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Biogas: Sustainable Alternative Renewable Energy of Today and the Future in Africa

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Abstract: In Africa organic biomass wastes represent an abundant underutilized bioresource, which has considerable potential as a source of renewable bioenergy, but currently constitute serious environmental pollution problems. The laıgest fraction of the waste is biodegradable and amenable to anaerobic digestion. Successful exploration and adoption of biogas technology within the African continent context could bioconvert the vast organic wastes generated into biogas, an alternative energy source that is renewable, economically feasible and sustainable. Therefore, the aim of this study was to review the potential of biogas as a sustainable alternative renewable energy of today and the future in Africa. This article highlights on contemporary status of energy production and consumption patterns across the globe. It also elaborates Africa's energy picture both immediate and in the future which currently relies heavily on biomass. Moreover, the paper summarizes briefly biogas process and biogas technology as a mature technology and complete system in itself. This paper provides comprehensive extensive detailed information about the diverse organic biomass, which is abundant allover Africa and their potential biogas yield. In Africa, animal manure is not the only viable biogas digester feedstock, but there are other substrates also, which have been shown to have a better biogas potential than animal manure. Finally, strategies to ensure pilot to full-scale potential application of biogas technology are explained. Also the areas where particular research and more attention are required in the near future are identified. It was concluded from this study that waste to biogas conversion through anaerobic digestion is feasible in Africa, when approached innovatively and responsibly. This energy revolution could consequently result in a major economic impact in Africa continent.

Key words: Biogas, substrates, energy, organic wastes, renewable energy, Africa continent.

There are triple interconnected crises facing the human kind worldwide now: the crisis in water security, the crisis in food security and the crisis in energy security. Energy use is the most fundamental requirement for human existence and is critical to economic growth and a powerful tool for human development. However, due to energy crisis cheap fuel has become a thing of the past. Additionally affordable commercial energy is beyond the reach of about two billion people of world population and many countries and individuals are vulnerable to disruptions in energy supply (UNDP, 2000). Nevertheless, as civilization develops in the society, mankind requires more energy and better environments. Moreover, the current food production systems are very energy intensive compounding even more the global energy needs. During the past few decades, the world energy demand sector has undergone significant changes due to ever increasing oil prices, deployment of new technology, global environmental concerns and changes in energy markets and the structural social-economic changes are also reshaping markets, business, economics and life styles (Cadenas and Cabezudo, 1998; Amigun and von Blottnitz, 2007; Demirbas, 2008). Energy demand is expected to increase by 50% or more in the next two decades, even if the global energy intensities continue to decrease. The growth rate of energy demand will depend on factors such as growth rate of global economy, measures taken to increase the energy efficiency as well as population growth rate. Vast energy investments will have to be made to meet such increases in energy demand. However, current energy system is unsustainable because of equity issues as well as environmental, economic, and geopolitical concerns that have far implications into the conservation of energy and the environment into

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the future (UNDP, 2000; Reijnders, 2006). Furthermore, current energy production and use have considerable negative impact at local, regional and global levels and threaten human health and the environment (UNDP, 2000). Therefore more efficient use of energy is the main option for global socio-economic sustainable development, long-term ecological balance and environmental protection in the 21st century and beyond. To that effect the need to explore and exploit new sources of energy, which are sustainable sources, renewable as well as eco-friendly is inevitable since energy production, deployment and distribution is both highly capital and technology-intensive (Yavdika *et al.*, 2004). Energy consumption has been growing rapidly in many developing countries during the last couple of rapid decades due to factors like population growth and industrialization (Bentzen, 2001). According to UNDP (2000) renewable energy sources (RES) are more evenly distributed than fossil and nuclear resources. The energy flows from RES are more than three orders of magnitude higher than current global energy use. Thus, RES have the potential to provide energy services and could sustain today's global ever-increasing energy demand, support economic growth and development as well as alleviate environmental pollution.

Amongst RES the biomass-to-bio-energy is addressed to be the most promising potential energy source due to its spread and its availability worldwide. Also it appears to be an attractive feedstock for solid, liquid and gaseous bio-energy because it is a renewable resource that could be sustainably developed in the future. Furthermore, biomass appears to have low environmental degradation and it appears to have significant economic potential role in the future (Cadenas and Cabezudo, 1998). Therefore, biomass technology has found wide application in everyday life worldwide. It is widely used as source of biomass energy for cooking, heating and electricity generation for lighting and running internal combustion engines (Okoroigwe *et al.*, 2009). Globally, biomass is, and will remain a major energy source in developing countries, particularly traditional biomass such as fuel wood and charcoal due to low-income (low purchasing power) which force households to use traditional biomass and inefficient technologies (UNDP, 2000; Bentzen, 2001; Okoroigwe *et al.*, 2009; Wiskerke *et al.*, 2010). Its use is still growing in absolute terms due to a rapid population increase (Rosillo-Calle *et al.*, 2007).

More than 2.4 billion people, generally among the world's poorest, rely directly on wood, crop residues, dung, and other biomass fuels for their heating and cooking needs. In rural sub-Saharan Africa, women carry on an average 11 pounds (5 kg) of wood 3 miles (4.8 km) every day to meet their household needs for fuel (FAO, 2005). According to another study by Malmberg Calvo (1994), women spend, on average, more than 800 hours a year (67 hours per month) in Zambia and about 300 hours a year (25 hours per month) in Gambia and Tanzania collecting firewood. However, recently firewood collection times and distance have been reported to have risen due to the increasing scarcity of locally available biofuels (Barnes and Sen, 2003; Lambrou and Laub, 2006). Consequently such a situation in most developing countries reduces the time available to women, who are traditionally responsible for wood collection, to participate in decision-making processes and income generating activities (Lambrou and Laub, 2006). Moreover, the need for traditional biomass energy places a high burden on forest resources in many developing countries such that of Africa (WHO, 2006). One of the major problems of current patterns of traditional wood fuel is a low energy efficiency of 7-12% and 11-19% for fuel wood and charcoal, respectively (Bhattacharya and Abdul Salam, 2002; Wiskerke *et al.*, 2010). Given the drawbacks of traditional biomass energy, it is of essence that the future energy strategy be premised on the production, supply, conversion and use of biomass energy in more sustainable, efficient and cleaner ways while expanding and accelerating a broader transition to clean and efficient use of renewable modern biofuels.

Energy Production and Use in Africa

Africa is relatively well endowed with energy resources and produces about 10% of the world's energy supply and various sources of energy are being utilized to meet the African population energy needs (UNESC, 2009). The three main sources of energy used in Africa are biomass, hydroelectric power and fossil fuel. Africa has good potential for hydropower (small and large-scale), specifically, medium size. The small-medium size hydro can meet the energy need in rural areas as these do not require any big investment for transmission line, if the solution of local network/grid is applied. However, the good potential for hydropower is limited due to the possible drastic fall of the water level of the hydroelectric power dams and/or drought. Only about 7% of Africa's enormous hydro potential has been harnessed and based on the limited initiatives that have been under taken to date, renewable energy technologies could contribute significantly to the development of the energy sector in Africa (UNESC, 2009). Thus Africa has been generally in the throes of a chronic energy crisis and some African countries are already deep into an energy crisis while others are faced with an imminent crisis for both commercial and traditional energy resources. The ever-increasing prices and scarcity of fossil fuels has further aggravated energy supply crisis in African continent. Kerosene (paraffin) is mainly used for lighting in the rural areas in Africa while in urban and peril-urban areas it is used for cooking. However, it is expensive for the resource-poor households. Its use is not sustainable because it is non-renewable resource and since it is imported, it drains the meager foreign exchange. On the other hand, the use of traditional forms of energy in Africa has compounded problems for the African economy due to unaffordability by both urban and rural poor, insufficiency and limitations due to the possible drastic fall of the water level of the hydroelectric power dams. Thus Africa's energy needs are enormous and largely go unmet. Africa accounts for about 5.5% of the world energy consumption (ADB, 2004) and it generates only 3.1% of the world's electricity (UNESC, 2009). The per capita energy consumption of 0.5 tones of oil equivalent is far lower than the world average of 1.2 tones of oil equivalent per capita makes the continent lag behind all others in energy use (UNESC, 2009). The energy demand growth in Africa averaged about 3.1% per annum between 1990 and 1997 (UNECA, 2004). Although Africa accounts for a small share of world commercial energy consumption, it has a large share of the world's biomass energy consumption largely dominated by combustible renewable resources (fuel wood or charcoal, animal waste, etc.), which represents 59% of the total. In many countries, biomass accounts for more than 80% of the total energy use (with exception of South Africa). Lack of access to modern energy results in air pollution, acute heath problems and environmental problems linked to over-consumption or inadequate management of wood resources (WEO, 2002; ADB, 2004; UNESC, 2009). Over-dependence on firewood/charcoal and booming populations has resulted in a sharp decline of woody biomass in Africa (ADB, 2004). According to IEA's 2004 report the total number of people relying on traditional biomass as a source of heating and cooking fuel will grow from just under 2.4 billion people in 2002 to over 2.6 billion in 2030. In Africa, the number is projected to increase from 646 million in 2002 to 996 million in 2030. Yet there is no significant parallel development or investment in conventional energy such as electricity and petroleum production and distribution infrastructure. Therefore, Africa's energy picture, both in the immediate and medium term, will significantly involve biomass energy. Nevertheless, some efforts are being made in response to the concerns of the current and future energy production and use in Africa. There has been increasing interest in renewable energy and related conversion technologies in recent years. Solar, wind, geothermal, hydro and biomass resources are among the renewable energy resources that have received attention. Biomass has been attractive on the premise that it may be converted to a variety of energy forms such as heat, steam, electricity, biofuels (biohydrogen, biogas, bioethanol, biodiesel and methanol). Biogas in particular, is distinct from the other energies on two fronts. Firstly, it is a high methane fuel, and methane is an ideal fuel for heating (cooking), generation of electricity and upgrading for transport fuel. Secondly, biogas reduces organic waste material pollution and producing fertilizer and water for use in agriculture. In addition, biogas has no geographical limitations and the technology of biogas production is relatively not sophisticated which can be modified to fit low technology environment(s) in Africa. Therefore, in relative terms, biogas holds the greatest promise as a modern household energy source because it is renewable, simple to generate, convenient to use and cheap.

