Chapter

Evaluating Waste-to-Energy Technologies as a Waste Management Solution for Uganda

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Abstract

Currently, the world generates 2.01 billion tonnes of waste annually and this is expected to increase to 3.401 billion tonnes of waste by 2050. The continual generation of waste is at the forefront of combating climate change because the waste generated is associated with GHG emissions among other environmental concern. Literature reports that developing countries are lagging the developed countries in waste management and yet these regions are expected to account for most waste generated by 2050. This chapter focuses on the application of Waste-to-Energy (WTE) Techniques in Uganda (developing country) as a way of managing waste, and recommends policies that the Government of Uganda could adopt from the UK to successfully implement these initiatives. The WTE technologies analysed are landfill gas recovery, anaerobic digestion, incineration, pyrolysis, and gasification. The chapter also reviews the current solid waste situation in Uganda with a comparative analysis of the technologies. Since Uganda is a low-income country, it is advised that the country enters Public-Private Partnerships where the developers build and own the technologies. The assessment is informed by literature and personal judgement. Recommendations are made to the GOU on how best to support stakeholders of WTE initiatives further areas of study are highlighted.

Keywords: waste management, waste management hierarchy, waste-to-energy technologies, technology applicability, policy adoption, research

1. Introduction

According to the World Bank, the world generates 2.01 billion tonnes of MSW every year and is expected to increase by 70% by 2050 [1]. The mean global temperature increased by 1.9°F since 1880 and is credited to an increase in human activities like waste generation [2]. Specifically, food waste is a global concern with up to 1/3rd of food produced being wasted in high-income countries and this makes it the world's third-largest emitter [3]. The global population, urbanisation, and economic growth are identified to have a strong correlation to how much waste is produced and yet by 2050, the world population is anticipated to increase to more than 9 billion people with developing economies accounting for 85% of the global population [4] and with the number of people living in urban areas increasing to 6 billion [5].

WTE technologies, through converting the waste generated to energy, are a partial renewable energy source because of the waste that comprises of biomass material like paper, card, and timber. Even though these biodegradable wastes might emit carbon dioxide when burned, the process of photosynthesis enables the plants to absorb the CO_2 and this is regarded as a short-term cycle. Note that the waste which is fossil fuel-based generates GHG and contributes to climate changes [6, 7].

Developing countries are failing to invest in waste management and the cry is to take immediate action to reduce this or the effects of waste on the environment through waste management techniques [8]. Also, developed countries are currently promoting economic and social wellbeing through energy supply yet the energy needs of developing countries are still straining to the respective governments [5]. The success of WTE in Europe is observed by determined investors who trust the technology could work in Africa [9] hence there is a need to exploit the possibility of applying sustainable WTE technologies to meet the growing energy needs while improving the SWM system.

2. Waste management hierarchy

The waste management hierarchy designates the best solutions for managing waste according to what is most suitable for environment [10] and is presented in **Figure 1**.

2.1 Prevention

Priority is given to preventing waste and this entails using less material, waste reduction at source, or retaining products for long [10]. Prevention of waste is advantageous from any waste management strategy such as energy recovery, recycle,

Figure 1.
Illustration of the waste hierarchy [10].

and landfill because the production of material that becomes waste as well as its treatment is circumvented. The definition of waste prevention includes avoidance of waste creating products, waste reduction at source, increasing the life cycle of a product, and reuse [11]. According to the World Bank Report, the fastest way to manage and decrease waste is to minimise economic activity because when countries urbanise, their economic wealth grows along with standards of living, disposable incomes, and consumption of goods and services which leads to an increase waste generated [12]. Another suggested solution is moving from a linear to circular economy that is by curtailing resource extraction and material inputs, and improving efficiency through developmental designs, recollection, and recycling [8].

2.2 Reuse and recycle

Under these stages, the waste producer is required to check, clean, repair, and reuse the material or shift the use of the material to another function. Useless waste is converted into useful materials, and hazardous waste is turned in harmless material hence improving utilisation [10, 11]. Resource recycling promotes economic, social, and environmental benefits because the country saves on natural resources, decreases energy consumption, promotes employment while decreasing waste and pollution. Useless waste is converting into useful materials, and hazardous waste is turned in harmless material hence improving utilisation [11]. An increase in recyclable material in the composition of waste requires reuse and recycle management, while an increase in organic waste or other unrecyclable material would require other management techniques [13].

2.3 Recovery

Recovery can be through energy recovery techniques and/or using waste for either agricultural purposes or backfilling [10]. Section 3 provides more insight on energy recovery techniques. It involves recovering usefulness from the waste through energy recovery techniques such as anaerobic digestion, fermentation, incineration, gasification and pyrolysis to produce energy (fuel, heat and power), and using waste for backfilling [10]. The recovery of biogas and heat energy from landfills and incineration plants, respectively, will reduce waste generation and help in the appropriate reutilization of resources. Resource utilisation of livestock and manure, agricultural waste, domestic sewage sludge, and other organic SWs during aerobic composting and anaerobic digestion and then recycling the organic substances and nutrients, etc. are some of the efficient ways to realise SW resources and materials recovery systems [11].

2.4 Disposal

Depending on a country's policies, waste is disposed of through grinding, milling, open dumping, landfilling, and compaction or burned in an incinerator without energy recovery. The waste can also be disposed of in other countries only when it has a market in those specific countries [8, 10, 11].

High income countries mostly dispose through landfilling and thermal treatments while middle- and low-countries mostly dispose by open dumping and poorly managed landfilling. However, the middle-income countries operate with managed dumping processes [12].

3. Energy recovery technologies

In 2016, the total investment in biomass and WTE technologies was 6.8 billion USD which was a decline from 19.9 billion USD in 2011, 14.9 billion in 2012, 12.4 billion in 2013, 10.8 billion in 2014 but an increase from 6.7 billion in 2015 [14]. Despite the increase, it is evident that interest in WTE is not growing across the globe and yet it is successful in European countries. Energy from waste can either be heat, power, or a combination of heat and power and/or secondary energy carriers of gas, liquid or solid. The choice is usually dependent on the energy requirements of the country or region [6].

