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# A Comprehensive Review of Biomethanation of Urban Food Waste in Nairobi City County, Kenya

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**Abstract:** Organic waste in Nairobi City County accounts for 58-63% of the municipal solid waste generated. Food waste is at the center of urban waste management in the city as it accounts for 64% of the recoverable material. The city is estimated to have a food waste generation per capita of 6.1 kilogram per year, which accumulates to 29.4 thousand tons yearly. It transpires that upstream activities of the food supply chain, mainly production, postharvest loss, processing and distribution are the major food waste hotspots, accounting for 95% of the food waste in developing countries. Additionally, downstream activities of the food supply chain show that hotels, restaurants and super markets are the most important food waste hotspots. Such food waste hotspots should become the primary targets for resource recovery in a circular economy. Currently, the exploitation of food waste for animal feed and composting is growing in Nairobi City County, which signifies that food waste is becoming a valuable urban resource that can be traded, thus creating employment. However, the application of food waste for energy recovery through anaerobic digestion is limited in the city due to lack of source separation of municipal solid waste. On average, food waste has a biomethane potential of 508.45 ml $CH_4$ /g VS. This implies that 29.4 thousand tons of food waste generated in Nairobi City County has the potential to yield 10.5 million $m^3$ of methane, and will demand a digestion volume of 4,299 $m^3$. Using global case studies of electricity generation from biogas, it is estimated that food waste in the city potentially yields 1.38 MW of electricity. In addition, about 26.1 thousand tons of bioslurry can be recovered from the digestion of food waste, which can be used for urban agriculture. Regardless of the liquefied petroleum gas enjoying a tax exemption, biogas at 32.78 USD per gigajoule of delivered energy demonstrates to be more economical, and this can be enhanced by upgrading it. The removal of liquefied petroleum gas from tax-exempt goods through the Finance Act 2020, and an addition of 16% value added tax on the fuel by Kenya Revenue Authority that became effective on 1st July, 2021 favors biofuels such as methane. However, long term realization of methane generation potential in NCC demands the adoption and implementation of more friendly biofuels policies and regulatory frameworks in the country.

**Keywords:** Nairobi City County, Food Waste, Anaerobic Digestion, Methane, Policy

## 1. Introduction

Waste is referred to as any material that is rejected or discarded [1, 27, 48]. Waste can be categorized into household waste and Municipal Solid Waste (MSW). Usually, urban waste and MSW are used interchangeably. MSW is composed of domestic, commercial, institutional, and street sweepings, among others [1, 92]. There is increasing waste generation around the globe, which partly is attributed to industrialization, and Kenya is no exception in this case [62, 76]. Kenya Vision

2030 seeks to promote industrialization, which will help to diversify the country's economy. However, waste generation implications of such economic development ambitions need to be considered in the urban areas, especially Nairobi City County (NCC), where most industries are located [80]. NCC, the largest city in Kenya, already is experiencing an upsurge in MSW generation, which is attributed to economic development, changes in lifestyle and urbanization [62, 69, 80]. The city has the largest waste generation per capita of 0.75kg per day [80]. The 0.75kg of solid waste generated by an individual each day in NCC accumulates to 2,400-2,500 tons of MSW every day, which demands for availability of reliable waste collection and disposal services [54, 64, 65, 80]. However, MSW management is not cheap as evidenced by inability by the local authorities in NCC to effectively manage solid waste [62]. Poor MSW management in the city is highly connected to lack of adequate resources and infrastructure [28, 65, 69, 84]. Therefore, the rising cost of waste management requires that NCC adopt sustainable waste management solutions. In this vein, financially viable, and interventions that will enable cost recovery in order to achieve sustainable waste management must be adopted by the local authorities [33, 69].

FW refers to any discarded food along the supply chain, which is a result of poor decisions and actions of stakeholders, consumers inclusive [34, 51]. Food is wasted at different stages along the food supply chain such as during production, processing, packaging and marketing [4, 24, 27, 40]. More food is wasted due to lack of infrastructure, and poor decisions taken by key stakeholders along the food supply chain in developing countries, Kenya inclusive [28, 29, 46].

In general, problems of food wastage are widespread in the Sub-Saharan Africa (SSA), as it is observed that up to 50% of the cultivated vegetables and fruits are wasted. In Kenya, it is estimated that about 30% of produce is rejected at farm level, while 50% of the food produce is rejected before exportation [29, 40]. In addition, about 44.5% of the food produced is rejected at farm and packaging stages in the country. This high rejection rate does not only reduce farmers and exporters income, but also contributes to generation of huge quantities of FW, which to be managed is also costly [24, 62, 69, 80, 87].

FW is one of the major challenges facing urban areas, especially at a time when cities are experiencing high rates of urbanization, yet resources are limited. Food wastage disrupts global food security efforts, while also damaging the environment through greenhouse gas (GHG) emissions. Therefore, there is a need to reduce FW, but also mitigate its effects on the environment through adoption of green technologies for managing biodegradable urban waste [22, 24, 40].

FW is inevitable in the urban set-up, especially for NCC that has become the regional financial hub. Significant quantities of FW will continue to flow in the urban waste streams. Turning the FW into an important urban resource is becoming more attractive as the concept of a circular economy is increasingly being promoted and adopted by cities around the globe. FW alone accounts for 64% of the recoverable materials from domestic waste in NCC, which means that FW is now considered as a valuable resource in the city. FW is mainly used as animal feed as well as for producing compost manure in the city. However, the energy dimension of the FW remains very important as the city is experiencing a growing energy demand amidst high rates of urbanization, and the requirement for the cities to transition to sustainable energy sources [39].

## 2. Literature Review

Anaerobic digestion (AD) is the most suitable waste-to-energy technology for treating FW, a MSW component that has high moisture content (MC) that ranges from 45 to 50% [83]. The technology enables energy recovery in the form of methane ($CH_4$) that can be used for heating, electricity generation, and as an alternative motor fuel. In addition, the AD process enables recovery of the bioslurry that can be used for urban farming, thus contributing to urban food security [4, 86, 87]. Therefore, this strengthens the rationale for promoting FW extraction from the MSW through source separation, as it has proved to be a valuable resource for energy recovery, composting as well as processing animal feed in the urban areas [19, 21, 28].

Biogas is generated through a process called AD, which is the biodegradation of organic materials in the absence of oxygen ($O_2$). The process takes place in a reactor also known as a digester [3, 74, 78]. Biogas is made up of $CH_4$ at 50-75%, carbon dioxide ($CO_2$) at 25-45%, hydrogen sulfide ($H_2S$) at 1-2%, moisture and other trace elements [15, 17, 20, 32]. $CH_4$ component of biogas is combustible, as such can be used as a fuel for different applications [15, 17, 21, 56]. Using an engineered approach and controlled design, the AD process is designed to treat organic material in airproof digesters. AD undergoes through four successive stages and these are hydrolysis, acidogenesis, acetogenesis and methanogenesis [20, 21, 60, 87].

