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Anaerobic digestion of organic waste: A kitchen waste case study

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ANAEROBIC DIGESTION OF ORGANIC WASTE: A KITCHEN WASTE CASE STUDY

A Thesis Submitted to

Center for Sustainable Development

in partial fulfillment of the requirements for

the degree of Master of Science in Sustainable Development

by

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Dedication

To my family

I would like to dedicate this thesis and all my life achievements to this stage, to my beloved parents, Mr. Bayiga Richard Francis and Mrs. Nakisendo Gloria. Without their immeasurable love, efforts, support and care, I wouldn't have made it this far. I am eternally indebted to them.

I also would like to express my sincere gratitude to my dear brothers and sisters for their continued guidance throughout the course of my research.

Last, but never the least, I am eternally indebted to my soul mate, best friend and best counsel, Luzige Shaima for her encouragement. Thank you for believing in me, being with me through this journey and for being proud of my achievements. Thank you for your love and patience.

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Abstract.

Rapid population growth, urbanization, improved living standards and a shift in the consumption patterns have accordingly escalated the intensity of waste generation. The 2012 World Bank report on solid waste estimated the annual municipal solid waste generation at 1.3 billion tons per year with a projection of over a 40% increase in the annual generation rate by 2025 and a 300% increase by 2100 worldwide. Nearly half of the generated municipal solid waste is organic, including food wastes. About 30% of the food produced annually is wasted at different stages along the food supply chain before human consumption. Kitchens serving the food needs of The American University in Cairo's New campus haven't performed any different in their yield of food waste, with on campus kitchens producing up to 150kg of food waste, mainly a composition of fruit and vegetable waste daily.

Agricultural development mainly driven by extensive mechanization, continued incentivization and growing demand for food on the other hand is also a significant organic waste generator. Recent data estimates the annual production of agricultural waste at close to 1000 million tons. Animal and poultry wastes in form of manure have been reported by different researchers for their negative environmental impacts resulting from their direct application in agriculture or mismanagement, raising concern over possible alternative means of sustainable management. Anaerobic digestion stands out as the most viable means of sustainable management thanks to the high moisture content and nutrient composition of the manures.

This study carried out in two phases aimed at investigating anaerobic digestion of the American University in Cairo's kitchen waste, market vegetable waste and animal and chicken manure. In Phase I of the experiment, batch setups of 100% animal manure (A), 100% chicken manure (B), 1:1 animal to chicken manure (C) and 1:4 animal to market vegetable waste (D) were digested for nine weeks. Biogas yield at the end of digestion was 285.33L, 300.54L, 329.95L and 0.00L respectively. Average methane composition in digesters A, B and C was 43.54%, 52.59% and 45.58% respectively.

Phase II of the experiment was exclusive to The American University in Cairo's kitchen waste. Three batch set ups; KW1, KW2 and KW3 of uniform amounts of kitchen waste were prepared. KW1 was inoculated with digested animal manure from A, KW2 with digested chicken manure

from B and KW3 inoculated with Chinese bokashi. Results of accumulated biogas yield at the end of a six weeks' psychrophilic digestion period were in the order KW2 > KW3 > KW1; 498.64L, 284.58L, and 65.54L respectively. Average methane composition was 41.63%, 40.33% and 25.55% in KW3, KW2 and KW1 respectively.

Following confirmation of the biological feasibility of anaerobic digestion of the University's kitchen waste, technical and economic studies make the project even a more daring venture for the university's engagement. A biogas production project satisfactorily blends into the university's sustainability goals with the potential to offset up to an equivalent of over 4% of the CO_2 emissions from the combustion of natural gas for on campus domestic and lab purposes. The many strengths and opportunities listed in the SWOT analysis of the project make it a viable step towards sustainable development. However, the noted weaknesses and threats demand for close collaboration of the University's offices overseeing food services, campus sustainability, landscape, and facilities and operation with technical help from the Center for Sustainable Development and the Research Institute for a Sustainable Environment if the project is to come to life.

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Glossary of Words

Ammonia nitrogen

A parameter used to express the amount of ammonia present in the organic waste sample. Ammonia is produced from the digestion of protein containing compounds such as proteins and lipids. When certain levels of concentration are exceeded, ammonia inhibits anaerobic digestion.

Anaerobic bacteria

A consortia of bacteria that breakdown organic materials under oxygen-free environments to produce biogas.

Anaerobic digester

An enclosed vessel/container/tank with the connected accessories designed specifically to contain organic materials undergoing anaerobic digestion. The digester provides an oxygen-free atmosphere, a constant temperature and other conditions optimal for microbial activity.

Anaerobic digestion (AD)

A biological process where anaerobic microbes breakdown organic material in the absence of oxygen. Biogas is produced a by-product of the process.

Animal manure (AM)

Organic matter derived from a combination of animal feces and urine that can be used as an organic fertilizer in agriculture and a feedstock in anaerobic digestion.

Batch digestion

An anaerobic digestion process where biomass is added to digester once at the start of the process and the digester sealed for the whole duration of the anaerobic degradation process. Biogas production is not constant.

Biogas

A mixture of gases produced from the anaerobic digestion of organic matter. Main components of the gas are methane and carbon dioxide present in ranges of 60 – 80% and 30 – 40% respectively.

Carbon to nitrogen ratio (C/N)

The relation between organic carbon and nitrogen essential for anaerobic digestion and biogas production. A C/N ratio of 20 – 30:1 is generally considered optimum for biogas production where other conditions are in their favorable ranges.

Chicken/poultry manure (CM)

Organic matter, a combination of chicken feces and urine used as an organic fertilizer in agriculture and in this case as an anaerobic digestion substrate.

Co-digestion

The anaerobic digestion of more than one organic materials together in the same digester. The practice increases digestion efficiency, biogas yield and methane content in the biogas

Composting

Microbial breakdown of organic material in the presence of oxygen to produce compost. Compost is used as an organic fertilizer and soil amendment in agriculture and landscape applications.

Continuous flow digestion

An anaerobic digestion process where biomass is either continually added to the digester or added at different stages of the process. There is continuous biogas production.

Digestate

Effluent material remaining after completion of the anaerobic digestion process. Digestate can be applied on agricultural lands as an organic fertilizer or further processed to extract humic and fulvic substances.

Effective Microorganisms (EM)

A mixed culture of fermentative, soil-based, beneficial micro-organisms which can be applied in many environments to break down organic matter

Feedstock material

Organic material in a liquid or solid state with biogas production potential fed to the digester.

Greenhouse gases (GHGs)

A combination of gases that are responsible for the greenhouse effect by absorbing infrared radiations. Carbon dioxide and methane are examples of GHGs

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Hydraulic Retention Time (HRT)
The amount of time that an anaerobic digestion feedstock material stays inside the digester. HRT

depends on the volume of the digester and volume of feedstock material.

Hydrolysis
Breakdown of complex organic compounds such as carbohydrates, fats and proteins into simpler

soluble molecules due to reaction with water.

Kitchen waste (KW)
Left over organic matter from cooking activities in kitchens in restaurants, households and

hotels. In this study, vegetable residues from local markets were also classified under KW.

Mesophilic digestion
Anaerobic digestion under temperature conditions between 20 and 45^0C

Organic carbon
The amount of carbon existing in different organic forms found in an organic compound

Organic loading rates (OLR)
Amount of organic matter added to the digester every day, expressed in Kg VS/m^3/day

Psychrophilic digestion
Anaerobic digestion under temperature conditions less than 20^0C

Slurry
The digestate.

Thermophilic digestion
Anaerobic digestion under temperature conditions between 45 and 55^0C

Total nitrogen (TN)
Sum total of all the forms of nitrogen present in the sample; including nitrate, organic and

ammonia nitrogen. Nitrogen is an essential nutrient required for microbial activity.

Total solids (TS)
Weight of dry matter in present in an AD feedstock material.

Volatile Fatty Acids (VFA)

A group of acids; acetic acid, propionic acid, butyric and valeric acid produced as intermediate compounds during anaerobic digestion. VFA concentration in the optimal amounts increases biogas yield, however, over accumulation inhibits the process.

Volatile solids (VS)

Portion of organic solids in the digestion raw material that can be anaerobically broken down to produce biogas. VS are lost when sample is incubated at 550^0C.

Chapter 1

INTRODUCTION

Rapid population growth, urbanization, improved living standards and a shift in the consumption patterns have accordingly escalated the intensity of waste generation. The 2012 World Bank report on solid waste estimated the annual municipal solid waste generation at 1.3 billion tons per year with a projection of over a 40% increase in the annual generation rate by 2025 (Hoornweg & Perinaz, 2012) and a 300% increase by 2100 (Hoornweg et al.,2013). The report also showed that 46% of the global solid waste generated in 2009 was organic. In this study, organic municipal solid waste (OMSW) is used as a point of reference to reflect the food waste generation.

OMSW is that biodegradable portion of municipal solid waste. Based on the composition of OMSW, different countries have adopted different definitions; for example, the United States of America defines OMSW as a composition of food, garden waste and paper, whereas by OMSW, Europe refers to waste from parks, gardens and kitchens (Campuzano & González, 2016). In general, OMSW has been used to refer to food waste from kitchens, cafeterias, institutional lunch rooms, and markets. Composition and quantity of OMSW varies between countries, geographical regions, cultures, seasons of the year, food habits, social and economic status of the population, and the social and economic activities in the region among others.

Food waste, which forms part of the organic portion of municipal solid waste has also followed an incremental trend through the years. About 30% of the food produced annually is wasted at different stages along the food supply chain before human consumption, resulting from inefficiencies in harvesting, storage, packing houses, transportation, marketing constraints, and weaknesses in the prevailing institutional and legal frameworks (FAO, 2017). The United States generate over 38 million tons of food waste annually. Only 5% of the waste is recycled through composting, 76% is landfilled with no record of the quantity of food waste recycled through anaerobic digestion (EPA, 2016). China generates almost three times the amount of food waste generated by the United States of America (over 90 million tons) (EPA, 2016). In the European

union, besides the health and environmental hazards associated with the close to 88 million tons of food wasted annually, a huge economic cost of close to 1.5 billion euros is faced in managing food wastage (Stenmarck et al., 2016).

According to (Gustavsson et al., 2011) causes of food wastage differ among countries, their levels of development and consequently standards of living. Among the causes studied are; excess production than demanded, premature harvesting common in developing countries, poor post-harvest food handling infrastructure, absence of food processing facilities and poorly established marketing systems among others. These causes can respectively be remedied through establishment of good communication channels among famers to reduce excess production, organizing farmers and setting in place initiatives to enable them upscale their production, prioritization of transportation and post-harvest food handling infrastructural development and establishment of farmer cooperatives along with improvement of marketing channels (Gustavsson et al., 2011).

Food wastage at the different stages along the food supply chain differs. Taking Sub-Saharan Africa, North Africa, West and Central Asia as examples, food wastage at the different stages of the supply chain of fruits and vegetables is illustrated in the figure 1.1 below. From the figure, most of the wastage in Sub-Saharan Africa is during processing, possibly due to poor processing facilities. Whereas in North Africa, West and Central Asia, wastage during agricultural production is dominant. This loss could be associated with the post-harvest grading of the fruits and vegetables to meet retailer quality standards.
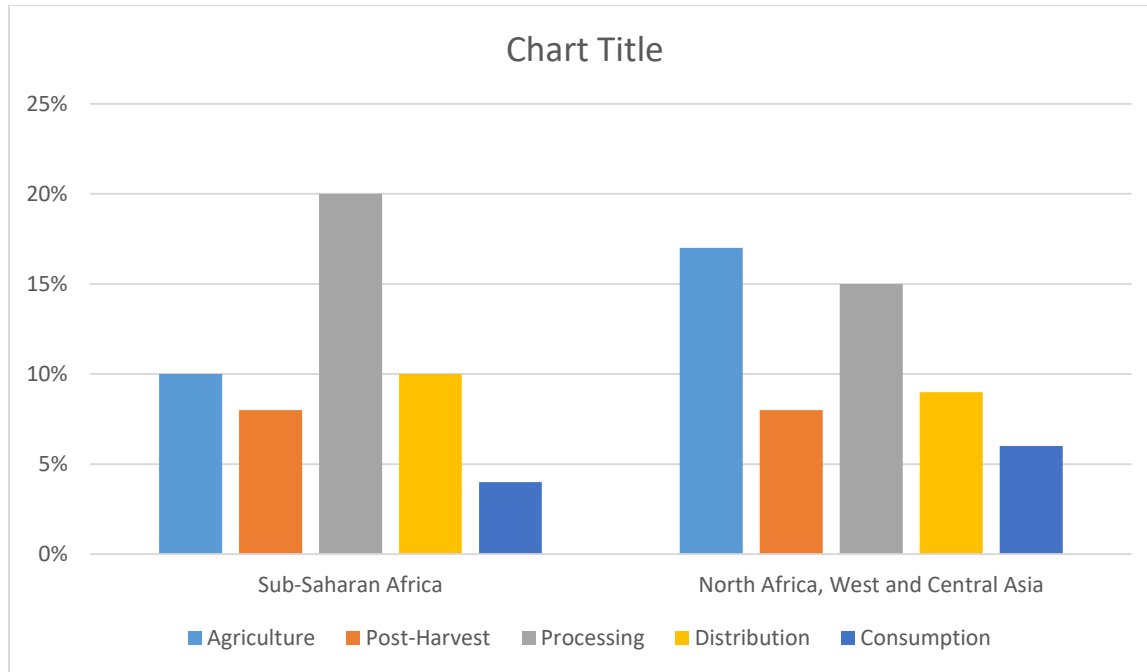
Figure 1. 1: Part of the initial fruits and vegetables production wasted at different supply chain stages in Sub-Saharan Africa, North Africa, the West and Central Asia. Extracted from (Gustavsson et al., 2011).

Food waste as a subset of OMSW contributes to about 15% of the total load of generated municipal solid waste (MSW) in the United States ("Municipal Solid Waste Factsheet," 2016). Making it the second largest municipal solid waste stream after paper (figure 1.2). Through time, a number of technologies have evolved targeting the diversion of food waste from landfill, to recover and utilize this precious resource for other applications. The most common of technologies include composting (nutrient recovery), anaerobic digestion (renewable energy production) and further processing into animal feed.
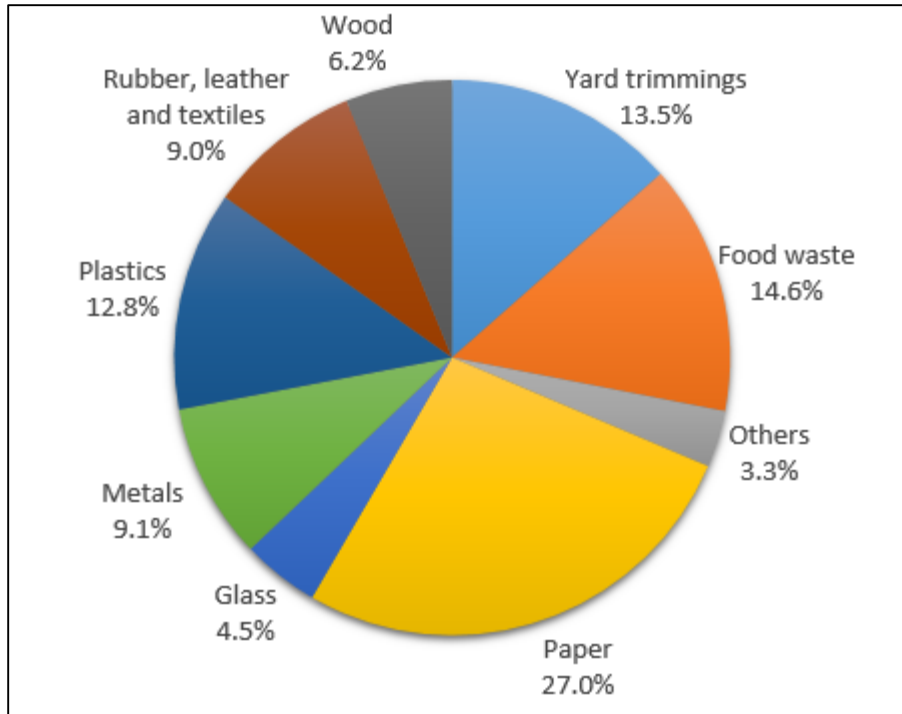
Figure 1. 2: U.S. Annual municipal solid waste composition 2013 ("Municipal Solid Waste Factsheet," 2016)

With the recovery technologies in place and of course the allocation of incentives to waste sustainable management, significant reductions have been recorded in the tonnage of OMSW and all forms of MSW in general being sent to landfill in different parts of the world. Taking the United States as an example, data collected from the state of Washington (figure 1.3) shows the progressive increase in the amount of organic materials being successfully recycled and diverted from landfills. Food waste being part of these organic materials, it goes without saying that the same fate directly applies to food waste as well.

The interest in finding sustainable OMSW management solutions among researchers and policy makers has increased in recent years because of the high risk of the possible environmental impacts that can result from its poor management. The high moisture content and ease of biodegradation characteristic to OMSW account for its adverse environmental impacts in landfills. These impacts include ground water contamination from the leachate, volatile organic compounds produced from the waste, climate change, toxic odors and fires (Alibardi & Cossu, 2015). As a result, different diversion channels have been created to tap into the numerous

benefits in sustainable management of OMSW without sending it to traditional landfills. Anaerobic digestion falls into one of these many channels that have been designed.
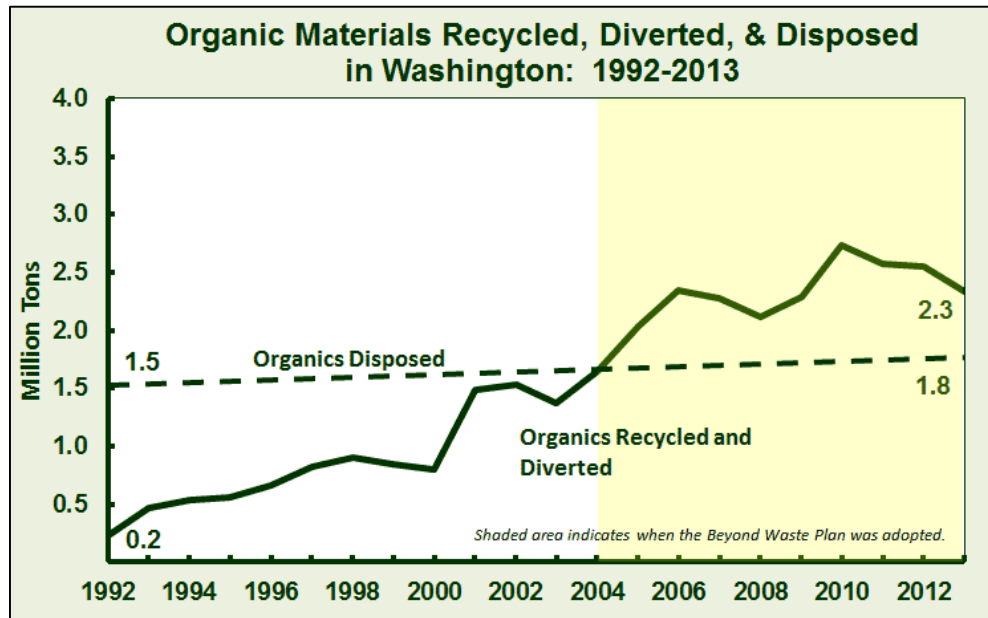
Figure 1. 3: Organic materials recycled, diverted and disposed in Washington between 1992 and 2013 (Newman, 2016)

In this study, kitchen or food waste is generically used to refer to all uneaten food (parts) that is discarded as waste during domestic food preparation for consumption. Sources of kitchen waste are not restricted to residential streams but rather include all food waste from restaurants, commercial and institutional cafeterias and lunchrooms. It is however important to note that food waste from different sources varies in its composition and characteristics. In many regions, composition of the generated kitchen waste is a function of the existent food habits, season of the year, culture, social class, type of diet and other related demographic factors.

Without prior separation, kitchen waste is a composition of both organic and inorganic (biodegradable and non-biodegradable) waste materials. Unsorted food waste contains plastics, glass ware, spoilt foods, fruit and vegetable skin, peels and trimmings, rotten fruits and vegetables, bones, egg-shells, teabags, bread and other pastries, oils, cooked and uncooked meat, leftover food, tissue paper, packing materials, and water among others (Ramzan, et al., 2010). This study focused on kitchen waste from two different sources; vegetable waste collected from a local market and fruit and vegetable waste collected from kitchens on The American University in Cairo (AUC) New Cairo campus.

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1.1. Agricultural organic waste

On the other hand, due to the extensive mechanization, continued incentivization of the sector and growing demand for food which have fueled the global agricultural intensity, the agricultural sector has emerged a relatively large generator of waste materials. In many developing countries, agriculture is among, if not the largest contributor of any resource sector to the countries' economy. Agricultural development is credited for increasing the economic development of developing countries (UNEP, 2009). As developing countries struggle to leap to better living standards, it is very likely that farming systems in these countries will be intensified. At this level significant increases in agricultural waste generation will be far from avoidable. Recent data estimates the annual production of agricultural waste at close to 1000 million tons (Agamuthu, 2009).

Agricultural waste is a general term used to refer to organic and inorganic byproducts of the different farming activities taking place on agricultural farms (Ashworth and Pablo., 2009). On-farm activities entail although are not limited to dairy farming, field crop production, horticulture, nursery production, crop and livestock breeding, seed growing, market gardens, aquaculture and woodlands. Byproducts of agro-based industries are also categorized under agricultural waste. Typically, agricultural waste comprises of; wet organic matter (food waste, sludge), dry organic matter (wood and straw), inert material (sand and soil), recyclable materials (plastic, glass, paper, and metal), and hazardous material (chemicals, asbestos). The hazardous part of agricultural waste is mainly due to surface runoff of pesticides and chemical fertilizers during rains and drifts during application. Therefore, the careful handling and management of agricultural based waste needs to be sustainably addressed to protect the environment and to save the neighboring societies from pollution and irritating odors stemming from rotting organic waste. It is worth noting that the nature of waste generated varies from one agricultural activity to another.

1.1.1. Classification of agricultural waste

The agricultural industry, being a vast industrial sector, is associated with almost all types of waste. Common examples of waste as shown in Table 1-1 can be generated from farming activities. From the table, it is evident that agricultural waste comprises not only the organic residues of farming, but also municipal waste and other types of waste related to the processing

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industry. The table also provides an overview of the conventional disposal methods of different types of agricultural waste. Based on this and other criteria, agricultural waste is further classified into hazardous and nonhazardous waste.

Hazardous agricultural waste is any sort of waste generated directly from agriculture or related activities that may pose a potential threat to public or environmental health (US EPA, 2016). Hazardous waste has the uniqueness that it requires special treatments before being disposed of. This pre-treatment is intended to reduce their harmful environmental effects, i.e. they require special disposal methods. Common agricultural hazardous wastes result from fertilizer run-off, pesticide drift and runoff, dust from both soil and dried manures, and livestock manure. Careful management of hazardous wastes is imperative given the many streams through which such waste can make its way into the ecosystem, for example; pesticides from crop fields can reach water streams in a number of ways, which include drifting during their application and runoff due to rains through soil erosion and leaching into the ground water supplies.

Pesticides are poisons by nature that affect insects and animals, and their intrusion into domestic water sources may cause serious health and environment damages. The US Department of agriculture points out that manure runoff from agricultural fields contributes to food-borne disease outbreaks when food crop fields are polluted by animal waste. Similar to manure, fertilizers may have devastating consequences on the environment and human health if not used in the appropriate quantities, especially regarding its concentration of phosphorous and nitrogen (Harmel et al., 2009). Fertilizer runoff, according to the North Carolina State University contributes to aquatic dead zones through eutrophication processes. Nonhazardous agricultural waste, on the other hand, includes types of waste that are not defined as injurious or of potential threat to human life and the environment. This research focuses on the non-hazardous part of agricultural waste.