3.1 Landfill with gas recovery

Landfills are semi-natural terrestrial ecosystems remodelled on lands that were formerly used for disposing of waste. Landfills exist in various regions and are commonly defined by their age, the composition of waste, design, and ecological operation. They are usually disposal for MSW and sometimes for hazardous solid wastes when they are secure [15]. The landfills are designed to make sure the waste is separate from the surrounding environment [16]. Also, two design structures are feasible for a landfill that is landfilling (where waste in packed in an unwanted hole) or land raising (where waste is directly dumped on the ground) [17]. The average landfill occupies 600 acres [18].

The by-products of landfills are landfill leachate produced when rainwater penetrates and channels through the decaying waste, and landfill gas produced through bacterial degradation under anaerobic conditions [15]. These products can be hazardous in the following ways. Firstly, when acids from degrading waste mix with other components waste, it could cause the leachate to become toxic. Secondly, landfill gas is a source of GHG emissions comprising methane and it is highly flammable its leakage poses a risk of explosions to the surrounding environment [17]. Since the by-products can escape or diffuse through cracks in the deposited material, landfills are designed to minimise their movement to protect the environment [15, 19]. Liners and a leachate collection system are installed to prevent leachate from moving to surrounding soil and water while a gas collection system or a landfill cap is installed to hinder the gas from escaping to the air. The system consists of vertical or horizontal wells used to access the gas which can be collected for 7–10 years. Also, its average efficiency is reported to be 70–85% [19]. **Figure 2** shows a typical landfill gas system.

The landfill gas produced contains 45–55% methane and is collected through a system of gas pipes and through combustion it produces electric power by running a gas engine and/or turbine. Also, the gas can be used for cooking in nearby communities, or boiler fuel for district heating and industrial purposes and this is demonstrated in **Figure 3** [6, 19]. The energy potential of landfills across regions ranges from 5 to 40 L/kg of waste depending on the organic composition and has a CV of about 4500 kcal/m^3. Also, it is key that the landfill gas is purified to remove any hazardous chemicals [16, 19]. **Figure 4** shows an example of a landfill recovery site in the UK managed by Viridor. Viridor operates 32 landfill sites in the UK which generate a total of 86 MW of power to supply 50,000 homes with power all year [23].

When landfills reach the maximum capacity, they are closed for replenishment through appropriate engineering designs and the older type is normally deserted [15]. Many disposal sites are poorly operated and stay as open dumps which pose a risk to the environment both in the short- and long-term [13]. Landfills must be closely monitored by the respective municipalities to prevent leakage of the by-products [15].

Figure 2.
Schematic of landfill treatment set-up [20].

Figure 3.
Set-up showing the use of gas recovered from a landfill [21].

3.2 Anaerobic digestion

Anaerobic digestion involves a sequence of biological processes through which biodegradable waste is digested by microorganisms in the absence of free oxygen to generate biogas [6]. The most suitable waste for this technology is organic waste that includes food and agricultural wastes like animal slurries and that the main end product of anaerobic digestion is biogas usually containing 60 and 40% of methane and carbon dioxide, respectively [24]. The composition of waste is comparable to

Figure 4.
Viridor Dunbar, a potential landfill energy recovery facility [22].

what is reported by [25] that is 55–70% for methane and 30–35% for carbon dioxide. Anaerobic digestion has relatively long digestion days ranging from 20 to 40 days [24] and because of this decomposition needs to happen by the action of an enzyme [11]. Other factors that affect the process are pH, temperature (35–38°C), loading rate, mixing rate, and toxic compounds [19]. When food waste is added to the process, the methane quantities will increase, and the process of methane production will speed up [24]. The typical amount of biogas produced usually ranges from 50 to 150 m^3/tonne of wastes and this also depends on the composition of the waste [19]. The plants emit residue gases which comprise nitrous oxides, hydrogen chloride, carbon monoxide, and the total organic carbon [25].

The biogas is used to produce electricity and/or heat with a biogas CHP gas engine. Also, the biogas can be used as a renewable natural gas or in the transportation sector as a fuel. The other product of the process is a nutrient-enriched digestate used as a soil fertiliser [19, 24]. **Figure 5** presents a typical illustration of a biogas plant.

This technology is considered to be environmentally friendly and solves the problem of disposing of the bio-degradable waste [11]. Also, anaerobic digestion is usually used to pre-treat the organic component of waste to reduce its weight, and reduce the

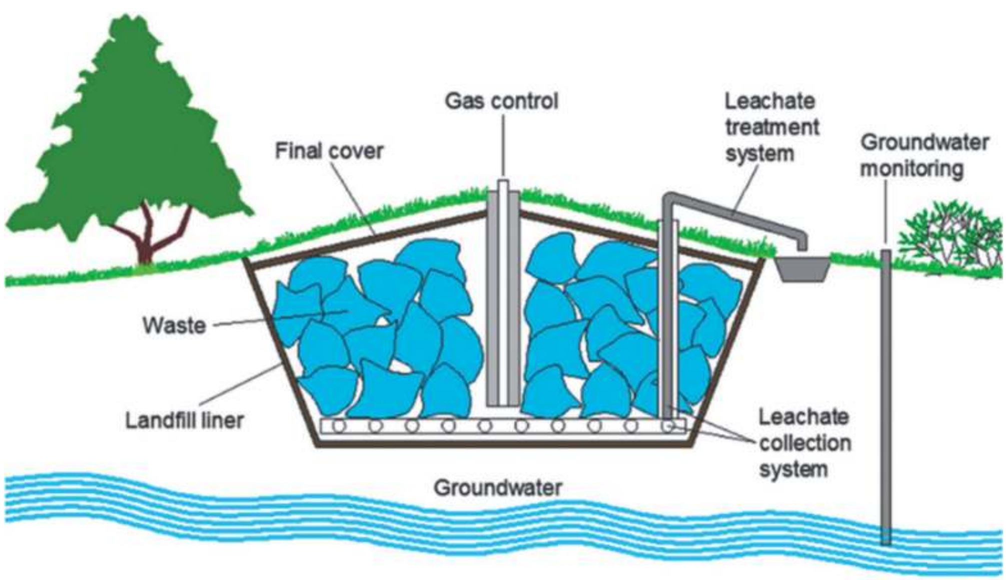

Figure 5.
Schematic of biogas plant [26].