Although, biogas potential is still under-exploited, it is a modern renewable, affordable, sustainable, decentralized, renewable energy for poor in rural and peri-urban areas. Biogas can be produced from nearly all kind of biological feedstock types from the primary agricultural sectors and from various organic waste streams from the overall society by anaerobic digestion in biogas anaerobic bioreactors (digesters/biogas plants). Therefore biogas production from various organic biomass and optimization of anaerobic digestion using different techniques and strategy is worthy of continued research and has been extensively reviewed by Gunaseelan (1997; 2004); Yadvika *et al.* (2004); Ward *et al.* (2008). Recently, Mshandete and Parawira (2009) reviewed biogas technology research in selected sub-Saharan African countries. The review provided an insight and update of the state of biogas technology research in some selected sub-Saharan African countries in peer reviewed literature. The methane-producing potential of various agriculturally sourced feedstock the advantages of co-digestion to increase biogas production and the use of pretreatment to improve the hydrolysis rates has been researched. There have been some researches in Nigeria, Tanzania, and Zimbabwe on optimization techniques associated with anaerobic digestion including basic design considerations of single or two-stage systems, pretreatment, co-digestion, environmental conditions within the reactor such as temperature, pH, buffering capacity. Nevertheless, there appears to be little research in biogas technology in many sub-Saharan African countries in internationally peer-reviewed literature. Biogas technology research will only have an impact if relevant and appropriate areas of research are identified and prioritized to tap biogas potential in Africa. The priority research areas should include the biogas production systems suitable and appropriate for Africa, and the available substrates. Furthermore, Parawira (2009) provided comprehensive information knowledge-based review of biogas technology status, constraints and prospects in Africa. It was found that the use of biogas is not widespread and marginalized in Africa mainly due to economic, technical and non-technical reasons. Moreover, despite demonstration by several programmes of the viability and effectiveness of biogas plants, large scale-up and biogas commercialization has not occurred in Africa. Therefore, it was recommended that large scale adoption for biogas technology in Africa should include; establishing national institutional framework, increasing research and development, education and training and providing loans and subsidies and major policy shift in the energy sector. Furthermore, Parawira (2009) concluded that biogas being modern energy source and main energy stream; biogas technology must be encouraged, promoted, invested, researched, demonstrated and implemented for sustainable energy future in Africa. The present paper is based on survey of literature and it highlights biogas as sustainable renewable energy of today and the future in Africa. This review will be an eye opener, mind set changer, an insight as well as an incentive towards establishment of triple helix biogas platform involving on the first part research and development institutions (to generate appropriate and cost-effective biogas technologies as the first step to promote small/medium/large scale promotion of biogas production), on the second part governments (policy makers/policy formulations/regulations) and on the third part, stake holders (end users such as general public, entrepreneurs, investors, etc.) to adopt biogas as a main stream renewable energy and an emerging major boon for African continent which can bring health, social, environmental, and financial benefits among the others. The triple helix biogas platform could enhance the development and uptake of environment friendly technologies and services for sustainable consumption and production of biogas in Africa.

The Biogas Process and Biogas Technology

Biogas technology is a complete system in itself with its set objectives (cost effective production of energy and soil nutrients), factors such as microbes, plant design, construction materials, climate, chemical and microbial characteristics of inputs, and the inter-relationships among these factors. Amongst the main biotechnological processes involved in the production of renewable energies, the biogas process is the most complicated compared to bioethanol and biodiesel processes (Börjesson and Mattiasson, 2008). In the biogas process, a complex consortium of microorganisms catalyses the bioconversions of almost all types of organic biomass into smaller entities that eventually are transferred mainly into methane and carbon dioxide (biogas) as well as some heat. Biogas production is a complex physico-chemical and biological process dependent on various factors like pH, temperature, hydraulic retention time (HRT), carbon/nitrogen (C/N) ratio, etc. It also involves various reactions and interactions that take place among the hydrolytic, acedogenic and acetogenic microorganisms, methanogens and substrates fed into the anaerobic digester as inputs (Yadvika *et al.,* 2004). This process of biogas alias biomethanization is summarized in its simplest form (Box 1).

Compared with other renewable energy technologies like solar, wind, biomass, the technology to produce biogas is a relatively mature in terms of year's use and promising technology. Although the technology to produce biogas has been around for a long time, the process still suffers from some technological/biological drawbacks; the low productivity and the sensitivity of the consortium to overloading. Due to these features, very little new biogas process technology has been

Box 1. The biogas process (Adapted from Börjesson and Mattiasson, 2008 with some modifications)

A complex mixture catalyzes conversion of biomass to biogas by consortia of microorganisms, each having a different role in the process:

- Hydrolysis: Degradation of complex organic macromolecules into monomers that are useful for the bacteria
- Acidogenesis: Conversion of soluble monomers into volatile fatty acids
- Acetogenesis: Production of acetic acid from volatile fatty acids
- Methanogenesis: conversion of acetic acid or hydrogen and carbon dioxide into biogas, a mixture of mainly methane and carbon dioxide.

Hydrolysis can become potentially limiting if the organic material contains high amounts of lignocellulose that are hydrolyzed slowly. However, when easily degradable materials are present or when soluble monomers are available, enrichment of acids might take place because methanogenesis becomes the rate-limiting step.

developed and there is still today lack of suitable high gas-producing anaerobic bioreactors (Gijzen, 2002; Bouallagui *et al.*, 2005). This process remains technically underdeveloped and several crucial aspects need to be addressed. Overcoming these limitations will result in the production of increased amounts of biogas, while generating digestate (biofertilizer) with a higher nutrient content. By employing proper process monitoring and control, it is possible to attain good control over the biogas process, which can allow realistic increase in the organic loading and while maintaining the process stability (Björnsson *et al.*, 2001; Liu *et al.*, 2004). High catalytic capacity in anaerobic bioreactor can be achieved through cultivation of methanogens as biofilms on solid/support carriers. This could lead to high producing methanogenic step, and design the hydrolytic step that efficiently supply methanogenic step with substrate (Bouallagui *et al.*, 2005; Mshandete *et al.*, 2008). Another viable option is to integrate a product-recovery step into the production process (Mattiasson and Holst, 1991). Taken together, these factors mean there is significant potential for improving the process of biogas production, which will also lead to considerable cost reductions.

Potential Sources/Feedstock (Substrates) Resources for Biogas Production Available in Africa

Sustainable production from biodiesel and bioethanol energy crops is limited, with uncertain future due to direct and/or indirect land use pressure. Furthermore, population booming, growing demand for food as well as water shortage compounds even more the un-sustainability of energy crops as renewable energy feedstock. On the other hand, biogas can be produced from multitude of biodegradable biomass even without competition to food and/or water compared to biodiesel and bioethanol produced from energy crops.

Biogas technology has been around for quite some long time in Africa. However, it has not been successfully adopted for both energy and economic strategies within the African continent and is still at its infancy due to economical factors as well as inadequate knowledge and hence over-reliance on animal dung as the principal biogas digester feedstock. Indeed current initiatives to revamp the biogas technology in the African continent have been solely modeled on livestock dung on the premise that animal manure is the only viable biogas digester feedstock (Nzila *et al.*, 2010). Basing the overall biogas potential on livestock numbers alone does not present the true biogas potential in African continent since various other substrates as evidenced in other parts of the world have been shown to have a better biogas potential than animal manure. Therefore the sustainability and future prospects of biogas in Africa calls for a paradigm shift hence the development of multi-feedstock for sustainable bioconversion of the vast amounts of organic wastes to renewable energy thus substituting (especially in the rural sector) the unsustainable conventional sources of energy (Nzila *et al.*, 2010). To that effect in Africa a wide range of substrates/feedstock/ organic biomass are available which can be considered as potential sources for sustainable biogas production. Some of the potential biogas sources/materials, feedstock, (substrates) range from animal dung to household, canteen wastes, bioorganic municipal solid wastes (BIOMSW), sludge wastes, crop residues, agro-industrial wastes, industrial wastes/effluent, fruit and vegetable solid wastes, grasses, wood, leaves, fresh water biomass, marine biomass, etc. Biodegradable waste has considerable potential as a source of energy in both developed and developing countries. Theoretical/laboratory data on maximum biogas yields from various organic materials show that anaerobic digestion is capable of achieving complete mineralization (Werner *et al.*, 1989). The theoretical maximum biogas yield can be ascertained by way of the basic composition of the biomass. Hawkes and Hawkes (1987) reported that if pure organic substrate were added and completely broken down to $CH_4 + CO_2$ then biogas yield can be calculated per kg VS of substance added as given in (Table 1). However, biogas yield as high as these in Table 1 are rarely achieved in practice, since generally the bioconversion of organic matter to biogas is incomplete. The energy recovered in the range of 90-140 m^3 CH_4 per tonne of fresh waste is very important, particularly at the level of a developing country (Parawira, 2009). It has been observed that generally there is an improvement in the quantity of biogas produced from a particular waste when it is mixed (co-digested) with other complimentary waste (Mshandete *et al.*, 2004; Parawira *et al.*, 2008). However, each substrate should be evaluated on its own merits and it is the overall feedstock mix that determines the biogas yield and quality. Nevertheless, uncontrolled decomposition of each biodegradable metric tonne of solid waste is known to release 50-110 m^3 CO_2 and 90-140 m^3 CH_4 into the atmosphere, contributing to global warming (Vieitez and Ghosh, 1999). It is estimated that global warming may be reduced by up to 20% by using discarded biomass and waste for the production of biofuel, as well as other benefits to society and the environment (Vieitez and Ghosh, 1999; Bouallagui *et al.*, 2003).

