugarcane leaves digestate in relation to the low biogas (CH_4) production implies that anaerobic digestion of the sugarcane leaves favours bio-mineralisation to biomethanation. Indeed it has been reported that sulphate reducers as well as nitrate reducing bacteria compete successfully for the hydrogen normally used for CO_2 reduction to CH_4 (Ranali 2007). Substrates with high sulphur content may therefore cause less CH_4 formation and considerable H_2S formation. The relatively lower CH_4 production from sugarcane leaves coupled with higher H_2S content in the resultant biogas is therefore not surprising. However further work is required to bring out more insight with a view to finding ways of optimising the biogas production from both sugarcane leaves and banana stalks.

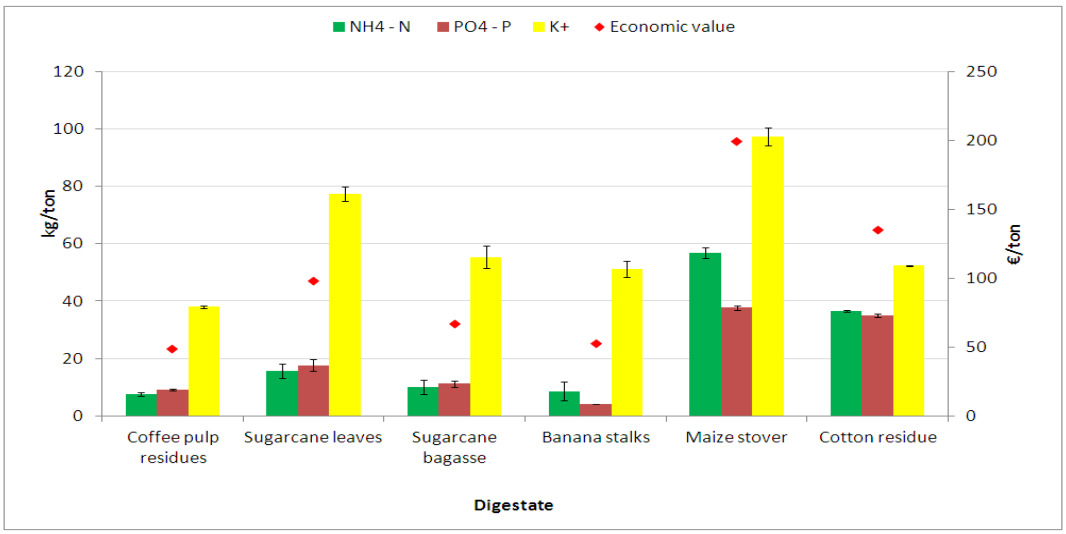


Figure 4: The digestate nutrient content (kg/ton) and corresponding aggregate economic value of mineral fertilizer that can be replaced by the digestate (€/ton) for different agricultural residues (Error bars are included with standard deviation, n=3)

Economic Value of the Digestate

The aggregate economic value of the digestate in terms of the capacity to replace mineral fertilizers is presented in Figure 4. While the digestate from coffee pulp residues, sugarcane bagasse and banana stalks are quite comparable they are lag behind the digestate from sugarcane leaves, cotton residues and maize stover. The economic value of the mineral fertilizer that can be replaced by the digestate can be discerned by considering the cost of the active ingredients in three standard straight fertilizers that is calcium ammonium nitrate (CAN), total super phosphate (TSP) and potassium chloride (KCl) as sources of nitrogen, phosphorus and potassium respectively (**Table 2**). Generally it suffices to say that nitrogen is the highest value nutrient followed by phosphate and potassium. The economic value of the different digestate is quite comparable however the digestate from sugarcane leaves, maize stover and cotton residue appear to be quite outstanding in terms of the economic value of mineral fertilizer that can be replaced. Several fertilizers have been used to meet the NPK requirements of different crops in Kenya (**Table 3**) as well as in the vast Sub-Saharan Africa (SSA). Nevertheless in spite of persistent low crop production in most of SSA, the use of commercial fertilizers is economically constrained thus only about 9 kg of fertilizer nutrients per Ha of cultivable land is used compared to 100 kg in South Asia and 73 kg in Latin America (Mathenge 2009). The application of the digestate to complement mineral fertilizers in Kenya and hence the vast SSA suffices as a viable option for mitigating the low fertilizer usage. Nevertheless the apparent differentiation in the nutrient content from the different digestate necessitates further studies with a view of evaluating nutrient optimisation during the production of the different crops as well as nutrient stability during the storage of the residues prior to their use as biogas feedstock.

Table 2: Fertiliser prices in Kenya

Fertiliser	NPK ratio (%)	Price per 50 kg bag (€)	Cost of active ingredient (€/kg)
CAN	26:0:0	20	1.53
TSP	0:46:0	29	1.26
KCl	0:0:60	20	0.67

Source of data: Ministry of agriculture, Government of Kenya (2014)

Table 3: Typical fertilizers used in Kenya

Type of fertilizer	NPK ratio (%)	Field of application
NPK	20:20:0 or 23:23:0	General application
	17:17:17 or 20:10:10	Coffee farming
TSP	0:46:0	General application
MAP	11:44:0	General application
DAP	18:46:0	General application
Urea	46:0:0	Top-dressing
CAN	26:0:0	Top-dressing
KCL	0:0:60	General application
Fowl manure	2.1:1.6:1	General application
Cow manure	1.0:0.4:0.5	General application

Source: Ministry of agriculture, Farm Inputs Division (2014)

CONCLUSIONS

The results of this study demonstrate a clear suitability for complementary biogas feedstock flows in Kenya. It is evident that coffee pulp residues, maize stover and cotton residues are most suitable for biogas production with corresponding methane yields (m^3 CH_4/ton substrate) of between 214 and 344. On the other hand the methane yields from banana stalks and sugarcane leaves are significantly lower as compared to the other feedstock. Pertaining to biogas quality in terms of H_2S content, the biogas from sugarcane leaves is deemed to be above the allowable upper limit for domestic applications, hence it might require desulphurisation prior to any combustion. On the other hand the biogas from coffee pulp residue, maize stover and banana stalks can be regarded to be suitable for direct domestic application since it is within the allowable limit of H_2S content. Furthermore, the digestate slurry from all the substrates screened presents a potential source of NPK nutrients. The economic value of the mineral fertilizer that can be replaced by the different digestate is quite comparable, however, the digestate from maize stover, cotton residues and sugarcane leaves appear to be quite outstanding. Nevertheless the apparent differentiation in the nutrient content from the different digestate necessitates further studies with a view to obtaining hindsight on nutrient evolution and stability during the storage of the residues preceding their use as biogas feedstock.

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