AD is dependent on the interactions of various microorganisms that are responsible for each of the aforementioned four AD stages. Hydrolysis, which is the first stage of AD, involves bacteria breaking complex organic materials into polymers and monomers in the form of carbohydrates, proteins and lipids (fats). Then acidogenic (fermentative) bacteria converts soluble monomers of amino acids and sugars i.e. ethanol, acids, acetate, hydrogen gas ($H_2$) and $CO_2$ during the second stage of AD, known as acidogenesis. Acetogenesis, which is the third stage of AD, involves the action of the acetogenic bacteria that converts fatty acids, volatile fatty acids (VFA) and alcohols into $CO_2$, $H_2$ and acetic acid. Methanogenic bacteria convert acetic acid and $H_2$ into $CH_4$ and $CO_2$ during the final stage of AD, known as Methanogenesis. An understanding of these AD stages is crucial as it enables optimization of $CH_4$ generation whenever $CH_4$ yields are not satisfactory. Different organic materials such as poultry droppings, cattle dung, agricultural wastes, kitchens waste, night soil wastes and MSW as well as grown purpose crops can be used to generate $CH_4$ [3, 15, 20, 59, 87].

Maintaining the right growth rate for microorganisms in the reactor is very crucial during AD process, as it helps to create a stable population of microbes [15, 20]. The growth rate of microorganisms is affected by a number operating parameters, which need to be optimized in order to improve $CH_4$ yield. Therefore, globally there is growing research interest on biomethane potential of different feedstock as well efficiency of biogas plants [60, 93]. Some of the AD parameters that impacts methane generation are shown in Table 1.

AD can be classified based on whether the system is separated, primary application of the AD, Total Solids (TS) of the feedstock being used and plant feeding procedure. Furthermore digesters differ based on specific designs, and some of the common ones are floating drum, fixed dome, balloon type, fixed dome with separate gas holder and channel type reactors [83]. Table 2 explains more about classification of biogas reactors.

***Table 1.*** *AD Parameters; Sources: [3, 15, 20, 61, 87].*

| AD parameter | Description of the Parameter | Optimisation Techniques | Implication |
|---|---|---|---|
| Temperature | AD microorganisms have two ideal temperatures for digestion and these are: (1) 30-40 C for mesophilic microorganisms; and (2) 45-60 C for thermophilic microorganisms. | Temperature Optimization is needed through heating | Heat addition impacts energy balance of AD. This will affect the cost of methane generation. |
| pH | An optimal pH for AD (covering all stages of AD) is 6.5-7.5 | Lime and sodium bicarbonate are used to optimise the pH. | The use of lime leads to clogging of pipes of the reactor, whereas sodium bicarbonate has cost implications. |
| Carbon-Nitrogen Ratio (C:N Ratio) | The C:N Ratio helps to determine the ammonium inhibition and nutrient deficiency in the reactor. | Co-digestion will be required in order to get an optimum C:N Ratio. | The need for searching for extra feedstock to be used for AD has cost implications. |
| Inoculation | At the beginning of feeding there is a need to inoculate the reactor in order to introduce the required population of the microorganisms. | Inoculum collected from an active digester must be used. | Lack of the required microorganisms in the reactor may slow down $CH_4$ generation. |
| Organic Loading Rate (OLR). | The right amounts of organic material must be introduced into the reactor in a given time. Overloading the digester leads to acidification. | Right quantities of organic material must be fed in line with the OLR design. | Proper biogas digester sizing and feeding is required. |
| Hydraulic Retention Time (HRT) | The HRT measures the time the organic material remains in the rector before exiting in order to allow complete digestion of the substrate. | The designed HRT of the reactor must be maintained. | Proper biogas digester sizing and feeding is required as it can affect the cost AD. |

***Table 2.*** *Classification of Anaerobic Digesters; Sources: [3, 15, 20, 21, 60, 61].*

| Whether AD stages are separated | | Primary AD application | Based on TS of the feedstock. | | Plant Feeding procedure |
|---|---|---|---|---|---|
| One-Staged: All AD stages (i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis) occur concurrently in one reactor. | Two Staged: AD stages are separated, thus effectively allowing separation of various microorganisms responsible for different AD phases. | Agricultural plants, Wastewater treatment plants, MSW treatment plants, industrial biogas plants, landfill gas recovery plants. | Convention Digestion (i.e. Low Solids/ Continuous digestion/wet). Convention AD is applied where the organic material being treated is liquid with TS content of up to 10-12%. Examples are covered lagoons, complete-mix digesters, fixed-film digesters, plug flow digesters etc. | High Solids Digesters (Batch reactors/dry). They are used to treat organic material that is mostly regarded as solid i.e. TS content of more than 12%. Therefore, high solids digesters are mostly in the form of batch reactors. | Batch digesters and Continuous digesters. Batch reactors are fed at the beginning of digestion and emptied once digestion is complete. Continuous digesters are fed on dairy basis and digestate is generated continuously. |

AD is a mature technology as it has been in use for many years around the globe, Kenya inclusive. However, AD technology is attracting the attention of researchers globally as there is a demand to assess the biomethane potential of different feedstock, as well as to improve methane yields of the feedstock available. In addition, the economics of biogas are connected to feedstock availability and its biomethane potential. The development of a field scale AD plant requires scientific backup in order to avoid risks of biogas plant failure. Therefore, this paper analyses FW in terms of its availability and its biomethane potential in NCC, methane generation cost competitiveness, relevant policies that may hinder or promote AD of FW, and global case studies that provide key lessons for Kenya and NCC.

# 3. MSW and FW in NCC and Other Regional Cities

## *3.1. MSW Composition*

In developing countries, MSW generated is mostly organic and biodegradable (Table 3). Usually, organic solid accounts for more than 50% of the MSW, and NCC are no exception. Organic waste in the city accounts for about 60% of the total MSW generated. NCC consumes the largest portion of national resources, as such; it is the largest producer of MSW in the country, FW inclusive. The abundance of organic waste, which is mostly FW, justifies the need for adopting AD technology for energy recovery in the city [1, 41, 44, 54, 61, 84, 87]. Table 3 summarizes MSW composition studies that were conducted in NCC and other regional cities.