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Table 1- 1: General characteristics of agricultural waste and methods of disposal (Loehr, 1978)

Agricultural activity	Type of solid waste generated	Common method of solid waste disposal	Pertinent components in the solid waste
Crop production and harvest	Straw Stover	Land application Plowing under the soil Burning	Biodegradable organics Bacteria, Residues of fertilizers and pesticides.
Grain processing	Biological sludge Spilled grains	Animal feeds Byproduct recovery Landfills	Biodegradable organics, Residues of fertilizers and pesticides
Fruit and vegetable processing	Biological sludge Trimmings, Soil, Seeds, peels, leaves &stems	Landfills, animal feeds, land application, burning	Biodegradable organics, bacteria, nutrients, salts, pesticides, Residues of fertilizers and pesticides
Sugar processing (sugar canes, sugar beet, cane sugar refining)	Biological sludge, bagasse, soil, pulp, lime, mud	Composting, animal feed, burning, landfill	Biodegradable organics, bacteria, nutrients
Animal production	Manures	Land application, processed feeds	Biodegradable organics, nutrients, bacteria, salts, medicinal, inorganic additives e.g. Copper
Dairy product processing	Biological sludge	Landfill, land spreading	Biodegradable organics
Meat processing	Biological sludge, feathers,	Rendering, byproduct recovery, landfill	Biodegradable organics, nitrogen, bacteria,

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Agricultural activity	Type of solid waste generated	Common method of solid waste disposal	Pertinent components in the solid waste
	product trimmings, hides, bones, grease		chlorides
Leather tanning	Fleshings, hair, raw and tanned hide trimmings, lime and chrome sludge, biological sludge, grease	Rendering, byproduct recovery, landfill, land spreading	Biodegradable organics, chromium grease, tannins, sulphide, nitrogen, bacteria, chlorides
Timber production	Branches, leaves, small trees	Left in place, burned in place, crushed	Slowly biodegradable organics
Wood processing	Bark, sawdust, small pieces	Burned, pulp, particle boards, landfill	Slowly biodegradable organics

1.1.2. Agricultural waste in Egypt

As is the case in many other countries of the world, rapid population increase, urbanization, industrialization and improved standards of living in Egypt have changed the country's consumption patterns and have consequently led to an increased demand for agricultural products. In addition, a considerable number of industries in Egypt are agriculture based, which is reflected in the percentage of workforce employed in agriculture, estimated at 27%, (Fadl, 2015). This percentage of workforce is the highest among all industrial sectors in Egypt. Consequentially, there are escalations in the amounts of agricultural solid waste generated in the country annually. According to a report by the Ministry of State for Local Development, MoLD, in 2010 (Zaki et al., 2013), of the approximately 95 million tons of solid waste generated in the

country, agricultural waste came second after construction and demolition waste. Agricultural waste accounted for over a third of the generated solid waste as shown in figure 1.4 below.
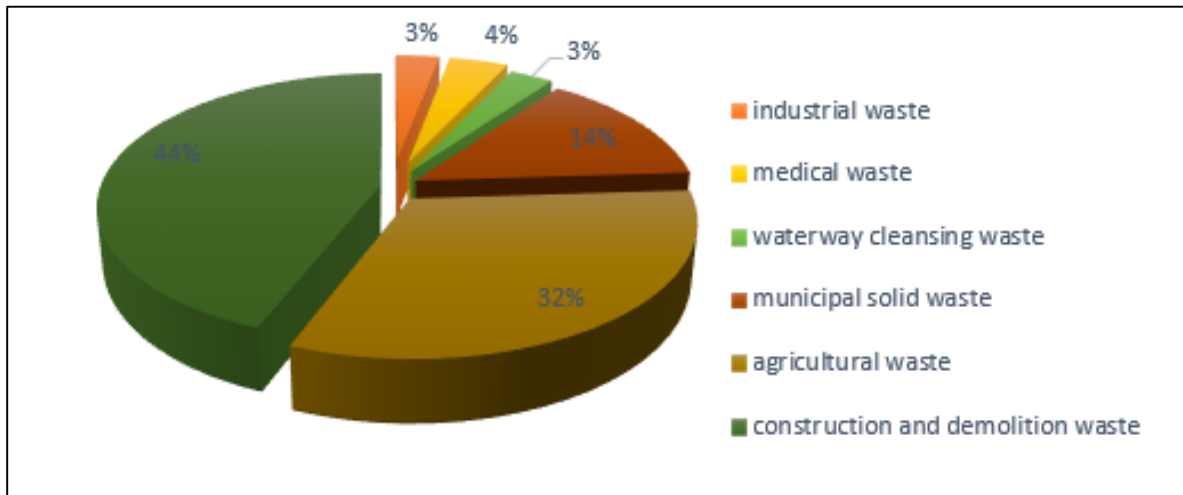
Figure 1. 4: Generated solid waste in Egypt, 2010 (Zaki et al., 2013)
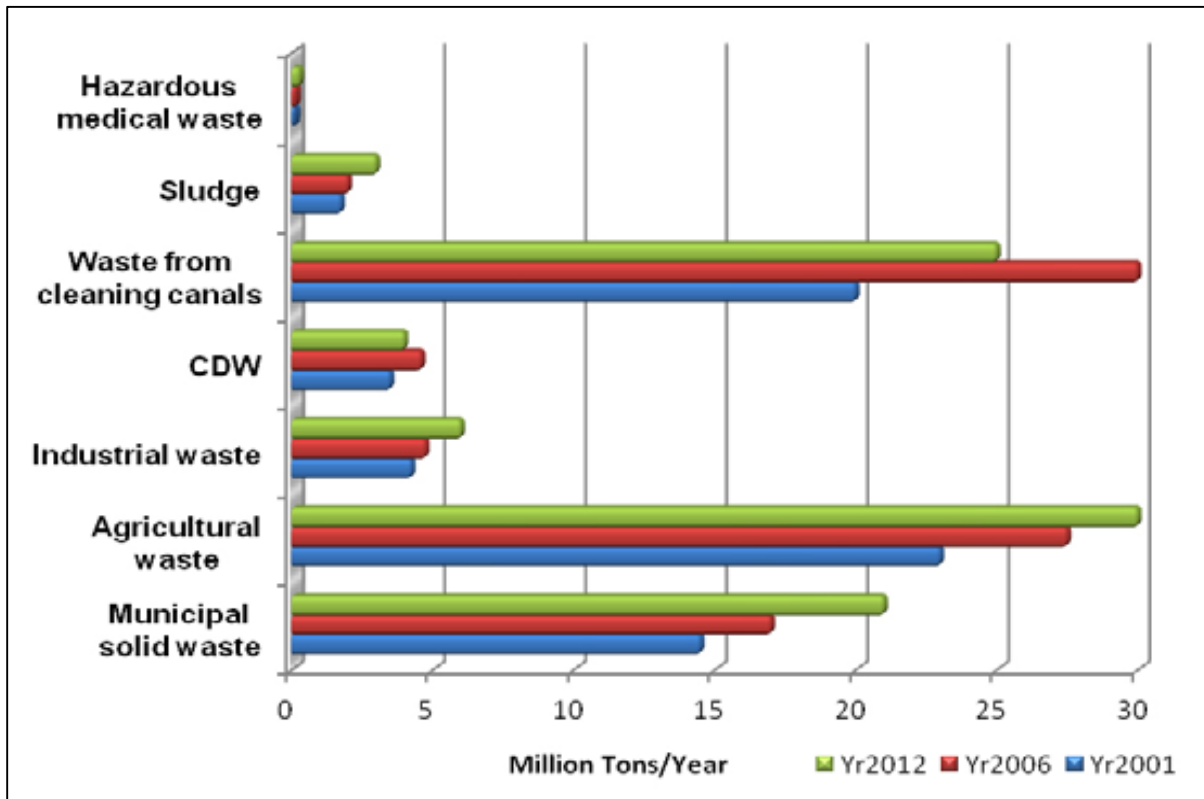
Figure 1. 5: Generated solid waste in Egypt, 2001, 2006 and 2012, EEAA. (Zaki et al., 2013)

The Egyptian Environmental Affairs Agency (EAA) reports an increase of over 30% e in the amount of agricultural waste generated over the years from 2001 to 2012, as indicated in figure

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1.5. The current devastatingly high amounts of agricultural waste in Egypt are a consequence of both the introduction and increased use of artificially synthesized materials that are not biodegradable, as well as the lack of sustainable management practices for the waste.

Agricultural waste continues to increase in Egypt for many other reasons. First, the government intervention in waste management is still low, which leaves the whole responsibility to individual farmers to manage their waste. Secondly, there is inadequacy in the required machinery to handle and prepare the crop residues. Thirdly, there is lack of awareness on the potential uses of agricultural residues. For this reason, especially rural farmers find no reason but to handle their residues in ways that they find most suitable. The other contributor to waste buildup is the poor unpaved dirty feeder roads between farms, which make it a 'mission impossible' to transport agricultural wastes to either processing stations, market centers or government handling sites as the case with straw (Zaki et al., 2013).

Unlike in Egypt's past, when crop residues were being utilized as fuel sources, re-used on the farm as fodder, fertilizer or as mulch, the increased use of gas stoves, ovens and artificial fertilizers today has decreased the reuse of farm waste and rendered its use impractical because of the low heating value compared to fossil fuels. As a result, there has been an increase in the open burning of agricultural residue and its accumulation in landfills (Zayani, 2010). The largest portion of agriculture generated waste in Egypt today is either being burned or illegally dumped. Inefficient collection of waste and illegal disposal of agricultural waste are among the major sources of land, air and water pollution and pose catastrophic effects on the environment and human health (Zaki et al., 2013). Illegal dumping of agricultural residues on the canal banks creates barriers to water flow and endangers water quality. Crop residues block irrigation systems and contribute to eutrophication.

1.1.3. Potential benefits of agricultural waste management in Egypt

Despite their tremendous damage to both the environment and human health, agricultural residues could be employed in the income generation struggle and could be holistic in the conservation of other nonrenewable resources. Some of the results of proper management agricultural wastes as discussed are;

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- A number of small agro industries can be established in the rural areas based on agricultural residue recycling, which in turn would create employment opportunities.
- Compost from organic agricultural waste can be used in the land reclamation process. This would facilitate in the extension of agricultural lands, and as a result increase agricultural production.
- Proper agricultural waste management can lead to a reduction in the expenditure on chemical fertilizer and their consequential negative impacts
- Proper waste handling reduces the adverse impacts on the environment and has the potential to provide alternative sources of clean energy production. Biogas produced from the anaerobic digestion of organic waste is one of such energies.
- Crop residue can be used as fodder for the animals. This lowers dependence on imported feeds and supplements.
- Anaerobic digestion of biodegradable agricultural waste material such as manure, crop residue, and sewage sludge produces biogas, a sustainable energy source.

1.2. Selected agricultural organic wastes.

From the agricultural waste stream, this research focuses on energy recovery from the dairy and poultry sub waste streams using animal (cow) and chicken manure. Energy recovery in the form of biogas through anaerobic digestion was investigated. In the study, a brief insight into the dairy and poultry sectors and their contribution to environmental pollution is given together, and the anaerobic digestion of both manure streams as mono ad co-substrates was explored.

1.2.1. Animal (cow) manure

The increasing global demand for livestock products as protein sources, income growth, improvement in livestock production technologies and the rapidly growing world population have been the main drivers to the steady growth of the livestock industry. It is estimated that at least a third of the earth's ice-free terrestrial surface area is dedicated to livestock production, with systems valued at $1.4 trillion in 2010. For this reason, the industry ranks among the fastest growers in developing countries (Thornton, 2010).

This fast growth has however come not without demerits. The consequential increase in animal manure produced has raised environmental concerns and demanded sustainable management

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approaches to keep the potential damage under check. Average cow manure production and composition based on animal size is shown in table 1-2. Amount of manure production remains a function of the digestibility of the diet, animal stocking density, yard cleaning frequency, moisture content, climatic conditions, age and size of the animal.

Table 1- 2: Average cow manure production and composition based on animal size (Department of Agriculture and Fisheries, 2011).

Animal size (kg)	Manure production (kg/day)	Total solids (kg/day)	Volatile solids (kg/day)	BOD* (kg/day)	Nutrient content (kg/day)		
					N	P	K
220	13.2	1.54	1.32	0.35	0.075	0.024	0.052
300	18.0	2.08	1.06	0.48	0.104	0.034	0.076
450	27.0	3.10	2.70	0.72	0.153	0.050	0.108
600	36.0	4.18	3.56	0.96	0.206	0.068	0.149

BOD* = Biochemical oxygen demand

Because of the rising costs and environmental impacts of commercial inorganic fertilizers, organic animal manure is being widely adopted to cover the gap. A number of studies in the past have been dedicated to the use of animal manure as a fertilizer (Seefeldt & Jerry, 2013), (Zhang, n.d.), (Araji et al, 2001), (Rosen & Peter, 2017). Preference for the use of animal manure is preferred for in crop fields is because of its wealth in nutrient composition. Animal manure as indicated in the table 2 above contains considerable amounts of the three major plant nutrient elements; nitrogen, phosphorous and potassium in addition to other essential micronutrients. Besides its nutrient contribution, animal manure also has positive effects on the soil organic matter content, water and nutrient holding capacity, fertility and tilth.

While applying animal manure as a fertilizer, caution should be taken to apply only the right dose. Application of dry manure during strong winds should be avoided, application should as well not be in the vicinity of water bodies and the manure should be free of grass and weed seeds. Incautious handling of animal manure has been reported to bear huge costs to the environment, animal and human health. (Sören & F., 2012) and (Brandjes, & H., 1996) detail the environmental impacts of manure storage and its use in soil amendment. Among those listed are

surface water pollution, air pollution from the ammonia emissions, ground water pollution from nutrient leaching.

1.2.2. Chicken/poultry manure

Globally, the poultry industry is one of the largest and fast growing agro-based industries. Growth of the industry is attributed to the increasing demands for poultry products in forms of meat and eggs. Statistics indicate that global production and consumption of poultry meat increased at a rate of over 5% annually between 1991 and 2001 (F.A.O., 2006). A report by OECD-FAO shows that per capita consumption of poultry products between 2005 and 2017 increased at a rate of 2% ("OECD-FAO Agricultural Outlook 2017-2026," 2017). Data plotted in figure 1.6 below adopted from the United States Department of Agriculture (USDA) also shows an average increase rate in the consumption of poultry products of about 2% between 2008 and 2018 in the United States. Consequently, compared to the 15% contribution to the world meat production three decades ago, the poultry industry as of 2006 contributed to over 30% of the global livestock meat supply (F.A.O., 2006).
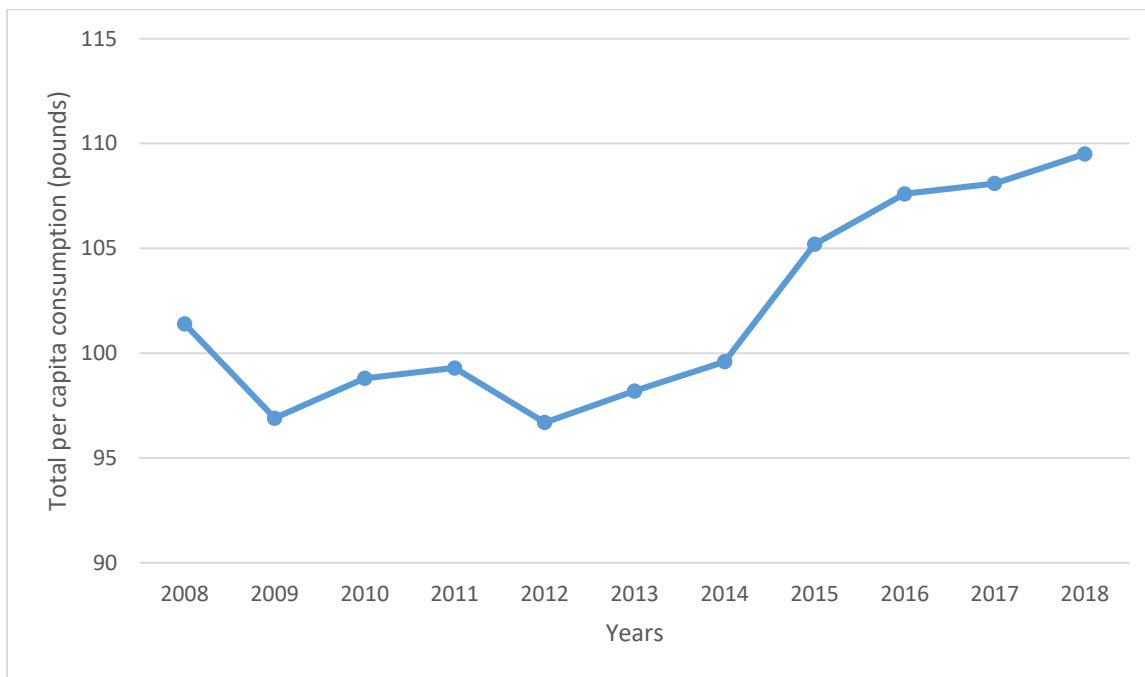
Figure 1. 6: Total per capita consumption of poultry products in the United States (USDA, 2017)

Egypt not being an exception has also experienced a steady increase in this industrial expansion. Credit for this increase has been given to the fact that red meat consumption alone cannot cover human protein needs in the country(Attia & Abd El-Hamid, 2005). Indirectly, the rapid population growth and resultant nutritional requirements could as well be held accountable. As of 2014, the commercial poultry industry of Egypt was valued at 2.5 billion Egyptian Pounds with the annual growth projected at a rate between 3-4%. On per capita basis, poultry products consumption in Egypt is 100 eggs and 10 birds annually, with the figures expected to double or even triple once considerations are taken for the growing national population, per capital income and the high quality vis-à-vis being a cheap protein source (Hassan, 2014).

However, the main challenge of the industrial expansion is the increased accumulation of waste from the different industrial activities. Waste from poultry farms comprises of poultry excreta (manure), spilled feed, feathers and bedding materials used in poultry houses.

1.2.2.1.   Poultry Manure production and nutrient contents

The quantity of poultry manure produced varies from one farm to another (Chastain et al., 2014). On the other hand, the quantity of manure produced from a poultry farm generally depends on the type and amount of material used for bedding, feed formulation, stocking density, type of housing being employed and litter management techniques in practice (Coufal & C, 2006).

One of the major concerns of the poultry manure is its high mineral nutrient concentration. Nutrients in poultry manure are mainly derived from the poultry feed, supplements, medications, and water consumed by the birds. For any given sample of manure, nutrient composition is dependent on the ration digestibility, age of the birds, amount of feed and water that goes to waste, the frequency of cleaning the poultry house and the type and amount of bed used (Chastain et al., 2014). Poultry manure ideally contains 13 nutrient elements; nitrogen (N) phosphorous (P) potassium (K) calcium (Ca) magnesium (Mg) sulfur (S) manganese (Mn) copper (C) zinc (Zn) chlorine (Cl) boron (B) iron (Fe) and molybdenum (Mo) all of which happen to be essential to plant growth (Nnabuchi et al., 2012). Therefore, the use of poultry manure as a fertilizer in plant growth could be a potential source for all or a considerable part of the plant nutrient requirements. It is worth noting that the fecal discharge from chicken is a composition of both feces and urine. Therefore, the nutrient composition of the manure is not affected by either the urine or feces as the two are the same (Chastain et al., 2014).

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On average, fresh manure from poultry has a higher nutrient content in relation to manure from other animals as shown in table 1-3a. In comparison with other manure sources, poultry manure has significantly higher amounts of potassium, nitrogen, phosphorous, calcium and magnesium. This makes poultry manure a better source of plant nutrition. Table 1-3b also gives an overview of the disparity in nutrient contents and approximations of manure production from the two different sources of poultry waste. From the table, laying chicken produce almost twice the dry matter produced by chicken raised for meat production. Layers also on average produce more nutrients as do broilers. This could be because of the difference in dietary requirements of both classes of chicken.

Despite the nutritive suitability of the manure as a fertilizer, the mineral composition of poultry manure has high negative amenities to the environment. The nutrients are reported to pollute both the soil and water. In addition, the pathogens from the manure and heavy metals that accumulate in the manure from the poultry feed and water cause soil, ground and surface water pollution. This is normally a consequence of poor manure handling practices and manure storage. The manure is also known to be a source of bad odors, a hub for flies, rodents and a lot of other disease carriers. The odors from manure storage or disposal facilities are a composition of ammonia, volatile organic compounds (VOCs) and Hydrogen Sulphide (H_2S) which are very toxic to human health. Leaching of the heavy metals into the ground water from the manure storage facilities is a common occurrence which pollutes ground water reservoirs and also compromises aquatic life in the nearby streams when residual water flows from the manure piles to the streams. This is because of the resultant eutrophication which claims a big percentage of aquatic lives (Maheshwari, 2013).

Table 1- 3a: Nutrient content in manure from selected animal sources. ("Manure is an excellent fertilizer," 2017.)

	Nitrogen (N)	Phosphorous (P_2O_5)	Potassium (K_2O)	Calcium (Ca)	Magnesium (Mg)	Organic matter	Moisture content
FRESH MANURE	%	%	%	%	%	%	%
Cattle	0.5	0.3	0.5	0.3	0.1	16.7	81.3
Sheep	0.9	0.5	0.8	0.2	0.3	30.7	64.8
Poultry	0.9	0.5	0.8	0.4	02	30.7	64.8
Horse	0.5	0.3	0.6	0.3	0.12	7.0	68.8
Swine	0.6	0.5	0.4	0.2	0.03	15.5	77.6
TREATED DRIED MANURE	%	%	%	%	%	%	%
Cattle	2.0	1.5	2.2	2.9	0.7	69.9	7.9
Sheep	1.9	1.4	2.9	3.3	0.8	53.9	11.4
Poultry	4.5	2.7	1.4	2.9	0.6	58.6	9.2

Table 1-3b: Nutrient content and approximate manure production of various types of poultry waste (Attia & Abd El-Hamid, 2005)

Type of manure	Chemical composition (%)				Manure nutrient content \bird \year (g)				
	N	P_2O_5	K_2O	Na	DM	N	P_2O_5	K_2O	Na
Broiler	4.88	4.86	3.0	0.6	4890	239	229	129	29.5
Layer hens	4.80	6.73	3.92	0.6	7000	336	471	275	42.0

**DM – Dry matter

From the poultry industry in Egypt, Nitrogen and phosphorous represent the highest amount of nutrients excreted with the chicken manure, (table 1-4) (Attia & Abd El-Hamid, 2005). Although

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these nutrients are essential for animal and plant growth and nutrition, there extreme abundance in the ecosystem poses adverse ecological threats. According to the soil conditions in the Egypt, these two nutrients account for the high pollution levels in the newly reclaimed desert agricultural areas where poultry manure is excessively used as a fertilizer and/or soil amendment (Attia & Abd El-Hamid, 2005). Nitrogen and phosphorous stand high chances of being leached to the ground water causing ground water pollution, a result of which is human and animal health problems.

Excessive Nitrogen build up in drinking water (ground water) in form of nitrates is very harmful to infants and livestock. They inhibit oxygen transportation in the blood stream which results in a condition commonly known as blue baby syndrome (Perlman, 2017). High phosphorous concentration on the other hand impairs micronutrient availability in the top layers of the soil for plant absorption and accelerates growth of algal blooms in water bodies causing eutrophication and death of aquatic animals (Busman et al., 2009). Given the aforementioned impacts of the high concentrations of nitrogen, phosphorous and heavy metals in poultry manure on the ecosystem, it is worth adding that their excessive accumulation in the soil also negatively impacts its agricultural abilities.

Table 1- 4: Estimated number of birds, manure produced and nutrients contents in Egypt (Attia & Abd El-Hamid, 2005)

Type of birds	No. of birds (M)	Manure produced g/b/yr.	Amount of nutrients produced annually, tons			
			N	P_2O_5	K_2O	Na
Broilers	800	4890	191200	183200	103200	23600
Broiler breeders	5	10500	2520	3533	2058	315
Layers	15	7500	5040	7065	4125	523
Laying breeders	0.25	8140	98	137	80	12.2
Turkeys	2	10860	1060	1056	652	108.6
Waterfowl	20	6500	6344	6318	3900	780
Total	541		206262	201309	114015	26426

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Despite the earlier quoted disastrous impacts that accompany poor handling of poultry waste, management of this waste has still proven a very big challenge to the industry especially the manure and the poultry litter. Figure 1.7 below shows some of the common poultry waste handling and management practices in most of the poultry farms.

From the figure, almost 89% of the waste generated from the poultry farms is in the solid form. Data from the table also shows that over 90% of the poultry waste is open dumped. As earlier explained in this chapter, open dumping of poultry waste has grave effects to both human health and the environment mainly due to the nutrient content carried in the waste. For this reason, there is need for legislative, and Research and development intervention to effectively regulate proper and sustainable handling and/or disposal of the waste.
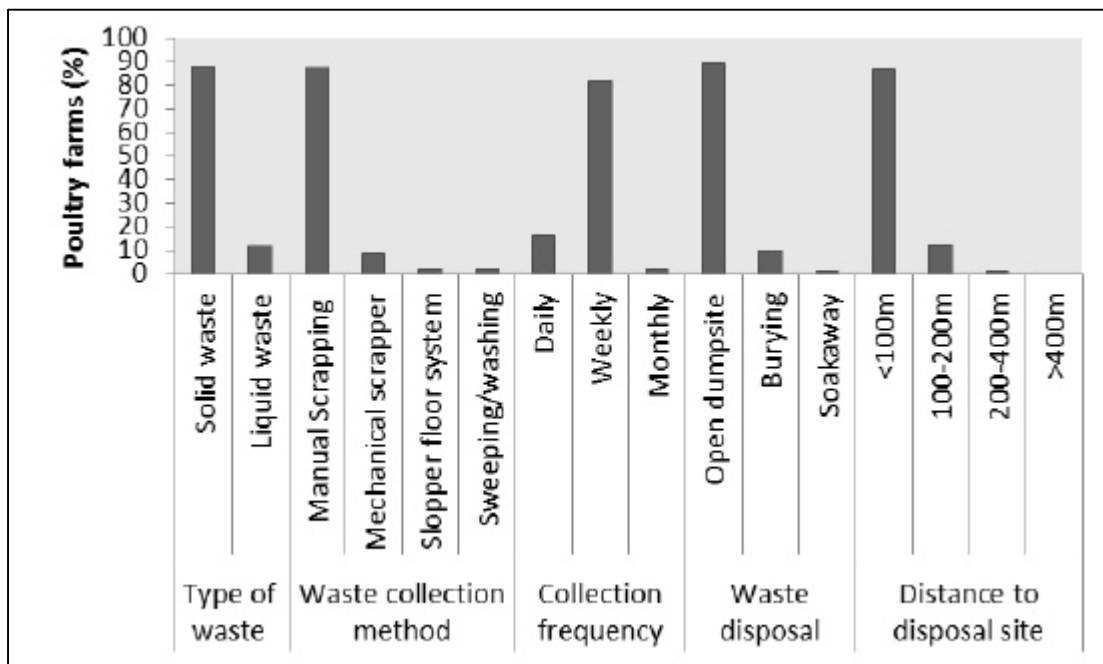
Figure 1. 7: Waste collection and disposal methods in most poultry farms (Mary et al., 2015).