methane and leachate emissions [27]. **Figure 6** shows a biogas plant established in Nakuru, Kenya which uses the crop residues of a farm to generate 2.2 MW of electricity used to cultivate 1740 acres of vegetables and flowers, supplies electricity to up to 6000 rural homes and sells surplus power to the Kenya National Grid [29]. **Figure 7** demonstrates small scale applications of anaerobic digestion in households in India.

3.3 Incineration

Incineration is the regulated burning of solid waste with sufficient oxygen under anaerobic conditions at high temperatures above 850°C to release heat. The process also leads to a high-temperature combustion flue gas consisting of CO_2 and water and bottom ash which consists of minimal amounts of leftover carbon [6, 11].

The waste burned can either be in a raw form that is waste immediately after the first three stages of the waste hierarchy or in a pre-treated for like RDF and for each case the plant configuration changes depending on the feedstock. The energy content of raw residue typically ranges from 8 to 11 MJ/kg and the energy content of the pre-treated feed is typically between 12 and 17 MJ/kg [6]. The higher energy content in RDF is because water, recyclable (metals and glass), and inert materials (stones) are removed leaving the waste with the higher energy content [6, 19]. The other advantage of RDF over raw residue is it provides an opportunity to remove most of the hazardous material that could be harmful when burned [19].

The major importance of incineration is to get rid of problematic waste [31]. Incineration decreases the initial quantity and weight of waste by 90% and by 75%, respectively [31] and this makes it suitable for disposing of waste especially in countries

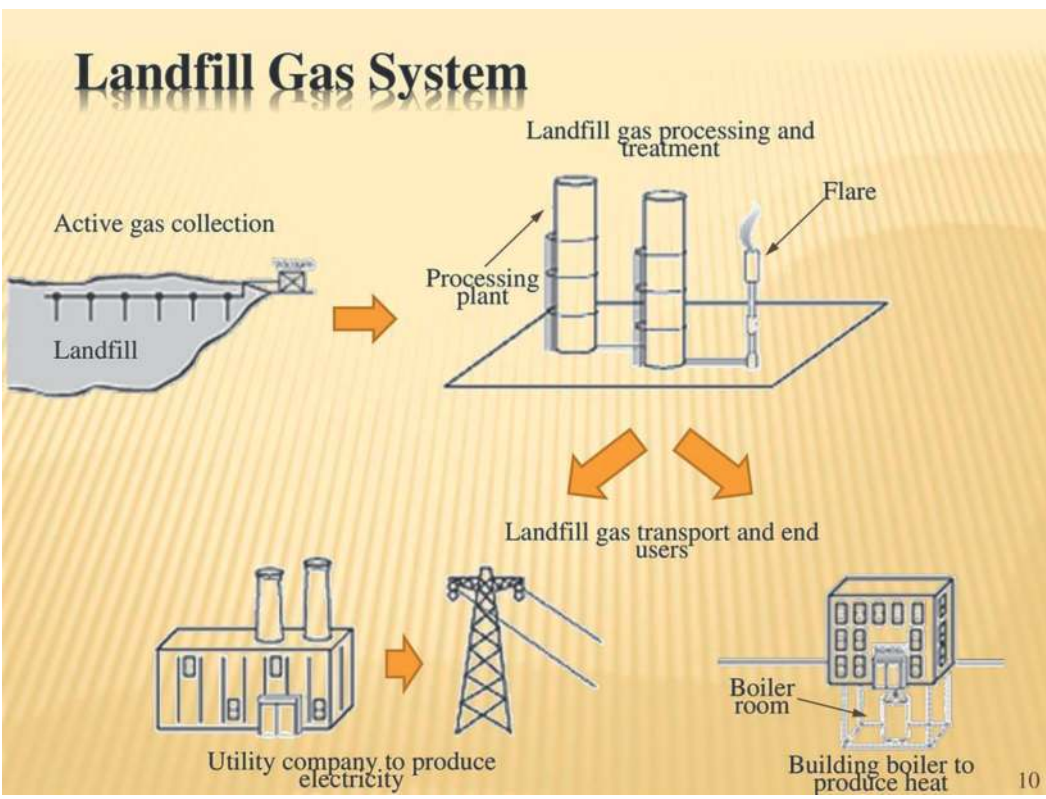

Figure 6.
Gorge Farm Energy Park, Nakuru Kenya [28].

Figure 7.
A family in Maharashtra, India cooking using biogas [30].

that are facing disposal management problems [32]. Typically, 65–80% of the organic waste energy content retrieved as energy. This process uses the combustion heat through a boiler to generate steam. The steam is either applied in steam turbines to produce power and/or used in the heat exchanger technologies to meet heating requirements of an industry or community [6, 19, 24, 33]. A CHP plant that generates heat and/or electricity and is reported to be the most efficient way of recovering energy using a steam boiler [6]. When the incinerator produces heat only, or electricity only, or a combination of both, the efficiency of the plants ranges from 70–80%, 20–25%, and 50–60%, respectively [34]. The choice on whether to produce heat or electricity or both will depend on the needs of the country. The residue bottom ash can be discarded in a landfill or applied as construction material [11]. **Figure 8** demonstrate a CHP incineration plant.