***Table 3.*** *A summary of studies on MSW composition in NCC and regional other regional cities.*

| Sources: | In NCC, Kenya | In NCC, Kenya | In NCC, Kenya | In Mombasa, Kenya | In Kampala, Uganda |
|---|---|---|---|---|---|
| Authors | [44]. | [41]. | [39] | [72]. | [47] |
| Organics (mostly FW) | 58.8% | 50.9% | 62.4% | 68% | 91% |
| Metals | | 2.0% | 0.7% | | |
| Plastics | 13.8% | 16.1% | 10.9% | 23% | 3.8% |
| Papers | 11.3% | 17.5% | 14.0% | | 1.1% |
| Glass | | 2.0% | 1.5% | | |
| In organics | 8.3% | | | 9% | |
| Other types of waste | 7.8% | 11% | | | |

### *3.2. Food Waste Generation*

FW is inevitable as some food wastes are unavoidable. However, FW reduction presents multi-faceted wins for cities like NCC, as it contributes to urban food security, economic and environmental benefits [4, 17, 25, 27, 51, 85]. Food is wasted at different levels, including during processing, distribution, and consumption. It encompasses food that is wasted before, during, as well as after cooking [30, 34, 46]. Generally, FW happens between "farm and fork" and is comprised of raw and cooked food [10, 95]. Geographically, FW generation varies from one place to another mainly due to socio-economic and cultural differences [4]. FW generated may differ from one place to another in terms of quantity and composition [71]. Therefore, there is a need for specific FW generation studies that target an area of interest. However, the bulk of organic solid waste generated in the developing countries is in the form of FW, accounting for more than 50% in some countries [27, 50].

Globally, it is estimated that one-third of food that is produced is wasted, a situation that contributes to food insecurity, which is a major concern for food insecure countries. In general, it is estimated that 30-50% of the food produced is wasted in SSA, and the region has a high postharvest loss of 20-30%. Furthermore, consumers in the SSA region have an average FW generation per capita of 6-11kg per year, which is much lower when compared with that for developed countries. However, the impact of this wastage on food security is unwelcome in developing countries as it is blamed for malnutrition and food insecurity [13, 22, 37, 46].

At a local level, data on FW generation is limited in Kenya as well as in NCC. However, FW generation is always higher in urban settings such as NCC than in the rural areas of Kenya, which can be attributed to socio-economic factors. In NCC, a higher FW generation is also reflected in the MSW recoverable material, as FW component of the MSW accounts for 64% of the total recoverable materials from the urban waste, which is attributed to FW recovery for animal feed and composting. A study conducted in Garissa Sub County (Kenya) found that the county has a FW generation per capita of 6.1kg/year. Therefore, in order to bridge the information gap in NCC regarding food waste generation, this paper uses research findings in Garissa Sub County to estimate food waste generation for NCC. Table 4 shows estimations of FW generation in NCC using the available data on FW generation per capita [22, 37, 39, 50, 85].

***Table 4.*** *Estimated FW generation of NCC based on Consumer FW generation per capita and NCC projected population in 2021; Source: [37, 65].*

| NCC population in 2019 | NCC average population growth rate | Projected NCC population in 2021 | FW generation/ Capita/Year | Estimated accumulative FW generation in NCC in 2021 |
|---|---|---|---|---|
| 4,397, 073 | 4.75 | 4,824,716 | 6.1kg/year | 29,430,766.8 kg/year (i.e. 29.4 thousand tons/ year) |

### *3.3. FW Hotspots along the Food Supply Chain*

In the developed world, FW generation is very high at consumption level, while in developing countries like Kenya, it is mostly during the upstream activities, which includes food production, handling and storage stages of the food supply chain. Significant quantities of food cultivated in developing world usually do not reach the consumer because of increased food wastage during the upstream activities. The increasing rate of food wastage along the supply chains is due to inefficiencies, and lack of roads, storage and refrigeration infrastructure [22, 24, 26, 27, 34, 40, 46, 51].

Understanding FW hotspots helps stakeholders identify areas of intervention for reducing food wastage. However, the same aids an entrepreneur in targeting FW for resource recovery. FW hotspots in the cities mainly are households, food retailers and catering establishments. However, a number of studies show that the hospitality industry contributes more to FW generation in the urban areas. Usually, hotels are regarded as major consumers of resources. Therefore, they are associated with generation of huge quantities of refuse, including FW. Therefore, there is a demand for the adoption of green strategies such as recycling and resource recovery in hotels for the benefit of the hotels as well as the environment [4, 40, 68, 88, 94].

About 10% of the FW purchased by the hospitality industry does not reach the customer due to wastage. In addition, one hotel guest produces about one kilogram of waste per day, which annually may accumulate to huge quantities of waste that has to be collected and disposed safely. A study conducted in

Kigali, Rwanda, found that hotels and restaurants are the FW hotspots in the city, producing 145kg/week and 113kg/week, respectively [28, 94, 98]. Figures 1-4 show FW hotspots in the urban area and along the food supply chain.