Bioorganic municipal solid wastes (BIOMSW)

Increased level of waste generation due to increased agricultural activities, growth of agro-industries, social and economic changes and population explosion has been witnessed during the past two decades in developing countries particularly in Africa. In fact, Africa is the fastest-urbanizing region in the world. The rural population is growing at a rate of 2.5% per year, while the urban population is experiencing 5-10% growth per year (UNESC, 2009). The high rate of urbanization in African countries implies a rapid accumulation of waste and increases in waste generated per capita. Consequently, there is intense scrutiny of possible alternative solid waste utilization through biogas production using the organic residues. In Africa BIOMSW are generated from consumer waste, domestic, commercial, institutional and industrial waste business, household, hotels, markets etc. With increasing urbanization and industrialization, the annual municipal solid wastes (MSW) generated will continue to increase.

In terms of composition, BIOMSW are heterogeneous materials, which vary widely. Composition of BIOMSW is affected by factors such as region/province differences, climate, and extent of recycling, collection frequency, seasons, and cultural practice as well as change in consumer goods production technology. Although composition of BIOMSW is variable they are highly biodegradable with 60-82% volatile solids (VS) content. Therefore, the most current serious solid waste management problem in most cities in developing countries is disposal, but since the largest fraction of the waste is organics (about 80%) and amenable to anaerobic digestion, it makes environmental and economic sense to explore the biogas technology option (Mbuligwe and Kassenga, 2004). Consequently higher biogas yield could be expected from anaerobic digestion of BIOMSW (Gunaseelan, 1997). The solid waste generation of selected cities in Africa ranges from 0.3 to 1.9 kg per person per day. The limited available data suggests that the content of municipal solid waste stream in the typical African city at point of disposal is high in bioorganic in a range of 60%-80% (UNESC,

Table 1. Biogas yield potential of organic compounds

Material	Biogas yield (m^3/kg VS added)	Volume fraction %		Methane yield (m^3/kg VS added)
		CH_4	CO_2	
Starch/cellulose/glucose	0.8	50	50	0.40
Fats (based on stearate/lauric acid)	1.5	68	32	1.02
		72	28	1.08
Protein (based on $C_5H_2NO_2$)	0.9	63	37	0.57

Source: Hawkes and Hawkes (1987); Werner *et al.* (1989); Wilkie (2008).

2009). This is equivalent to 0.18-0.24 to 1.14-1.52 kg per person per day generation of BIOMSW. Assuming 30% of current projected that populations of one billion in Africa lives in urban areas a low range between 54,000-72,000 tons and high range of 342,000-456,000 tons of BIOMSW are generated daily in Africa. A typical biogas yield of 400 m^3 per ton VS is generated from the organic fraction of MSW with composition typically 55% methane, 45% carbon dioxide, with traces of hydrogen, hydrogen sulfide, and water vapor. Based on 55% methane content it is equivalent to 220 m^3 per ton VS, which translates to 12-100 million m^3 of methane production daily from BIOMSW.

In Africa land filling is generally considered the most practical waste management method. In landfill uncontrolled anaerobic digestion takes place that produces biogas, known as landfill gas in this case. Most disposal sites in Africa are simply open dumps, although some countries have moved towards improved landfill practice recently. However, land filling is becoming a less attractive option due to scarcity of available land in close proximity to areas of waste generation, increasingly rising costs of construction and operation, leachate emissions and uncontrolled landfill biogas release into the atmosphere. One ton of mixed solid waste is estimated to produce in total about 300 m^3 biogas, containing 55%~65% of CH_4 during the entire landfill duration (Raninger *et al*., 2006). It has been reported by Willumsen (2003) that as of 2001 there were about 955 landfills in the world that recovered biogas. The landfill gas is used to operate generators, which range from 0.3 to 4 MW. Unfortunately there is scant information on gas wells in Africa that capture landfill gas used to supply energy with exception of few involved in carbon trading. Nevertheless, assuming that all the 19,764,000 to 166,896,000 tons of BIOMSW produced per year in Africa are landfilled, and using experimental landfill methane gas yield data of 20 m^3 ton^{-1} of wet waste (Borzacconi *et al*., 1997) a range of 395,280,000 to 3,337,920,000 m^3 of methane can be generated in landfills annually. At least some of this biogas can be captured through gas wells and be used to supply energy. From a global point of view, landfill biogas is one of the anthropogenic sources of green house gases. The population explosion of African countries is another factor that detrimentally impacts the function of landfill sites. As the population keeps increasing, the waste quantity also increases, which, in turn, exhausts the landfill sites. To that effect governments, municipalities and industries in Africa, as it is elsewhere in the world, are constantly searching for technologies that will allow for more efficient, cost-effective as well as environmental friendly waste treatment.

Anaerobic digestion is one that technology which can successfully treat the BIOMSW. It has the advantages of producing energy, yielding high quality fertilizer and also preventing transmission of disease as well as reduce pollution burden. Generally in Africa even though the organic content (bioorganic) of the municipal solid waste in the typical African city may exceed 70% (wet basis), centralized composting, anaerobic digestion and biogas recovery are not significant components of African municipal solid waste management practice (UNESC, 2009). Therefore African countries should emphasize treating BIOMSW as a priority issue within their waste management policies. Anaerobic digestion as a biological treatment technology applied to the BIOMSW has become an established treatment process worldwide. The products generated from this technology comprise biogas (methane), which is a potential energy source, which can be used to substitute fossil energy, renewable CO_2 will replace fossil CO_2 and a nutrient-rich sludge, which has beneficial value as a fertilizer. Thus, the recovery of biogas as well as the recovery of nutrients makes anaerobic digestion of organic waste a sustainable waste treatment concept (Hartmann and Ahring, 2006; Narayana, 2009). Biogas production may therefore be a profitable means of reducing or even eliminating the menace and nuisance of urban wastes in many cities. Regarding biogas generation from BIOMSW, the authorities should give a high priority to landfill biogas recovery clean development mechanism (CDM) projects, especially for landfills closing soon, and which will produce high gas yields, before there is large scale recycling to remove the landfill gas creating organic materials. The aim should be to follow the success in many industrialized countries, which routinely utilize the energy from landfill biogas (Narayana, 2009).

Animals dung, human excreta and urine

When untreated or poorly managed, animal manure becomes a significant source of air and water pollution. Nutrient leaching, particularly nitrogen and phosphorous, ammonia evaporation and pathogen contamination are some of the major threats. The animal production sector is responsible for 18% of the overall green house gas emissions,

Table 2. Wet animal dung feedstock potential for biogas proa.ıction in Africa

Manure	Livestock/ Population ('000)	Source	Dung (kg/day/ animal)	Source	Estimated quantities per year ('000 tons)
Cattle dung	191,348	FAOSTAT, 2000	3-40	Cárdenas-Lailhacar and Lahoti, 2010; Werner *et al.*, 1989	210,100-2,801,334
Pig dung	21,000	BOA, 2003	0.6-5	Werner *et al.*, 1989	4,612-38,430
Sheep dung	158,682	FAOSTAT, 2000	0.1-3	Werner *et al.*, 1989	5,808-174,233
Goat dung	182,086	FAOSTAT, 2000	0.1-3	Werner *et al.*, 1989	6,664-199,930
Chicken droppings	15,474	FAOSTAT, 2000	0.08-0.2	Thomsen, 2004; Cárdenas-Lailhacar and Lahoti, 2010	453-1,133

measured in CO_2 equivalent and for 37% of the anthropogenic methane, which has 23 times the global warming potential of CO_2 (Holm-Nielsen *et al.*, 2009). Furthermore, 65% of anthropogenic nitrous oxide and 64% of anthropogenic ammonia emissions originate from animal production sector worldwide (Steinfed *et al.*, 2006). If handled properly, manure can be a valuable resource for sustainable renewable energy production and a source of nutrients for agriculture. In agriculture, particularly cattle, sheep, goat, pig, duck, rabbit and chicken rearing, significant quantities of wastes are generated. Domesticated animals viz; dog, camel, horse also generate considerable waste. The quantity of livestock dropping depends on the type of feed and frequency, age of the animal, region, breed, species, degree of confinement, if animal are only kept in night stables, only about 1/3 to 1/2 as much manure can be collected. For animal stalls with litter, the total daily yields will include 2-3 kg litter per animal and day (Werner *et al.*, 1989; Ojoro *et al.*, 2007). The percapita generation of dung for buffalo range between 12-21 kg/animal/day, for horse 12 kg/animal/day while for ox it is about 14 kg/animal/day (Werner *et al.*, 1989; Cárdenas-Lailhacar and Lahoti, 2010). The rest of the percapita generation of dung of some animals is presented in (Table 2). Biogas yield of some livestock on average range from 23-40 m^3 ton^{-1} for cattle, 40-59 m^3 ton^{-1} for pig dung and 65-116 m^3 ton^{-1} for poultry chicken dung (Update guide book on biogas development, 1984). A range of 4.8×10^8 to 1.1×10^{10} m^3 of biogas can be projected from cattle dung generated annually in Africa.