1.3. Research motivation and objectives

The major aspects behind the motivation for this research have been (1) the grave closely similar environmental impacts associated with the unsustainable handling of kitchen waste, chicken and animal manure waste stream in general, (2) the increasing agricultural systems' intensification especially in the developing world, with an aim of closing the loop - producing bio-fertilizers in the end to replace the chemical fertilizers especially in the newly reclaimed agricultural lands as the need to expand cultivable lands increases, (3) absence of sustainable and strategic measures put in place to manage the huge amount of organic waste generated from the kitchens of the food outlets operating on AUC New Cairo campus, and (4) the world's increasing demand for cleaner and renewable energy resources, in response to the rising global awareness of the likely environmental impacts associated with the use of fossil based fuels and the need to decouple food prices from fuel prices

1.3.1. Kitchen waste from AUC New Cairo Campus and its potential impacts

The food needs of The American University in Cairo's (AUC) New Cairo campus are served by eight food vendors. These serve fast foods, fresh vegetable and juices, complete meals, snacks and hot beverages. Fortunately, all vendors have kitchens on campus. However, these kitchens generate considerable amounts of organic waste daily. Waste from the kitchens is largely a composition of spoilt food, fruit and vegetable peelings, offcuts and low quality undesired fruits or vegetables.

The current KW management hierarchy in place is only a three stage process. (1) The unsorted waste is collected in bins present in the kitchens, (2) the bins are collected by the campus services to the university waste collection facility where it is mixed with waste from other streams on the university campus that will not be recycled and (3) the waste is all together sent to the Zabaleen area/landfill.

Landfilling of organic waste has been linked to serious environmental impacts. This is mainly because of the high moisture content, biodegradability and methane production potentials of the waste in the landfills. Because of this, under the uncontrolled anaerobic conditions inside the landfills, organic wastes can be broken down through microbial activity releasing gases (40-70% methane) and leachates (El-Fadel et al., 1997). Methane is a combustible and greenhouse gas

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with the potential to cause fires hazards and contribute to global warming and climate change. In addition, other components in the gas produced in landfills, may contribute to air pollution causing health and more specifically respiratory hazards. The leachate on the other hand contributes to ground water pollution as it seeps through the soil. (El-Fadel et al., 1997)

1.3.2. Alternatives for on campus kitchen waste recycling.

Owing to its high moisture content, composting (aerobic digestion) and/or anaerobic digestion are the most feasible means of recycling kitchen waste on campus. The process of composting produces compost; a rich organic soil amendment. With AUC's devotion to sustainable landscaping, on campus compost production from the kitchen waste presents a complement to the many efforts undertaken in that pursuit. Similar efforts are already being taken by the university's landscaping department, which composts over 80% of the waste it generates from its usual maintenances. However, the downsides of the practice are; (1) the process consumes a lot of water especially during the summers to maintain the necessary moisture content inside the compost pile, (2) the process requires mechanization to turn the pile to ensure uniform air circulation inside the pile for effective microbial breakdown and (3) if not properly controlled, the process of compost production may take up to eight weeks. All these make the process somewhat costly when related to the cheap price of compost on the Egyptian market, where a ton is only about 26$.

Anaerobic digestion on the other hand yields both biogas and an organic bio fertilizer at the end of the process. Biogas is a sustainable energy source with a considerable potential to cover some of the university's energy needs. Besides, the production of biogas on campus may open gates for new cutting edge research in this field of sustainable energy under the auspices of the university's accredited school of engineering and sciences' programs.

1.3.3. Research aim and objectives

The main aim of this research is (1) to investigate the production of biogas from animal manure, chicken manure and kitchen waste, (2) to explore the biogas production potential of organic waste generated by kitchens on AUC New Cairo campus. and (3) to achieve an environmentally sound zero waste on campus food production system.

To reach this aim, the study was divided into a list of main objectives as stated here below;

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- Experimental anaerobic degradation of different combinations of animal manure, chicken manure and kitchen waste to produce biogas and a bio fertilizer from the slurry at the end of the digestion process.

- Experimental anaerobic digestion of kitchen waste from AUC kitchens for biogas production with the aim of closing the cycle of waste generation to reach a zero waste food production system.

- Proposing avenues to achieving an organic waste free food service system on AUC New Cairo campus – proposing a feasible anaerobic digester design to digest the food waste produced on campus.

1.3.4. Research methodology

A combination of different research methodologies was employed to ensure adherence to meeting the target research objectives. Literature review in the early stages of the study was the most important method employed to align the research with the scope of action. Preliminary baseline data was also obtained through literature review. Secondary data sources were journal articles, conference papers, books, government published reports, published international statistics and websites.

A pilot scale experiment was set up in two phases (I and II) to investigate biogas production from animal manure, chicken manure and kitchen waste. Primary data was collected from the experiments. Results of the experiment were used as in put to recommend anaerobic digestion as a very viable organic kitchen waste management strategy for AUC.

Chapter 2
Literature Review

2.1. Anaerobic digestion of organic waste

Anaerobic digestion (AD) is a naturally occurring microbial process in which organic matter is broken down into simpler chemical compounds in an oxygen free environment under ideal conditions (Monnet, 2003). The process aims at biologically transforming almost all forms of organic waste from one form to another (Khalid et al., 2011). Anaerobic digestion process naturally takes place in many anaerobic environments such as the marine water sediments, peat bogs, mammalian guts and water courses (Al Seadi et al., 2008), (Ward et al., 2008). During the process, a mixture of gases including; methane, carbon dioxide, hydrogen sulfide and ammonia in varying percentages is produced. This mixture of gasses is what is called Biogas.

Biogas is a mixture of gases, primarily methane and carbon dioxide along with traces of other gases. Biogas is combustible and it is for this reason that the gas is used as a fuel in gas engines, heating and lighting. Chemically, biogas from the anaerobic digestion of agricultural waste comprises of 60-75% methane (CH_4), 19-33% Carbon dioxide (CO_2), 0-1% Nitrogen (N_2) and less than 0.5% Oxygen (O_2). This chemical composition however varies according to the type of feed (The Biogas, 2009). Besides biogas, an organic residue (digestate) is left at the end of the digestion process. The residue is highly rich in nitrogen. For this reason, coupled with its low moisture content, the digestate has been applied as a soil amendment/fertilizer (Li et al., 2011).

Anaerobic digestion (biogas production) is a four-stage process (figure 2.1), which starts with hydrolysis, followed by acidogenesis, acetogenesis and completed by methanognesis. The chemical reaction below summarizes the anaerobic digestion process.

$$C_6H_{12}O_6 \ \rightarrow 3CO_2 \ \ + \ \ 3CH_4$$

Glucose   Carbon dioxide   Methane
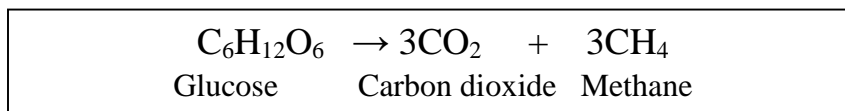
2.1.1. Hydrolysis

Hydrolysis is the first stage of the anaerobic digestion process, where the hydrolytic bacteria break down the complex organic compounds such as carbohydrates, fats and proteins into simpler soluble molecules (Monnet, 2003). The stage is enzyme controlled; the hydrolytic microorganisms release enzymes that breakdown the complex polymers into soluble monomers setting pace for the acidogenic microorganisms in the next stage (Al Seadi et al., 2008). Substrate-specific enzymes break down the complex polysaccharides, proteins, lipids or proteins in the presence of water (moisture) to simpler soluble monosaccharaides, amino acids or fatty acids respectively. Hydrolysis follows the reaction below.

Complex Insoluble polymers	Hydrolytic enzymes Lipase, cellulose, amylase, protease →	Simpler soluble monomers
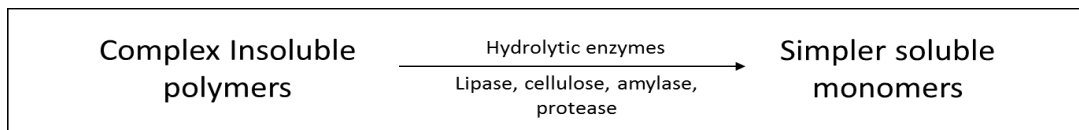
2.1.2. Acidogenesis

The second stage of the process is acidogenesis, usually the fastest stage of an anaerobic digestion process (Chen & Howard, 2014). The acid forming bacteria (acidogens) convert the products of hydrolysis (fatty acids, amino acids, simple sugars) into simple organic acids, hydrogen and carbon dioxide (methanogenic substrates). The principal organic acids produced during this stage are acetic acid, butyric acid, propionic acid and ethanol, an alcohol (volatile fatty acids) (Monnet, 2003).

2.1.3. Acetogenesis

Acetogenesis is the second last stage before methanogenesis. During acetogenesis, products of acidogenesis that could not be directly converted are converted into methanogenic substrates along with minor production of H_2 and CO_2. Methanogenic substrates being referred to are acetate, hydrogen and carbon dioxide (Al Seadi et al., 2008). The last stage of the anaerobic degradation process is methanogenesis. This stage is accomplished by methanogenic bacteria which convert the methanogenic (intermediate) substrates into CH_4 and CO_2. Methanogenesis is the slowest yet most critical of all anaerobic digestion biochemical processes (Adekunle & Okolie, 2015).

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2.2. Factors affecting the Anaerobic Digestion (AD) process

The efficiency of an anaerobic digestion reaction similar to any biochemical reaction is a factor of a number of parameters. For successful microbial growth and activity therefore, certain conditions must be ideal to keep the many different microorganisms involved in balance. Critical parameters affecting microbial activity and growth are temperature, pH, nutrient supply (C/N ratio), complete absence of oxygen, presence of toxic compounds and inhibitor concentration during the digestion process.

2.2.1. Temperature

The anaerobic digestion process can be operated at three different temperature ranges; psychrophilic range ($<25^0$C), mesophilic (25-45^0C) or thermophilic ranges (45-70^0C) (Al Seadi et al., 2008). Mesophilic (32-43^0C) and thermophilic (49-60^0C) temperature ranges are however the most preferred for biogas production. These respectively offer the optimum working environments for the mesophilic and thermophilic bacteria involved in the process (Chen & Howard, 2014). Digester operation temperature is largely dictated by the feedstock. Temperature stability during operation is very critical for optimum results since different digestion stages have different optimum temperature ranges. For example, most of the acidogens grow and perform well under mesophilic temperatures whereas the methanogens prefer higher temperatures (Adekunle & Okolie, 2015).

The temperature of the process is directly linked to the hydraulic retention time (the average time a given volume of digestion feedstock stays in the digester.) (Table 2-1) Running the digester at thermophilic temperatures gives a higher biogas yield with a lower retention time as opposed to mesophilic temperatures (Krich et al., 2005). Figure 2.2 shows the relation between temperatures, hydraulic retention time and biogas yield.
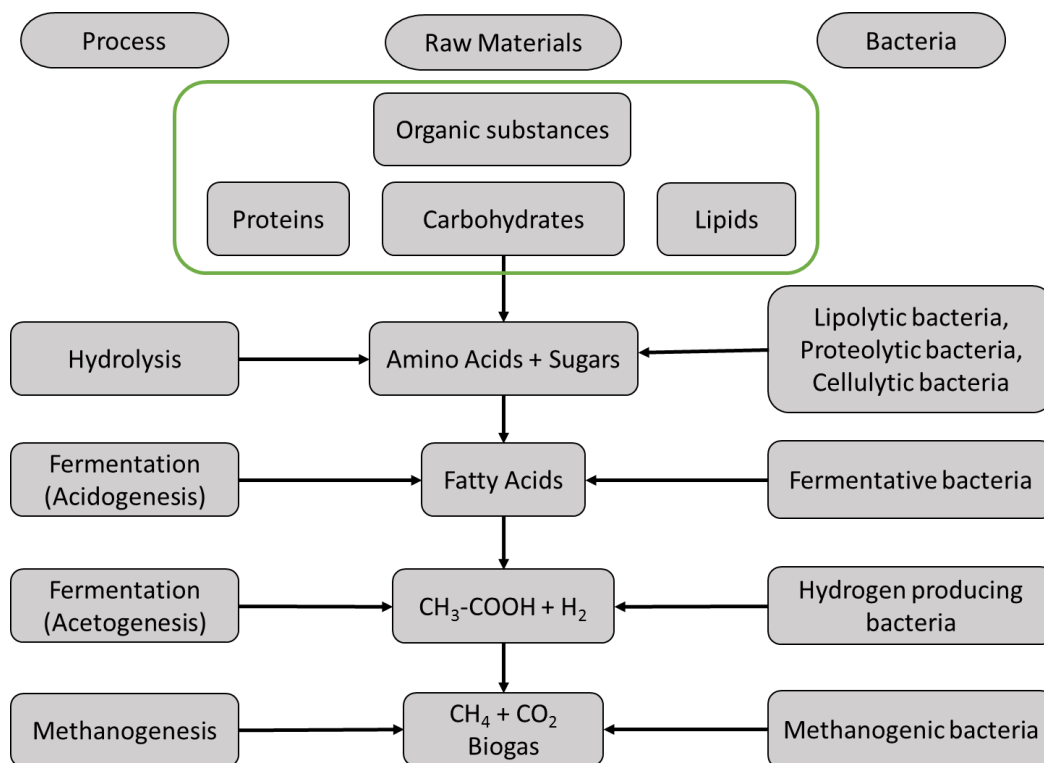
Figure 2. 1: Anaerobic digestion process flow diagram (Adekunle & Okolie, 2015)

Table 2- 1: Digester thermal stage and temperature retention time (Al Seadi et al., 2008)

Thermal stage	Process temperatures (^{0}C)	Minimum retention time (days)
Psychrophilic	Less than 20	70 to 80
Mesophilic	30-42	30-40
Thermophilic	43-55	15-20

Operating the biogas digester at thermophilic temperature ranges has a number of advantages over mesophilic conditions as listed below.

- High temperatures in thermophilic ranges kill all pathogens in the sludge
- Shorter retention time with an increase in process efficiency and biogas yield
- More effective substrate digestion with better substrate utilization
- There is a direct relation between higher temperature and growth of methanogenic bacteria

- Improved digestibility and substrate availability

- Higher possibilities of solid and liquid fractional separation

The main disadvantages of operating the biogas digester at thermophilic temperatures are; the high energy demand to maintain high temperatures, secondly at high temperatures, there are higher risks of ammonia inhibition and there is a large degree of imbalance in the system (Al Seadi et al., 2008).
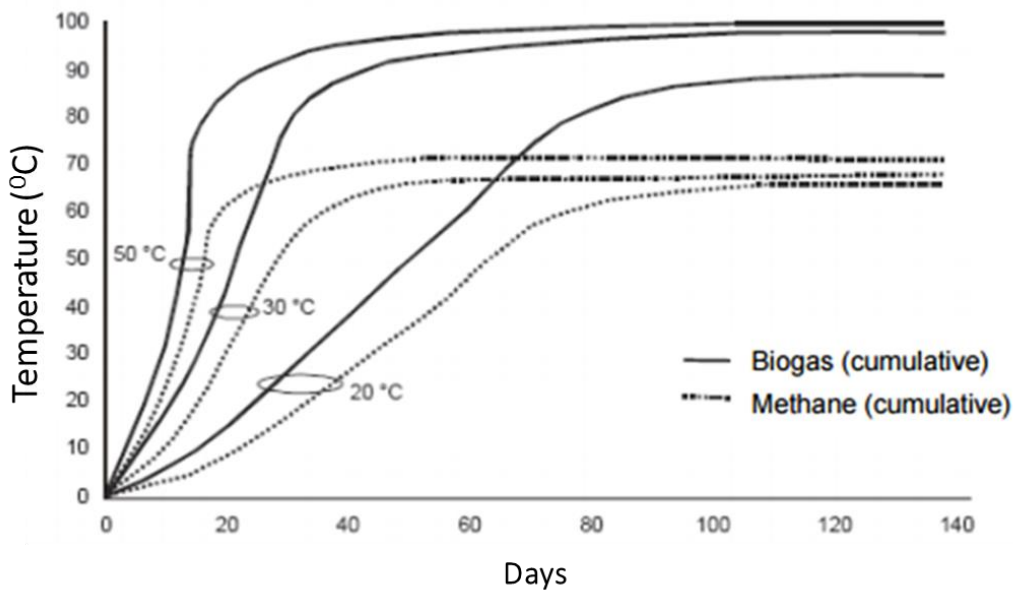
Figure 2. 2: Relative biogas yields depending on temperature and hydraulic retention time (Al Seadi et al., 2008)

2.2.2. pH

A near neutral pH is ideal for most AD process (Rapport et al., 2008). However, pH requirements vary across the different process stages and thermal stages at which the process is conducted. A pH of 7.0-8.0 is optimum for the methanogens. Acidogenic bacteria require lower pH values for optimum performance. Optimum pH for mesophilic bacteria is 6.5-8.0. A slight drop to 6.0 or rise to 8.3 triggers an inhibitory effect to the process. The pH in thermophilic digesters is lower as a result of the formation of carbonic acid upon reaction of the dissolved CO_2 with water. This is a reaction initiated by an increase in temperature (Al Seadi et al., 2008).

2.2.3. C/N ratio

Carbon and Nitrogen are the main nutrient sources for anaerobic bacterial growth and stability during digestion. A balance in availability of these two nutritional sources is very critical for efficient degradation while preventing ammonia build up and inhibition (Rapport et al., 2008). A C/N ratio of 20-30:1 has generally been considered optimum for microbial activity, and largely dependent on the feedstock and inoculum (Zhang et al., 2014).

2.2.4. Presence of process inhibitors (ammonia)

In the digester, ammonia exists in two forms, free ammonia (NH_3) and ammonium (NH_4^+) both forms resulting from the breakdown of proteins and other nitrogen-rich organic substrates present in the feedstock (Zhang et al., 2014). Free ammonia is a good nutrient source for the AD bacteria; however, its high concentration during digestion inhibits the process. Ammonia inhibition is common in the AD of animal manure coming from the high ammonia concentration in their urine (Al Seadi et al., 2008).

2.2.5. Total solids

Total solids (TS) refer to the weight of the dry matter of an anaerobic digestion substrate. This weight is expressed as a percentage of the total weight of the substrate sample (Schmidt, 2005). TS content of the substrate can be used to define two different anaerobic digestion processes; wet and dry digestion. The wet digestion process occurs at a substrate TS content of less than 15% whereas dry digestion occurs at a TS content between 15% and 20% (Karthikeyan & Visvanathan, 2013). The TS content of any given biogas feedstock directly contributes to the performance of the system and yield of biogas during microbial degradation. There is an inverse relation between the TS content and biogas yield (Ugwuoke et al., 2015). There is an optimum value of TS for each feedstock to maximize biogas production.

2.2.6. Volatile solids

Volatile solids (VS) refers to that percentage of the solid material of the digestion raw materials inside the digester that can be broken down by the bacteria to produce biogas. This portion varies from one organic waste material to another. VS content is calculated by diving the weight of volatile solids in the raw material by the total weight of solids in raw material and normally expressed as a percentage of the total solids content (IRENA, 2016). VS content of an anaerobic

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digestion substrate is often an essential parameter in predicting methane production from the substrate (Schmidt, 2005).

2.2.7. Volatile fatty acids (VFA)

VFA are the main intermediate compounds formed during the anaerobic digestion process. They are the main product of the acidogenesis stage in the anaerobic digestion process of organic wastes. They include acetic acid, propionic acid, butyric acid, and valeric acid (Monnet, 2003), (Zhang et al., 2014). Of these acids, acetic and propionic acid play the most significant roles in biogas production, and therefore tracking their concentration could be basis for determining the success of an anaerobic digestion process (Zhang et al., 2014). Under ideal conditions, the VFA are transformed into CO_2 and CH_4 by the methanogenic bacteria. Under high organic loading rates, as the common case in fruit and vegetable wastes, the VFA could accumulate inside the digester. As a result of their amplified accumulation, the pH inside the digester is lowered, which may eventually inhibit the whole digestion process (Alvarez et al., 2000; Zhang et al., 2014). It therefore right to conclude that VFA have the potential to determine the pH inside the digester.

2.2.8. Hydraulic Retention/Residence Time

Hydraulic Retention Time (HRT) refers to the amount of time that the digestion substrate material stays in the digester. HRT depends on the volume of the digester and the volume of the substrate fed to the digester in a given time period. The HTR can be calculated from the formula below.

$$HRT \quad \frac{Digester\ volume\ (m^3)}{Substrate\ feeding\ rate\ (\frac{m^3}{day})}$$

The HRT is based on the biological oxygen demand (BOD) of the feedstock material and the slurry at the end of the process, and the chemical oxygen demand (COD), which is the measure for the average time needed for the organic to reach full decomposition (Arsova, 2010). Substrate feeding rate can also be referred to as the organic loading rate (OLR). OLR is a very important parameter in digester operation. It is a measure of the efficiency of an anaerobic digestion system at biomass conversion. OLR is important in determining the right volatile solids loading into an anaerobic digestion system for optimum biogas yield. Overloading the system has been reported

to contribute to the accumulation of inhibitory substrates in the digester which result into low biogas yields (Arsova, 2010).

From the equation above, knowing the HRT and OLR it is easy calculating the required digester volume. Also from the equation, increasing the OLR decreases the HRT. Depending on the substrate under digestion, the HRT must be long enough to maintain a balance between the bacterial population in the digestate (effluent) and the amount of bacteria being reproduced. The reproduction cycle of the bacteria is usually 10 or more days (Adekunle & Okolie, 2015; Al Seadi et al., 2008). A short HRT would mean a good flow of substrates through the digester, but with a low biogas yield. It is therefore imperative to align the HRT with the COD of the substrate under digestion (Al Seadi et al., 2008).

2.3. Advantages of anaerobic digestion

AD as listed below has a number of social, economic and environmental benefits.

a. AD cuts back on the irritating odor emissions from decayed agricultural waste, indirectly improving air quality

b. The use of biogas greatly reduces on the GHG emissions into the environment coming from the use of fossil fuels in the same applications.

c. Use of manure in AD preserves soil and water quality by preventing the pathogens in the manure from directly entering these resources upon unsustainable disposal.

d. The energy generated (biogas) in the process has numerous applications and can also be sold to provide a source of income

e. The manure produced at the end of the process is free of pathogens and weed seeds yet rich in nutrients. This saves fertilizer costs and the negative impacts of synthetic fertilizers.

f. Use of agricultural waste saves the costs of waste storage and disposal

g. According to the Kyoto protocol, biogas generation has the potential of earning carbon credits based on its potential towards reducing GHG emissions.

h. AD also has the potential of reducing VOC emissions into the environment.

The one possible downside of AD lies with the digesters that burn biogas. During the combustion of biogas, oxides of nitrogen (NO_x) are given off. These negatively impact the environment due

their ozone formation potential (Krich et al., 2005). Ozone is an irritant and upon reaction with water forms nitric acid. This process is responsible for the acidic rain formation.

2.4. Types of anaerobic digesters

Four types of anaerobic digester designs are commonly used for large scale on-farm biogas production; the covered lagoon digester, complex mix, plug-flow and temperature phased anaerobic digesters (Chen & Howard, 2014), (Pillars, n.d.). For on-farm/household small scale production, the Indian (fixed dome) and Chinese (floating drum) biogas digesters are the most widely adopted. However, the technology and design of biogas (anaerobic) digesters varies from country to country and is influenced by factors such as local climate, legal frameworks, energy policies, availability and affordability(Al Seadi et al., 2008).

Anaerobic digesters can further be classified basing on the substrate feeding schedule; into batch, continuous and semi –continuous feed digesters. In the batch type of digesters, the digester is loaded once with a batch of fresh substrate and closed. Substrate is left to digest to/close to a stage of no further reaction and completely removed for a new batch to be loaded and the process continues. Batch digesters have the advantage in their simplicity of design. In continuous feed digesters, feedstock is continuously added to the digester without any interruptions to the digestion process. In such type of digesters, substrate flow through the digester is by means of either mechanical force or pressure from the newly applied feedstock which forces out the already digested feedstock. Unlike the batch type, there is steady and continuous biogas production in the continuous feed digester (Al Seadi et al., 2008).