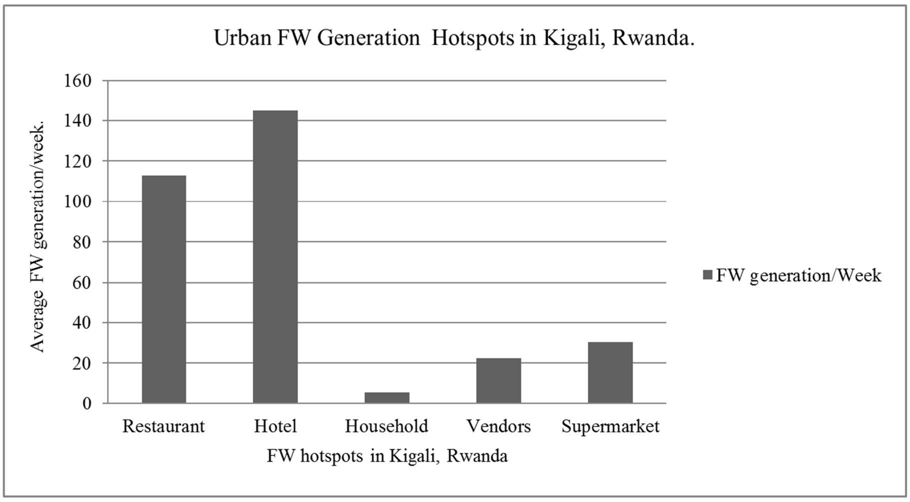


***Figure 1.*** *Urban FW Generation Hotspots in Kigali, Rwanda; Source; [28].*

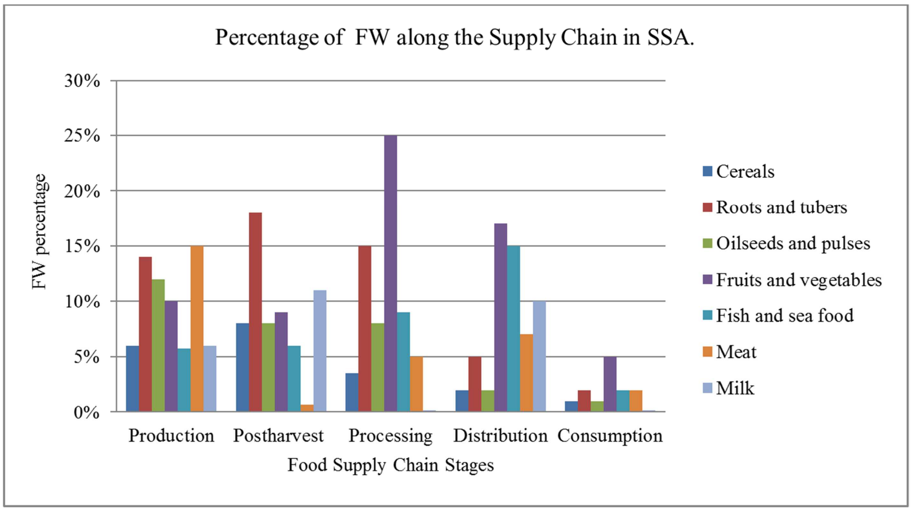


***Figure 2.*** *FW Hotspots Along the Food Supply Chain; Source: [22].*

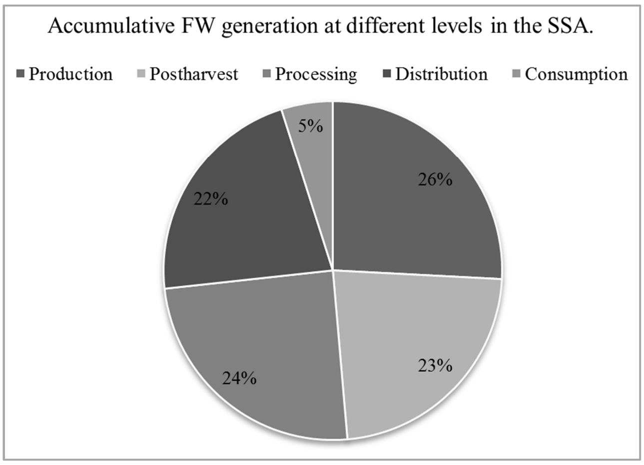


***Figure 3.*** *FW Accumulation at different stages in the SSA; Source: [22].*

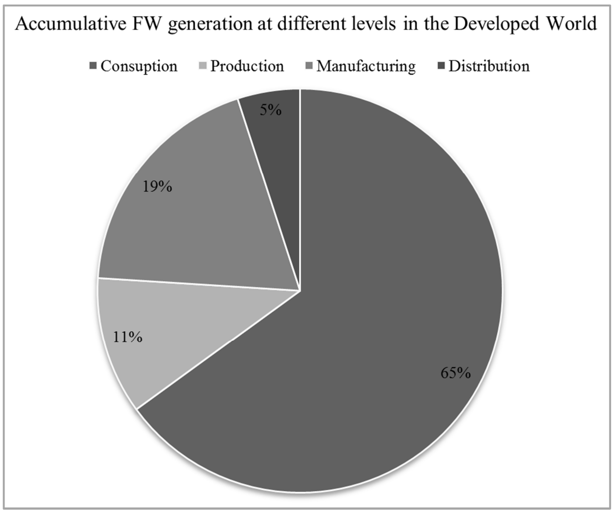


***Figure 4.*** *FW accumulation at different levels in developed world; Source: [4].*

### *3.4. Food Waste Composition*

FW composition usually is determined through compositional analysis, which involves sorting and grouping FW by type [4, 73]. Understanding the characteristics of FW generated is crucial in a situation where the resource is to be used for AD. Currently, FW generation and composition data for NCC is limited. However, a study conducted in NCC on food consumption patterns by households, found that the percentages of consumers of ugali (made from maize flour), green vegetables and protein sources are 88%, 92% and 46%, respectively. Such consumption pattern must also reflect in the FW composition of NCC [67].

In general, FW generated in SSA countries, Kenya inclusive, is composed of 36% fruits and vegetables, 37% roots and tubers, 13% cereals, 6% milk and dairy, 5% meat and fish, and 4% oilseeds and pulses [34]. In addition, a study conducted in Garissa Sub County in Kenya found that urban FW mainly is composed of bakery, grains/cereals, vegetables, fruits and tea/coffee. However, studying FW generation must be continuous in NCC, as quantities and compositions of FW change with socio-economic development, and advances in technologies [27, 37, 40, 41, 71]. Figures 5-6 shows food waste composition of SSA and Garissa Sub County in Kenya.