Even though incineration is efficient, the long-term consequences of pollution become evident and suggests the need to improve the fuel compositions, reduce the moisture in the fuel, reduce the sizes of the waste fuel particles, and modify incinerator designs to reduce pollution [24]. The importance of cleaning the flue gas before letting it out in the environment by placing pollution control devices (electrostatic precipitators), or placing an appropriate furnace configuration, or by controlling the combustion process [11]. This flue gas can also be retrieved in the form of energy to generate electricity [24].

Incineration is considered very expensive in terms of capital, and O&M. The process is reported to be more expensive than controlled landfilling and that for the project to economically feasible the energy recovered must be sold. Also, technology is not efficient when the waste composition has low calorific values [33]. **Figure 9** shows a CHP incineration plant in Sweden that handles 700,000 tpa, produces 2174 GWh of heat used in district heating, and 197 GWh of electricity, yearly [36].

3.4 Pyrolysis

Pyrolysis is the thermochemical degradation of organic waste at high temperatures with no oxygen [24, 37, 38]. Also, the process is usually powered by the energy

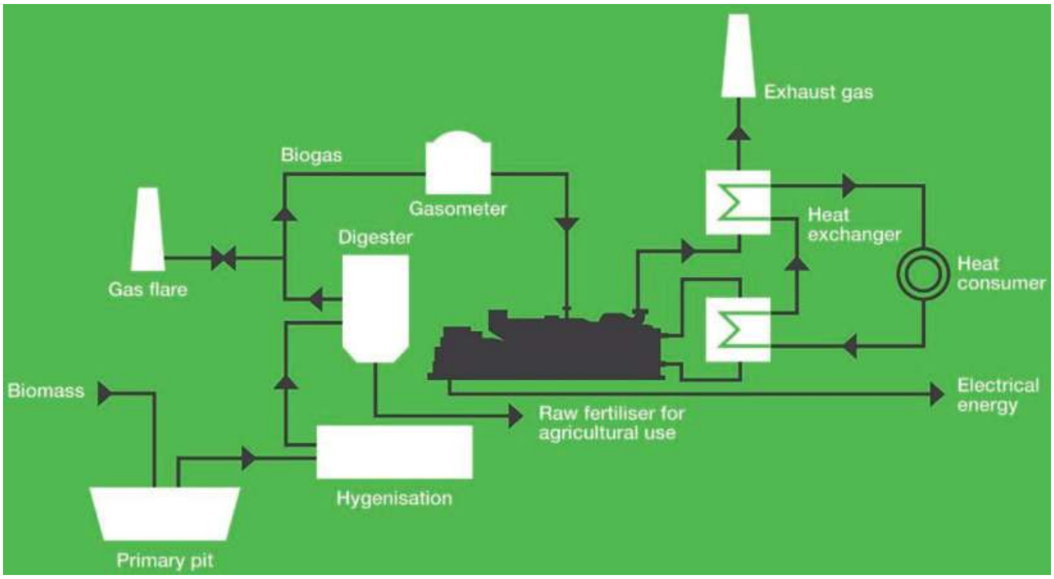

Figure 8.
A schematic illustration of a typical incineration plant [35].

Figure 9.
The Högdalen CHP-plant in Stockholm, Sweden [36].

produced during thermal degradation (endothermic process) [38, 39]. It is reported that the process requires consistent feedstock which limits its commercial-scale applicability from accepting MSW since MSW in its raw form is usually not suitable for pyrolysis and normally would need pre-treatment through mechanical preparation and separation to remove inert materials as well as glass, and metals [6]. However, the process is gaining more attention than incineration because of its ability to use a vast range of industrial and domestic waste and its ability to generate different products

[37]. The by-products are either gases (syngas), liquids (bio-oil), or solids (bio-char) and the process comprises a secondary chamber that where the gases or oils are burned to generate electricity or usable heat [24]. **Figure 10** presents a schematic of pyrolysis plant and the variation in yield depend on parameters such as heating rate, the pyrolytic temperature, and evacuation of the product from the reaction zone [37, 40, 41].

The biochar comprises non-combustible components plus carbon while syngas comprises combustible matter that is CO, H, H_4, and other volatile organic compounds. The bio-oil has high heat value and is used as industrial fuel oil [6, 19]. Also, the products can be a fuel to generate power using gas engines and gas turbines [24]. The CVs for syngas, bio-oil, and biochar range from 10–15 MJ/Nm^3, 15–20 MJ/Nm^3, and 34 MJ/kg, respectively. Even though char's CV is comparable to coal, it is limited by the complex nature of waste which might comprise hazardous elements that pose risk to humans and the environment and care must be taken [37]. Nonetheless, the products are ready to use and specifically, the waste polymers generate the best oil product.

The pyrolysis technology is expensive compared to commercial ways of treatment [24] and the need to pre-treat waste. The pre-treatment devices are expensive and complex [37]. Also, the syngas causes tarring which can easily lead to blockages and operational challenges. Because of this, pyrolysis facilities have been associated with failures and inefficiencies [6]. Failure to sort waste before the process could lead to the production of dangerous nitrogen compounds in the products hence the need gas cleaning devices [37].

Figure 11 shows a pyrolysis plant located in Bulgaria that converts plastic waste into diesel oil [42] and despite the various pilot plants and industrial-scale developments, it is reported [37] the process is still not economically viable.

3.5 Gasification

Gasification is the process through which combustible gas is produced through partially oxidising waste at high temperatures of 800–900°C [24]. Gasification could be considered in-between pyrolysis and combustion because oxygen added neither

Figure 10.
Illustration of the pyrolysis process [38].