Beside livestock dung, human excreta is yet another natural resource which is always available in all societies, even in the poorest ones (Tanski and Sijbesma, 2005). Generally, the quantity and the composition of excreta is directly related to the social and economic conditions, living habits of the community, through the effects on diet, time of the day, local climate, physical activity, body size and health. The generation rate of faeces in Africa and other developing countries range between 0.12 and 0.52 kilograms (wet weight) feces/capita/day (Feacham *et al.*, 1983, Schouwbat et al., 2002, Heinonen-Tanski and van Wijk-Sijbesma, 2005, Heinonen-Tanski *et al*. 2007). Furthermore, urine generation rate was reported to be between 0.6 and 1.3 liters urine/capita/day. Based on current population of one billion in Africa, generation of human excreta can be estimated as 44-190 millions tons per annum equivalent to 120,000-520,000 tons daily. On the other hand, an equivalent of 220-476 millions m^3 of human urine can be generated per annum. Human excrete in certain cultures, especially in the Far East have for centuries been utilized for biogas production under anaerobic conditions and is currently finding increasing use worldwide. Already remarkable demonstration of biogas production from human excretes has been shown in Africa particularly in Rwanda. Biogas yield from human faeces ranges between 20-28 m^3 ton^{-1} faeces (Update guide book on biogas development, 1984). A biogas potential equivalent of between 0.9-5 m^3 billion of biogas could be projected annually in Africa from human feces.

Agricultural and agro-industrial wastes

Beside BIOMSW, livestock manure and human excreta; large amounts of other organic waste streams represent a constant pollution risk with a potential negative impact on the environment, if not managed optimally. To prevent emissions of greenhouse gases (GHG) and leaching of nutrients and organic matter to the natural environment such organic wastes can be utilized as biogas energy renewable resources. The wastes and by-products derived from conventional agricultural, forestry, yeast waste liquor, wine pot still liquor, and spent wash from molasses distillery, sisal processing are utilized as feedstock for production of biogas. For example in Tanzania and Kenya, production of sisal fiber from the sisal plant (*Agave sisalana*) is a high waste industry currently using only about 2% of the sisal plant as fiber and the rest being various wastes, including decortications wastes (wastewater, sisal leaf decortications, sisal short fibers and sisal dusts) and post harvest waste (sisal stems or sisal boles). The traditional wet sisal leaf decortications process generates about 100 m^3 and 25 tons of wastewater and solid wastes, respectively, per ton of sisal fibers produced. In Tanzania and Kenya, about 20 million m^3 of sisal decortications wastewater and 5 million tons of solid sisal decortications wastes are generated annually. Methane yield up to 220, 320 and 400 m^3 ton^{-1}VS added have been reported for sisal fibers wastes, sisal leaf decortications wastes, sisal processing wastewater, respectively (Kivaisi and Rubindamayugi, 1996; Mshandete *et al.*, 2004; 2006). Annual generation of post harvest sisal (stems) boles in both Kenya and Tanzania is also significant and estimated at 4-8 million tons.

Pineapple is a season fruit contributing to over 20% of the world production of tropical fruits and nearly 70% of the pineapple is consumed as fresh fruit in producing countries. On average one ton of pineapple generates 0.5 ton of solid wastes (Chaiprasert *et al.*, 2001). With production of 2,707,407 tons of pineapples in Africa in 2003 (FAOSTAT, 2004) it means that 1,350,704 tons of solid wastes were generated in Africa. Pineapple wastes have proved to be a potential substrate for methane production by anaerobic digestion (Gunalaseelan, 2004). Currently pineapple waste in Africa is underutilized and dumped, left on open land for natural biodegradation to take place, thus posing a serious environmental pollution problem. However, elsewhere, solid pineapple wastes have been reported to posses average on 12% total solids out of it 94% volatile solids (Chaiprasert *et al.*, 2001; Gunaseelan, 2004) with the ultimate methane yield of up to 0.40 m^3/kg VS added (Paepatung *et al.*, 2009). In Africa about 152,359 tons of VS can be projected from solid pineapple wastes generated annually with a potential to produce 60,944 m^3 methane.

Since the economy of the African continent is agriculture-dependent, there are more vast amounts of organic residues generated such as coffee, maize, rice straw, barley, cotton, tea and sugarcane which can be converted to biogas. Sugar industry generates large amounts of residues, which include sugarcane crop residues (sugarcane tops biomass and trashes) and the sugar cane industrial wastes (filter cake/press mud, bagasse, sugarcane waste water and molasses). Around 1, 350 million tons of sugar cane is processed every year in the world for sugar production (WADE, 2004). This is associated with the production of more than 266, 313, 33.3, 33.3 million tons of sugar cane bagasse, sugar cane crop residues, molasses, filter cake, respectively (UNIDO, 2007). For example in Africa sugar processing industry has a potential to generate annually 445,597 x 10^3 tons of bagasse (WEC, 2001). Methane yield of about 230 m^3 ton^{-1} VS has been reported from sugar filter cake/press mud at laboratory scale in Tanzania (Kivaisi and Rubindamayugi, 1996). Coffee processing done by wet and dry methods discard away 99% of the biomass generated by the coffee plants at different stages from harvesting to consumption. This includes cherry wastes, coffee parchment husks; sliver skin, coffee spent grounds, coffee leaves and wastewater. Wet processing uses up to 15 m^3 of water to produce one ton of clean beans (Hue *et al.*, 2004) and for every ton of beans produced, about one ton of husks are generated. With projected 1.1 millions tons coffee production in Africa by 2010, it is estimated that coffee processing will generate about 17 million m^3 of wastewater and 1.1 millions tons of husks annually. Biogas yield up to 131 m^3 ton^{-1} of fresh coffee pulp have been reported, with 65% methane content, it translates 85 m^3 CH_4 ton^{-1} fresh coffee pulp (Gauthio *et al.*, 1991). Therefore about 94 millions cubic meters of methane can be generated in Africa annually from fresh coffee pulp wastes.

Rice has a high potential for development in Africa, as it is a tropical crop. However, its production generates straw and rice bran as residues. Sub-Saharan Africa rice (paddy) production capacity by 2006 was about 14.2 million tons, however, demand still outstrips supply. Plans are underway to double production to 28 million tons by 2017/2018. The annual generation of rice straw (excluding stubble) is estimated by multiplying the residue coefficient of 0.447 by the rice product yield (Bhattacharya *et al.*, 1989). Rice straw residues generation was estimated to be

6.3 million tons in 2006 in Africa. Recently Paepatung *et al.* (2009) reported mean total solids of 94% out of which 87% being VS and methane yield of 340 m^3 ton^{-1} VS added. Therefore Africa with annual generation of 6.3 millions tons of rice straw, could anticipate generating about 1.8 billion m^3 CH_4 per year if anaerobic digestion of rice straw is applied. Generally in Africa a small fraction of rice straw is used as low grade animal feed with the rest, which is abundant, being left to rot and/or burnt in paddy fields to prepare the fields for a next crop cycle.

Recently crop residues/wastes in a range of 32-4185 x 10^3 tons/year have been estimated for barley, maize, tea, sugarcane, seeds cotton for Kenya (Nzila *et al.*, 2010). These five residues were evaluated at laboratory scale for their energy potential through biomethane potential analysis. It was found that methane yields for maize, barley, cotton, tea and sugarcane residues obtained under experimental conditions employed were 363, 271, 365, 67 and 177 m^3 per ton VS added, respectively. The evaluated residues have a combined Kenyan annual potential of up to 1313 million cubic meters of methane. Conversion of methane obtained annually using the conversion factors adapted, annually about 3916 Gigawatt hour (GWh) of electricity and 5887 GWh of thermal energy could be generated (Nzila *et al.*, 2010). It follows that such findings, although they remain to be demonstrated at large and full scale, provides baseline data and facts for feasible application of biogas technology for electricity and thermal energy production in the rest of Africa with similar crop residues and/or wastes.

Coconut industry generates (waste of coconut fiber, coconut pith, and coconut wastewater (consisting of both coconut sap and wash water). The coconut sap contains 1.5% fat and very valuable minerals, such as iron, sodium, potassium, magnesium, calcium and small quantities of phosphorous. Coconut husks liquor (rich in sugars and tannins), oily waste, coconut chaff, shells, leaves and tender coconut waste and coconut husk. The coconut husk is available in large quantities as wastes from coconut production and accounts for 37-50% of weight of the coconut produced. World production of coconuts was around 40 to 50 million tons in 2003, which produced around 15 to 20 million tons of husks (FAO, 2003). A typical factory with a daily capacity of 50,000 nuts, discharges around 40,000–60,000 liters of wastewater, consisting of both coconut sap and wash water. Utilization of the coconut and its waste has been a problem in the coconut industry especially in Sub-Saharan Africa. However, elsewhere in other parts of the world it has been shown that coconut husk liquor (CHL) biogas production stand at 20 m^3 of biogas or 130 KWh per m^3 of CHL with 75% of the biogas composition being methane which translates to 15 m^3 of methane/m^3 of CHL (Leitao *et al.*, 2009).