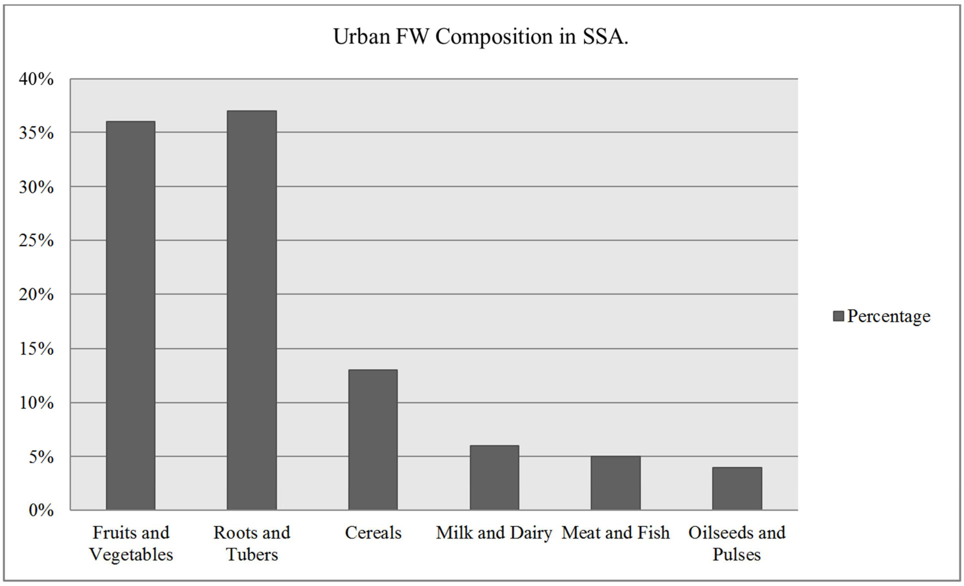


***Figure 5.*** *Urban FW Composition in SSA; [34].*

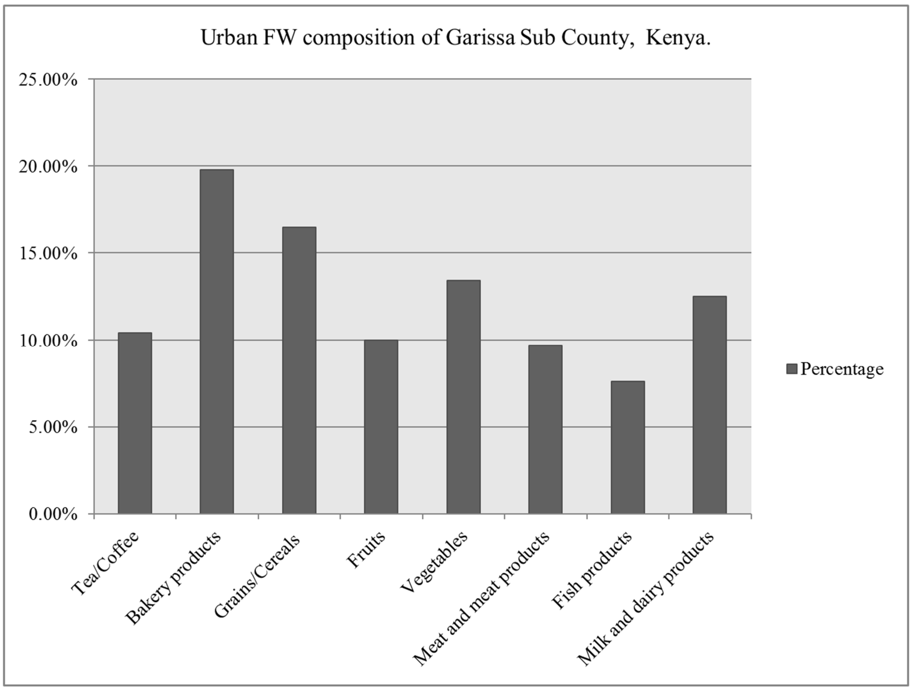


***Figure 6.*** *Urban FW Composition of Garissa Sub County in Kenya; Source: [37].*

### *3.5. Current FW Uses and Treatment Methods in NCC*

The FW management hierarchy proposes using FW as a resource. As such, FW must be used as animal feedstock before being considered for composting and energy recovery options. The AD treatment method of FW is preferred over composting treatment techniques, especially for cities experiencing both food and energy poverty. AD enables recovery of energy (biogas), and provides addition on-farm paybacks in form of bioslurry that is produced as a bio-product of AD process, which can be used for soil conditioning, thus enhancing urban farming and food security in the urban set-up [3, 4, 12, 17, 36, 43, 82, 86].

#### *3.5.1. Processing FW into Animal Feed*

FW prevention remains the priority globally, but it is also an entry point for innovation and entrepreneurship as the discarded food can be processed into animal feed that is more affordable to smallholder livestock farmers. Currently, data for NCC regarding food waste generation rate is limited, as most studies have focused on MSW waste generation and composition in general. However, a study conducted in Thika (Kenya), reported that 15% of the MSW generated is food [4, 18, 23].

According to FW hierarchy, if FW cannot be prevented, then the next best option is to use it as animal feed considering that it has high nutrient contents. This concept is being applied in NCC as FW is increasingly being used as animal feed. A study conducted in Thika on FW reported highest rate of FW recovery for animal feed application. There is expectation that more farmers will employ innovative means of turning FW into animal feed as imported animal feed becomes unaffordable to smallholder farmers [4, 18-19, 30, 77, 89].

#### *3.5.2. FW Composting*

Urbanization is associated with challenges related to urban food supply. Therefore, urban agriculture is increasingly being adopted in NCC at a time when food supply systems are challenged by lack of proper infrastructure such as roads and refrigeration. In addition, Kenya continues to experience rising costs of inorganic fertilizer, which is attributed to the volatility of oil prices [2, 38, 40, 65].

Compost manure is becoming an alternative for smallholder farmers. In NCC, composting is done on small scale by residents, Community Based Organizations (CBOs), and through pilot plants, especially in low income areas where there are limited employment opportunities for the youths [39-41, 66]. It is estimated that composting alone diverts more than 10 tons of MSW per day in NCC, thereby helping alleviate waste management problems while also supporting urban agriculture [39, 59, 91]. However, compost manure has been unattractive to urban farmers in NCC because it is proven to be too expensive due to lack of robust composting infrastructure [65-66]. AD that enables recovery of energy and compost manure has the potential to reduce the cost of composting, and contribute to the city's ambitious goals of food security and energy resilience [21, 23].

#### *3.5.3. FW Energy Recovery*

Source separation of MSW in NCC is almost non-existent, yet it is very crucial for sustainable waste management. Source separation of MSW simplifies the extraction of FW for $CH_4$ production [17, 41, 54, 61, 80, 84]. In general, FW mixed with other types of waste is of low quality, thus unsuitable for $CH_4$ generation through AD technology. Currently, most of the anaerobic digesters located in the city rely on cow and poultry manure as feedstock, as such, most of the digesters are farm-based. A few biogas plants use cow dung that is generated in the animal slaughter houses [78, 87]. FW resource remains untapped for energy recovery in the NCC, thereby, wasting a resource that can help the city address waste, climate and energy challenges [4, 31]. Currently, composting is proven to be expensive in urban Kenya, which has led to low user adoption of the organic manure [66]. Therefore, AD remains the most suitable option as it enables production of compost manure as a process by-product, which helps reduce the cost of compost manure while also maximizing revenue for entrepreneurs through a combination of feedstock, biogas, and compost sales [17]. In addition, producing biogas from FW does not compete with food crop cultivation unlike cultivated energy crops that strain local resources in terms of water, land, farm inputs and labour [42].

### *3.6. Conclusion on FW Generation*

Organic waste, which mostly is FW accounts for 58-63% of the MSW generated in NCC. Locating the FW hotspots in city is crucial as it aids planning in terms of FW reduction, recovery for different purposes and disposal. Along the FW supply chains, production, postharvest loss, processing and distribution account for 95% of the FW. At consumption level little amounts of food is wasted (i.e. 5%) in developing countries, as not enough of the cultivated food reaches the targeted consumer. Furthermore, downstream activities of the food supply chain show that hotels, restaurants and super markets emerge as the hotspots of FW. Fruits, vegetables, roots, tubers and cereals are the major components of FW in the urban Kenya. FW composition impacts the physio-chemical characteristics of the FW generated and the biomethane potential of the FW. Currently, there is a growing use of FW in NCC for animal feed and composting, which signifies that FW is becoming a valuable urban resource. However, AD of FW is very minimal partly due to lack of source separation of MSW in the city.