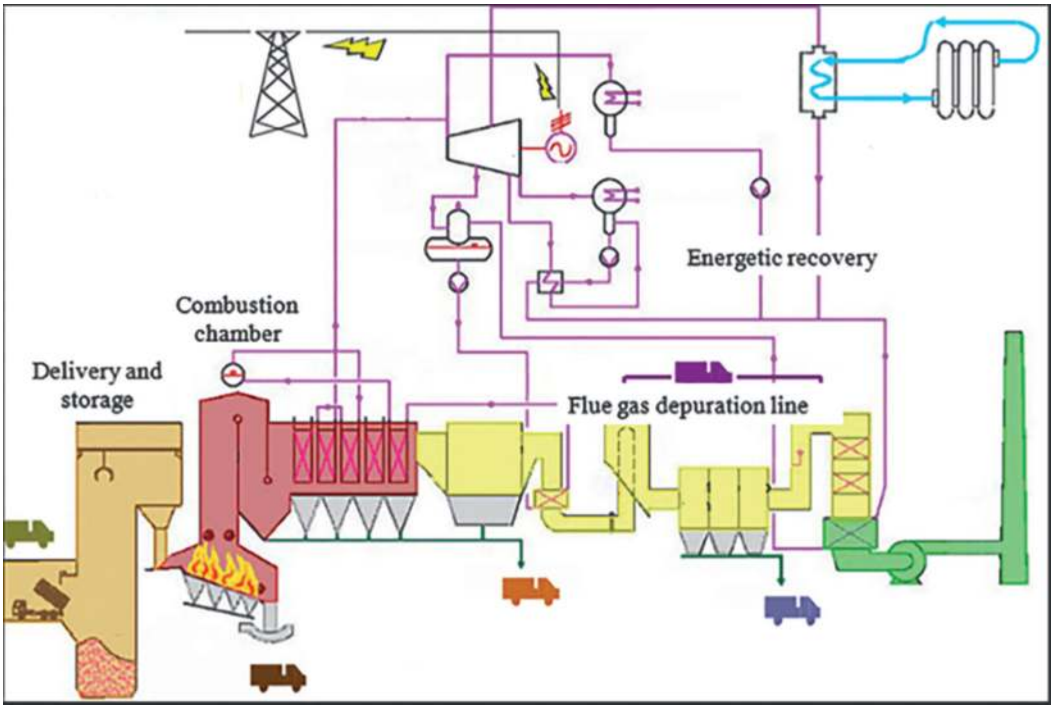

Figure 11.
Huayin plastic to diesel oil plant, Bulgaria [42].

allows full oxidation nor allow full combustion. The gasification process mainly produces its heat however part of the heat is needed to start and continue the process [6]. The gas produced is known as syngas which can be burned to generate heat or in gas engines and gas turbines as a fuel to produce electricity [24]. **Figure 12** illustrates the process of MSW gasification to generate power [43].

The gas generated from gasification is reported to have Net CV varying between 4 and 10 MJ/Nm^3. Another product is a solid residue of ash which is non-combustible and has relatively low levels of carbon [6]. The produced gas can be utilised to generate power using IC engines [19].

The gasification process has advantages of reasonable costs, and flexibility of integrating the working conditions of temperature and equality ratio, and the reactor

Figure 12.
Schematic of MSW gasification to produce power [43].

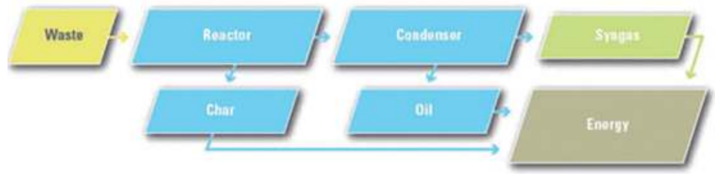

Figure 13.
Waste gasification plant in Lebanon, Tennessee [44].

arrangement to obtain syngas [24]. The process is reported to improve the heating value of gas produced and has lesser quantities of residues compared to incineration and pyrolysis [19].

A report [24] indicates it is associated with the complexity to adapt to various characteristics of different waste and these usually prevent it from commercial applications. The issue is that the source of fuel for gasification will change over time due to variations in waste. Also, MSW in its raw form is usually not suitable for gasification and normally would need pre-treatment through mechanical preparation and separation to remove inert materials as well as glass, and metals [6]. The process suffers disposition of tars that causes blockages leading to operational challenges. This problem has been linked to plants failing and inefficiencies in some pilot and commercial-scale plants. However, it has been observed that when higher temperatures are applied, the tars 'cracks' and generate a relatively clean syngas. The plasma gasification technology is a high-temperature process that is potentially used at different stages in different configurations in the gasification process and the ash generated can be transformed into an inert residue under extremely high-temperature thermal methods. Also, other initiatives are set to ensure that the efficiencies of energy recovery from Gasifiers are maximised by using hydrogen fuel cells and gas engines [6]. **Figure 13** shows a waste gasification plant in Lebanon which has a capacity of 64 tonnes/day to generate 420 kW. The waste (wood and tires) is collected and shredded into 1–3 inches and the sludge is blended on the site as well. The target moisture for post-treated waste is 30% for this specific site [45].

4. Feasibility analysis and the application of the WTE technologies in Uganda

4.1 Uganda's waste generation and management

Uganda's current waste management system involves both the private and public sectors and that the estimated solid waste generation rates for Uganda range between 0.55 and 0.6 kg/person/day [46–48]. The respective generation rates were based on studies done on Kampala district and Mukono district, respectively but this could be comparable to other districts. Further, a study revealed that waste generation rates in Uganda are 0.3 kg/day for low-income homes, and 0.66 kg/day for high-income homes and that the domestic (residential) sector of the country contributes 52% (ref. **Table 1**) of the waste generated [49]. However, this study was carried out from only the 9/15 of urban cities from the political-administrative regions of Uganda.

The different sectors generate mainly organic wastes (food waste) and the dry wastes are the minor forms of waste. Also, the waste composition of the industry sector varies depending on the type and all this data is illustrated in **Table 1** [49]. Results in

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Sector	Contribution by weight	Characteristics
Domestic	52	Majority: food wastes
		Minority: plastics, paper, textiles, glass, ceramic, ashes, leather, compound wastes.
Markets	20	Major: vegetable and fruit waste
		Minor: damaged packaging material like sacks and poly-ethene bags.
Commercial minus markets	8	Major: packaging material, food waste, scrap metal
		Minor: glass, hazardous waste, containers
Institutional	5	Major: food waste and stationery
		Minor: packaging material
Industrial	3	Varies depending on the industry
Health care	1	Major: domestic type
		Minor: hazardous wastes
Others	11	Street sweeping, public park and construction waste.