Oil palm (*Elaeis guineensis*) originated in the tropical rain forest region of West Africa. Africa led the world in production and export of palm oil throughout the first half of the 20th century, leading countries being Nigeria and Democratic Republic of Congo (DRC). Depending on local conditions, oil palms start producing three to five years after planting. The first crop usually amounts to about 50 kg of fruit per tree, but this usually increases to 90 and 110 kg/tree in the second and third crops and to 120 kg/tree in the fourth crop. Productivity increases to a maximum of 175 kg/tree after about 10 years of cropping (Pameyun, 1988). Nevertheless, so far, the oil palm wastes auditing and characterization from palm industry in Africa is virtually limited. Up to 90% of the biomass from palm oil industry is considered to be waste, which include palm fronds, kernel shells, empty fruit bunches (EFB)/spent fruit bunches, fibers, trunks, decanter cake, sludge waters effluent known as palm-oil mill effluent (POME). These wastes in most cases are discarded without recuperating the bioenergy contained in them. Pamayun (1988) in Indonesia estimated the most important waste produced on fresh weight basis to be EFB 34.9%, fibers 26.7%, shell 13.9% and POME 24.5%. On the other hand, Fairhurst and Mutert (1999) reported that for every ton of palm oil produced from fresh fruit bunches, a farmer harvests around 6 tons of waste palm fronds, 1 ton of palm trunks, 5 tons of empty fruit bunches, 1 ton of press fiber (from the mesocarp of the fruit), 0.5 ton of palm kernel endocarp, 0.25 ton of palm kernel press cake, and 100 tons of POME. Recently Chavalparit *et al.* (2006) reported that average values of waste generation rate (per ton fresh fruit bunches (FFB) from palm oil mills in Thailand were 0.14 ton of fiber, 0.06 ton of shells, 0.24 ton of EFB and 0.042 ton of decanter cake. So far, the oil palm industry in Africa has not used its vast waste streams in such an efficient manner particularly in production of renewable energy. In fact, it uses less than 10% of the available energy from its plantations (that energy is contained in the oil). However, some work on bioenergy production from palm oil wastes have been reported in Asian continent, which shows the potential feasibility for biogas production. Paepatung *et al.* (2009) reported in Thailand, methane yield of 370 m^3 ton^{-1}VS added for EFB and decanter cake. Although POME is highly polluting it provides a very interesting input feedstock for anaerobic digestion processes and potentially yields some 200 m^3 of biogas per hectare of palm oil produced.

On the other hand, potato industry also generates significant quantities of both wastewaters and solid wastes. Potato rejects which are either unmarketable or unfit for human and animal consumption for various reasons are always estimated at 20% of the annual potato production (Guenthner, 2003). In Africa with annual potato production of 16.7 millions tons in 2007 (FAO data FAOSTAT) about 3,340,000 tons of potato rejects can be estimated (http://www. potato2008. org/en/world/africa. html). A methane yield of up to 200 m^3 ton^{-1} COD (chemical oxygen demand) have been recently reported from potato waste leachate (Mshandete *et al.*, 2004b). According to Stewart *et al.* (1984), the gross energy of potato is 16.4 MJ kg^{-1} TS and the energy in methane produced from potato is 15.5 MJ kg^{-1} TS of potato, giving an energy conversion efficiency of 95% with the assumption that biogas yields 410 l/kg TS potato and has a methane content of 50%. The energy content of methane is 37.7 kJ/l. A methane yield of 430 m^3 ton^{-1} VS added has been reported from solid potato wastes in Australia and New Zealand continent, which can be extrapolated for Africa continent. Parawira *et al.* (2008) reported 2.5 and 3.4 kWh/kg VS from unpeeled and peeled solid potato waste, respectively in pilot-scale two-stage anaerobic digestion. Total solids 3% out of which 88.5% VS and 19% TS out of which 95%VS have been reported for potato waste leachate and potato solid wastes, respectively (Mshandete et al., 2004b; Parawira *et al.*, 2004). Using methane yield data of 430 m^3 ton^{-1} VS added the potential for methane production in the order of 38,131,110 m^3 (from potato waste leachate) and 259,234,100 m^3 (from potato solid waste) of methane could be projected from 3,340,000 tons of potato rejects generated annually in Africa continent.

Municipal sewage sludge

Municipal sewage is a mixture of human excreta and household wastewater that is transported via pipes to a treatment or disposal point. Sewerage systems are common in industrialized countries and often occur in urban areas of less-industrialized countries. Therefore, municipal sewage sludge is yet another feedstock for biogas production by anaerobic digestion. Worldwide the anaerobic stabilization of sewage sludge is probably the most important anaerobic digestion process. Treatment of sewage sludge by anaerobic digestion is common in industrialized countries, for example in Europe; typically between 30% and 70% of sewage sludge is treated by anaerobic digestion. In developing countries, anaerobic digestion is in most cases, the only treatment of wastewater. In Africa, virtually wastewater receives no treatment before it is discharged with the exception of few countries such as South Africa, Zimbabwe, etc. (WHO, 2000). Therefore, in some cities of Africa sewage sludge is treated by anaerobic digestion. For example all the four major towns in Zimbabwe, which are: Harare, Mutare, Masvingo and Bulawayo, daily generate 300,000; 30,000; 16,800 and 35,000 tons of sewage, respectively, which are treated by anaerobic digestion (Southern Centre for Energy Environment, 2001). In Africa, as elsewhere in other third world, information on sewage/capita/day generation is scanty. However, based on daily sewage production data from four major Zimbabwe towns an estimation can be made based on 2002 census population of Harare (1,963,510), Mutare (1,566,889), Masvingo (1,318,705) and Bulawayo (676,787) (http://www.citypopulation.de/Zimbabwe.html). Therefore per capita daily sewage generation can be estimated in the range of 0.012 to 0.150 tons. However the figures could vary from city to city and could be over or underestimated since in many areas, municipal sewage is often mixed with industrial waste. With projected population of one billion in Africa 4-55 billion tons sewage sludge can be anticipated. The total solid of undigested sewage sludge is about 11%, out of it volatile solids account for 70%. This translates into about 0.3-4.0 billions volatile solids of sewage sludge. Biogas yields from anaerobic digestion of sewage sludge can vary from 250 to 350 m^3 ton^{-1} of organic solids (Murphy and McCarthy, 2005). Thus, there is a potential to produce substantial quantities of biogas from sewage sludge in Africa in order of 7.5×10^{10} to 1.4×10^{12} m^3 of biogas per annum if sewage digested anaerobically. The biogas produced at sewage treatment plants is not used for commercial purposes at all. A small share of the biogas is in some cases used to preheat the digesters, whilst most of the biogas is vented into the atmosphere. This represents wastage of energy as well as underutilization of an energy resource. Wastewater is yet untapped potential for biogas production in Africa. Percapita generation of wastewater stands at 30-70 m^3 annual. With projected one billion populations in Africa annual wastewater generated may range between 30-70 m^3 billions.

Aquatic weeds

Certain water bodies harbor abundant aquatic vegetation, a crop that requires no tillage, seed, or fertilization, which is of little use at present in Africa. Aquatic weeds are wide spread in Africa's rivers, lakes, oceans, stream banks, dams, wetlands swamps, rice paddies, ditches, depression areas, marshes and in other water bodies. Some of the prominent aquatic weeds include; water hyacinth (*Eichhornia crassipes* Mart), azolla *(Azolla pinnata)*, papyrus *(C. papyrus, C. antiquorum)*, scirpus *(Scirpus grosses)*, cattails (such as *Typha latifolia* Linn. and *Typha domingesis* Pers.) and water lettuce (*Eupatorium odoratum*) and marine weeds such as brown algae, red algae and green algae. These weeds can utilize solar energy effectively and grow luxuriant with ubiquitous growth thus rapidly producing a large amount of biomass. It is difficult to control or destroy or eradicate the aquatic weeds through chemical or biological agents since the conditions that allow them to proliferate are not being controlled and result of global climate change may be factors that also contribute to the proliferation of weeds. Periodical harvesting and utilization is apparently the best strategy for keeping the weeds under control, and amongst the various utilization options the one involving anaerobic digestion to produce bioenergy appears to be the most promising. Thus aquatic weeds can help fulfill the biomass requirements for biomethane (biogas rich methane) production although their use as potential bioresource of biomass for anaerobic digestion is rather a recent concept and in some cases there is little published information. Methane yield between 62 to 410 m^3 ton^{-1} VS added has been reported for fresh aquatic biomass species such as *Eichhornia, Pistia, Azolla, Salvinia, Lemna, Ceratopteris* in India (Gunaseelan, 1997).

Elsewhere in USA in batch studies of anaerobically digesting water hyacinths, NASA has found that 350 to 411 liters biogas per kg dry weight can be obtained (Wolverton *et al.*, 1975). This biogas contains approximately 60% methane. Therefore, one hectare of water hyacinths grown in an enriched environment in a warm climate for seven months of the year can be used to produce approximately 58,400 m^3 of biogas containing 35,100 m^3 methane. In Sudan, Nigeria and Tanzania water hyacinths have been demonstrated as a major bioresource for potential bioconversion to produce methane for energy. Accordingly, an average methane yield of 440 m^3 ton^{-1} VS digested have been reported from water hyacinth in Tanzania at laboratory scale (Kivaisi and Mtila, 1998). In the field the possibility of producing biogas with water hyacinth and using it, instead of firewood for cooking, has been demonstrated to be a viable option in the context of Sahelian countries threatened by desertification. The biogas produced replaced 20 kg of wood per day with 8 m^3 per day of biogas from anaerobic digestion of water hyacinth in 5 m^3 digester at a maternity facility in Niamey, Niger (Almoustapha *et al.*, 2009). In Eastern Africa up to 250 t ha^{-1} are possible, in Kenya for example 17,000 ha are covered by water hyacinth. Biogas technology adapted to low technology environment and the field experience with scaled-up 5 m^3 digester in Sahelian countries in West Africa on the utilization of water hyacinth for biogas production to meet local energy needs can be extrapolated to the rest of Africa with the weed biomass.