## 4. Potential FW Recoverable $CH_4$ and Its Cost Competitiveness.

### *4.1. Physical and Biochemical Characteristics of FW and Its Potential $CH_4$ Yield*

In order to design proper FW treatment methods, there is a need for accurate chemical and biochemical analyses. An understanding of the biochemical and elemental composition of FW helps to predict $CH_4$ yield of the feedstock, which is a very important in the development of large scale (i.e. field and commercial scale) biogas digesters [4, 15, 20, 53, 83].

Usually, the chemical and biochemical analyses involves the determination of parameters such as moisture content MC, total solids (TS), volatile solids (VS), proteins, lipids, carbohydrates and fiber; macro and trace elements. FW of different origins usually show similar distribution of proteins, carbohydrates, fats and essential elements. The physical and biochemical composition of the substrate such as FW, apart from the operating parameters, has an impact on $CH_4$ yield. Therefore, a number of studies conducted around the globe have tried to relate the physical and biochemical characteristics of the substrate to $CH_4$ yield [4, 20]. Table 5 shows physical and biochemical characteristics of FW and potential $CH_4$ yields.

***Table 5.*** *FW $CH_4$ yields from different studies.*

| Authors: | [70] | [49] | [8] | [9] | [6] |
|---|---|---|---|---|---|
| TS % | 85.2 ± 6 | 19.33 | 28.65 | 29.4 | 14.83 |
| VS% | 44.3±2.8 | 94.47 | 25 | 95.3 | 91.89 |
| VS/TS | | | 0.88 | | 1.088 |
| pH | 5.1±0.1 | 4.9 | | 4.1 | 4.7 |
| C% | 47.0±2.4 | 49.93 | 47.9 | 49.58 | |
| H% | 7.3±0.4 | 6.63 | 6.65 | 7.32 | |
| N% | 2.7±0.4 | 4.17 | 3.05 | 3.53 | |
| O% | 42.9±3.3 | 34.20 | | 34.88 | |
| C/N Ratio | 18:1 | | 15.85 | 14.2 | |
| Proteins | - | 16.77 | | 18.1 | |
| Carbohydrates | - | 19.37 | | 59.0 | |
| $CH_4$ Yields | 506.60 ml $CH_4$ /gVS | 439.63 ml $CH_4$ /gVS | 508.00 ml $CH_4$ /g VS | 498.00 ml $CH_4$ /g VS | 590.00 ml $CH_4$ / g VS |
| Average $CH_4$ Yield | 508.45 ml $CH_4$ /gVS | | | | |

Generation of methane from FW is commercially done in a number of countries around the globe. In some cases, FW is co-digested with other available feedstock such as wastewater. In Naivasha (Kenya), the biogas plant that produces 2.2 MW of electricity does not use FW feedstock. However, the locally available commercial biogas plant in Kenya that uses crop residuals offers important lessons to NCC [42]. Some of the important global case studies related to AD of FW are outlined in Table 6.

***Table 6.*** *Field scale AD of FW around the Globe.*

| | AD Technology Details. | Feedstock Details | Outputs | Economics-Payback Period | Sources: |
|---|---|---|---|---|---|
| Australia | This is wet in vessel mesophilic AD. It is 5000m$^3$ in size. | The AD system demands 35,000-50,000 tons of FW annually. | 2 MW of electricity and 100 m$^3$ of bioslurry (biofertiliser) per day. | Total capital is 7.2 million USD and has a payback period of 5 years. | [59]. |
| Westwood-Biogen Greenfinch in Northamptonshire. | - | 45,000 tons of household and commercial FW per year is used to feed the AD plant. | 2.1 MW of electricity is generated plus 40,000 tons of digestate. | | [17]. |

### *4.2. NCC FW Recoverable $CH_4$ Based on City's FW Generation per Capita and Commercial AD Global Case Studies*

The sustainability of biogas generation depends on the availability of feedstock and its biomethane potential, as such studies focusing on the quantification of biodegradable waste needs to be undertaken in an area of interest. Usually, MSW generation is proportional to the size of the population and economic growth of a city. Therefore, based on NCC's projected population of 4, 824, 716 in 2021, FW generation of 6.1 kg/capita/year, the city potentially generates about 29.4 thousand tons of FW per year (Table 4). Out of this FW, recoverable energy through AD can be estimated by using average $CH_4$ yields of FW obtained from different research studies conducted in Kenya and other countries (Table 5). In this case, theoretically NCC has the potential to generate 10.5 million m$^3$ of $CH_4$ per year at generation rate of 508.45m$^3$/ton of VS, and 26.1 thousand tons of bioslurry that can be used for urban farming in the city. Using average potential of electricity generation from biogas (methane) based on the global case studies, it is estimated that NCC has the potential to generate 1.38 MW of electricity from FW alone (Table 7) [37, 41, 59, 75].

***Table 7.*** *Estimated $CH_4$ potential of FW in NCC for 2021; Source: Authors.*

| Average $CH_4$ Yield of FW. | Average VS of FW. | FW generated in Nairobi/Year. | Calculated % of VS of NCC FW. | NCC FW Potential $CH_4$ Yield in m$^3$/Year | Electricity Generation Potential in MW |
|---|---|---|---|---|---|
| 508.45 ml $CH_4$/gVS (Table 5) | Based on a number of studies conducted around the globe (Table 5) average VS content of FW is 70.13%. | NCC generates 29,430, 766.8 kg of FW per year which is equivalent to 29, 430.8 tons (Table 4) | 20,601,536.76 kg of VS, equivalent to 20,601.54 tons. | 10,474,853 m$^3$ (10.5 million m$^3$) of $CH_4$ per year, and $CH_4$ generation is at a rate of 508.45m$^3$ per ton of VS, and 26.1 thousand tons of bioslurry. | Using average potential of electricity generation from case studies (Table 6), NCC FW has the potential to generate 1.38 MW of electricity. |

### *4.3. The Required Digestion Volume for NCC FW*

Using FW generated in NCC (29,430 tonnes/year), the required volume and number of digesters in NCC can be calculated. Total volume of a digester required is calculated using the following equations [79]:

$$V_d = V_s \times T_r \quad (1).$$

Where $V_d$ is volume of the digestate;
$V_S$ is volume of substrate; and
Tr is the Retention Time in days.