2.4.1. Covered lagoon digester

A covered lagoon is a large, in-ground, earthen or lined lagoon with a flexible or floating impermeable gas-tight cover (Chen & Howard, 2014) (Figure 2.3). The cover acts to trap the biogas. This design is most suitable for feedstock in liquid form with <2% solids (Pillars, n.d.). Such digesters do not have the potential to be heated. For this reason, they have longer hydraulic retention times (30-45days) and suitable for warmer regions; where atmospheric heat can assist in stabilizing digester temperature (Chen & Howard, 2014).
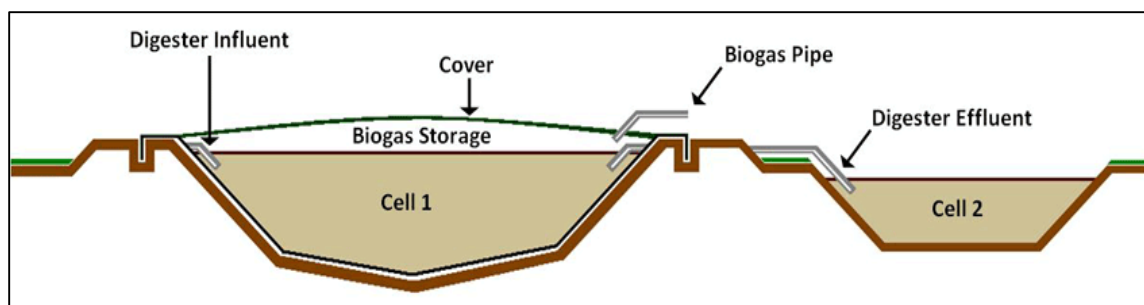
Figure 2. 3: Covered lagoon digester ("lagoon covers | Ieccovers's Blog," 2010)

2.4.2. Plug-flow digester

The plug-flow type is the most suitable for solid substrates with 11-14% solids content (Pillars, n.d.). The system comprises a cylindrical tank and a hot water piping network to maintain a stable temperature in the tank. New in-fed manure from one end pushes the biogas and slurry through the other end (Chen & Howard, 2014) (Figure 2.4).
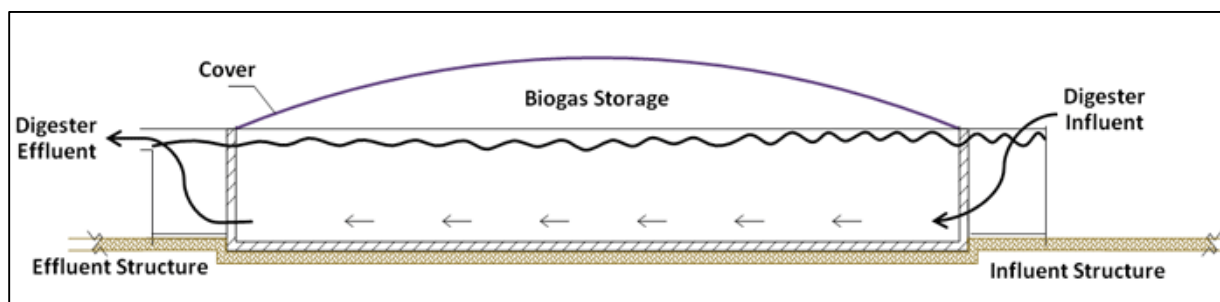
Figure 2. 4: Plug-flow digester (("lagoon covers | Ieccovers's Blog," 2010)

2.4.3. Complete mix digester

The complete mix design of digester exists in two forms, either as cylindrical tanks above the ground or below the ground as rectangular pits (Chen & Howard, 2014). The design consists of an enclosure from a rigid or flexible material and a heated tank with a mechanical, hydraulic, or gas mixing system ("lagoon covers | Ieccovers's Blog," 2010) (figure 2.5). This type of digester can be operated at both mesophilic and thermophilic temperature ranges (Chen & Howard, 2014). Best results are reached when the feedstock manure is diluted with water to 3-10% solids (Chen & Howard, 2014), ("lagoon covers | Ieccovers's Blog," 2010).

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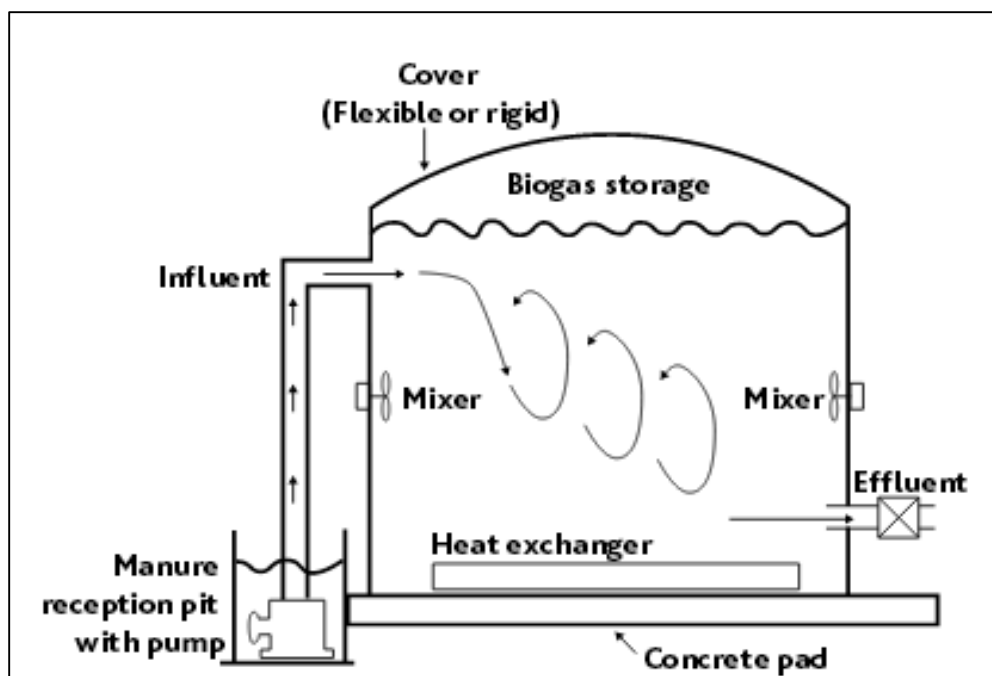
Figure 2. 5: Complete mix digester (Chen & Howard, 2014)

2.4.4. Floating dome/ Indian type digester

The floating dome/drum (figure 13) type of digesters is the mostly commonly used in India. This is primarily because the first digester of this type to ever be built was in India in the 1950s by Joshbai Patel (Abbasi et al., 2012). The principal of biogas production in this type of digesters is gas production at a constant digester pressure with variations in volume inside the digester (Rajendran et al., 2012).

The design comprises mainly of a cylindrical dome-shaped digester and a movable inverted floating drum. The drum moves up and down depending on the amount of gas produced inside the digester, also from this movement the amount of gas accumulated in the digester can be detected. The drum moves up when there is gas production and down when the gas is being consumed. In majority of the cases, the drum is made of steel. This drum is also vital in regulating biogas flow during use.

The digester is a construction of bricks and sand. The inside walls of the digester are plastered with sand and cement to seal the digester from any gas leaks during production. In high volume digesters, there is a partition wall in the middle of the digester (figure 2.6) which is in most cases

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absent in low volume digester (below 4m^3). The gas produced is stored in the gas holder and let out for use through the outlet pipe on the gas holder.

This reactor model is preferred because of the ease in utilizing the gas produced since it is produced at a constant pressure. The demerits of these digesters are the high maintenance costs e.g. the timely painting of the drum to prevent it from rusting, the high initial cost of constructing the reactor and the short service life of the reactor.
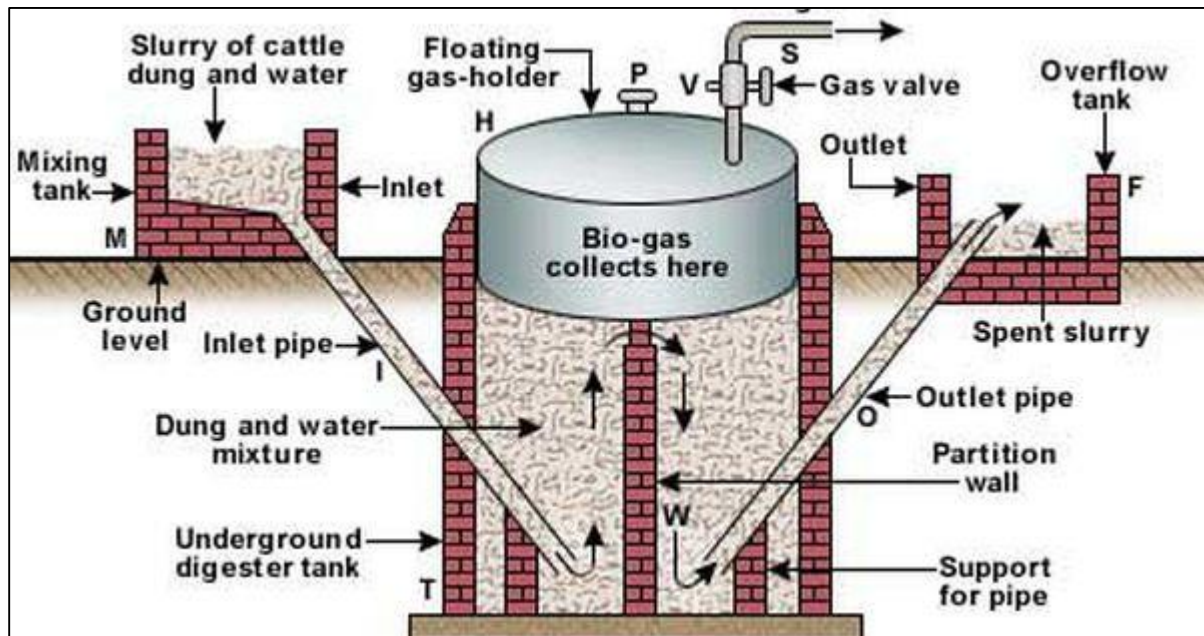
Figure 2. 6: Floating dome biogas digester (Kumar et al., 2015)

2.4.5. Fixed dome/Chinese type biogas digesters

According to (Marchaim, 1992), the fixed dome, also called the constant volume digester is the most widely used biogas digester in developing countries. From their name, they are also the most used type in China (Rajendran et al., 2012). The digestion principal is gas production at constant slurry volume inside the digester. As a result, the gas is produced at varying pressures. The typical design of a fixed dome biogas digester is shown in figure 2.7

www.manaraa.com
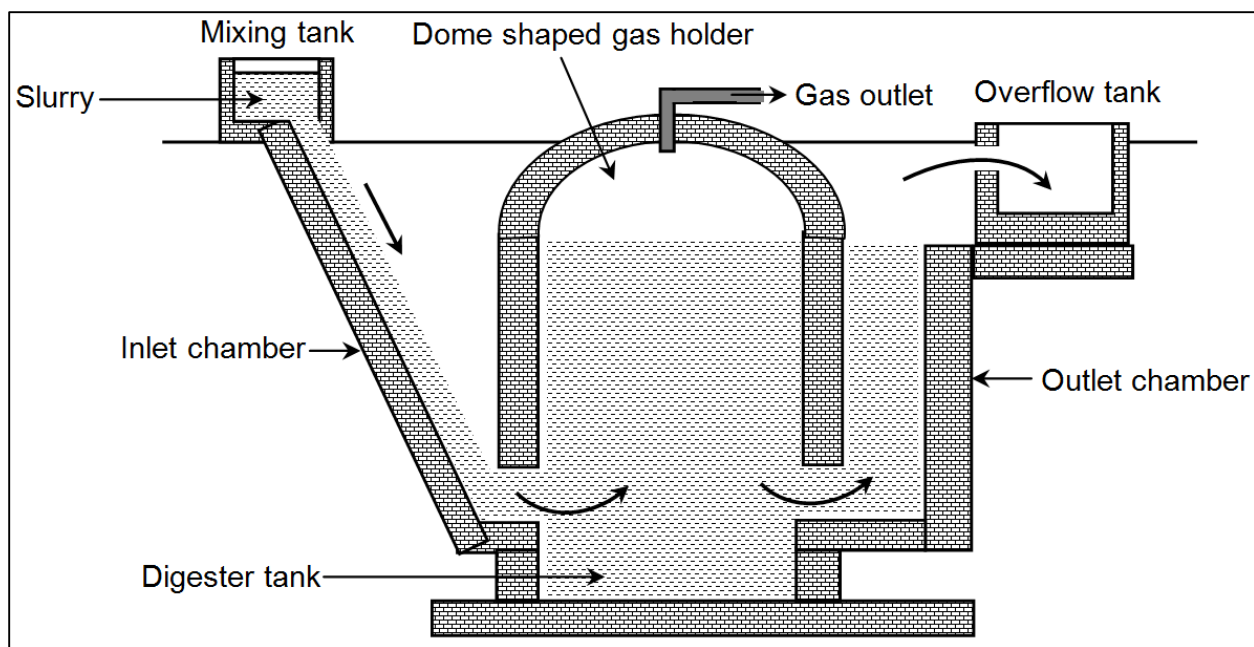
Figure 2. 7: Fixed dome biogas digester (Gupta & Rahul, 2017)

Different from the floating dome type, this mode has the gas collection dome fixed. Digester construction is normally with bricks, sand and masonry. The top and bottom ends of the reactor are in most cases dome shaped, although flat bottom ends are also being used. The digester walls are plastered from the inside with sand and cement to seal the digester making it air tight. During digestion, the gas produced is stored under the dome at the top end of the digester. Gas buildup in the dome creates a pressure which displaces off some of the slurry into the outlet chamber. The gas outlet valve or pipe in the dome is used to collect the gas into a storage balloon or to any point for direct use.

The advantages of fixed dome digesters are their low initial costs, long service life, compact design that is space saving, high methane yield and the lack of moving parts or parts prone to rusting as the case in floating models. The downside of these digesters is the high technical skills needed to ensure a gas tight seal, difficulties in using the produced gas because of its inconsistent pressure, occasional gas leakages that may occur if the digester wasn't properly sealed, and the cost of excavation in case of systems failure.

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2.5. Enhancement of biogas yield

The unceasing efforts undertaken by scientists to increase the efficiency of energy recovery from organic waste products have continuously revealed that AD of pre-treated and co-composted organic feedstock significantly increases the biogas yield. This binary approach is based on the chemical, physical and biological properties of the respective organic waste sources.

2.5.1. Pretreatment of organic waste

Pretreatment of AD feedstock has been widely adopted in the biogas production processes because of a number of reasons such as;

- Some feedstock material contains chemical compounds that inhibit AD microbial activity
- The cellular structure of lignocellulosic feedstock from agricultural and forestry waste for example, makes it difficult for microbial breakdown during AD. For successful digestion, the chemical and physical bonds in the plant cell wall constituents have to be broken to fasten the hydrolysis process (Jönsson & Martín, 2016).
- Increase biogas yield
- Optimize biogas production from the new or locally available organic substrates.

Biological, thermal, chemical, and mechanical pretreatment technologies have until today been exhaustively investigated. Results show that efficiency of the different pretreatment methods varies depending on the nature of organic waste, temperature range at which the digester is operated, type of digester, physico-chemical properties of the waste and method of digestion. (Whether mono-substrate digestion or co-digestion)

2.5.1.1. Biological pretreatment

Biological pretreatment of AD substrates is done under both aerobic and anaerobic conditions along with addition of specific enzymes such as lipases, peptidases, cellulases among others to the AD process (Jönsson & Martín, 2016). Biological pretreatment primarily aims at amplifying the hydrolysis stage of main digestion (Liqian, 2011). In the case of lignocellulosic biomass, biological pretreatments have been proved to be the most sustainable alternatives of breaking down their lignin structure compared to the high energy physical-chemical conventional methods (Maurya et al., 2015). Besides enzymes, micro-organisms such as white, brown and soft rot-fungi have also been used for their degradative action on lignin and hemicellulose (Harmsen et

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al., 2010). Biological pretreatment in many cases has been preferred over other pretreatment methods because it can be carried out at low temperatures without any chemical additions. However, the downside is the relatively slow treatment rate (Montgomery & Bochmann, 2014).

2.5.1.2. Thermal pretreatment

Thermal treatment acts to break the cell membranes to increase the solubility of organic compounds during AD (Ariunbaatar et al, 2014). Heat treatments aid in the hydrolysis of complex organic compounds in organic wastes. This improves their solubility while enhancing their biological conversion into biogas under anaerobic conditions (Salihu & Alam, 2016). Temperatures between $60\text{-}180^0C$ have been reported to give optimum results. Above 180^0C, compounds with an inhibitory effect are formed, slowing down the process (Salihu & Alam, 2016). Temperature requirements for pretreatment vary from one substrate to the other. Thermal pretreatment of organic waste is in most cases done together with chemicals or mechanical agitation (Montgomery & Bochmann, 2014).

2.5.1.3. Chemical pretreatment

Chemical pretreatment is accomplished by strong organic acids, alkalis and oxidants which are added to organic substrates during AD with the objective of breaking down the complex organic compounds (Ariunbaatar et al., 2014). The efficiency of a chemical pretreatment is a function of the chemical pretreatment method and chemical characteristics of the AD substrate. This pretreatment method is ideal for lignocellulosic and other lignin rich substrates as opposed to substrates with high carbohydrates and easily biodegradable molecular structures. Amplified biodegradation in the later state accompanied by an accumulation of volatile fatty acids negatively affect the methanogenic stage and consequently the entire AD process (Ariunbaatar et al., 2014).

Acid pretreatment plays to chemically hydrolyze lignin and hemicellulose, increasing their solubility and eventually availing cellulose for enzyme degradation (Maurya et al., 2015). In acidic pretreatments, strong and dilute acids vary in their applications with dilute acids preferred over strong acid solutions. Sulfuric and hydrochloric acids have been the most widely used in concentrated pretreatments. Despite being strong hydrolysis agents, concentrated acids are not suitable for the job mainly because of their high corrosiveness, toxicity, and hazardous nature. For that reason, working with strong acids requires equipment that are resistant to corrosion,

which hikes the costs of the process. This is in contrast with the high dilute acids applications on industrial scale.

Alkali pretreatments of biomass involve the addition of alkali solutions mainly hydroxides of sodium, potassium, calcium and ammonium at ambient temperature and pressure (Maurya et al., 2015). This pretreatment approach aims at the removal of lignin from mainly the lignocellulosic biomass. The first stage of the alkali pretreatment reaction process results in the swelling of the lignocelluloses and partial solubilization of lignin (Montgomery & Bochmann, 2014).Two reactions; solvation and saponification occur during this stage (Ariunbaatar et al., 2014). Alkali pretreatment is credited for its ability to significantly increase cellulose solubility, flexibility in operation temperature, pressure, and time ranges, the alkalis being inexpensive and its provision of protecting cellulose and hemicellulose from total solubilization (Maurya et al., 2015). Although (Kumar & Wyman, 2009) suggest that sodium hydroxide is the most efficient of the alkali solutions for biomass pretreatment, (Liqian, 2011) reports study that discovered a 66% in methane yield with treatment of digested manure biofibers with calcium oxide. The kink in using alkali pretreatments exits in the huge amounts of water needed to wash the salts of sodium and calcium, and the high costs of materials and mineral recovery at the end of the process (Maurya et al., 2015).

Oxidative pretreatment is accomplished with the application of hydrogen peroxide or ozone. The action of these two compounds is very similar in their lignin degradation effects to alkali pretreatments. Oxidative pretreatment is not widely applied because of high costs and the high CO_2 content in the biogas produced from feedstock subjected to this pretreatment. The high CO_2 is a result of the extra oxygen added into the system from the decomposition of hydrogen peroxide (Montgomery & Bochmann, 2014).

2.5.1.4. Mechanical pretreatment

Mechanical or physical pretreatment of organic waste aims at particle size reduction through grinding, shredding and milling of organic solid waste and feedstock homogenization in organic sludge (Salihu & Alam, 2016). The grinding, milling as well as homogenization processes act to increase the specific surface area and expose the cellular components of the organic waste for microbial breakdown. An elaborate surface area increases the substrate-bacteria contact which speeds up the AD process (Ariunbaatar et al., 2014). A particle size in the range of 1 to 2 mm has

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been found most ideal for AD of lignocellulosic material (Montgomery & Bochmann, 2014). Mechanical pretreatment of sludge is most commonly applied through high pressure homogenization (Salihu & Alam, 2016). The main disadvantage of mechanical treatment in the high energy requirements in running the pretreatment equipment, which make the process expensive.

2.5.2. Anaerobic co-digestion of organic waste

In the anaerobic digestion, co-digestion has been employed to mainly enhance biogas yield and reduce the inhibitory effects by some substrates during the process. Co-digestion is also very helpful in the adjustment of the C/N ratio to the optimum ranges for efficient digestion (Ward et al., 2008). This is because feedstocks vary in their carbon and nitrogen contents. Organic materials higher in lipids and fats have higher methane production potentials than organic materials richer in carbohydrates and fats (Atandi & Rahman, 2012). Therefore to harness methane yield, co-digestion if of both organic materials is of absolute importance.

During anaerobic co-digestion, organic substrates with higher biogas production potentials per unit mass are co-digested with the base (main) substrate to increase the overall biogas production per unit volume of the digester (Atandi & Rahman, 2012). The mixture of the two co-digestates creates a positive synergism between the two substrates, since they complement each other in terms of nutrients, moisture, pH, and buffer action among others (Alvarez et al., 2000). Co-digestion offers a number of primary benefits, including dilution of toxic compounds that may be present in any of the substrates, adjust the moisture content and pH of the feedstock, supply the necessary buffer capacity to the feedstock and diversifying the bacterial population taking part the process (Esposito et al., 2012). Secondary benefits include the reduction on greenhouse gas emissions, enhanced efficiency in biogas production, reduction in quantities of organic waste sent to landfills, savings on costs related to organic waste handling and disposal, saving on costs related to substrate pretreatment before anaerobic digestion, and improved quality of the fertilizer produced at the end of the process.

According to (Esposito et al., 2012) all organic substrates with carbohydrates, cellulose, hemicellulose, proteins ad lipids as the main chemical structural compositions can be anaerobically digested and therefore make good co-digestion substrates. Success of co-digestion is largely dependent on the quality and quantity of the co-substrates (Atandi & Rahman, 2012).

To best achieve the objective of increasing biogas and methane yield from co-digestion, it is imperative to mix the co-substrates in the most optimal ratios. There are no standard ratios for co-digestion substrates, but rather this can be achieved through prior experimentation (both lab and pilot) with different ratios of the substrates under study. Other factors behind the success of anaerobic digestion are; full homogenization of substrates, absence of inhibitory conditions, optimum operation temperature and optimization of other anaerobic digestion process parameters earlier explained under factors that affect anaerobic digestion.

Animal manure is most preferred among anaerobic co-digestion substrates because of its abundance and physical, chemical and biological properties such as the high moisture content, good buffering action and its wealth of the essential elements and nutrients as required to successfully steer the anaerobic digestion process (Atandi & Rahman, 2012).

2.5.3. Use of anaerobic digestion starters

The use of starters (starter cultures) has for a long time been employed in both aerobic and anaerobic degradation process to hasten organic materials breakdown. In anaerobic digestion particularly, the use of starters is aimed at enhancing biogas production from the process. An anaerobic digestion starter, also called inoculum is a substrate with low concentration of biodegradable organic matter but with a wealth of various essential bacteria required for the anaerobic degradation process (Rojas et al., 2010).

In most anaerobic digestion studies, animal manures have been the most commonly used as starters mainly because of their high populations of essential anaerobic microorganisms. Impacts of animal manures as starters on the progress of anaerobic fermentation processes, biogas and methane yield from different substrates have also been studied. For example; (Phetyim et al., 2015) experimented biogas production from vegetable waste using dog manure mixed with cow manure as starters. Results of their experiment concluded that a higher percentage of dog manure recorded the highest methane. Besides the direct use of animal manures, starters can also be derived from digested slurry of a biogas plant or sewage sludge (Rojas et al., 2010).

In their experiment to determine the efficacies of various anaerobic starter seeds for biogas production from different types of wastewater, (Chaiprasert et al., 2017) used five starter seeds; rubber starter seed, cassava starch seed, palm oil starter seed, swine starter seed and soymilk

starter seed sourced from fully established waste water treatment plants (anaerobic reactors) with five years of operation. Results of the experiment showed that all starter seeds showed the potential to produce methane from waste water of different sources. (Halim et al., 2017) investigated the anaerobic digestion of palm oil mill effluent with lampung natural zeolite as microbe immobilization medium using digested cow manure as a starter. In his experiment to study the possibility of biogas production through the use of seas water to dilute organic wastes, (Gamal-El-Din, 1986) used a starter prepared from effluent of a cattle manure fed actively running lab-scale digester. Other starter cultures being used in anaerobic digestion are; activated carbon (charcoal) with a buffer acetate under guidelines outlined by (Geluk et al., 1992), yeast in the fermentation of food waste (Suwannarat & Ritchie, 2015) and effective microorganisms (Widjaja et al., 2016), (Maalim et al., 2015) and (Gates et al., 2014).

Effective Microorganisms (EMs) have earned different definitions based on their application. In gardening, EMs are defined by (The Recycle Works Ltd, 2017) as "*a mixed culture of fermentative, soil-based, beneficial micro-organisms which can be applied in many environments to break down organic matter*". (Higa & Wididana, 2017) explain theories of the positive impacts of EM administration to the soil, including the increase in crop yield, plant protection from diseases and pathogens and induction of disease resistance in soils. (Permaculture Research institute, 2016) also adds that EMs in the soil increase soil fertility in addition to improvement in the availability of essential mineral nutrients and other organic compounds required for plant health, through enhancement of organic matter breakdown. In municipal waste management, EMs have been applied in composting and anaerobic fermentation of food waste. During anaerobic methanization, the co-existent groups of microorganisms in the EMs breakdown the complex organic matter to release CO_2 and CH_4 (Shalaby, 2011).