Cattails such as *Typha latifolia* Linn. and *Typha domingesis* Pers. which are emergent weeds with rapid growth rate are yet potential bioresource for biogas production at laboratory scale demonstrated recently in Africa. Mshandete (2009) reported methane yield of up to 288 m^3 t^{-1} VS added from whole cattail weeds. Fresh cattail weed has been estimated to be 193 t ha^{-1} in Tanzania, which is equivalent to 33 tons volatile solids (whole cattail weed total solid of 21.97% out of it 78% volatile solids), which have a potential to produce 9,500 m^3 of methane per hectare. Marine biomass/ weeds have relatively high sugar content. Theoretical annual biomass yield of algae in Denmark range of 200 to 500 tons of wet biomass/hectare. It has great potential for biogas production which does not require irrigation and avoids food versus fuel issue and are yet untapped biomass for biogas production in Africa. With the exception of countries such as South Africa, Senegal, Namibia, Cameroon, Ghana, Egypt, Togo and Tanzania, there is limited information on exploitation, cultivation and utilization of seaweeds in African continent. There is poor state of research on seaweeds in Africa implies limitation in terms of production of value added bioproducts such as biogas and biogas manure. However, recent studies on bioconversion of marine macroalgae as potential sources for methane have demonstrated in other continents of the world. Methane yield in range of 100-480 m^3 ton^{-1} VS have been reported from macroalgae egg brown algae *Macrocystis pyrifera, Sargassum, Laminaria* and *Ascophyllum*, green algae *Ulva, Cladophora* and *Chaetomorpha* and red algae *Gracilaria* (Gunaselaan, 1997). Furthermore, based on stoichiometry, the theoretical yield for biomethanation of kelp has been found to be 510 m^3 ton^{-1} VS added.

Terrestrial weeds

These weeds are non-conventional crops, which are aggressive and invasive in cropland, wasteland and overgrazed pasture. They grow profusely without any management on a variety of soils and in different climates, sometimes where nothing else grows. The use of weedy plants as a potential bioresource for biogas production in anaerobic digesters is a rather recent concept. Weeds have ability to trap a significant amount of solar energy thus high biomass productivity. They are capable of growing on marginal soils generally unsuitable for conventional crop production. The genetic base of weeds is such that many can grow under a wide range of cultural and climatic conditions. Weeds grow in natural stands without inputs and irrigation. Large-scale utilization in production of value added bioproducts is one of the best strategies for weed management. Some weeds such as *Parthenium hysterophorus, Lantana camera, Cannabis sativa, Eupatoriu modoratum,* have been studied as sources for methane production and have been found to produce 100 to 240 m^3 methane ton^{-1}VS added elsewhere in other parts of the world particularly in Asian continent (Gunaseelan, 1997). Terrestrial weeds are cosmopolitan and distributed all over Africa continent are yet other anaerobic digestor feedstock's, potential of which is little exploited and demonstrated for renewable energy biomethane production (Manikandan and Arumugam, 2010)

Grasses

It is unlikely that a single biogas feedstock may provide all of the bioenergy needs. Grasses with their ubiquitous distribution could be an alternative feedstock for biofuel production in Africa. Grasses are monocotyledonous plants counting about 11 thousands of species. This family is the most important of all plant families to human economies, including lawn, forage grasses and the staple food grains grown around the world. That whole enormous potential of grass species presents bioresource, which could integrate conversion processes to produce biofuels and value-added bioproducts in biorefinery process. Biorefineries are similar to petroleum refineries in concept; however, birefineries use biological matter (as opposed to petroleum or other fossil). Various grass species are perennial thus can be highly sustainable. They have broad environmental tolerance and genetic diversity for their improvement. Additionally grasses are suitable for growth on marginal land/soils leading to large biomass production (Barney and DiTomaso, 2010; Ahn *et al.*, 2010). As such grasses if utilized have great potential as sustainable bioenergy/biofuel crop and could relieve the pressure on arable land. Thus production of biogas from grass must be seen as a holistic approach to agriculture and bioenergy production (Murphy and Power, 2009; Nizami *et al.*, 2009; Ahn *et al.*, 2010). The energy potential based on a grass feedstock could far exceed the energy potential of other energy crops if grass could be used as a component feedstock in an anaerobic digestion plant to produce biogas (Nizami *et al.*, 2009; Murphy and Power, 2009; Ahn *et al.*, 2010).

The production of methane enriched biogas is also termed biomethane. This renewable biogas may take the place of gas in electricity production at power plants, or in home heating, or as a transport fuel. Grass may also have potential for use as a co-digestion substrate in anaerobic digestion by supplementing manure biomass resources and potentially increasing biogas production (Nizami *et al.*, 2009). Optimal biogas production from various grass species typically related to one ton of volatile solid produces up to 300 to 610 m^3 of methane in batch and semi continuous bioreactors (Mähnert *et al.*, 2005; Nizami *et al.*, 2009; Murphy and Power, 2009; Ahn *et al.*, 2010). A study by Mähnert *et al.* (2005) on fresh and ensiled grass species showed that every year 390 tons of silage would be produced on 6.5 ha of grass, which would produce 47,970 m^3 of biogas or 27,447 m^3 of biomethane, which would displace an equivalent quantity of diesel. Various species of grasses have received much attention in recent years and has been a focus of bioenergy research for over a decade mainly in Europe and United States of America. In particular, the effects of, mapping and auditing grass, harvest time, frequency, age, ensiling and clonal variations on biomethane production (Nizami

Table 3. Leaf litters aboveground productivity of some plants stands

Plant	Annual production (t ha^{-1})		Reference
	Dry	Fresh*	
Shorea robusta	6.9	34.5	Singh *et al.*, 1992
Tectona grandis	7.7	38.5	Singh *et al.*, 1992
Eucalyptus	6.5	32.5	Singh *et al.*, 1992
Populus deltoides	5.3	26.5	Singh *et al.*, 1992
Acacia nilotica	5.6	28.0	Singh *et al.*, 1992
Propopis juliflora	6.1	30.5	Singh *et al.*, 1992
Dalbergia sisso	4.9	24.5	Singh *et al.*, 1992
Terminalia arjuna	5.3	26.5	Singh *et al.*, 1992
Bamboo (various species)	4.5-47		Scurlock *et al.*, 2000

* Calculated from the relationship that mean leaf litter harvest potential of 6 dry tons/hectare/year is equivalent to 30 fresh tons/hactare/year.

et al., 2009; Murphy and Power, 2009; Ahn *et al.*, 2010). Africa has rich diversity of native grass species, which have not been explored and exploited as bioenergy crop. Therefore, research on grass species as feedstock for biofuel production could involve inventory, mapping, quantification, characterization, and bio-climatic predictions of habitat suitability for the biofuel grasses, optimization of laboratory and up-scale biomethane production. Feasibility to erect biogas production facilities alongside with livestock farm for co-digestion of field biomass together with animal manure could also be of interest.

Leafy waste biomass

Huge quantities of leaf biomass waste are generated in the African continent from various plants, which are associated with little or no production costs and they are either unused or utilized inefficiently. Large amounts of leafy wastes are burnt resulting in air pollution while the remaining part is dumped releasing nutrient to the environment and generate methane, a powerful greenhouse gas. In a review by Gunaseelan (1997) on anaerobic digestion of leafy biomass for methane production it has been postulated that methane yields and kinetics were generally higher in leaves than in stems. Recently the data of Mshandete (2009) on anaerobic digestion of cattails weeds, *Typha domingesis* Pers leaves and stems also confirmed the above concept in Tanzania. A maximum methane yield of 447 m^3 ton^{-1}VS added obtained from leaves was higher by 1.4% than that obtained for stems, which confirmed the above concept.

However, leafy biomass from various plants is traditionally used for green leaf manuring in some parts of African continent as well as in Asia. As the result the enormous energy trapped and fixed in plant tissues from the sun through photosynthesis is lost. To reverse such bioresource wastage it is recommended that anaerobic digestion of leafy biomass waste should be employed first for biomathane renewable energy production, which will result digester residue (biogas manure) of high manure value. Proximate quantity of leaf litters production from some plants has been reported as shown in Table 3. Some advantages of leaf litters include their availability all year round and availability to captive area, which reduces human efforts to collect them and thus reducing the cost of gathering them. The mean leaf litter harvest potential stands at 6 dry tons/hactare/year or 30 fresh tons/hectare/year (Singh *et al.*, 1992). Only 2/3 (67%) of the 6 dry tons/hactare/year (4 of the 6 dry tons/hactare/year) can be used/removed for biogas production and the anaerobic digested leaf litter biomass slurry can be returned to the plantations. The rest 1/3 (33%) of leaf litter is left in plantations for *in situ* decomposition (Singh *et al.*, 1992). Biogas production from fresh leaf biomass has been reported to be 60 m^3 ton^{-1} fresh leaves in India (Asian continent) (Chanakya *et al.*, 1993). A review on evaluation of bamboo as overlooked bioresource potential for bioenergy feedstock revealed that above-ground net primary productivity (ANPP), including leaf turnover, for bamboo productivity is scarce, with most reports coming from various parts of Asia. Elsewhere in American continent, notably Central America a range between 4.5-47 tons/hectare/year have been reported (Scurlock *et al.*, 2000). Although non-fuel applications of bamboo biomass may be actually more profitable than bioenergy recovery, there may also be potential for co-production of bioenergy together with other biomass. However, information on biogas production from abundant leaf litters generated in African continent is limited and not researched thoroughly. A geospatial mapping of bioenergy potential from leaf litter in Africa is paramount to ensure ultimate utilization and sustainable biogas production.