It should also be noted that the ratio of digester volume to the gas volume is between 3:1 and 10:1. In this case, a ratio of 3:1 is selected for this paper.

$$V_g > \frac{V_d}{3} \quad (2).$$

Total volume of the digester Vt in cubic meters ($m^3$) is the sum of Vg and Vd:

$$V_t = V_d + V_g = \frac{4}{3} \times V_d \quad (3).$$

When the $T_r$ chosen for AD is 40 days,

$$\text{Then } V_t = \frac{160}{3} \times V_d \quad (4).$$

Therefore, 80.6 tons of FW generated per day in NCC mixed at a ratio of 1:1 gives $V_d$ of 80.6 $m^3$. This $V_d$ requires a Vt of 4,299 $m^3$ when the HRT is set at 40 days. The required total volume of a digester to treat FW in NCC at 80.6 tons/day (29,430 tonnes per year) is in line with the Richgro's commercial biogas plant that is located in Australia. The plant has a total volume of 5,000$m^3$ and capable of treating a minimum of 95.9 tons/day (i.e. 35,000-55,000 tons/year) of FW (Table 3). Table 8 and Figure 5 show the pathway for AD of FW in NCC, and the potential recovered energy and bioslurry.

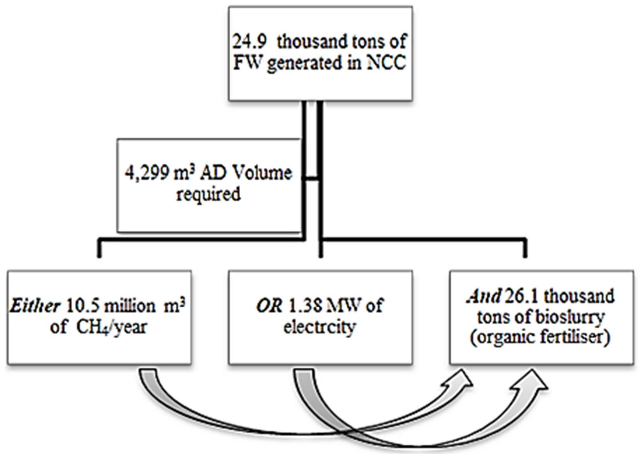


***Figure 7.*** *Energy recovery pathways and potentials of FW in NCC; Source: Authors.*

***Table 8.*** *AD of FW Potential in NCC; Source: Authors.*

| NCC Annual FW generation | Retention Time | AD Volume | Energy Outputs | Bioslurry Outputs |
|---|---|---|---|---|
| 29.4 thousand tons | 40 days | 4, 299.6m3 | 10.5 million m3 or 1.38 MW of electricity | 26.1 thousand tons |

### *4.4. Cost Competitiveness of Methane (Biogas) in NCC*

Energy content of biogas at 19.83MJ/Kg is much lower when compared to that of Liquefied Petroleum Gas (LPG), Kerosene, and charcoal. However, biogas cost at 32.78 USD per delivered energy in Gigajoule (GJ) is more competitive when compared with LPG (at 30.93 USD/GJ of delivered energy) and other fuels, regardless of LPG enjoying a value added tax (VAT) exemption. Methane (upgraded biogas) at 50-55 MJ/Kg has higher energy content when compared with the aforementioned fuels, LPG inclusive. Therefore, upgrading biogas will make it more competitive against LPG, with or without leveling the ground for competition through related energy policies. Table 9 shows a comparison of methane (biogas) with other fuels in NCC, in terms of its cost competitiveness.

***Table 9.*** *Cost-competitiveness of $CH_4$ in NCC.*

| Fuel Source | Fuel Energy Content | Fuels cost in USD/Kg & per litter for ethanol. | Fuel Average Cost in USD per delivered GJ of Energy. | Sources |
|---|---|---|---|---|
| $CH_4$ | 50-55 MJ/kg | Not known | Not known | [96] |
| Biogas | 22.8MJ/m3 i.e. equivalent to 19.83MJ/Kg | 0.65/kg | 32.78 | [35, 52] |
| LPG | 46-51 MJ/kg | 1.25-1.75/kg | 30.93 | [5, 16, 52, 96] |
| Kerosene | 43MJ/kg | 0.75-0.92/kg | 19.42 | [16, 52, 90] |
| Fuel wood | 16 MJ/kg | 0.50/kg | 31.25 | [16, 52, 96] |
| Charcoal | 30 MJ/Kg | 0.30-0.50/kg | 13.33 | [5, 16, 53] |
| Ethanol | 16.7-21.2 MJ/litter | 0.90-1.0/litter | 50.13 | [14, 97] |

### *4.5. Conclusion on Recoverable $CH_4$ from FW*

Based on the FW generation per capita in NCC, the city generates 29.4 thousand tons of FW per year. A digestion volume of 4,299 $m^3$ with a HRT set at 40days is required to treat such FW. Furthermore, using an average $CH_4$ yield of FW (i.e. 508.45 ml $CH_4$ /gVS) it is estimated that 10.5 million $m^3$ of $CH_4$ can be recovered from the FW. Using global case studies of electricity generation from biogas, NCC FW can yield 1.38 MW of electricity. In addition, 26.1 thousand tons of bioslurry can be recovered and used for urban agriculture in the city. The analysis of heating value of fuels consumed in NCC, shows that upgrading biogas to $CH_4$ has the potential to increase its heating value from 19.83MJ/Kg to 50-55MJ/Kg, which is greater than that of other fuels, LPG inclusive. Regardless of imported fossil fuels such as LPG enjoying a tax exemption, biogas proves to be more competitive when considering the cost per delivered energy (USD/GJ delivered), and this can be enhanced by upgrading biogas.

# 5. Policy Implications of AD of FW in NCC

### *5.1. Biofuels Incentives Versus National Fossil Fuel Subsidies National Policies*

Kenya ranks poorly in the SSA region when it comes to biofuels policy friendliness due to unrealistic value added tax (VAT) and duties. Regardless of bio-ethanol having comparable profits to LPG, the cost of bio-ethanol is exaggerated by a 25% import tariff and 16% VAT treatment, unlike LPG that has enjoyed a VAT exemption for many years. Usually, fossil fuel subsidies undermines the development of RE. The removal of LPG from tax-exempt goods through the Finance Act 2020, and an addition of 16% VAT on the fuel by Kenya Revenue Authority (KERA) that became effective on 1$^{st}$ July, 2021, favors biofuels industry in the country. However, in order to realize this great potential of $CH_4$ generation, GoK and NCC must adopt biofuel policies that create conducive environment for investment [7, 16, 81].

### *5.2. MSW Source Separation Policy Adoption and Implementation*

The 2015-2020 Draft Strategy and Action Plan for Bioenergy and Liquefied Petroleum Gas Development in Kenya encourages counties to effectively collect and use MSW for energy recovery and composting. However, source separation of MSW is almost non-existent in NCC, which hinders stakeholders' efforts to extract FW for energy recovery as mixed MSW is not suitable for AD. Therefore, NCC needs to adopt and implement policies that promote source separation of MSW. Such efforts will be in line with the Nairobi City County Solid Waste Management Act, 2015, the County Annual Development Plan (CADP) of 2020/2021, the Sustainable Waste Management Policy, and the 2015 National Solid Waste Management Strategy which promote zero-waste principle in NCC [17, 41, 54, 61].