EMs exist under different brand names in the commercial markets, for example; (Randjawali & Waris, 2016) used Green Phoskko as the starter in their experiment to produce biogas when designing and testing mini-biogas plants. Green Phoskko is a brand name for an EM sold in Indonesia. Bokashi is one of the many such brands of EM, developed by Prof. Teruo Higa in 1982. Bokashi is developed by combining a EM-1 (a group of microorganisms particularly lactic acid bacteria, photosynthetic bacteria, yeasts, actinomycenes and fermenting fungi derived from naturally decomposing systems into a water-based product) with a high carbon material

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preferably saw dust or rice bran and addition of a suitable nutrient source before subject to fermentation (Merfield, 2012). Despite its wealth of essential anaerobic digestion microbes and over all suitability for anaerobic fermentation, a lot of research has focused on the use of Bokashi in composting and little efforts have been invested in exploring the its use in anaerobic digestion to produce biogas.

2.6. Anaerobic digestion of animal manure

Because of the high risks of environmental pollution associated with the application of animal manure as a fertilizer and the high moisture content of fresh manure, AD of animal manure has proved an economically yet environmentally efficient and effective mitigative measure in reducing these risks. Use of animal manure as both a mono-substrate and co-digestate in AD has been widely studied. (Recebli et al, 2015) investigated the production of biogas from a breeding farm. Results of the study showed a daily 6.33 m^3 of biogas production obtained from fermentation of bovine animal manure from 70 cattle with a heating value of 21,000 KJ/m^3. The slurry at the end of the AD process was applied to the farm fields as a fertilizer. (Abubakar & Ismail, 2012) investigated the effectiveness of cow dung for biogas production using a 10L laboratory scale bioreactor operating at both batch and semi continuous modes. Results of their investigation established the feasibility of cow dung as an AD feedstock with biogas production of 0.15 L/kg VS added and a 47% methane content at 1.7 kg volatile solids (VS)/L d organic loading in a 10 days' hydraulic retention time during the semi continuous phase.

Despite the undoubted suitability and performance of animal manure as an anaerobic digestion substrate, (Atandi & Rahman, 2012) report that biogas digesters run on dairy manure as a mono-substrate have a low biogas yield per unit mass of manure which keeps their returns on investment low. Therefore, to optimize biogas production from dairy manure and consequently the returns on investment from the venture, considerations for anaerobic co-digestion with other organic substrates are indispensable. Co-digestion of animal manure with substrates such as chicken manure, food waste, and agricultural waste has also been extensively studied.

Research conducted by (Gashaw & Libsu, 2016) concluded that anaerobic co-digestion of food waste and cow dung ameliorates biogas potential when compared to digestion of cow dung as a mono substrate. (Eyalarasan et al, 2013) studied anaerobic co-digestion of Eritrea's cafeteria

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food waste with cow dung under mesophilic conditions in a batch mode. Results of their study showed the highest methane yield with the 1:1 cow dung to cafeteria waste mixture at TS of 8%. Highest biogas was recorded when the organic loading rate was 0.34m^3/kgVS added.

This study seeks to investigate and build on this previous research to assess the feasibility of biogas production from animal manure in three states, as a mono-substrate, as a co-substrate with kitchen waste, and as a starter for kitchen waste digestion.

2.7. Anaerobic Digestion of kitchen waste

The use of food/kitchen waste as both a mono and co-digested substrate in the production of biogas has been extensively experimented and reported. Kitchen waste is a widely used feedstock in AD because of its wealth in calorific value, nutrients and high biodegradability. Food waste has been quoted to have a composition of 7 to 31 weight percentage of total solids with a biomethane production potential estimated at 0.44-0.48 m^2 CH$_4$/kg of the added volatile solids (Baky et al, 2014). Compared to biosolids, food waste has three times the methane production potential (Kuo et al., 2017). Besides, the relatively high moisture content in kitchen waste estimated at 74-90% (Zhang et al., 2007) qualifies AD as the most suitable way of energy recovery from the waste when compared to other conversion technologies such as gasification and combustion (Zhang et al., 2007) (Ramzan et al., 2010).

Kitchen waste from different sources varies widely in its chemical, physical and biological composition. For example, composition of food waste from a university cafeteria would most unlikely be similar to that from residential sources. Similarly, different foodstuffs vary in their biogas production potentials. Composition and methane production potential of two different food waste streams reported by (Xu et al., 2018) is shown in table 2-2 below.

An experiment conducted by (Cho et al., 1995)concluded that at the same temperature and retention time, methane yield was different for all the food wastes studied. The observed methane yields for cooked meat, boiled rice, fresh cabbage and mixed food wastes were 482, 294, 277, and 472 mL/g VS respectively (Cho et al., 1995). In the same manner, a number of other scientists have studied kitchen waste from different sources for its biogas production abilities. Results of their chemical, physical and biological analytical characterization of the

waste are shown in table 2-3 below. Characterization of food waste before AD is a very crucial step after the collection and separation of food waste for a number of reasons;

1- For prior assessment of the suitability of food waste as an AD feedstock
2- To appropriately adjust process parameters for optimal microbial activity
3- To best examine the feasibility of converting the collected food waste into biogas production.

Table 2- 2: Composition and methanogenic potential of two food waste streams (Xu et al., 2018)

Stream	Components	TS (%)	VS/TS (%)	C/N ratio	pH	Methane yield $(m^3/kgVS_{feed})$
Fruit and vegetable waste	Leaves, peels, pomace, skins, rinds, cores, pits, pulp, stems, seeds, twigs, and spoiled fruits and vegetables.	7.4–17.9	83.4–95.3	15.2–18.9	3.7–4.2	0.16 - 0.35
Household and restaurant food waste	Nonedible portions of food (e.g. banana peels, egg shales) and uneaten food such as plate waste.	4.0–41.5	88.7–95.1	11.4–36.4	3.3–5.7	0.46 – 0.53

To balance the efficiency of the AD process within the acceptable retention time period while maintaining the right digester volumes may be a challenge in cases of direct digester feeding without prior feedstock pretreatment. Extensive research into AD food waste preparation methods and their feasibility has been conducted to probe into the unusually long retention times, increase biogas yield and aid in proper designing of AD digesters.

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Table 2- 3: Average characteristics of food waste from different sources

Parameter	Source	Averages
Moisture content (MC) %	(Ramzan et al., 2010)	85.6
	(R. Zhang et al., 2007)	70
	(Thenabadu, 2010)	77.9 - 92
C/N ratio	(Ramzan et al., 2010)	23.3
	(R. Zhang et al., 2007)	14.8
	(Thenabadu, 2010)	-
Volatile Solids (VS) %	(Ramzan et al., 2010)	89.5
	(R. Zhang et al., 2007)	26.35
	(Thenabadu, 2010)	14.6
Total Solids (TS) %	(Ramzan et al., 2010)	14.4
	(R. Zhang et al., 2007)	30.9
	(Thenabadu, 2010)	15.23
pH	(Ramzan et al., 2010)	6.3
	(R. Zhang et al., 2007)	-
	(Thenabadu, 2010)	5.7

Mechanical pretreatment is an important preliminary step especially in non-source-separated kitchen waste to sort the organic component for AD from other impurities such as plastics, glass, and paper among others. This step also plays to maintain stability of the digestion process and protect the digester from unanticipated mechanical failures (Ramzan et al., 2010). The use of catalysis to enhance biogas yield from vegetable waste was studied by (Das & Chanchal, 2013). Results of their study confirmed an increase in production of biogas which was mainly a result of the increase in the rate of bacterial growth and consequently the rate of biomass degradation into biogas.

Vegetable wastes, because of their high carbohydrates content are characterized by a tendency of fast production and accumulation of volatile fatty acids (VFA), which lower the pH inside the digester (Alvarez et al., 2000). This greatly affects the anaerobic digestion of vegetable waste as a result of rapid acidification during the process. Lowering the pH in the digester most

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specifically affects the methanogenesis stage of reaction, causing process inhibition (Velmurugan & Ramanujam, 2011).

In their research, (Raynal et al., 1998) characterized fruit and vegetable waste to be a composition of 75% hemicellulose, 9% cellulose and 5% lignin. All these carbohydrates are rich in energy, which is good for the anaerobic digestion process. However, for successful biodegradation a balance in the C/N ratio has to be achieved, which is hard in the case of vegetable wastes with a very high carbohydrate content. In this case, co-digestion of vegetable waste with other materials rich in nitrogen is necessary. The second phase of this study is entirely focused on kitchen waste because of its higher biogas production potential in relation to other substrates such as animal manure, crop residues and other organic streams (Paritosh et al., 2017).

However, in the anaerobic digestion of fruit and vegetable wastes, a common challenge has been reported by a number of researchers; process inhibition resulting from a decrease in pH inside the digester caused by an accumulation of organic acids. High organic loading rates have been pointed out as the main causes of this phenomenon (Sridevi et al., 2015) (Bouallagui et al., 2009). Derived from the cause, the most recommended remedy to volatile fatty acid accumulation has been the reduction in organic loading rates.

2.7.1. Co-digestion of kitchen waste with animal manure

In their experiment, (Callaghan et al., 2002) found out that in the co-digestion of cattle slurry with a mixture of fruit and vegetable waste, increasing the concentration of the fruit and vegetable waste to over 30%, increased the volatile fatty acids production in the digester. In the same experiment they also established that despite the VFA accumulation, with fruit and vegetable waste concentrations of up to 50%, methane production yield was still good although with a slight decrease in the volatile solids reduction rate. (Li et al., 2009) experimented the anaerobic co-digestion of kitchen waste and cattle manure at both batch and semi-continuous reaction modes on five different feed stocks under mesophilic conditions. The five feed stocks were mixtures of kitchen waste with cattle manure at different ratios; 0:1, 1:1, 2:1, 3:1, and 1:0 labelled R1, R2, R3, R4 and R5 respectively. Results of their experiments showed that R2, 3 and 4 exhibited the highest specific methane potential and biodegradability in the batch tests resulting from the addition of kitchen waste. In the semi-continuous tests, the highest methane

yield was 233 ml/g volatile solid obtained from R4. Their study recommends a kitchen waste to cattle manure ratio of 3:1 as the optimum for the co-digestion of kitchen waste and cattle manure.

(Zhang et al., 2013) studied anaerobic co-digestion of food waste and cattle manure in search for the key parameters responsible for the production of biogas and methane during the process at both batch and continuous modes. They established that at both modes, co-digestion increased total methane yield while the enhanced biogas production is a result of the C/N ratio and higher lipids breakdown. They also suggested 2:1 as the optimal food waste to cattle manure ratio for enhanced methane production at both batch and continuous modes of digestion.

2.8. Anaerobic digestion of poultry manure

Poultry manure can be utilized in biogas production in two different ways. The manure could be used alone without addition of any other organic materials to produce biogas, or could be used along with other organic wastes to enhance the biogas production potential of the system. The latter approach is called *co-digestion.* During co-digestion, organic waste from crop residue, sludge, animal manure and other similar organic sources could be used along with the poultry manure in the digestion process. Utilization of poultry manure in anaerobic digestion is based on the biodegradability of the organic matter component of the manure. In this study, chicken manure is considered because, chicken among the poultry are the most intensively raised and have for a long time been the main manure sources for biogas production from the industry (House, 2010).

On a daily basis, chicken excrete between 80-125g (wet) per chicken. The excreta contain over 25% dry matter, around 20-25% total solids (TS) and 55-65% volatile solids (VS) of total solids. These are the essential parts of the excreta for energy production (Abouelenien et al., 2009). Anaerobic digestion of chicken manure to produce energy is mainly inhibited by the low C/N ratio of the manure and the high ammonia levels in the digester. The organic matter is rich in nitrogen compared to manure from other animals which makes it hard for anaerobic digestion of the chicken manure as a substrate in comparison to other manure substrates (Abouelenien et al., 2009). During the anaerobic degradation, ammonia is produced from the degradation of the proteinaceous composition of the organic matter (Dalkılıç & Ugurlu, 2015) which is very toxic

and has an inhibitory effect (Ripley et al., 1984). The C/N ratio of chicken manure is between 8-10, which range is lower than the optimum range of 15-30 (Dalkılıc & Ugurlu, 2015) To steadily operate the digester, measures such as dilution of the manure to reduce TS content, maintaining a neutral digester pH, increasing the temperature of the process and other countermeasures like supplementary buffering or maintenance of a longer retention time are essential to keeping the digester in stable operation (Ripley et al., 1984). Co-digestion of the manure with carbon rich substrates to raise the C/N ratio is also essential in the enhancement of biogas digestion from chicken manure.

Temperature is one of the environmental factors that affects anaerobic digestion. Experiments have proved more efficiency with thermophilic ($50\text{-}55^0$C) anaerobic digestion as compared to mesophilic ($37\text{-}40^0$C) anaerobic digestion. Thermophilic anaerobic digestion is more effective at destroying the volatile solids which guarantees improved biogas production and removal of pathogens. The advantage of mesophilic digestion over the thermophilic one is the tolerance of the mesophilic bacteria to environmental conditions and high total ammonia nitrogen concentrations.

There is an inverse relationship between the rate of biogas production and the levels of total solids loading during the digestion process. As the levels of total solids in the manure increase, a reduction in the biogas production rates are observed. It is written that the threshold value for chicken manure is 5% total solids (Abouelenien et al., 2009). Experiments conducted by (Bujoczek et al., 2000) indicated that the feasibility of anaerobic digestion at total solids loadings higher than 10% was inhibited. This is because at loadings higher than 10%, a longer acclimation period is needed even after which the digestion process could still be inhibited. On the other hand, dilution of the of the manure to 0.5%-3% total solids as commonly practiced is an effective approach at blocking the inhibitory effect of ammonia during digestion, but uneconomical due to the resultant large volumes of wastes (Asyraf, 2010). A summary of results from previous research conducted on the total solids concentration in chicken manure for anaerobic digestion is shown in table 2-4. From their experiments, (Bujoczek et al., 2000) concluded that optimum digestion was most feasible at total solids loadings between 4%-6%.

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Table 2- 4: Results from different total solids loadings experiments in the anaerobic digestion of chicken manure (Asyraf, 2010).

Total solids loading	Author	Results
20-25%	Hill, 1983; Jewell & Loehr, 1977; Morris et al., 1975	Reduction in process performance caused by ammonia accumulation
11.4%	Converse et al. (1981)	High volatile acid content of the digestate and low volatile solids (VS) reductions obtained indicated the need for optimization of the digester's biogasification efficiency
5.9%	Safley et al. (1985)	Reported better performance of their full-scale digester
Different total solids levels; 21.7 %, 10%, 5%.	Bujoczek et al. (2000)	The highest total solids at which the digestion was still feasible was around 10% total solids.
30-35%	Jantrania and White (1985)	Hydrogen sulphide to inhibitory levels in most of the reactors and overall reduced conversion efficiency very long retention times employed pointed out the limitation of the application
Broad range of solids from 1 to 10%	Webb and Hawkes (1985)	showed optimum substrate Bioconversion to methane at 4-6% influent TS
Diluted manure at different solids concentrations	Huang and Shih (1981)	Maximum CH4 production can be obtained at 6% VS

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An alternative to successful anaerobic digestion of chicken manure is the two stage systems approach (Dalkılıc & Ugurlu, 2015). This approach is primarily aimed at accelerating the degradation of volatile solids and methane production in anaerobic processes (Carrère et al., 2010). In the approach, the first stage of the system is the pre-digestion. During this 1-2 days' stage, the organic matter is biologically pre-treated to increase acetate production at a pH of 5.5-6.5 (Yadvika et al., 2004). Hydrolysis and acidification of the organic matter are the main processes that take place during this stage. In the second stage of the system (the methanogenic phase) production of intense high volatile fatty acids is suppressed which enhances the activity of the free methanogens (Carrère et al., 2010)

2.8.1. Co-digestion of chicken manure with animal manure

In their research, (Callaghan et al., 2002) point out that the co-digestion of chicken manure and diary manure could be among the most promising alternatives for anaerobic co-digestion. Co-digestion has been in many cases suggested in the digestion of chicken manure as an alternative to prevent ammonia inhibition (Chen et al., 2008). (Chomini et al., 2015, p.) investigated the effect of co-digestion of cow dung and poultry manure on biogas yields along with the proximate and amino acid compositions of the by-products. In their study, triplicates of mixtures of cow dung and poultry manure in ratios of 1:0, 0:1, 1:1, 3:1 and 1:3 were named A, B, C, D and E respectively and loaded in 13.6L locally fabricated digesters. Results of their research concluded that after an eight weeks' retention period, ratio C (1:1) yielded the highest biogas significantly influenced by co-digestion as well as mixture ratios. They concluded that order of cumulative average volume of biogas production after the 8 weeks across the mixtures was highest in C followed by E, B, A and least in D.

(Miah et al., 2016) experimented the biogas production from the co-digestion of poultry litter with cow dung. In their experiments, four digesters were fed with blends of poultry litter, poultry droppings and manure in ratios of 100% poultry litter, 75% poultry litter with 25% cow dung, 50% poultry litter with 50% cow dung and 70% poultry litter with 30% poultry droppings. The reactors were respectively branded R1, R2, R3 and R4. Results of cumulative biogas yield after a 50 days' retention period showed that R2 gave the highest biogas yield, followed by R3, R1 and R4 recorded the least gas yield. This difference in gas yield was linked to the differences in VS

destruction efficiencies in the respective reactors. VS destruction efficiencies for the four reactors respectively were 46%, 51.99%, 51.96% and 43%.

Research conducted by (Nnabuchi et al., 2012) in Nigeria on the effect of co-digestion of chicken manure and cow dung on biogas generation concluded that maximum biogas yield was attained at a ratio of 1:4. In their experiments, they also tested a series of regression models to derive one that best described cumulative biogas production from animal waste streams. Their research concluded that the polynomial function with $R^2 = 0.78$ was most accurate when predicting biogas yield from animal derived wastes.

Various other studies have been conducted on the co-digestion of chicken manure with animal waste (Bujoczek et al., 2000), (Ofoefule et al, 2010) and (Sadaka & S., 2000). However, little research has been published in Egypt as regards to energy recovery from chicken litter despite the country's very large and fast growing poultry industry. The objective of this research is to experimentally investigate the feasibility of poultry and animal manure co-digestion in Egypt building on literature from research conducted around the world in this field under Egyptian conditions.

2.9. Utilization of products from anaerobic digestion

The flowchart in figure 2.8 summarizes potential benefits from a successfully operated anaerobic digestion plant. From the chart, the main products of a biogas plant are power and an organic fertilizer. The power is fed into the electricity grid whereas the fertilizer is applied on agriculture fields and in landscape. In the chart, CO_2 a waste product from the process can also be utilized to improve growth of crops grown under greenhouses, culturing of algae and in power-to-gas plants (Rutz, 2015). This research focuses on the use of biogas in heating and electricity production.
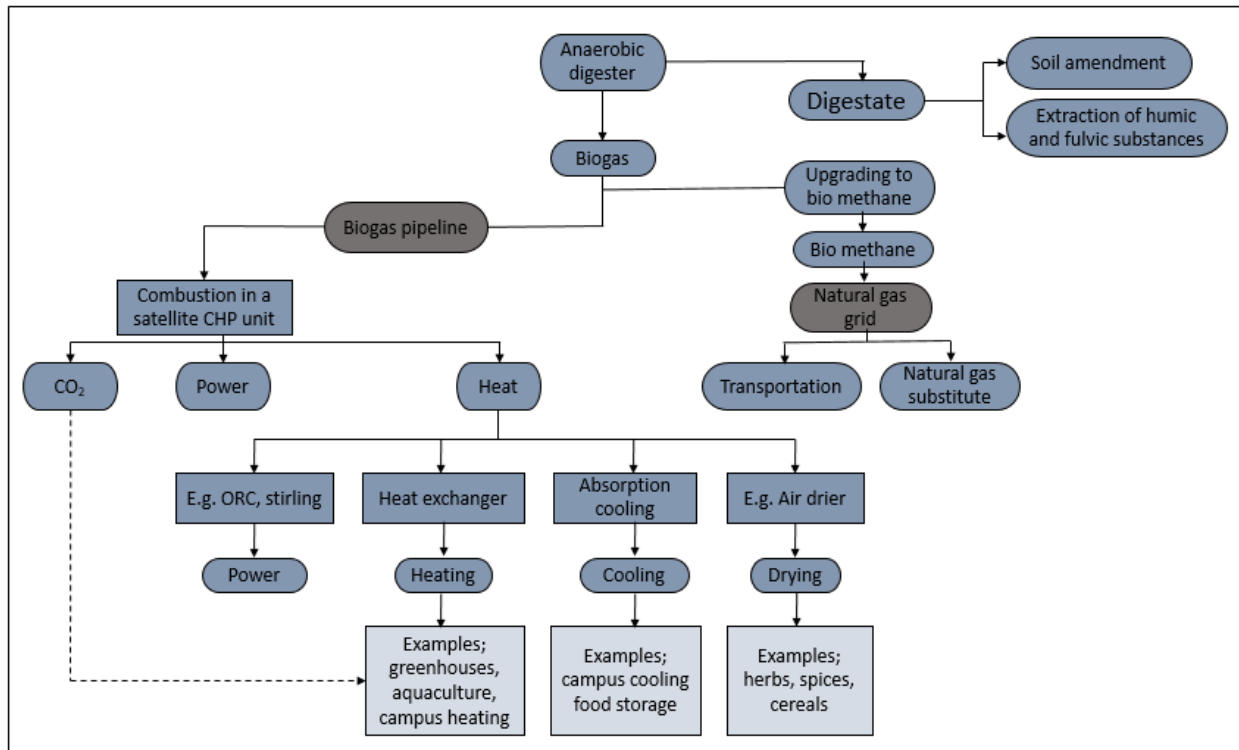
Figure 2. 8: Flow chart for the utilization of anaerobic digestion products (extracted from (Rutz, 2015)).

Chapter 3

Experimental Work

This chapter presents the experimental work carried out to confirm biogas production from the selected organic waste streams. The experimental model is based on lab scale biogas production process models. This is the first experimental setup of the kind to be used for the same investigation in the American University in Cairo. Because of its fairly simple structure of locally fabricated metallic digesters and plastic bottles as gas collection chambers, the model showed an acceptable degree of accuracy in terms of gas production. As for use in biogas experimentation, the model needs to be studied and adjustments made to meet the scope of future research. The model design will be discussed in details in this chapter.

3.1. Experimental model

The experiment was carried out in two phases, I and II. In both phases, experiments were carried out in batch pilot scale digesters of volume 88L under mesophilic conditions. The digesters were made of steel sheets and painted black on the outside for maximum heat absorption. In experimental phase I, the effective working volume of the digesters was maintained at 80L, whereas in phase II a working volume of 75L was used. Figures 3.1 and 3.2 illustrate phase I experimental setup in two different views; schematic diagram of the experimental digesters with the parts labeled and an actual visual of the final setup.

As illustrated in figure 3.1, the four digesters were fitted with suitable accessories for feeding, gas collection, sample collection and drainage of residues at the end of the process. The top plates of the digesters support the feeding and gas collection valves. The sample collection valves were fitted along the digester height while the drainage valve was fixed at the bottom end of the digester. Each digester was connected to two 19L plastic bottles by silicone tubes. Each of the digesters was fed with a different feedstock as labeled in figure 3.1. Of the two plastic bottles attached to the digesters, one bottle contains a solution which is a mixture of 15L of water, 250ml of 1.00N standard potassium dichromate solution and 50ml of 95% concentrated sulfuric acid, while the second bottle was kept empty.