Peels

The amount of one type of organic waste generated at a particular site at a certain time may not be sufficient to make anaerobic digestion cost-effective all year round. Enormous quantities of wastes peels from the processing of agricultural materials for food such as banana, citrus, mango, cassava, potatoes, sweet potatoes, beans, yams, etc. are generated throughout the world, which could fill the gap. About 1,900,000 tons of peels from banana, yam, sweet potatoes, potatoes and plantain food commodities can be generated annually alone in Tanzania based on annual production of those five food commodities obtained from FAO data (Mshandete and Mgonja, 2009). The mean 17 to 40% fresh peels of the original fresh weight of five foods commodity and the their proximate chemical compositions obtained in that study could be used as a baseline data to quantify peel in other countries in Africa based on annual production data per country. These food commodity peels are concentrated source of putrescible organic waste, ideal for anaerobic digestion to produce bioenergy in the form of bioethanol and biogas.

Cuzin *et al*. (1992) reported biogas yield of 661 m^3 ton^{-1}VS from anaerobic digestion of raw cassava peels in Republic of Congo. Africa with potential to produce annually about 97,000,000 tons per annum of fresh cassava could anticipate generating about 20,370,000 tons of fresh peels annually (based on 21% fresh peels of the original fresh cassava weight). The cassava peels weight is equivalent to 555,286 VS tons (based on total solid of 29% out of which 94% VS) reported by (Mshandete and Mgonja, 2009). Therefore African continent could anticipate to generate biogas yield of up to 3,670, 441,782 m^3 annually based on biogas yield from raw cassava peel reported from Republic of Congo. The methane yield from the peels of various banana varieties in the range of 190 to 266 m^3 ton^{-1} VS have been reported in Australia and New Zealand and Asian continents (Gunaseelan, 2004; Clarke *et al*., 2008). On the other hand, in Africa methane yield of 322 m^3 ton^{-1} VS has been reported recently from banana peels in Uganda (Khan *et al*., 2009). About 8,850,000 tons banana were generated in African continent in the year 2005 (FAO, 2007). With 40% fresh peels of the original fresh weight of banana (Mshandete and Mgonja, 2009) it translates to generation of 3,540,000 tons of banana peels per annum. Based on (total solid 15% out of it 90%VS) reported by (Mshandete and Mgonja, 2009) of banana peels about 477,900 tons VS could be estimated equivalent to production of up to 153,883,800 m^3 of methane annually based on the methane yield reported from Uganda. Banana peels and banana wastes generated in Africa continent are yet renewable and abundant bioresources, which can be utilized for biogas production if anaerobically digested.

Waste from fish and animal product processing industries

In fish and in the three types of animal-product-processing industries (slaughtering, tanning and milk) processing activities inevitably produce wastewater, frequently in large quantities. Globally more than 91 million tons of fish and shellfish are caught each year. Some of the by-products are utilized today, but huge amounts are wasted. Annual discard from the world fisheries were estimated to be approximately 20 million tones (25%) per year according to FAO. In East Africa, Nile perch processing into fish fillets for export generates large proportions of both solid and liquid fish wastes estimated at 36,000 tons and 1,838,000 m^3, respectively (Gumisiriza *et al*., 2009a). These wastes include; fish rejects, wash-off water, skin, flame/bony skeleton, bloody water, caucus, fats/lipids, fillet rejects, pieces of bones, viscera, fats roes/eggs, head, breast, fins, deteriorated fillets, very little carbohydrates. All aforementioned wastes currently are improperly utilized and/or disposed off untreated leading to environmental pollution problems.

However, solid waste and wastewater from Nile perch processing represent a high potential energy resource if they can be properly and biologically converted to methane (Gumisiriza *et al*., 2009a). Methane yield of 560 m^3 ton^{-1}VS have been reported from raw fish processing wastewater (FPW) while with pretreatment methane yield was increased up to 2,380 m^3 ton^{-1} VS (Gumisiriza *et al*., 2009b). With total solids (TS) of 0.006 tons/m^3 and 95%

VS (% of TS) reported for FPW (Gumisiriza *et al.*, 2009b), about 11,028 tons TS and 10,477 tons VS can be estimated annually from FPW. If FPW is anaerobically digested a range of 5,867,120 up to 24,935,260 m^3 of methane could annually be anticipated from Nile Perch processing only in Eastern Africa.

Abattoir are one of the industries that generate huge quantities of wastes which include; condemned organs, carcasses, blood, hides, paunch contents, caracass trimming, wastewaters, condemned products, hides, bones, horns, hoofs, urinary bladder, gall bladder, uterus, rectum, udder, fetus, snout, ear, etc. In South Africa alone 42 million m^3 are generated per year as abattoirs waste materials (Robert and de Jager, 2004). Turning abattoir wastes into bioenergy (biogas and biofertilizer) has been demonstrated in Nigeria (Heid, 2006; Streets, 2008). The United Nations Development Programme (UNDP) in Nigeria is providing full funding for the biogas plant at the city's Bodija Municipal, Ibadan, Oyo State. The project, called "Cows-to-Kilowatts" will run biogas plant believed to be one of the largest biogas installations in Africa (Heid, 2006). The biogas plant will transform the waste produced by the abattoir into low-cost household cooking gas and organic fertilizer. About 1,000 cows are slaughtered at the Bodija Market abattoir on a daily basis, which would daily provide 1,500 m^3 of biogas (900 m^3 of pure methane) (Heid, 2006; Streets, 2008). This, in turn, amounts to 5,400 cylinders of cooking gas per month, which will provide gas to 5,400 families a month at around a quarter the cost of liquefied natural gas. On the other hand in terms of electricity 900 m^3 of pure methane daily would be equivalent to production of approximately 3,600 KWh of electricity per day (Heid, 2006; Streets, 2008). The biogas manure (sludge) from the biogas reactor, transformed into organic fertiliser, will be sold to urban low-income farmers at a reduced price of about 5% of the standard price of chemical fertiliser in Nigeria (Heid, 2006; Streets, 2008). Plans are underway to replicate the project in 6 other major Nigerian cities. Other African countries including Cameroon and Ghana are seeking for advice on replication and have contacted the 'Cows to Kilowatts' team.

Tannery industries generate huge quantities of organic and chemical wastes consisting of wastewater, and solid waste flashings', waste skin trimmings, chrome shaving, chrome splits and buffing dust and hair, the former two being composed mostly of lipids and proteins (Zupancjicj and Jemec, 2010). During the tanning process at least 300 kg of chemicals (lime, salt, etc.) are added per ton of hides processed and 25 to 80 m^3 process water required per ton hides. One ton of raw hide yields 0.2 ton leather plus a range of 35 to 50 m^3 wastewater made up of high concentration of salts, chromium, ammonia, dye and solvent chemicals, suspended solids, etc. is produced per ton of raw hide and the solid waste produced per ton of raw hide is about 0.45 to 0.60 ton. About half of this contains 3% chrome on a dry matter basis (UNIDO, 1991). About 165 million cattle are found in Africa (PATTEC, 2001) while Sub-Saharan Africa (SSA) goats population is estimated at 180 millions (Muema *et al.*, 2009). However, it has been previously projected that, by 2025, the total number of cattle in SSA is expected to increase from 162 million in 1988 to 239 million, while sheep and goats are expected to increase to 562 million from 270 million (Winrock, 1992). A recent survey conducted revealed that in Africa there are around 629 tanneries (Cipriani, 2002). Disposal of the vast amounts of tannery waste that are currently generated is a significant problem and major challenge to the environment globally. On the other hand, anaerobic digestion systems of different types of tannery wastes are mature and proven processes that have the potential to convert tannery wastes into energy efficiently, and achieve the goals of pollution prevention/ reduction, elimination of uncontrolled methane emissions and odor, recovery of bio-energy potential as biogas, production of stabilized residue for use as low grade fertilizer (Thangamani *et al.*, 2010). However, information on biogas yield from tannery wastes in Africa is scanty. Nevertheless, elsewhere in the European Union the specific methane production potential from tannery wastes is estimated for tannery waste sludge to be 617 m^3 ton^{-1} of volatile suspended solids, 377 m^3 ton^{-1} for tannery waste trimmings and 649 m^3 ton^{-1} for tannery waste flashings (Zupancjicj and Jemec, 2010).