### *5.3. Imported Fossil Fuels Versus Biofuels*

The imported petroleum accounts for 25% of the national import bill in Kenya. However, the contribution of petroleum to the national energy mix is only 21%. Furthermore, these fossil fuels are not helping the government meets its climate goals. GoK contradicts itself by subsidizing the imported fossil fuels while also voicing its commitment to reducing national GHG emissions. $CH_4$ just like fossil fuels can be used for different purposes, including heating, electricity generation as well as a fuel for motor vehicles. Therefore, GoK must adopt policies that are clear enough on energy diversification, energy security and decarbonization of the energy sector, where biofuels sector is identified as priority area. In this case, investment in clean and sustainable energy sources such as biofuels must be a priority for the government, counties and development partners [15, 17, 57, 61, 63].

### *5.4. Universal Energy Access by 2030 Policy*

Policy has a great impact on the adoption of energy technologies. The National Energy and Petroleum Policy (2015) as well as the Energy Act (2019) suggest that $CH_4$ and MSW can help meet Kenya's energy needs. However, GoK policy underestimates the potential of $CH_4$ and other biofuels in the country. For instance, GoK projects that biogas contribution to cooking energy will account for 0.8% only in the national RE mix by the year 2030. This projection creates a weak rationale for investment in the $CH_4$ generation, regardless of having great potentials to contribute more to Kenya's ambitious goal of universal energy access by the year 2030. Therefore, NCC and GoK policies must target a higher contribution of $CH_4$ in order to create a momentum for increasing the adoption of $CH_4$ and other biofuels [11, 55, 58].

### *5.5. Food Versus Energy and the Use of FW*

NCC through the Nairobi City County Urban Agriculture Promotion and Regulation Act, 2015 and the Nairobi City County Food System Strategy seek to promote urban food security. These interventions have led to an increase in the adoption of urban farming in NCC. However, one of the bottlenecks to achieving urban food security in NCC is the rising cost of fertilizers. Compost manure too is considered as expensive partly due to lack of proper composting infrastructure. However, the cost of compost manure can significantly be reduced if it is produced as a by-product of AD in NCC. AD of FW will enable NCC to address the dilemma of food insecurity and energy poverty by promoting sustainable energy production, and urban agriculture [66].

### *5.6. Research and Development (R&D)*

The National Energy and Petroleum Policy of Kenya that was adopted in 2015 recognises that inadequate R&D in the field of biogas hinders the development of the biofuels industry in the country. R&D gap in Kenya is evidenced by lack of adequate data related to biogas. Therefore, there is a need to adopt and implement deliberate national policies that support R&D in biogas generation in order to enable NCC and stakeholders realise biofuel potentials that remain unexploited.

### *5.7. Climate Change and Environment Policy*

Kenya has emerged as a leader in climate change issues globally, and has made commitments to reduce GHG emission. However, the focus has been on decarbonization of the energy sector. Therefore, the waste sector as a potential area for reducing the national GHG emissions remains neglected. FW is a global issue as it impacts the environment through GHG emissions, especially $CH_4$, which is a more potent GHG than $CO_2$. Usually, more GHGs are emitted during the final disposal of MSW in landfills, where uncontrolled biodegradation takes place in NCC. In addition, energy sector is the largest contributor to GHG emission, especially due to extraction and consumption of fossil fuels. Clean and renewable energy technologies shall play a pivotal role in meeting GHG emission reduction goals. In this regard, WtE options such MSW management based biogas plants that contribute to waste reduction can be employed to solve multiple problems including energy, sanitation and climate change in NCC [15, 33, 45, 54-56, 73].

### *5.8. Policy Conclusion*

The NCC with support from GoK must adopt and strengthen policy and regulatory frameworks that facilitates source separation of MSW, and development of adequate waste management infrastructure in the city. This should be supported by proper R&D policy that enhances FW resource recovery at a time when urban areas are becoming resource constraint. Furthermore, energy policies must reconsider removing subsidies on fossil fuels in order to make the locally produced biofuels competitive and attractive in the urban Kenya, where consumers have a wide range of energy options. Any policy that encourages biomethanation of FW also favors sustainable urban agriculture through the use of bioslurry for crop production in NCC.

## 6. Recommendations

1) Sustainable energy recovery from FW in NCC requires the adoption of appropriate policies, strategies, and regulatory frameworks that promote source separation of MSW; and support R&D in biofuels generation.
2) In NCC, biogas demonstrates to be more competitive when considering the cost per delivered energy. However, commercial biogas generation is still lacking in the city, partly because of poor policies that disadvantage biofuels. Therefore, deliberate national policies that create a momentum for development and adoption of biofuels such as biogas must be adopted and implemented.
3) Currently, biogas generation is mainly done on small scale (household), and mostly given as a gift to communities by development partners. However, this model has proved to be unsustainable in many developing countries, as beneficiaries lack the required capacity (i.e. financial and technical capacity) to operate and maintain such biogas systems in the long term. Therefore, with proper government and stakeholders' support, NCC needs to transition to commercial biogas generation in order to promote sustainability.
4) GoK should consider waste sector as a priority area for GHG emission reduction in order to meet its climate goals. In this case, AD of MSW should become part of an integrated solid waste management plan for the cities, NCC inclusive.

## 7. Conclusion

Organic waste, which mainly is FW, constitutes the largest component of MSW in NCC. FW is becoming a valuable urban resource in NCC as evidenced by increasing utilization of the material for animal feed and composting. However, the application of the FW for AD is still very low due to lack of source separation of MSW in the city. Efforts to utilize FW for energy recovery along the food supply chain in the city must target the upstream activities, which account for 95% of the FW. Furthermore, considering the downstream activities of the food supply chain, hotels, restaurants and supermarkets emerge as the FW hotspots, which must be targeted for FW recovery. Accumulatively, based on FW generation per capita of 6.1 kg per year, NCC generates 29.4 thousand tons of FW per year, which potentially yields 10.5 million $m^3$ of $CH_4$, and will demand a digestion volume of 4,299 $m^3$ when HRT is set at 40 days. The digestion of 29.4 thousand tons of FW yields 26.1 thousand tons of bioslurry that can be used for urban farming in the city. If conversion of biogas to electricity is the preferred option, then 1.38 MW of electricity can be generated. Biogas is more competitive regardless of Kenya having unfavorable environment for the development of biofuels. However, biogas competitiveness can be enhanced through the adoption and implementation of policies and regulatory frameworks that promote source separation of MSW, biogas investment and biogas utilization in NCC**.**

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