The digesters were operated by a draw and fill method. Biogas production was monitored daily by solution displacement method. During anaerobic digestion, the biogas produced inside the digester flows through the gas outlet valve into the solution filled plastic bottle. Here the gas exerts a pressure on the solution and by displacement action, the solution overflows through a silicone tube into the empty plastic bottle. The over flown solution volume was recorded on a daily basis for ten weeks. Each time, after recording the volume, the solution was poured back into the solution filled bottle. The experimental theory is that the volume of displaced solution at any specific time represents the volume of biogas produced.
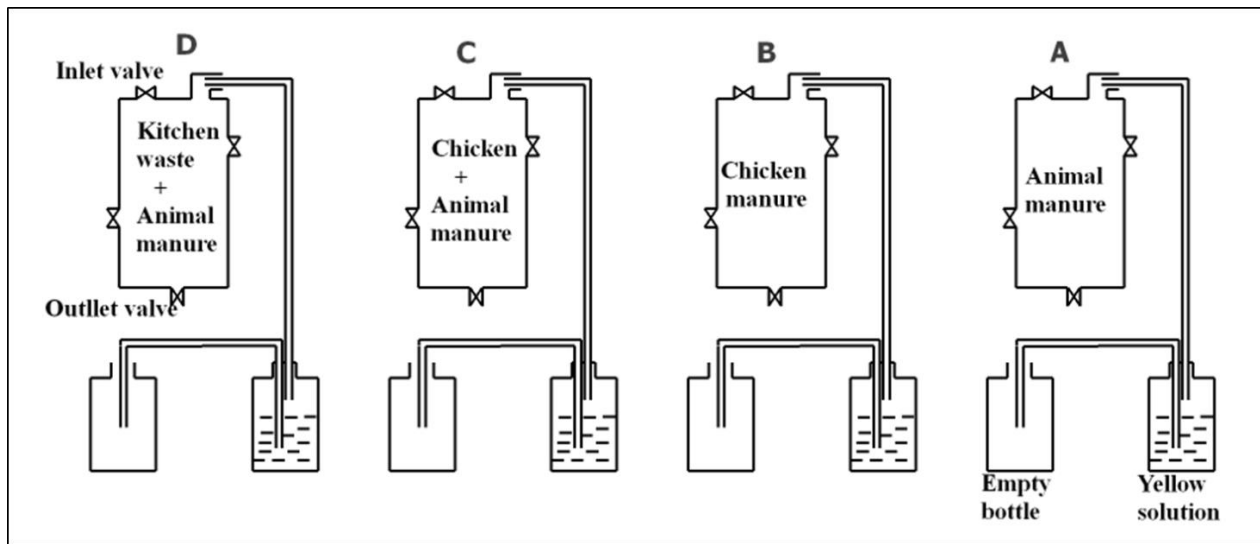
Figure 3. 1: Schematic diagram of Experimental setup

Figure 3. 2: Experimental setup.

3.2. Phase I Feedstock Material and preparation

Animal manure (cow dung) (AM), chicken manure (CM) and kitchen waste (KW) were used in the experiment. AM and CM were collected from a local dairy and poultry farm respectively in Banha, Qalyubia governorate of Egypt. KW was 100% composition of vegetable market waste from a local market in Kattameya, Cairo governorate. Vegetable waste consisted of tomatoes, cabbage leaf scrap, arugula, pepper, onion scraps, parsley, and mint among other components.

Basing on the literature review, KW was first sorted to remove inorganic impurities and then mechanically pretreated by shredding to reduce particle size before feeding. Four feedstock materials were prepared for the experiment as summarized in table 3-1 below. The AM in digester 4 was added as a starter to facilitate the anaerobic digestion process of the vegetable waste.

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Table 3- 1: Table 3-1: Feedstock material preparation

Digester	Description	Ratios
A	Animal Manure (AM)	1 : 0
B	Chicken manure (CM)	1 : 0
C	AM + CM	1 : 1
D	AM + Kitchen waste (KW)	1 : 4

Building on the significance of raw materials characterization in any anaerobic digestion process, initial characterization of the raw materials under experiment was conducted to determine the composition of the respective feedstock materials. Also a pathogenic bacterial count in the raw materials with respect to coliform forming bacteria (total and fecal), salmonella and shigella was done to establish the population of these pathogenic bacteria in the feedstock material. Results of the initial biological and chemical raw material characterization are shown in tables 3-2 and 3-3 respectively.

Table 3- 2: Pathogenic bacterial count in the digesters

Digester	T. Coli (cfu/ml)	F. Coli (cfu/ml)	S & S (cfu/ml)
A	113×10^{-2}	13×10^2	12×10^2
B	53×10^2	7×10^2	13×10^2
C	92×10^2	11×10^2	3×10^2
D	Not detected	Not detected	Not detected

Table 3- 3: Feedstock material characterization

Test	Units	A	B	C	D
Total Solids (TS)	%	8.60	8.00	7.60	1.80
pH		6.84	6.87	7.59	5.97
EC	dS/m	7.12	22.00	16.98	12.28
Total nitrogen	%	2.04	2.32	2.06	1.59
Ammonia nitrogen	ppm	156	3619	2134	564
Nitrate nitrogen	ppm	Nil	53	26	6

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Test	Units	A	B	C	D
Organic matter	%	62.38	52.95	58.0	44.75
Organic carbon	%	36.18	30.71	33.64	25.96
C/N ratio		18:1	13:1	16:1	16:1
Total phosphorus	%	0.45	2.09	1.7	0.7
Volatile Solids	%	47.36	39.71	40.50	33.56
Volatile Fatty Acids	mg/L	5	0.00	0.00	0.00

3.3. Analytical methods

Volatile Solids (VS), Total solids (TS), Ammonia nitrogen, Nitrate Nitrogen, Volatile Fatty Acids (VFAs) Organic matter, Organic carbon, total phosphorous and potassium tests were carried out in the microbiology lab at the Soils, Water and Environment Research Institute (SWERI) in the Agricultural Research Center (ARC), Giza – Egypt following standard test procedures as detailed below. All tests but the TS, pH and EC on feedstock samples during characterization were carried out based on dry weight. Temperature inside the digesters was recorded by inserting a clinical thermometer inside the digester (slurry) and taking readings at the respective intervals.

3.3.1. Chemical analyses

3.3.1.1.   pH
As explained in section 2.2.2 of chapter 2, pH is an important parameter in AD for its role in creating ideal conditions for microbial activity. A near neutral pH is optimum for the process. During the experiment, pH was measured using a laboratory bench top pH/mV meter model CP-511 shown in figure 3.3. Samples for pH measurement were prepared in ratios of 1:10 feedstock material to distilled water.

3.3.1.2.   Electrolytic conductivity (EC)
EC measurements were carried out on samples prepared from feedstock material and distilled water mixed in ratios of 1:1. In each of the tests, the mixture was filtered using a filter paper, and the EC of the filtrate measured using a combined pH/mV and EC/TDS/NaCl meter model HI 255 as shown in figure 3.4.

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Figure 3. 3: pH meter used in the experiments

Figure 3. 4: Combined pH/mV and EC/TDS/NaCl meter used during the experiments

3.3.1.3.   Total and Volatile solids

As earlier discussed in sections 2.2.5 and 2.2.6 of chapter 2, total and volatile solids play a significant role in biogas production. Total solids refer to the dry matter weight on an AD substrate expressed as a percentage of the total weight of a substrate sample, whereas volatile solids are the solid parts of the anaerobic digestion material that are broken down to produce biogas. In the determination of total and volatile solids content in the AD material, standard procedures outlined by (Water Pollution Control Federation, 1985).

Determination of VS content was by evaporation of a weighed sample of AD material on an evaporating dish in a muffle furnace. When working out the TS and VS composition of the substrate material, initially, fresh weight of 30ml of an evenly mixed AD sample was recorded. Then the sample was dried under a steam bath by evaporation at 103^0C for an hour before being cooled to be weighed again. From this the TS content was computed from the differences in weights.

The cooled substrate sample was used to determine the VS content of the feedstock material by placing it in a muffle furnace at 550^0C until sample completely burned out. The crucible after the furnace was allowed to partially cool in air and then returned to the desiccator to be cooled to room temperature. The crucible was then weighed and the difference in weight calculated. This loss in weight represents the VS content from which the VS percentage was computed.

3.3.1.4.   Ammonia nitrogen

Ammonia in the digester originates from the biological degradation of nitrogen –containing matter such as proteins and lipids present in the digestion substrate (Ghyselbrecht et al., 2017). Nitrogen present in the form of ammonia is essential in process monitoring. As discussed in section 2.2.4 of chapter 2, when the concentration of ammonia inside the digester exceeds a certain level, it becomes a process inhibitor. For this reason, it is important to closely monitor its concentration inside the digester.

Ammonia nitrogen content was determined following procedures outlined in (Water Pollution Control Federation, 1985). 100ml of the sample were clarified by addition of 1ml zinc sulfate solution followed by 0.5ml sodium hydroxide solution, mixed and filtered. 30ml of the filtrate were diluted in a Nessler tube to 50ml with distilled water. 3 drops of Rochelle salt solution were

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added to the solution in the Nessler tube followed by Nessler's reagent. the content of ammonia nitrogen was determined by spectrophotometric from comparisons with a series of standards.

3.3.1.5.   Total nitrogen

Total Nitrogen refers to the sum total of all the forms of nitrogen present in the sample; including nitrate, organic and ammonia nitrogen. Kjeldahl nitrogen is another term that refers to the summation of ammonia and organic nitrogen present in the sample. Total nitrogen was determined using the Kjeldahl sulfuric acid digestion method following procedures detailed in (Jackson M.L., 1973).

In this method, three gram samples were digested using concentrated sulfuric acid and a digestion mixture, which consisted of potassium sulfate, copper sulfate and selenium in a ratio of 100: 10: 1. During digestion, the organic nitrogen present in the samples was converted to ammonium ions. (NH_4^+) Distillation was then carried out with a 40 % sodium hydroxide solution to convert the ammonium ions into ammonia (NH_3). The evolved ammonia was absorbed in 10 ml boric acid (2%) with few drops of mixed indicator containing bromo-cresol green and methyl red indicator. Nitrogen content was determined from the concentration of the trapped ammonium ions obtained by titration with a standard solution of sulfuric acid.

3.3.1.6.   Nitrate nitrogen

Biological nitrification happens inside the digester producing nitrites which are rapidly oxidized to nitrates. The oxidative conversion of nitrites to nitrates is very rapid process that in some case not even traces of nitrites can be observed during the process. Nitrates are good indicators of process progress and stability (Water Pollution Control Federation, 1985). To determine nitrate nitrogen content in the samples, standard procedures of the Ultraviolet Spectrophotometric Screening Method detailed in (A.P.H.A.., 1998).

In this method, 1ml of hydrochloric acid solution was added to 50ml of a clear filtered sample and the two mixed thoroughly. Nitrate standard calibration curves were prepared in the range of 0 to 7mg NO3–-N/L by diluting a range of volumes of intermediate nitrate solutions from 0, 1.00, up to 35.0 l to 50 ml. Standard Nitrates (NO_3^-) were also treated in a manner similar to samples. This process was followed by the spectrophotometric measurement. Nitrates were read using the 220nm wavelength whereas for the case of dissolved organic matter interference, the 275nm wavelength was used.

3.3.1.7. Total phosphorous

Phosphorous content in the digester was measured following procedures listed in (EPA, 1978, p. 365). A mixture of 50ml sample, 1 ml sulfuric acid and 0.4 g ammonium persulfate was gently boiled in an Erlenmeyer flask for 30 minutes. After boiling, the mixture was cooled, diluted to 40ml and filtered. To the filtrate, 2 ml of ascorbic acid solution were added and the solution left to stand for 5 minutes. Total phosphorous content was then determined through spectrophotometry from the standard curve.

3.3.1.8. Organic carbon content

Total organic carbon is a composition of different organic compounds existing in range of oxidation states, some of which can undergo further oxidation while others cannot (A.P.H.A., 1998). Analysis of organic carbon content was conducted with employment of the wet-oxidation method outlined by the (A.P.H.A., 1998).

In this method, the AD sample was first acidified, purged to expel the inorganic carbon from the sample and then autoclaved with persulfate starting with a temperature of 116^0C and then increasing gradually to 130^0C. The resulting carbon dioxide was then measured by non-dispersive infrared spectrometry (A.P.H.A., 1998). This represented the organic carbon present in the AD feedstock material.

3.3.1.9. Volatile fatty acids (VFA)

As earlier discussed in section 2.2.7 of chapter 2, VFA play a significant role in biogas production yet as well have an inhibitory potential to the process should their concentration inside the digester exceed the desired limits. VFA are the main precursors of methane formation in AD. VFA concentration was determined by the distillation method following standard procedures outlined in (A.P.H.A, 1998).

During analysis, 200ml of AD samples containing various known concentrations of acetic acid were steam distilled following steps detailed in (A.P.H.A., 1998). The distillate was titrated with standards 0.1 sodium hydroxide solution to determine the VFA composition which was expressed as the acetic acid portion in the sample.

Biogas chemical composition tests were done at the central labs of the Egyptian Petroleum Research Institute in Nasr City, Cairo – Egypt by Gas Chromatography method. Gas samples were analyzed using a CP 3800 Varian - Gas Chromatograph shown in figure 3.5 below. Gas

samples were collected using 60ml clinical syringes. Rubber stoppers were used to seal the tips of the syringes to prevent the collected gas from escaping. Gas samples were taken for analysis on the same day of collection in all cases.

During analysis, standard test procedures for chromatographic natural gas analysis were followed in reference to (ASTM D1945, 2017). During the analysis, only CO_2 and CH_4 gases were specifically studied. The rest of the sample component gases were labeled as other gases – including nitrogen, hydrogen sulfide, oxygen and hydrogen. The GC method used measured CO_2 present only in the range of 0.01 Mol% to 20 Mol% and CH_4 in the range of 0.01 Mol% to 100 Mol%. TS and VS were determined according to Standard Methods reported by (Clesceri et al., 1989)

Figure 3. 5: Varian CP 3800 chromatograph used in the chemical analysis of biogas samples

3.3.2. Biological analysis

Coliform bacteria, salmonella and shigella were the main only bacteria studied during the biological characterization of the AD samples. These three forms of bacteria are normally present in manures, but have pathogenic effects on human, animal and plant health. Direct application of untreated manures to farm land as an organic fertilizer greatly increases these pathogen loads in the soil, which in the long run affects yields, and encourages proliferation of animal diseases. In this study, the populations of coliforming bacteria (fecal and total), salmonella and shigella are studied before and after AD purposely to investigate the effect of AD

on the bacterial loads in the slurry. The levels of pathogenic bacteria in the slurry could also be used as a parameter to define slurry quality for its application as an organic fertilizer in agricultural and landscape operations.

Coliform bacteria (total, T. Coli and fecal, F. Coli); Six plates were inoculated with 1 ml of the suitable dilution and poured with Mac Conekey's medium. Half of them were incubated at 35 – 37^0C for 24 hours for counting total coliform bacteria while the other plates were incubated at 44^0C for 48 hours for counting fecal coliform bacteria. Red, pink or nearly colorless with a pink center colonies were considered as coliform group bacteria (Difco laboratories, 1977)

Salmonella and Shigella (S & S); The inoculated plates containing Salmonella and Shigella agar medium were incubated at 35 – 37^0C for 24 hours. Black centered colonies were counted as Salmonella and Shigella microorganisms. (Difco laboratories, 1977)

3.4.   Phase II of the experiment.

The second phase of the experiment was prepared after completion of phase I digestion period and data collection. The experimental setup was exactly the same as in Phase I. However, in this phase different starter materials were investigated and only three reactors were operated. Unlike phase I, where the experiment was conducted outdoors, experiments in phase II were conducted indoors under psychrophilic condition. Experimental setup is shown in figure 3.6 below.

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Figure 3. 6: Phase II experimental setup

Phase II of the experiment mainly focused on KW material from three kitchens to three food outlets on AUC New Cairo campus. The kitchen waste, mainly a composition of fruit and vegetable waste and other impurities was collected from Catering Co., Formula Onederful and Tarwe2a kitchens located in the University's Parcel 17. Catering Co. has a diverse menu, serving fast foods, fresh vegetables, whole meal plates and fresh beverages. Formula Onederful serves fresh beverages and fast foods whereas Tarwe2a serves fast foods (sandwiches). As can be derived from the menus of the respective outlets, the biggest percentage of waste from formula Onederful was fruit waste, waste from Catering Co. was dominated by vegetable peelings, rotten fruit and vegetables while waste from Tarwe2a was mainly vegetable offcuts and other byproducts.

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3.4.1. Raw materials preparation

Mixed waste after collection was sorted to remove all inorganic impurities such as used surgical gloves, used tissue paper, foil and stored at 5^0C before further preparation for feeding. Before mechanical pretreatment, the waste was again secondarily sorted to separate vegetable from fruit waste. Vegetable waste was peelings from potatoes, onions, pepper, rotten tomatoes, carrots, lettuce, squash, cauliflower and broccoli. Fruit waste was a composition of orange pomace, apple offcuts, watermelon and cantaloupe pericarps, mango peels and rotten mangoes. The fruit and vegetable wastes were then each mechanically processed by shredding without addition of water.

At feeding, mixtures of equal portions of fruit and vegetable waste were prepared for each of the three digesters; KW1, KW2 and KW3 (ratio 1:1). Residual material from the digested feedstock of digesters A and B in phase I of the experiment were used as starters for digesters KW1 and KW2 in phase II setup respectively. A Chinese starter of the Bokashi type was used for digester KW3. pH of the raw materials after preparation was found to be 3.5, 3.7 and 3.4 respectively. The acidic pH of the feedstock material after preparation was adjusted using Calcium Carbonate. The experiment was run for a digestion period of six weeks. With all other conditions similar across the three digester, the only variables in this phase were the different starter materials used to inoculate the digesters as explained above.

Results of the initial characterization of the feedstock material are shown in table 3-4 below. In this phase, only chemical characterization of the material was conducted. Same analytical procedures as in phase I of the experiment were followed. The digesters were operated at psychrophilic temperatures (inside the digesters) fluctuating between 20 and 22^0C. The main reason for operating the digesters under psychrophilic temperatures was because, the experiment was conducted in winter. No extra provision of heating was attempted given the excess energy requirements to heat the setup and difficulty in maintaining and operating thermophilic systems (Arsova, 2010). Active digester volume was maintained at 75L.

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Table 3- 4: Characteristics of shredded raw materials for Phase II feeding.

Tests	Units	KW1	KW2	KW3
Total solids (TS)	%	10.5	11.2	10.8
pH		5.21	5.15	4.77
EC	ds/m	11.32	14.24	9.79
Total nitrogen (TN)	%	0.65	1.13	0.64
Ammonia nitrogen (NH_4^+)	ppm	531	2258	148
Nitreate nitrogen (NO_3^-)	ppm	67	Nil	54
Organic matter (VS)	%	38.58	14.25	50.39
Organic carbon	%	22.78	8.27	29.23
Ash	%	61.42	85.75	49.71
C/N ratio		34:1	27:1	45:1
Total phosphorous	%	0.14	0.43	0.18
Volatile Fatty Acids (VFA)	mq/l	6.2	5.9	3.8

3.5. Experimental Limitations

Since the experiment was carried out at a batch mode, the possibility of studying the effect of kinetic parameters on the progress of the process was very minimal. Therefore, in this experiment only biogas production rate could be measured on a daily basis. Chemical and biological composition analyses on the slurry during the process were limited to keep the degrees of error as low as possible.

Chapter 4
Results and discussion

As elaborated in the preceding chapter, the experiment was conducted in two phases. The main aim of phase I setup was to investigate the feasibility of producing biogas on a small scale from AM, CM and KW while as well testing the efficiency of low tech locally fabricated digesters at biogas production. Phase II on the other hand concentrated on producing biogas from AUC kitchen waste through three digesters KW1, KW2 and KW3 inoculated with digested AM, digester CM and Chinese bokashi respectively. Basing on the experimental assumption, record for the volumes of overflown solution in all the seven different digester was taken to represent the amount of biogas produced. Pathogenic microbial population counts done herein were aimed at studying the effect of methanogenesis on the respective microbes. This in turn would be used to grade the quality of organic fertilizer (slurry) building on its freedom from E. coli, salmonella and shigella. This chapter discuses results from both phases of the experiment.

4.1. Results from experimental phase I

During the experiment, record of weekly biogas production from the respective digesters was taken. Results of biogas production recorded over the ten weeks of experimental phase I digestion for three of the feedstock materials are shown in table 4-1 in the appendix. Besides biogas yield, included in the table is the cumulative biogas production from the three reactors through the experimental digestion period.

Relations between weekly and cumulative biogas production in all the digesters were plotted as in the chats shown in figures 4.1, 4.2 and 4.3 below to better track the behavior of all raw materials with respect to their biogas yield during the digestion process. Figure 4.4 compares the cumulative biogas yields from the three digesters throughout the experimental detention time.

Data collected revealed that in the first week of the experiment, the highest amount of biogas produced was recorded in digester A at 34.48L of biogas (figure 4.1). The quantity of biogas produced from the same digester varied weekly as the process advanced, reaching a maximum of

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44.62L in the fifth week of the experiment as shown in figure 4.1. After attaining peak, the following weeks recorded a gradual decline in gas production reaching the lowest mark at 14.79L during the last week of the experiment (figure 4.1).

On the other hand, digester B recorded the least biogas yield (0.49L) in the first experimental week as indicated in figure 4.2. Gas production then increased drastically through the second and third weeks, a production peak of 49.24L (figure 4.2) of biogas in week five of the experiment. The peak record as was the case in digester A was followed by a gradual and steady decline in biogas production reaching 23.83L in the last experimental week as shown in figure 4.2. Biogas yield from digester C in the first week of the experiment in figure 4.3 was second to digester A recording only 32.74L of gas. Successive weeks witnessed a steady increase in biogas yield reaching the highest recorded figure in the fifth week of the experiment (50.46L) (figure 4.3). Although this was the most superior yield of biogas recorded from any of the digesters in experimental week five, the trend of biogas yield in digester C wasn't any different from that of both A and B. There was also a decline in biogas yield through the successive weeks of digester C experimental activity until the last week of the experiment. In the last week of the experiment, biogas yield from digester C was 13.31L (figure 4.3) and also the lowest among the three digesters in the same week.

As observed from the results in figures 4.1 – 4.3, anaerobic degradation in all the three digesters followed a similar trend; gradually increasing at the start of the process, reaching a peak and then gradually decreasing until the end of the experiment. The reason for such behavior is the direct relation between biogas yield and specific growth rate of methanogenic bacteria in batch anaerobic digesters (Nordberg & Edström, 2005). The initial general increase in biogas production is in conformity with a research conducted by (Li et al., 2011) which attributed the change to the presence of readily biodegradable organic matter and a considerable population of methanogens in all the digestion substrates. The gradual decline in gas production recorded between the sixth and tenth week meshes well with research conducted by (Xie et al., 2011). This is partly due to the low content readily biodegradable organic compounds in the slurry.

The highest biogas yield from all the digesters was reached in the fifth week. In the first half of the experiment (between week one and five), average increase in biogas yield was highest in digester B and least in digester A. One conclusion that can be drawn from this is that although

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initial biogas yield was very low in digester B, the degradative microbial population in digester B showed the highest corporation in the first half of the digestion process. The average decrease in the second half of the process (between week five and ten) on the contrary was highest in digester C and least in B.

A step further to calculate, tabulate and plot (figure 4.4) the cumulative biogas production during the ten-week digestion period best elaborates the total gas yield from the respective reactors while giving account for the gas accumulation in each successive week. Similar to the records for the daily biogas production from each digester, calculations of the cumulative gas yield also show highest biogas production from all reactors to have been reached in the week five of the experiment. From the cumulative biogas graph in figure 4.4, digester C accumulated the highest biogas at 329.95L. This was followed by B with 300.54L. Digester A accumulated the least gas at 285.33L. These results are in agreement with results reached in the experiments conducted by (Chomini et al., 2015) as detailed in the literature, which showed that a 1:1 mix of poultry manure and cow dung gave better yield of biogas than each digested singly as a monosubstrate.

As in (Chomini et al., 2015) experiment, digestion of CM as a monosubstrate showed better results when compared to the digestion of AM also as a mono substrate. Achieving similar results in their experiments, (Hobson et al., 1981) ascribed the inferior yield in biogas from AM to a low biodegradable materials composition. Research by (Nnabuchi et al., 2012) credits the superior biogas yield from CM to a presence of special micro flora characteristic of the manure.
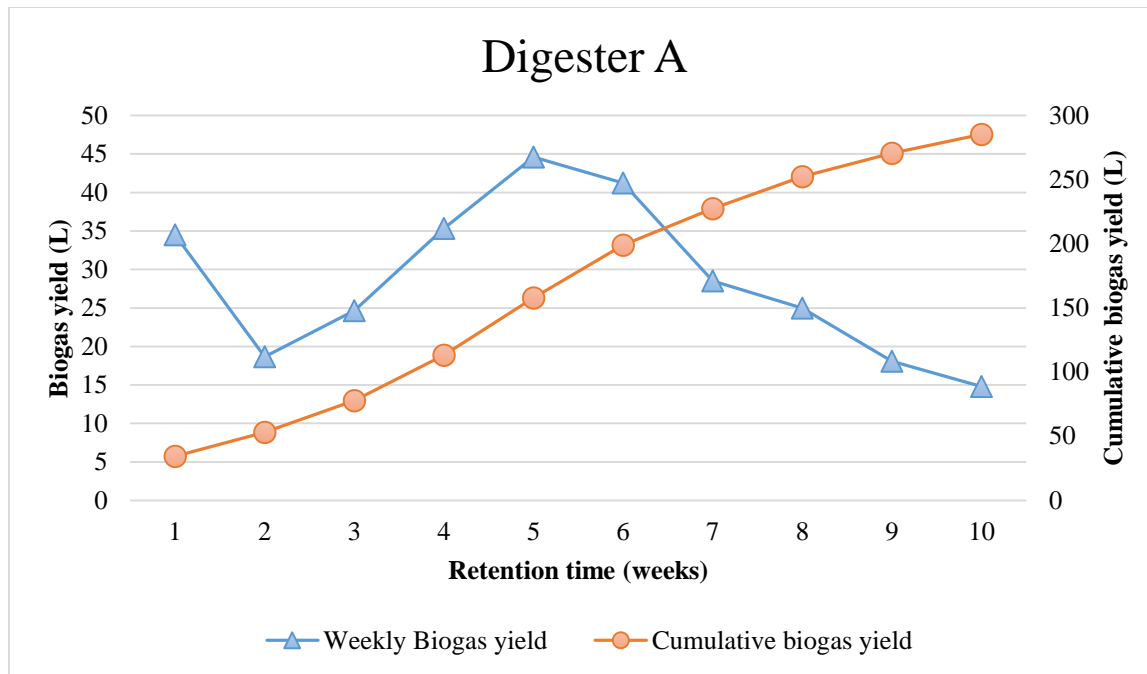
Figure 4. 1: Weekly and cumulative biogas production from digester A

There was no gas production observed/recorded from digester D throughout the experimental period. A number of factors could be pinned for this. From literature, the particle size of the feedstock material plays a big role in orienting the success of a kitchen waste degradation process. (Yadvika et al., 2004) mention that large particle size of the material makes it difficult for the bacteria to perform their digestive role, and therefore affecting the hydrolysis and acidogenesis stages of the process (Basaria & Priadi, 2016) and consequently the overall progress.