Table 1.
Waste in Uganda.

Table 1 are relative to a study carried out, by Okot-Okumu [46], to assess waste management in three significant towns in Uganda (Kampala, Jinja, and Lira) which revealed that the biodegradable composition of waste was higher that is 77.2, 78.6, and 68.7%, respectively. Also, a study [50] discovered that Kampala generates up to 28,000 tonnes of waste/month with an organic composition of 92.1% while plastic and paper account for only 5.9%. The reason for the difference could be that the former [46] examined solid waste from its origin to final dumping and was carried out using existing publications and reports while the latter [50] was carried out through sampling, field measurement, and laboratory tests of waste disposed at the Kiteezi landfill in Kampala for a year (July 2011–June 2012) to obtain the chemical composition. Nonetheless, both studies could imply that waste in Uganda mainly comprises of organic waste.

The most sought-after way of collecting waste is when waste producers move their waste to community collection sites such as bunkers or skips, and the waste is taken to landfills by the respective municipalities. In some cases, the private sector waste management companies collect waste from house to house but this is normally at a fee, or the larger institutions and commercial businesses hire the private companies to handle the waste [46]. It was found that communities with bad road access are avoided by collecting trucks which leads to high rates of open dumping as a means of disposal by the waste producers [50]. Also, reports point out that apart from poor road access, unaffordability when a waste collection fee is required is another cause of poor solid management [51]. Most of the urban areas in Uganda have waste released in gardens, along the road, open dumps, and channels. **Figure 14** is an illustration of open dumping in urban areas of Uganda [48]. Open dumping poses environmental and health risks for the respective communities through pollution of soil, and surface water, degradation of the ecosystem as well as GHG emission when the organic waste decomposes [51, 53].

Reports [54] reveal that landfilling is the only authorised form of disposal currently in the country and other forms such as open dumping, uncontrolled

Figure 14.
A display of open dumping in Kampala [52].

burning, relative recycling, and composting which take place at unknown extents. Also, 40–45% of waste generated is gathered and thrown away to the landfills and that 11% is recycled by waste pickers [50, 51, 54]. This is comparable to a report that indicates 50% generated waste is collected. For Kampala city, all the waste collected is usually dumped on one landfill, Kiteezi, which is about 12 km from the city centre [50, 55]. This landfill is a sanitary landfill occupying 0.146 km^2 of land with a leachate treatment system that decreases the biological oxygen before the leachate is discarded to the nearby wetland. Despite this initiative, residents around complain of bad odour, leachate leakages, and increased scattering of wastes by marabou stocks causing their land to lose value. Also, the openness and mismanagement of the landfills cause a problem of air pollution through GHG emissions which pose a health risk [46, 50].

The 2010 audit report for SWM in Kampala credits the inefficiencies in waste management to the lack of awareness which has led to aimless littering and uncontrolled burning of waste [56]. A study [46] points out that the record of waste collected accounts for that which reaches the community collection points and the uncollected waste is not recorded. This could be problem when identifying suitable management techniques due to insufficient waste data.

The mentioned studies are specific to just a few cities in the country with a major focus on the capital city Kampala. However, it is plausible to conclude that majority of waste produced in Uganda comprises organic waste with an overall composition of above 70%. This could also be assumed since the major economic activity is agriculture which is usually associated with organic waste.

A study [46] reports that the majority of the waste is mixed and there is no official structure of sorting waste in the country. Sorting may happen when workers segregate wastes of value on the way to the landfills or at the waste bunkers, road verges, skips, or at the landfills and this is illustrated in **Figure 15**. Most wastes hand-picked are plastics comprising of jerry cans, and bottles as well as cardboard. In some cases, the separation is done only when the producer is looking to reuse the plastic material or glass bottles or use food leftovers as animal feeds [46, 51]. **Figure 16** is an image of plastic bottles collected for recycling.

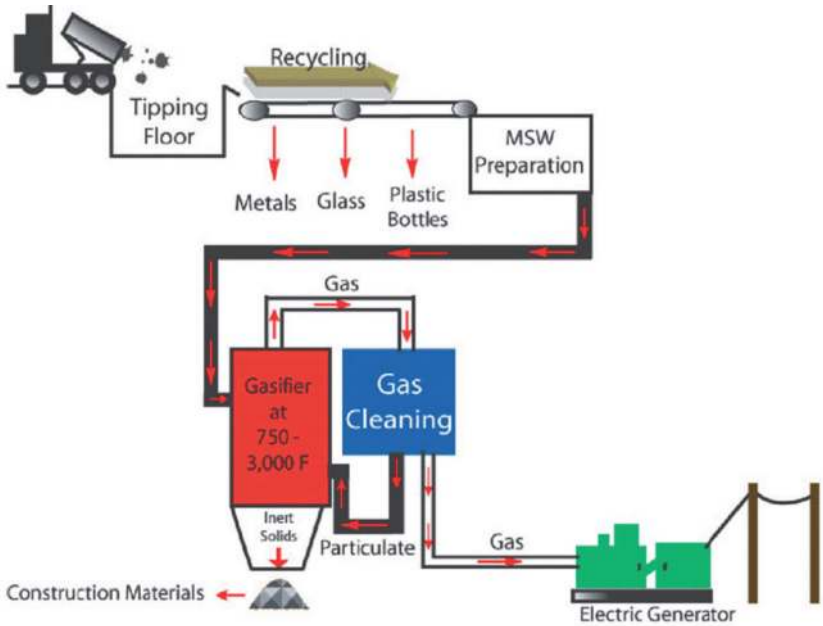

Figure 15.
Waste picker segregating waste at Kiteezi landfill [57].