As a result of the growing poultry industry in Africa continent, poultry slaughterhouses are producing increasing amounts of organic solid by-products and wastes. Poultry industry wastes result from slaughtering in developing countries such as in Africa includes total offals (head, intestine and feet), blood, feathers and trimmings, condemned carcass. In this regard, anaerobic digestion is a promising alternative for the treatment of these materials, as the process combines material recovery and energy production. Little literature is available on the characteristics and quantification of poultry slaughterhouses wastes as well as anaerobic digestion of those wastes in Africa. Elsewhere in Europe continent methane yield in the range between 40 to 250 m^3 ton^{-1} wet weight of slaughterhouse wastes has been recently reported in a review by Salminen and Rintala (2002). Dairy industry is generally considered to be the largest source of food processing wastewater in many countries of the world including those from African continent. It consists of mainly high concentrations of organic materials such as cheese whey consists of high organic matters, mainly lactose, proteins, lipids/fats, suspended oil and grease contents (Najafpour *et al.*, 2009). Whey is considered as highly pollutant effluent with respect to COD level (60 to 80 g L^{-1}) (Mc-Hugh *et al.*, 2006; Gannoun *et al.*, 2008). The enriched nutrients in cheese whey create suitable environment for anaerobic microorganisms to convert organic sources into methane via anaerobic process. Biogas yield averaged 423 m^3 ton^{-1} COD and the methane content of the biogas varied between 57 and 63% has been reported from whey in South Africa (De Haast *et al.*, 1985).

Other organic feedstock's potential for biogas production

Considering organic biomass yield as one of the parameters that makes organic biomass to methane bioconversion economically viable, the number of biomass to be explored is still enormous. There are several other biogenic materials occurring in abundance and appear to be potential feedstock for biogas plants. Amongst these biogenic materials is coastal mud sediment (organic sediment in muds). Pollution of coastal waters results in accumulation of large amounts of organic mater in sediment mud resembling landfills on land (terrestrial). Mud layers could attain 2-3 meters thickness in Japan (Takeno *et al.*, 2001). Therefore, the removal of organic matter from mud sediments is very important for protecting the environment in coastal waters. Feasibility of methane production from mud sediment is possible, as was recently demonstrated in Japan using acclimated methanogenic sludge. The results obtained showed anaerobic digestion could be advantageous for the stable removal of organic matter and the recovery of bioenergy resources in form of methane with a yield of 112 mmol methane from the wet mud liquor (278 g L^{-1}) (Takeno *et al.*, 2001). Such a bioresource for biogas production in Africa is yet to be tapped despite its abundance along coastal waters in Africa.

Other organic biomass suitable for biogas production singly or in combination includes; maize bran, garden cuttings, lawn mowing, paper shreds, dish washing, fruits and vegetables rejects, road sweeping, wastes flowers and roadside plantations. Moreover, other significant biomass waste include; wastes shells from fruits, oilseed cakes wastes (edible and inedible), peanut shells, corncobs, maize stalk, grass trimmings, cotton leaves/stalks, etc. Industrial wastes, such as from breweries, paper production (black liquor/pulp and paper mill effluents), wineries, bakeries, confectioneries, tomato processing, distilleries, tea processing factories, sweet potato vines, yeast waste liquor, wine pot still liquor, and spent wash from molasses distillery, noodle factories and fruit processing/ canning. Timber industry generates considerable biomass, which utilizes only 30% of the product of tree felling (excluding roots). The rest (70%) is waste, which includes sawdust, wood chips and other wood residues that can be obtained from the forest. Likewise rice chaff (which account for about 5% per ton of rice harvested) etc., can be used for biogas production. Since biogas is produced from organic materials, therefore there are huge quantities of other feedstock for digesters in Africa continent, which are yet to be researched and properly harnessed for biogas production. In fact any organic material, which is biodegradable, can be used for anaerobic digestion to produce biogas a renewable, sustainable as well as decentralized modern energy.

Field Application of Biogas Research

Biogas, which is green energy, can be part of feasible solution for Africa's power shortages. Urban areas have been seriously affected by energy challenges and yet these areas have the potential of producing large amounts of biogas as they generate abundant organic wastes feedstock for biogas plants. Recent advances in anaerobic digestion technologies have made it possible to treat an increasing diversity of organic wastes. If operation conditions are carefully optimized and economic viability achieved, anaerobic digestion could compete well with other alternative renewable energy technologies. Utilization of biogas technology is no longer in doubt as was recently revealed in review on biogas research in Africa by Mshandete and Parawira (2009), Parawira (2009). However, more basic and applied research should be undertaken to establish biogas potential of biogas feedstock yet researched. Adoption and modification of appropriate cost-effective and efficient biogas technology in the context of low technology Africa environment should be given top priority in biogas research agenda. This is due to the fact that the cost of anaerobic digestion depends greatly on local circumstances, including biogas feedstock available, construction and labor costs, treatment capacity, possibilities of energy recovery, energy prices, and taxes as well as energy purchase tariffs, land price, markets, etc.

In Africa lowest-technology, low investment cost and efficient biogas systems have high potential for application and acceptance in rural, peri-urban and urban settings where the population might have no other option for sustainable energy supply. In Africa findings from various studies have demonstrated the feasibility for biogas production from some organic wastes, but there are only a handful pilot-scale and full-scale plants, which exist so far. The construction and successful operation of full-scale demonstration plants and at commercial scale is essential for gaining confidence and experience. However, lack of economic sustainability has so far limited the full-scale implementation of anaerobic digestion of organic wastes, in particular of solid wastes in Africa. This has partly resulted in little involvement of private sector in full-scale and commercial scale biogas production investment in Africa. Then awareness campaign for potential users should be undertaken to encourage the use of biogas production and utilization at family, community, and institutional and industrial levels. To promote awareness there is need to evaluate the present institutional framework for renewable energy education in Africa and make suggestions for a shift in policy toward increasing its adoption rate.

Future Research/Challenges in Africa

There is great need for biogas as energy source and anaerobic digestion technology is practicable for the treatment of organic wastes to combine waste management and energy production. Even though organic wastes generated in Africa could provide quite high power generation, however, there challenges ahead which need to be addressed and future research to be implemented:

Geospatial mapping and auditing of potential biogas feedstock

Critical issues are the amount of wastes that is available for energy use, their composition, collection of wastes from point of generation and transport to the biogas plants. Another challenge involves finding the best technology to overcome the long-term storage problem of wastes. The moisture content of the feedstock affects all supply chain elements such as collection, storage, pre-processing, handling and transportation.

Substantial water requirements of slurry-type biogas plants

The use of substantial water in biogas digesters current widely applied in Africa in most cases is under-estimated as factor, which impedes wide spread of biogas technology. Beside, the slurry-type digesters are not suited for solid organic wastes feedstocks because of incompatible bioreactor/ digester design, problems with crust and scum formation, leading to lower maximum loading rates and poor decomposition. Switching to anaerobic digestion of high-solid feedstocks would not only alleviate a lot of the problems inherent with slurry digestion, but more biogas production per unit biogas digester could be achieved. It would also un-limit biogas technology to animal-based biogas digesters in which animal manure could be limiting in some places.

Financial and technical barriers in the production of biogas from organic wastes

The use of some biogas technologies is quite expensive and needs high initial investment. Africa has very limited equipment and lack proper technical knowledge to implement diverse and new biogas technologies. Long-term plan for the implementation of biogas projects and continuous monitoring will ensure that the projects are financially capable to run, which require credit system, the principal reason for better performance of biogas project at any level.

Poor follow-up services and management of biogas digesters

The follow-up services and management of biogas digesters, is an issue for rural energy construction and development. The prevailing development of biogas technology in Africa focuses mainly on construction of various digester types and fails in most cases to consider management. Thus, a number of biogas projects have broken dawn due to a lack of follow-up services and management. This also seriously affects the efficiency of biogas construction and sustainable development. For small-scale systems, it is important to limit scope of initial dissemination efforts to minimize maintenance cost.

Technology innovation in the design and construction of appropriate biogas bioreactors

The key issues should be achieving much higher treatment efficiency, handling larger quantities of waste and generating high quality biogas at a faster rate than traditional biodigester technologies currently employed in Africa. The traditional digesters, beside their performance being uncertain, are not suitable for commercial-scale biogas production. This will entail employment and retention of microorganisms in biogas bioreactors using various support materials, which are available in Africa. The use of anaerobic fixed film bioreactors (AFFB) for biogas production would be ideal and feasible to start with since it can be modified and adapted depending on organic waste to be treated.

Conclusions

Decreasing energy supplies and environmental impacts associated with use of fossil energy forms are encouraging renewed interest in renewable energy. Alternative energy resources like the different biomass wastes discussed in this review should be considered for economic and sustainable biogas adoption and utilization in Africa. Organic wastes can be part of the renewable energy resources for today and tomorrow's sustainable society due readily abundance and feasibility as a source renewable energy locally. Biomass and wastes represent a large potential energy resource that is renewable on a sustained basis. Biogas can be produced from nearly all kinds of biological feedstock types, within these from the primary agro-industrial sectors and from different organic waste streams from various societies of all walks in Africa continent. Biogas technology represents one of the low environment technologies that offer the technical possibility of more decentralized renewable modern energy production in Africa. Biogas has definite advantages, even if compared to other renewable energy alternatives such as biodiesel and bioethanol. Thus biogas technology offers a very attractive route to utilize certain categories of biomass for meeting partial energy needs. In fact proper functioning of biogas system can provide multiple benefits to the users and the community resulting in resource conservation and environmental protection. Biogas can be utilized for renewable electricity and heat production. It can also be used directly as a low-cost fuel in any country for any heating purpose, such as cooking in Africa. At the same time, the plant nutrients of the organic matter after biogas production can be used as biofertilizers replacing petro-based fertilizers.

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