Secondly, the TS level in the prepared sample was lower than the optimum TS recommendations from (Babaee & Shayegan, 2011a) who established that running a vegetable waste digester at 8% TS gave good and stable results. The uneven improper shredding of the kitchen waste material during preparation could as well have contributed to the low TS percentage. (Li et al., 2016) point that higher pungency degrees (PDs) in kitchen waste originating mainly from capsaicinoids present in peppers and chilies may exhibit inhibitory effects to microbial activity during digestion. Higher PDs according to the research showed a negative impact on the anaerobic degradability of kitchen waste. Therefore, existence of considerable amounts of peppers and chilies in kitchen waste is very likely to affect the kinetics of the anaerobic digestion process.

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Another assumed cause of the failure to produce biogas in digester D was the possibility that the vegetable waste from the market was contaminated by chemicals which may have killed the anaerobic bacteria, hindering the anaerobic digestion process. The chemical contaminants may have been from two main sources, residues of pesticides applied during production or foliar applied fertilizers. Owing to the sensitivity of anaerobic bacteria to any forms of toxicity, presence of chemicals in such levels that induce toxicity would very much account for a failed digestion process.
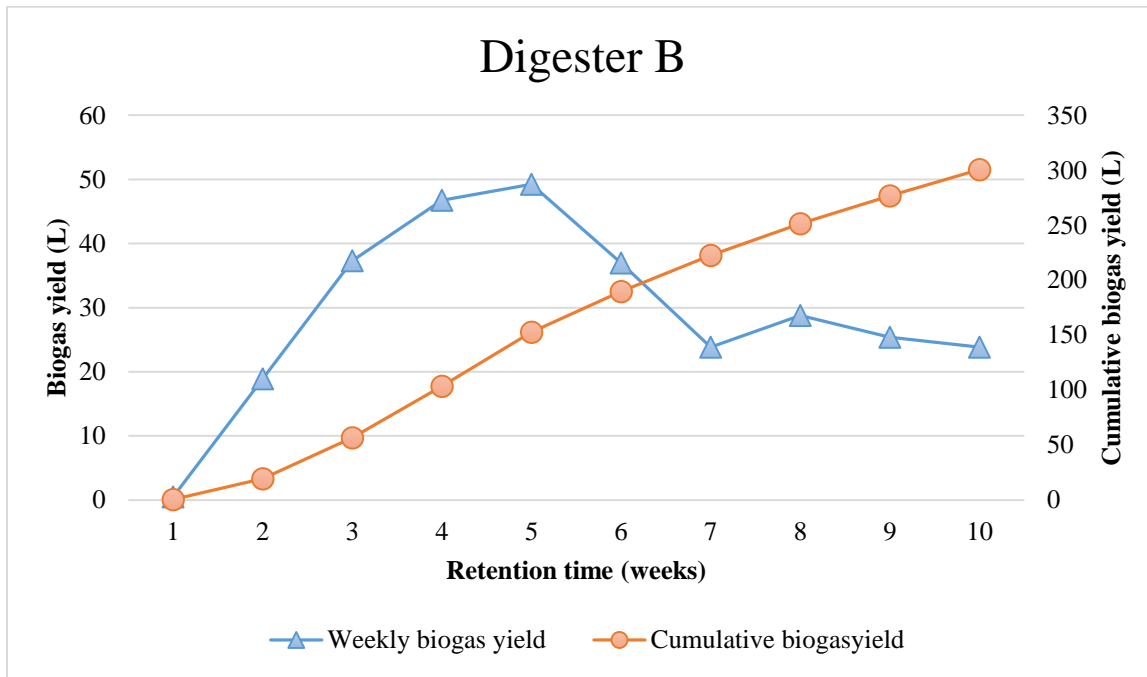
Figure 4. 2: Weekly and cumulative biogas production from digester B
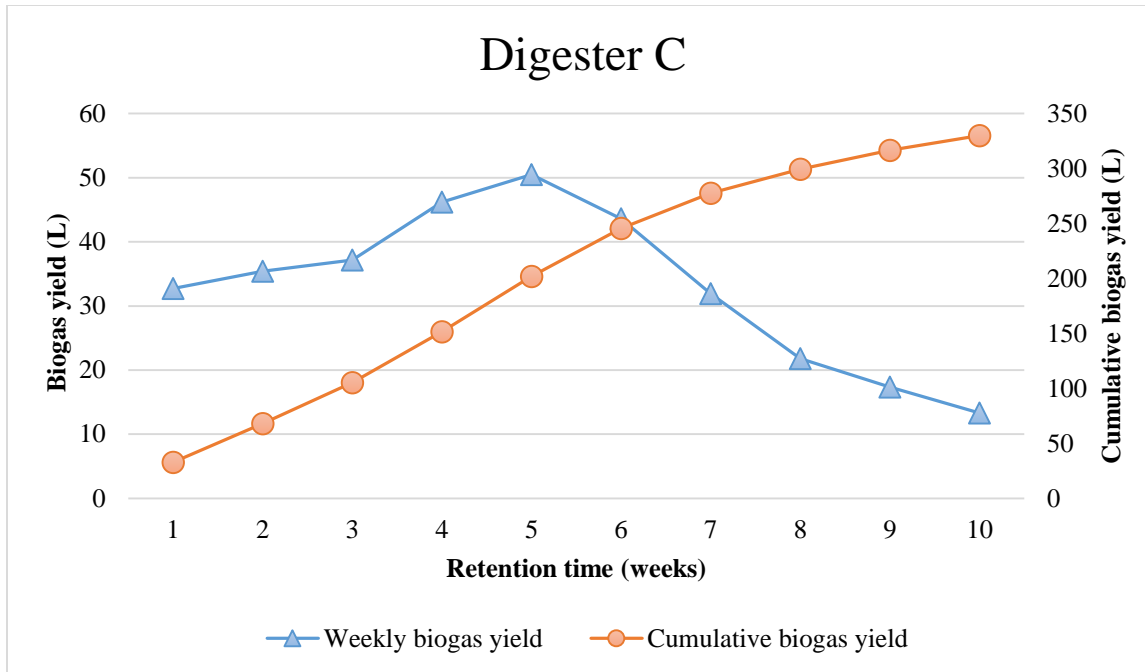
Figure 4. 3: Weekly and cumulative biogas production from digester C
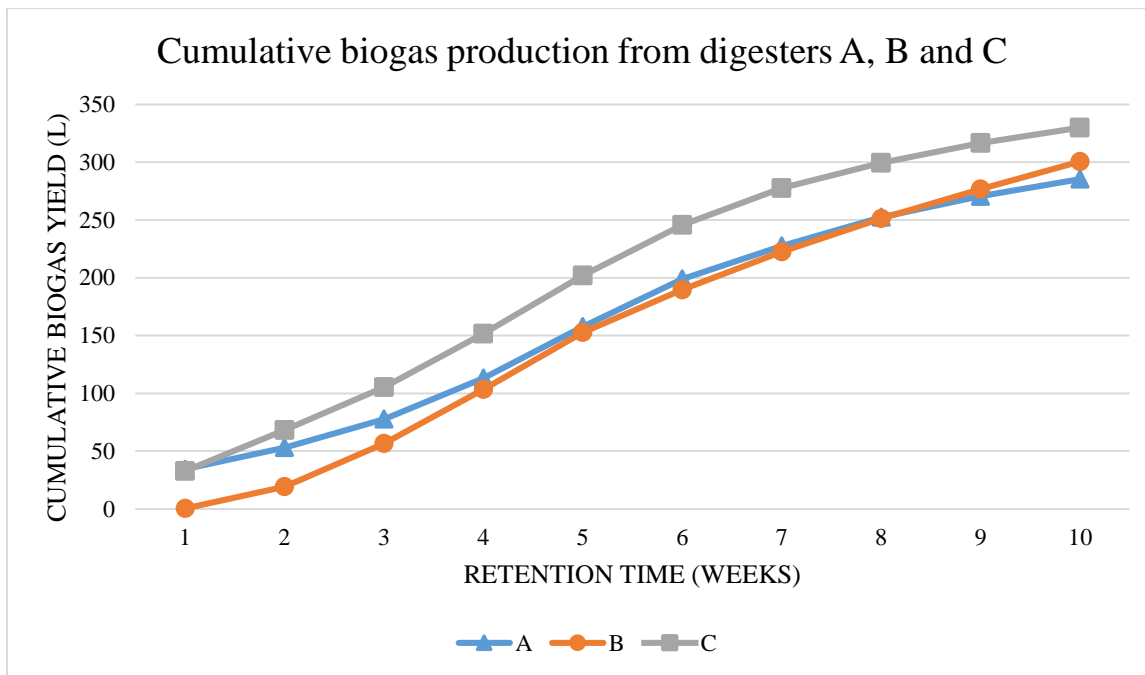
Figure 4. 4: Cumulative biogas production from three of the digesters throughout the retention time.

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4.1.1. Phase I biogas analysis

The biogas produced during the experiment was analyzed for its chemical composition with respect to CH_4 and CO_2. Only the two gases were studied because these are the principle gases of which biogas is composed. Three gas samples taken in the fourth, seventh and tenth weeks of the experiment respectively were analyzed. The results are shown in table 4-2 in the appendix. Relations between CO_2 and CH_4 in the respective digesters are also graphed in figures 4.5, 4.6 and 4.7.

CH_4 yield in all digesters followed an increasing trend from the first to the last month of the experiment. CO_2 on the other hand follows a decreasing trend throughout the experimental period with the accumulation of CH_4. Digester B showed superior methane yield, with the peak reached at 81.94% methane followed by C with 68.5% methane and A with 63.55%. Peaks in all the reactors were recorded in the last week of the experiment. (Nelson, 2005) credits superior methane yield to high TS/VS values. Table 4-3 reflects the role of TS/VS ratio the high methane yield from digester B relative to C and A. From the table, average TS/VS ratio through the experiment is higher in reactor B than in C and A. Gas analysis shows that the peaks in gas accumulation were not reached until the last week of the experiment.
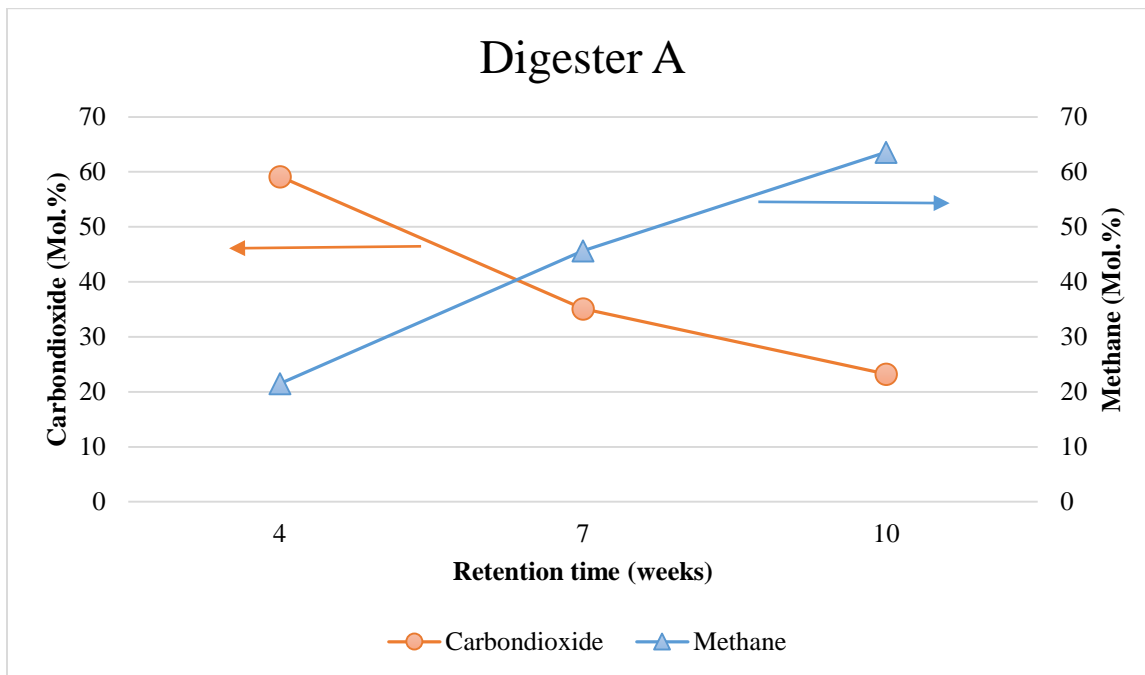
Figure 4. 5: CO$_2$ and CH$_4$ production from digester
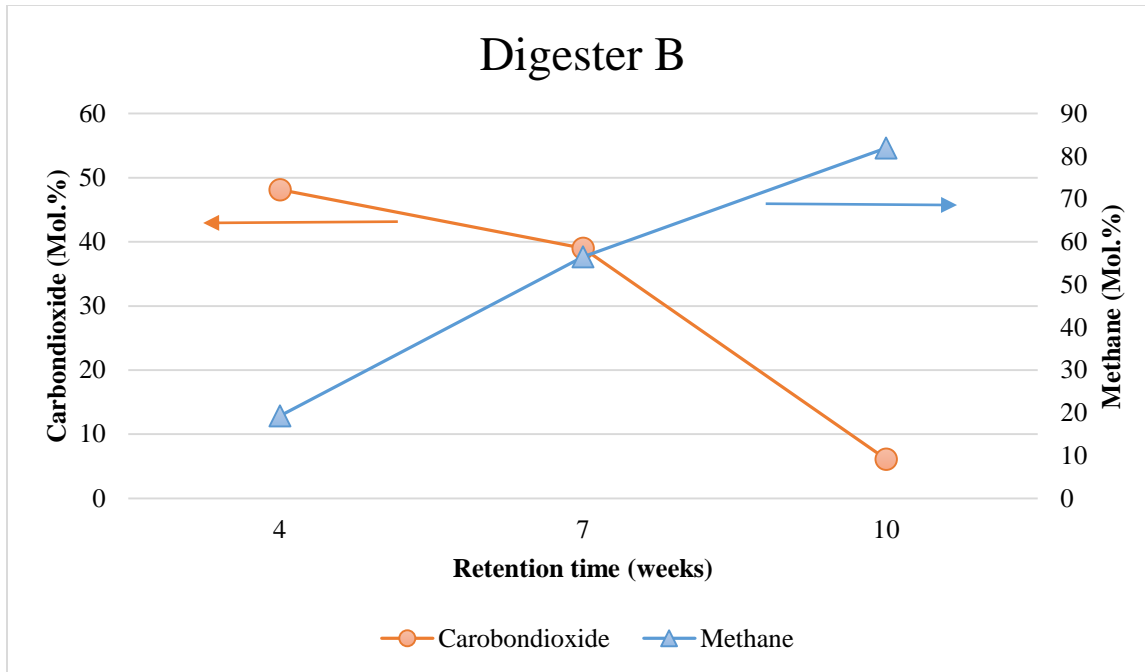
Figure 4. 6: CO₂ and CH₄ production from digester B
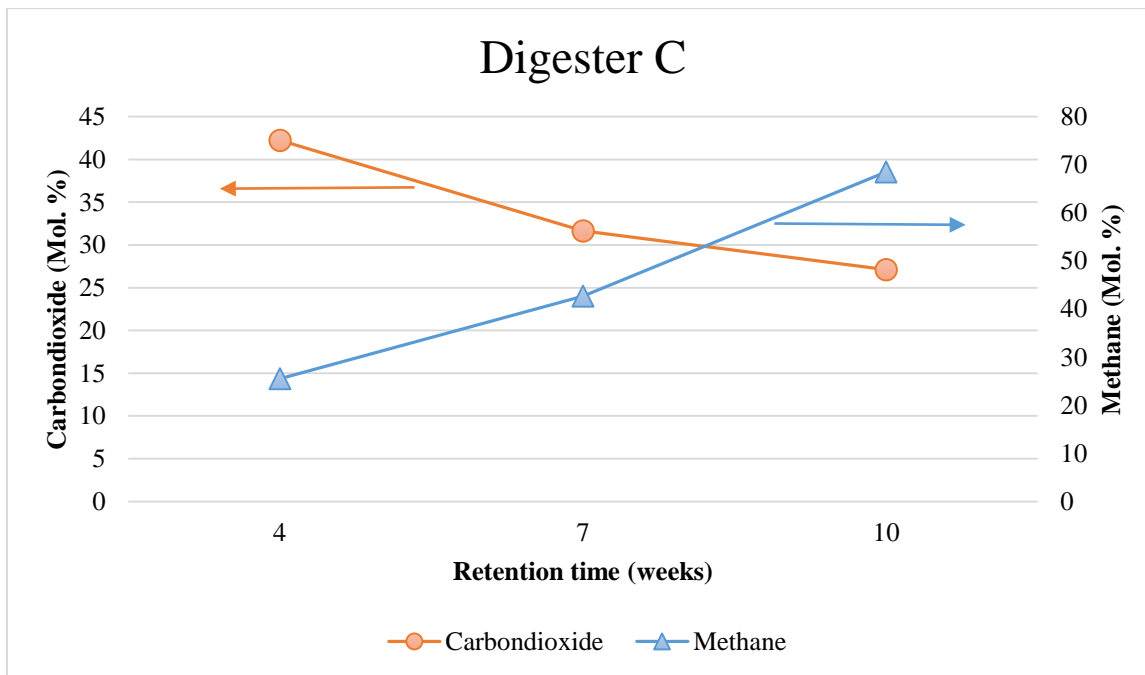
Figure 4. 7: CO₂ and CH₄ production from digester C

4.1.2. Organic material decomposition inside the digester.

The rate of organic matter decomposition inside the digester at different digestion stages was traced with reference to the changes in TS, VS (organic matter) and Total Nitrogen (TN)

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concentration inside the digester. Values of TS, VS and TN by weight in kilograms were calculated as a function of the total solids concentration in the digester using formulas (1), (2) and (3) respectively and the results tabulated in table 4.3 below.

$$TS\ (Kg) = \frac{TS\%\ X\ Substrate\ weight}{100} \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)$$

$$VS\ (Kg) = \frac{TS(kg)\ X\ VS\%}{100} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (2)$$

$$TN\ (Kg) = \frac{TS(kg)\ X\ TN\%}{100} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

Decomposition rates and percentage losses in TS, VS and TN by weight at different stages of the degradation process were calculated following equation (4) and (5) below. Results of the deductions from mathematical application of formulas 4 and 5 are tabulated in tables 4-4, 4-5 and 4-6 below.

$$Decomposition\ rate$$
$$= \frac{original\ value - new\ value}{original\ value}\ X\ time\ between\ values\ (weeks)\ X\ 1000.. (4)$$

$$Percentage\ loss = \frac{initial\ value - value\ at\ specific\ time}{initial\ value}\ X\ 100\% \ldots \ldots \ldots \ldots \ldots (5)$$

Table 4- 1: TS, VS and TN values from the three digesters expressed in percentage and weight

Time (weeks)	TS %	TS (kg)	VS %	VS (kg)	TS/VS ratio	TN %	TN (kg)
Digester A							
1	8.6	1.72	62.38	1.07	1.61	2.04	0.035
4	7.3	1.46	58.68	0.86	1.70	1.53	0.022
7	4.1	0.82	53.88	0.44	1.86	0.33	0.003
10	2.7	0.54	53.14	0.29	1.86	0.02	0.000
Digester B							
1	8.0	1.60	52.95	0.85	1.88	2.32	0.037

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4	7.4	1.48	49.55	0.73	2.03	1.65	0.024
7	6.0	1.20	44.45	0.53	2.26	0.15	0.002
10	5.1	1.02	42.96	0.44	2.32	0.02	0.000
Digester C							
1	7.6	1.52	58.00	0.88	1.73	2.06	0.031
4	6.8	1.36	55.30	0.75	1.81	1.30	0.018
7	5.2	1.04	53.50	0.56	1.86	0.28	0.003
10	4.1	0.82	52.45	0.43	1.91	0.02	0.000

Table 4- 2: Percentage loses and decomposition rates of TS, VS and TN in digester A calculated at different stages during the digestion period

Digestion time (weeks)	TS % loss	TS DR (g/week)	VS % loss	VS DR (g/week)	TN % loss	TN DR (g/week)
1	-	-	-	-	-	-
4	15.12	604.65	19.63	785.05	37.1	1485.7
7	52.33	1315.07	58.88	1465.12	91.4	2590.9
10	68.60	1024.39	72.9	1022.73	100.0	3000.0

Table 4- 3: Percentage loses and decomposition rates of TS, VS and TN in digester B calculated at different stages during the digestion period

Digestion time (weeks)	TS % loss	TS DR (g/week)	VS % loss	VS DR (g/week)	TN % loss	TN DR (g/week)
1	-	-	-	-	-	-
4	7.50	300.00	14.12	564.71	35.14	1405.4
7	25.00	567.57	37.65	821.92	94.59	2750.0
10	36.25	450.00	48.24	509.43	100.0	3000.0

Table 4- 4: Percentage loses and decomposition rates of TS, VS and TN in digester C calculated at different stages during the digestion period

Digestion time (weeks)	TS % loss	TS DR (g/week)	VS % loss	VS DR (g/week)	TN % loss	TN DR (g/week)
1	-	-	-	-	-	-
4	10.53	421.05	14.77	590.91	41.94	1677.4
7	31.58	705.88	36.36	760.00	90.32	2500.0
10	46.05	634.62	51.14	696.43	100.0	3000.0

There was a uniform decreasing trend in the concentrations of TS, VS and TN inside the respective digesters through the digestion period. This can be linked to the increasing microbial population and activity inside the digesters at the different stages of digestion. At the start of the experiment, the level of volatile solids is high in all the three digester, but rather falls gradually as the anaerobic digestion process progresses. Relating results of table 4-3 with the methane production through the detention time, there is an inverse relation between methane yield and TS, VS and TN reduction during the process. The negative relation between TS reduction and

methane yield was also observed by (Liotta et al., 2014).

Although the percentage losses and decomposition rates for all the three parameters increase through the digestion period, the percentage decrease of TS, VS inside the digester only increased until the seventh week, after which they started declining. This was a signal of digestion process failure. Relating results of tables 4-4 to 4-6 to methane production, increase in the decomposition rate of VS seems to have an impact on the methane yield. The inverse relation between methane yield and VS loses and destruction is also reported by (Gray et al., 2008).

4.1.3. Cumulative biogas production predictive mode

Cumulative biogas produced and recorded from the different digesters was used to derive statistical predictive models for biogas production from the respective substrates at different retention times. Regression analysis models were used to observe the nature of relationship between biogas production and retention time as a basis to establish a mechanism for predicting or forecasting biogas yield (Ali & Rundong, 2016). Regression functions including linear,

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polynomial, exponential, power and logarithmic were studied using Microsoft excel software. While analyzing biogas production using regression models, models with the highest level of coefficient of determination (R^2) between the model type and the actual data generated from the experiments are sought (Nnabuchi et al., 2012). R^2 statistically expresses how close the experimental data is to the fitted regression line. The value of R^2 ranges from 0 to 100%; the closer to 100% the better the model fits the experimental data (Frost, 2013). When conducting the regression analyses in this research, CBP stood for the Cumulative Biogas Production, whereas T represented the Retention Time.

R^2 values generated from the respective regression functions to predict the cumulative biogas yield are shown in table 4-7 below. After conducting regression analyses, a comparative study was done for R^2 values generated to obtain the highest values, which would be selected as the best fits to the experimental data. It was observed that R^2 values in all cases but the exponential function in digester B were high. However, in all digesters the polynomial function showed the highest level of reliability when compared to the rest because of its very high R^2 values. In the prediction of cumulative gas production based on the data from this research therefore, the polynomial function would be most genuine.

Table 4- 5: Values of coefficient of determination (R2) generated from the different regression functions

Digester	Polynomial	Linear	Logarithmic	Power	Exponential
A	$R^2 = 0.9879$	$R^2 = 0.9835$	$R^2 = 0.9038$	$R^2 = 0.9833$	$R^2 = 0.9137$
B	$R^2 = 0.9935$	$R^2 = 0.9887$	$R^2 = 0.9157$	$R^2 = 0.8904$	$R^2 = 0.6461$
C	$R^2 = 0.9932$	$R^2 = 0.9725$	$R^2 = 0.9420$	$R^2 = 0.9903$	$R^2 = 0.8541$

4.2. Results from experimental Phase II

The experiment only focused on kitchen waste sourced from AUC kitchens. Three different samples were prepared, each inoculated with a different starter. Figures 4.8 and 4.9 below show results of the daily and cumulative biogas production respectively from the three digesters. In addition to the initial characterization of the feedstock materials, two other samples for material

characterization were taken in second and sixth weeks of the experiment. Table 4-8 shows changes in material characteristics inside the digesters during the digestion process.