Figure 16.
Coca-Cola recycling plant at Kyambogo-Kampala Uganda [55].

4.2 Technology capabilities in Uganda

The choice on which technology to adapt depends on the local conditions and energy requirements of the communities and/or sectors of a country. Because of these reasons, the Government of the UK always maintains an attitude of being technology-neutral when promoting private investment unless the technology shows evidence of market failure [7]. Also, knowledge of the organic fraction, calorific value, and chemical composition enables a country to know how best to manage the waste [11].

Therefore, the successful implementation of anaerobic digestion in Uganda would largely depend on waste generated from agriculture and reports that the residential and market sectors generate more than 72% of the waste which largely comprises of food waste. The waste from these sectors has a high moisture content which would accelerate production of biogas.

It would be suitable to meet the energy needs of these market structures while solving the problem of food waste management. Also, in Section 3 it is mentioned that the yield of anaerobic digestion is higher when food waste is fed into the digesters along with MSW could make this technology a reliable source of energy in residential households, and markets in Uganda since they generate mostly food waste. The country could adopt large scale anaerobic digestion like the Gorge anaerobic digestion plant in Kenya highlighted in (Section 3) where the waste from farms is used to generate electricity for farm activities. In the long run, the biogas generated from large scale projects can used in the transportation sector as a source of fuel which could introduce flexi-fuel vehicles that use both petroleum and bio-methane [58].

Regarding WTE incineration, the technology is more efficient when the CV of the waste is high. Uganda's waste has a CV of 6.2 MJ/kg which is below the typical range for raw waste highlighted in Section 3 hence the country could apply the circulating fluidised bed combustion technology which permits waste with low CV. However, this type of incinerator processes lower quantities of waste compared to the grate-based combustion technology. An alternative would be to pre-treat the waste to increase the efficiency of the plant. Overall, the application of incineration would generate electricity that would meet the demands of manufacturing industries and surrounding communities to promote energy security. For example, a similar project like the Reppie plant in Ethiopia could be set up in Uganda to process waste to generate about 20 MW of electricity. Such a project is comparable because Ethiopia is reported to have waste compositions comprising of 60% organic waste [59, 60] which is similar Uganda. Also, this plant has a pre-treatment section to increase the energy content in the waste. Such a plant could process waste from Kampala which is estimated to generate 28,000 tonnes/month ≈ 930 tonnes/day [50]. Such projects could be implemented around the country to reduce the quantity of waste that goes to the landfills and to improve energy security.

In Section 3 it is noted that the incineration plant is more efficient when it generates heat or both heat and power. The heat produced may be wasted since district supply heating systems are not necessary as the country's temperatures are relatively warm throughout the year (26°C [61]) hence household or commercial heating is not required. However, the heat produced can be used for heating processes in nearby factories.

Concerning landfill gas recovery, this technology would require sufficient land to implement. In Section 3 an average landfill site occupies 600 acres but with the current size of Uganda and the high rate of population increase, the application of landfill gas recovery would be affected by shortage of land. Also, the landfill sites would have to be away from the growing cities due to the high rates of urbanisation in the country. Nonetheless, this mechanism would still be applicable in parts of the country that are less populated and have sufficient land. This would however incur costs to transport waste generated to such locations. Comparing landfills and anaerobic digestion, the former generates lower fractions of methane than the latter and so it would be advisable to consider anaerobic digestion.

Turning now to pyrolysis and gasification, Section 3 reveals that the processes are difficult to scale up hence cannot be used for large scale purposes and commercial purposes due to their complexities in fuel requirements. However, these technologies could be adopted by industries, specifically the rotary kiln type of reactor which offers the advantage proper heat transfer allowing it to process waste polymers (plastics) which have low thermal conductivity and generate the best quality oil suitable for industrial purposes. However, Uganda has low generation rates of waste polymers (dry waste) and projections indicate low dry waste generation in the next decade hence such technologies could be unsustainable in the long run.

Regarding waste as a fuel, [7] the waste needs to be appropriate for the technology in question. Reports state that the inadequacy in the supply of feedstock to biogas plants is a barrier to the technologies. This could be comparable to the other technologies [62]. Anaerobic digestion, incineration, and pyrolysis need the waste to be pre-treated through separation, sorting, processing and mixing with additives to optimise efficiency, increase the calorific values, and reduce levels of pollution [31]. In observed that fossil fuel-based wastes emit GHG which contribute to climate change, which is another reason to why waste should be separated. Literature reports that lack of waste separation has led to the failure of large-scale bio-methanation in India [63]. Therefore, Uganda would have inconsistencies in the waste fuel due to lack of separation leading to mixed wastes and this could affect the sustainability in the long run. This will also increase costs incurred by the plants to mechanically treat waste. Nonetheless, these technologies could still be adopted by manufacturing industries in Uganda which are more consistent in the characteristics of waste as per industry, for example, Kakira Sugar factory processes bagasse to produce heat and electricity.

Also, lack of separation could lead to hazardous materials in the waste which pose the risk of generating toxic chemicals in solid and gaseous residues from the processes that are later disposed of. However, Uganda has low levels of industrialisation and it would seem unlikely to have large quantities of harmful material in the waste which could make mechanical separation easier. In addition, Uganda would need to improve her collection efficiencies from 45% to the daily target of 80% to ensure the plants have a consistent supply of fuel. A study [24] claims that when technology can work with inconsistent fuels then it is feasible for such communities and in this case landfill gas recovery would be the most suitable.

Lastly it is noted in Section 3 that the different designs and configurations of anaerobic digestion require the use of water to optimise the digestion of MSW. This is a could be a major problem since reports [53] show that the availability of water is limited in densely populated regions of Uganda and that 76% of Ugandans have water within reach of 1 km. To solve this, the country could focus on using the high solid continuous digestion systems which require little water (Section 3(1)). The supply of biogas is inadequate to meet the needs of a community, they resort to the rudimentary sources of fuel [62]. This concern would be comparable to the other WTE technologies as the choice by beneficiaries to adopt any technology is most likely dependent on reliability.

4.3 Policies review

Regarding consistency, that waste-sorting has a significant effect on the efficiency of all technologies and since Uganda lacks waste separation regulations this will affect the output of the technologies which will in turn affect the revenue flows [64]. The National Environment (Waste Management) Regulations, S.I. No 52/1999 under sections 53(2) and 107 of the National Environment Act, Cap 153 [65], shows no mandate which directs a waste producer to explicitly separate the waste generated according to physical or chemical composition. This causes a problem of delivering mixed waste that makes it hard for plants to have consistency in the physical and chemical composition of waste which could affect the sustainability of plants in the long run. A lot of effort would then be needed to sort waste before extracting the energy and these extra costs may not be attractive to investors. Also, these extra costs may lead to a rise in the cost of electricity purchased by the customers. To mitigate these, the GOU could enforce some of the UK's policies (**Table 2**) to enhance better SWM. Also, awareness campaigns through media platforms and community focus groups can help solve the problem of waste segregation to improve the efficiency of WTE initiatives [62].

	Policy	Impact
1	Keep waste at minimum through prevention, recycling, or recovery through policies like placing charges on carrier bags has pushed for recycling within communities	This could prevent WTE from competing with recycling
		It could lessen the volume of waste sent to landfills
2	Store waste securely, use suitable containers to avoid leakages, ensure containers are waterproof. Containers must be labelled clearly to indicate the type of waste contained.	This will enhance waste separation allowing WTE technologies to have consistent fuels
		Promotes consistency in waste fuels and eases the mechanical separation of the WTE plants
3	Store different types of waste separately to avoid contamination, and to permit reuse and recovery	This will enhance waste separation allowing WTE technologies to have consistent fuels
4	Waste producer must classify their waste to the waste contractor before sending it for disposal or recycling	Promotes consistency in the waste fuels and eases the mechanical separation at WTE plants
5	It is illicit to mix hazardous and non-hazardous waste and there are guidelines to enable a waste producer to identify the types.	Mitigates the pollution that would arise
		Protects the environment from harmful substances
6	The Government of the UK provides a platform to report fly-tipping (illegal waste dumping). In Northern Ireland, it is required to report a waste producer who intentionally labels waste inappropriately. Also, the law permits reporting littering along local streets	Reduce open dumping
		Ensures that all waste is collected appropriately allowing plants to have enough waste fuel
7	For an operator to carry out waste treatment, some rules and regulations that must be followed to protect the environment	Ensures all waste is collected appropriately allowing plants to have enough waste fuel
		Ensures pollution control systems are in place

Table 2.
A review of some of the UK's waste management regulations [66].

5. Recommendations for further research

A limitation of this study is the lack of sufficient data on SWM in Uganda. The research has identified that little effort has been directed towards the implementation of WTE in Uganda as most studies have been focused on the waste generation and composition and specific to just a few major cities in the country. Another limitation is that majority of the data is not up to date. Greater efforts are needed to ensure that more resources are directed towards SWM studies all over the country with a special emphasis on promoting designs and programs to mitigate the weaknesses in the system as a way of easing the work of potential developers.

An alternative area of research could be a case when the GOU partly or fully finances the projects to waive the financial burden on the citizens. With this, the government could register the projects under CDM and gain carbon credits that can be sold to the open market. Also, such projects would be associated with job creation, improved energy security, and reduced deforestation. It is important to realise that the economics and environmental benefits could be difficult to evaluate by the GOU however success in SWM by a municipality was noted as a guarantee to thrive in other sectors.

6. Conclusion

The purpose of this chapter was to evaluate how and why Uganda could adopt WTE technologies to reduce waste volumes. The continual increase in the waste generation rate is evidence that there is a need for Uganda to assess different waste management techniques. The proposed WTE techniques are landfill gas recovery, anaerobic digestion, incineration, pyrolysis, and gasification, and the following are the observations.

Firstly, all WTE technologies are applicable in Uganda because the different sectors differ in energy needs. From this, the GOU needs to remain technologically neutral when promoting WTE. Anaerobic digestion would be the most reliable since most of the waste in Uganda is organic waste mainly from agricultural activities. It is also feasible in residential homes on a small scale to meet heating and cooking needs and in turn, would reduce the use of wood fuels which are associated with health risks and deforestation. Incineration is also considered but because of the reported low CV of Uganda's waste, such a plant would need to pre-treat the waste to increase the CV. Gasification and pyrolysis are noted to be more advanced and better in terms of the products but difficult to scale up due to the technological limitations and their complexity in adapting to inconsistent waste. However, pyrolysis and gasification could be applicable in industries to improve energy security and reduce the demand on the national grid. Landfill gas recovery could be applied at any abandoned site, but it would be limited by a shortage of land near the cities especially with the growing populations. Also, the by-products like biogas and bio-oil could be adopted in the transportation sector in the long run. This would reduce the country's dependency on imported fuels.

Secondly, it is noted that the sustainability of these technologies is greatly affected by the composition of waste as a fuel and the waste must be consistent in physical and chemical composition. Consistency can be guaranteed when Uganda improves waste collection techniques by enforcing the proposed laws and regulations that promote waste separation and efficient waste collection. This would also ensure that WTE plants have enough waste to maximise efficiency. Also, the separation of waste is key in limiting pollution associated with the thermo-chemical processes since it enables the removal of hazardous material.

Finally, WTE must not rival prevention, recycling, and reuse but should complement them when the possibilities are exhausted. This could in turn decrease the amount of waste taken to the landfills. Also, WTE initiatives should not be used as an excuse to generate waste. The country could adopt the waste management hierarchy through awareness programs and enforcing laws and regulations to impact people's behaviours and attitudes leading to reduced quantities of waste generated, to mitigate the issue of open dumping and other associated issues rising from poor waste management.

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