Biogas production in all three reactors started right from the first day of experimental set up. Production then decreased before again rising to hit the highest marks in the respective digesters. The decrease periods and time to reach maximum gas yield were different in the three digesters.
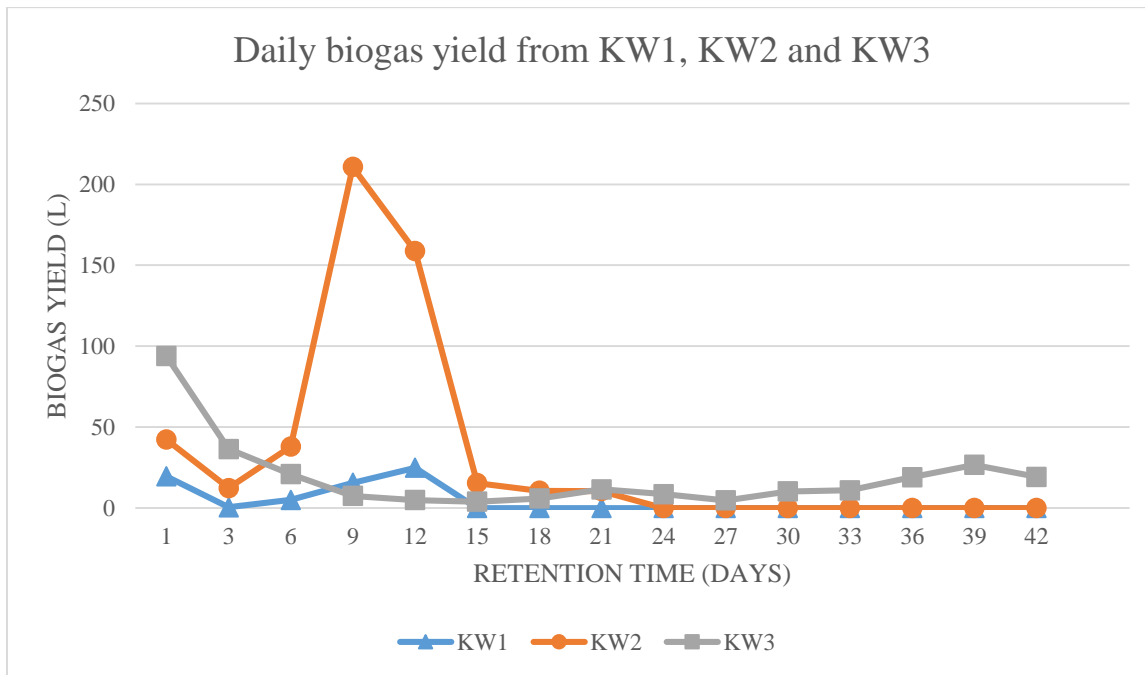
Figure 4. 8: Daily biogas production from KW1, KW2 and KW3
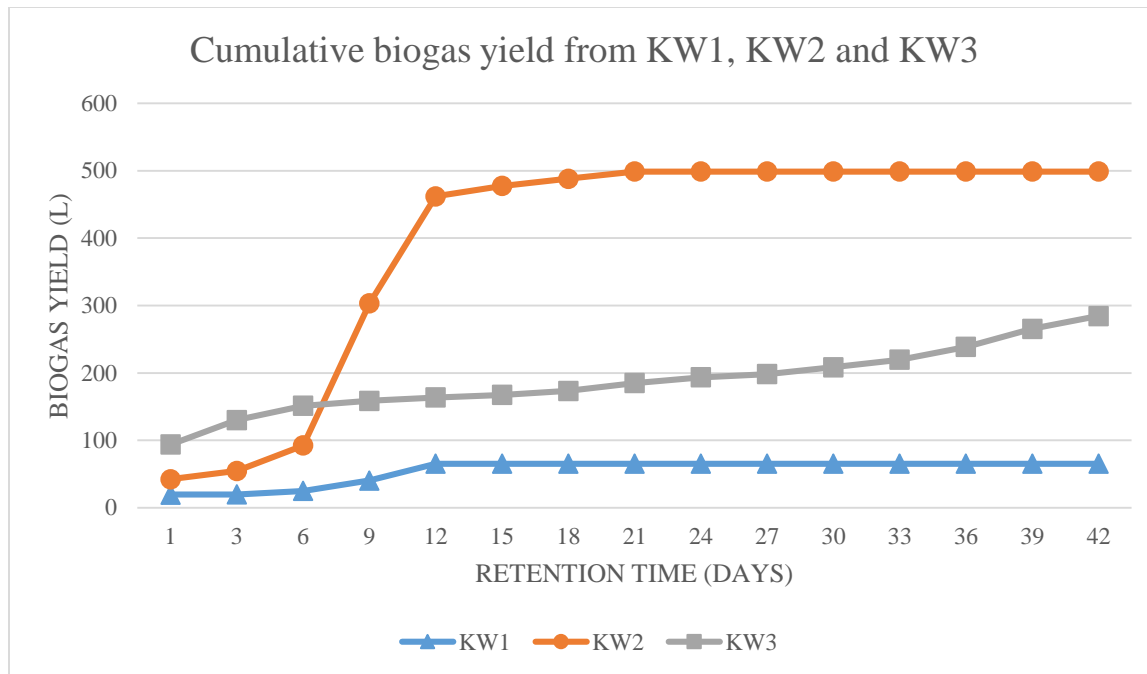
Figure 4. 9: Cumulative biogas production from KW1, KW2 and KW3.

From figure 4.9, on the first day of the experiment, KW3 recorded the highest biogas yield of 94L yet the least gas production on the same day was observed in KW1 at only 20L of gas. Until the third day, gas production decreased in KW2, after which it gradually increased through day six. A drastic increase in gas production was then observed after the sixth day of digestion to reach the highest biogas yield in KW2 (211L) on day nine of digestion. This was followed by a gradual and then rapid decline in gas production before again gradually declining at the end of the second week of digestion. Gradual decrease in gas production continued in KW2 up to day 24 of the experiment when production died out.

Biogas production from KW1 similar the behavior in KW2, also decreased through day three followed by a gradual rise to the highest recorded mark of 25L immediately after which production died out completely for the rest of the experimental detention time. KW3 displayed quite a different gas production pattern than did KW1 and KW2. Despite the high initial gas yield, gas production gradually decreased through the first two weeks of digestion. Production then fluctuates until the end of the experiment without any significant peaks or troughs.

Table 4- 6: Characteristics of feedstock material at different stages inside the digesters during digestion.

Tests	KW1			KW2			KW3		
	Initial	2nd week	6th week	Initial	2nd week	6th week	Initial	2nd week	6th week
Total Solids (TS) %	10.5	10.6	10.5	11.2	8.1	13.0	10.8	7.8	9.1
pH	5.21	5.4	5.17	5.15	5.54	5.29	4.77	5.11	5.35
EC (dS/m)	11.32	10.79	12.84	14.24	14.35	14.97	9.79	10.158	11.17
Total Nitrogen (%)	0.65	1.2	2.12	1.13	1.18	2.59	0.64	0.92	1.95
Ammonia Nitrogen (ppm)	531	-	-	2258	-	-	148	-	-
Nitrate Nitrogen (ppm)	67	-	-	Nil	Nil	Nil	54	-	-
Organic Matter (%)	38.58	44.97	43.72	32.89	14.25	32.87	50.39	50.45	71.01
Organic Carbon (%)	22.78	26.8	25.36	8.27	19.08	19.07	29.23	29.26	41.19
Ash (%)	61.42	61.42		85.75	85.75		49.71	49.71	
C/N Ratio	34:1	22:1	12:1	7:1	16:1	8:1	45:1	32:1	21:1
Total Phosphorous (%)	0.14	0.17	0.46	0.43	0.41	0.36	0.18	0.17	0.39
VFA (mq/l)	62	266	32.5	59.2	312	32.0	37.6	69	13.6

Results of VFA in table 4-8 show that there was a rapid accumulation of VFAs in the second week of the experiment. In KW2 for example, the concentration of VFA increased over fivefold from 59 to 312mq/l. This rapid accumulation of VFA as was mentioned in the literature may have constituted an inhibitory effect which may have slowed down the process at the end of the second week of the experiment in all digesters. The accumulation of VFA in KW3 however was much lower than in KW1 and KW2, it could be for this reason that biogas production continued in KW3 even when production died out in KW1 and KW2.

Plotting the cumulative gas production (figure 4.9) shows that, KW2 accumulated the highest gas production through the experiment even though production stopped only three weeks after feeding. KW3 on the other hand produced biogas throughout the experimental period. In KW1

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and KW2, highest gas production was recorded between day 2 and 15 of the experiment. This suggests that the best retention time in the digestion of AUC kitchen waste should be between 7 and 15 days. For its high biogas yield, the use of digested chicken manure as a starter in anaerobic digestion of AUC kitchen waste would be most viable. Under conditions identical to those observed during the experiment, the use of bokashi as the starter would require longer retention times and consequently a larger digester. All this translates into higher capital and operation costs, which makes the starter undesirable.

Anaerobic digestion of kitchen food waste has not been alien to low retention times as observed from this study. In their experiment (Gray et al., 2008) suggested a 10 days retention as ideal.

4.2.1. Phase II biogas analysis

Four gas samples collected in the first, second, third and sixth weeks of the experiment were analyzed using Gas Chromatography for their composition of CH_4 and CO_2 respectively. Results of the analyses are shown in table 4-9 in the appendix.
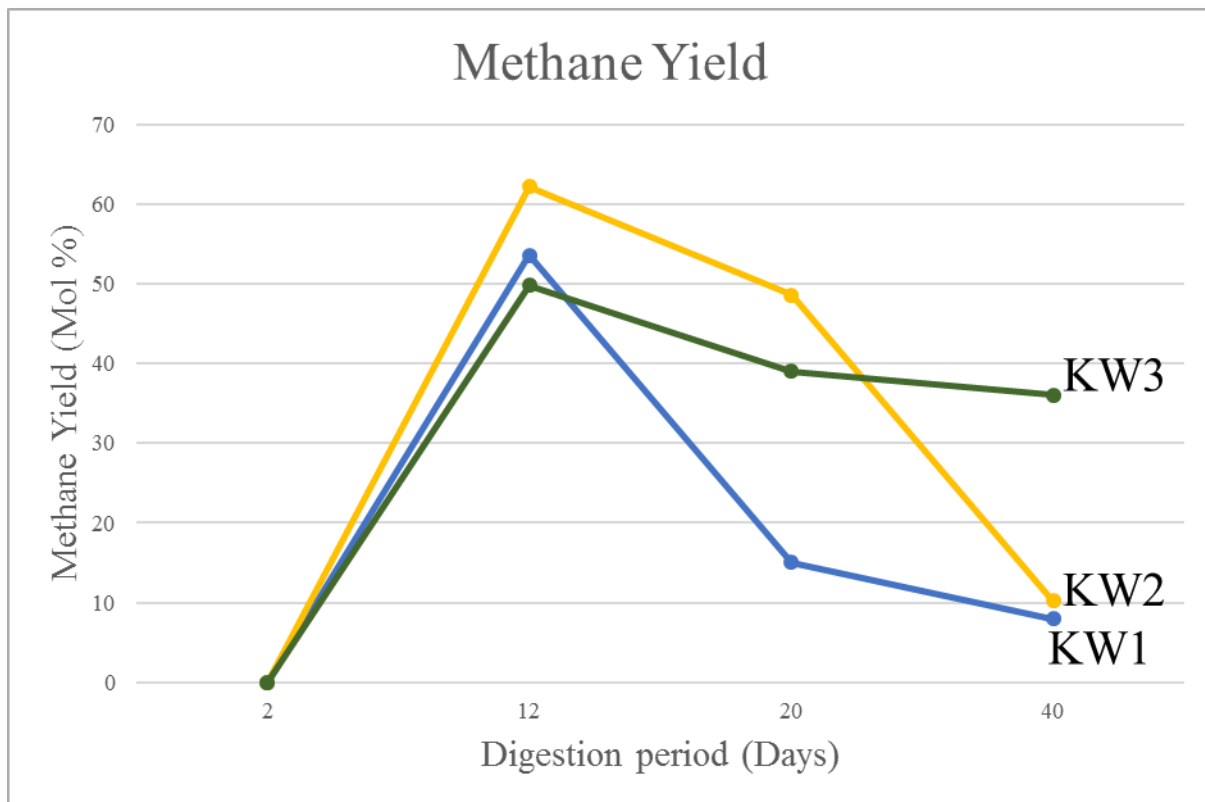
Figure 4.10: Methane yield in the biogas in phase II experiment

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From figure 4.10 above, there was no methane yield in the first two days of the experiment. This was because of the slow growth rate of methanogens (Bajpai, 2017) and the low initial digester pH which affects methane formation (Nelson, 2005). This form of lag phase is followed by an exponential methane production phase in the second week of the experiment, which may be attributed to the stable pH and temperature conditions inside the digesters at the time. Fluctuations in temperature that followed this period could as well have been the causes of the sudden declines in methane production in all digesters, owing to the sensitivity of methanogens to such sudden changes (Bajpai, 2017). Also the survival of methanogens is exclusively dependent on the continued proliferation of acetogens and acidogens - these convert the products of hydrolysis into substrates required by the methanogens in the methane forming stage (Bajpai, 2017). A reduction in their population observed from the reduction in biogas production would also provide a valid account for the drop in methane production mainly in KW1 and KW2.

The superior performance of KW2 in biogas production may be credited to the quality of the starter inoculum (digested CM). (Nnabuchi et al., 2012) reports that CM contains special microflora essential to methanogenesis, whose collective effect may have contributed to the high methane yield in KW2. Although KW3 had an inferior methane yield compared to KW1 and KW2, the rate of decline in methane yield after the second week was also the least. The sustained methane yield in KW3 routes from the rich and seemingly tolerant microbial consortium in the Chinese bokashi starter used as inoculum. From its composition, Chinese Bokashi constitutes a population of essential anaerobic bacteria and other effective microorganisms all which play significant roles in the anaerobic degradation process. Low temperature and pH may have retarded the efficiency of methane production by either inhibiting the multiplication of methanogens or setting stage for growth and multiplication of some undesirable microorganisms inside the digester which negatively impacts methanogenesis.

Although (Das & Chanchal, 2013) argue that fruit and vegetable wastes have the highest methane potential when compared with other organic municipal solid wastes, the observed average methane yields from all three digesters do not conform with the statement. Methane yields from the experiment as can be seen in table 4-9 (appendix) are slightly below that reported in most of the literature from the digestion of other organic materials - take for example in phase I of this very experiment, where methane yield was up to 82% in the digestion of chicken

manure. The low methane yield may have resulted from both the low temperature at which the reactors were operated, which affects the methane forming microbial consortia and hence the process itself (Kashyap et al., 2003) (Dhaked et al., 2010), and the fluctuations in temperature which have a significant negative impact on the reaction kinetics and yield of methane (Khalil et al., 2016) (Bouallagui et al., 2004).

Methanogensis under psychrophilic conditions is presumably accomplished by mesophilic bacteria which adapted to the low temperatures to facilitate methane formation (Kashyap et al., 2003) (Dhaked et al., 2010). For this reason, (Kashyap et al., 2003) charges the low methane yield on the inability of the methanogens to adapt to the low temperatures. (Kashyap et al., 2003) also point out that at temperatures below those optimum to their kind for growth, micro bacteria lose the ability to ingest materials from their surrounding because of impaired affinity, causing starvation and lowered performance. The role of this phenomenon in the low recorded methane yield from the experiment cannot therefore be ruled out. However, literature also notes that a mere increase in digester temperature from psychrophilic to mesophilic or thermophilic ranges would significantly increase both biogas and methane yields (Bouallagui et al., 2004). Therefore, biogas and methane production potentials of the same setups under mesophilic or thermophilic conditions would be significantly higher than observed from the experiment.

Despite the complexity in biogas and methane yield under low temperatures, anaerobic digestion at psychrophilic temperatures is hailed by (Khalil et al., 2016) for its lower operation cost relative to mesophilic and thermophilic systems given that no heating is required and their suitability for use in warmer climates let alone their very high methane yields in temperatures between 22^0C and 28^0C while digesting food wastes.

4.3. Slurry characterization at the end of phase I experiment.

Results from the analyses to characterize the slurry at the end of the digestion period are shown in table 4-10 and 4-11 below. Table 4-10 focuses in the chemical analysis of the slurry whereas 4-11 focuses on the biological composition of the slurry in terms of pathogenic bacterial population. Similar experimental procedures during slurry characterization were followed as was the case in feedstock characterization. Comparing results of slurry and feed stock analysis, there was an overall reduction in the TS and VS percentages from all digesters. This was expected

because as a result of microbial degradation, both TS and VS are broken down during anaerobic digestion to produce biogas.

Table 4- 10: Slurry chemical characterization after a 10 weeks' digestion period

Test	Units	A	B	C	D
Total Solids (TS)	%	2.70	5.1	4.10	0.7
pH		7.18	7.90	7.60	7.42
EC	dS/m	6.17	18.65	14.18	9.07
Total nitrogen	%	0.02	0.02	0.02	0.16
Ammonia nitrogen	ppm	156	3619	2134	564
Organic matter	%	53.14	42.96	52.45	24.43
Organic carbon	%	36.62	24.92	30.42	13.93
Total phosphorus	%	0.61	2.32	1.88	0.29
Total potassium	%	0.93	1.21	1.24	1.53
Volatile Fatty Acids	mg/L	5.50	3.00	5.00	1.40

Table 4- 11: Pathogenic bacterial count in the slurry after a 10 weeks' digestion period

Digester	T. Coli (cells/ml)	F. Coli (cells/ml)	S & S (cells/ml)
A	Not detected	Not detected	Not detected
B	Not detected	Not detected	Not detected
C	Not detected	Not detected	Not detected
D	Not detected	Not detected	Not detected

Pathogenic bacterial analyses on the slurry detected no presence of any of the principle pathogens. This was as well expected following findings by (Extension, 2013) which concluded that anaerobic digestion of manures has an efficiency of up to 98% in reducing pathogenic bacteria populations under mesophilic digester conditions.

Judging from the wealth of slurry from all digesters in terms of the primary nutrients required for health plant growth; nitrogen, phosphorous and potassium, and absence of pathogenic bacteria in the slurry, the slurry is ideal for use as a bio fertilizer. Nitrogen, phosphorous and potassium

under this study are expressed as ammonia nitrogen and nitrate nitrogen for nitrogen, total phosphorous and total potassium. Studies for other micro and macro plant nutrients were not studied during this research. However, since not only the nutrient and pathogenic bacteria compositions determine the fertilizer value of the slurry, concluding that the bio slurry from the experiment can substitute any form of fertilizer would be incorrect. Further studies on the bio slurry itself backed up by results of its field application would offer the best conclusion on its quality.

Chapter 5

A scenario of AUC biogas production

5.1. Feasibility of biogas production

After a successful demonstration of the potential of biogas production from AUC's kitchen waste, the study went ahead to attempt a cost-benefit analysis for the project under AUC budget financing. The purpose of the analysis was to review the feasibility of incorporating the facility in the campus' electric, heating and cooking energy generation processes. The generated energy in all three forms as discussed in this chapter is to be utilized by the kitchens in the main kitchen area in the University's Parcel 17. The cost benefit analysis was based on information from literature around the world, material prices available in Egypt and raw data collected during the experiment. A few assumptions were made to reach the final figures displayed in this section of the study. Figure 5.1 represents the schematic layout of the proposed system.

A scouting done to establish the total amount of kitchen waste generated on the AUC New Cairo campus concluded that the kitchens on campus combined produced 450Kg of waste daily (Sunday to Thursday) in the spring 2018 academic semester. The waste is mainly a composition of fruit and vegetable waste in forms as described in section 1.3.1 above. To reach this figure, a week long survey of the waste collected from the kitchens on campus was conducted; where waste was continually collected at a designated site close to the waste collection point in parcel 17, sorted and weighed. Waste collected from Sunday to Thursday was considered for the experiment, since the university is closed on Fridays, yet less than half of the students are on campus on Saturdays. Monthly waste generation therefore was estimated at 450 X 22 = 9900Kg/month.

According to information provided by the University Registrar's office, the Fall and Spring semesters register the highest number of students compared to the winter and summer semester. Therefore, since student population in Spring and Fall semesters is almost the same, the above monthly figure recorded in the Spring semester (9900Kg/month) has been as well assumed to apply to the Fall semester.
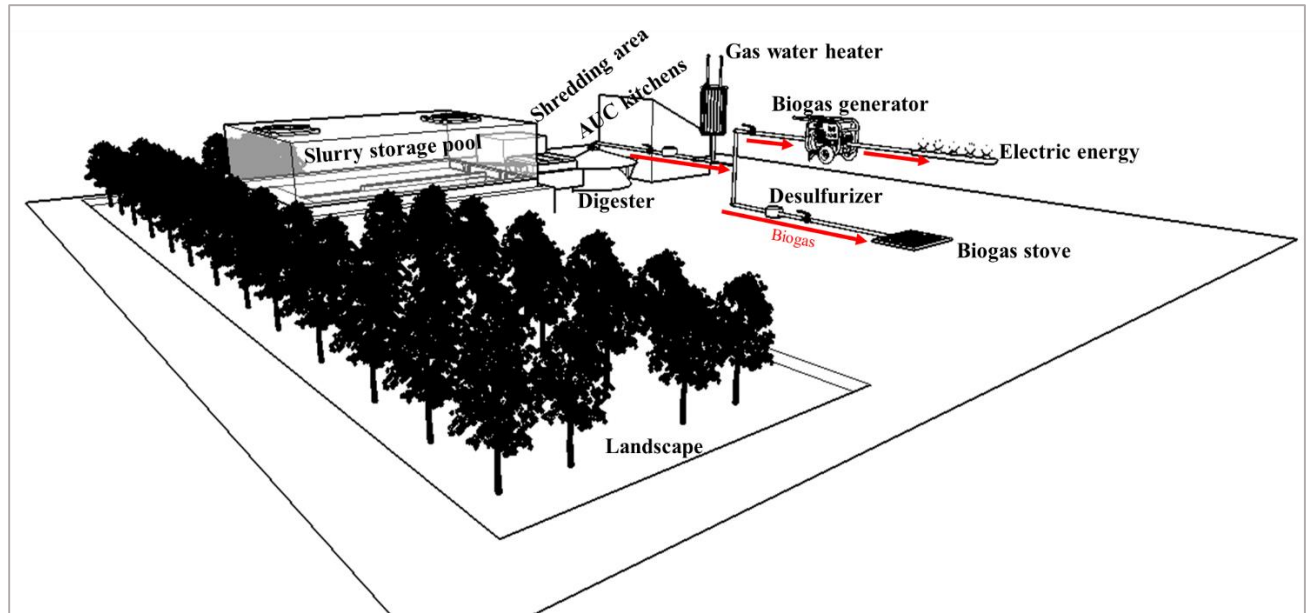
Figure 5. 1: Schematic layout of proposed biogas energy production and conversion system

From figure 5.1 above, waste collected from the kitchens on campus is sent to the digester to be located in the Parcel 17 area. Anaerobic breakdown of the waste yields biogas which directly flows to the piping network through a desulfurizer to remove the H_2S gas, before flowing to the gas water heater, generator to be converted into electric energy or the biogas stoves to be utilized in cooking. The study focused on biogas utilization in electricity energy for lighting and cooking. At the end of the digestion process, the slurry at the outlet shall be collected into a storage pool before being applied as a fertilizer in landscape and other agricultural applications available on campus.

During application, the slurry would be first buried in trenches along the trees for about a month, after which it can be dug out and applied as a soil amendment in landscape. The storage pool is covered and vented to prevent attraction of flies and other bugs yet as well allowing for air circulation within the pool. The leachate from the storage pool is to be sent back to the digester since it contains high loads of nutrients which may be dangerous to the environment if their disposal or application is not carefully managed. The trees around the site would act as wind breakers to reduce the nuisance from bad odors.

5.1.1. Calculations of digester size and biogas yield

The size of an anaerobic digester (digester volume, V_m) is a function of two main factors – the retention time (RT) and the daily amount of feedstock material (FD) added to the digester. The amount of feedstock material in this case will be a combination of the kitchen waste collected mixed with water in a ratio of 1:1. A continuous flow digester is most ideal for the job so as to minimize digester volume. This is because of the shorter retention times in continuous flow reactors compared to batch reactors and therefore relatively smaller digester volume requirements (Arsova, 2010).

5.1.1.1. Feedstock flow rate (FR)

FD = 450kg (wet weight), TS = 20%

If the material is mixed with water in a ratio of 1:1,

FR = (1 X 450) + (1 X 450) = 900kg/day

Assuming that 1kg of waste = 1L, FR = 900L/day, also = $0.9m^3$/day

5.1.1.2. Retention time (RT)

From the second phase of the experiment, a RT of 15 days was found ideal under all the three starter cases for maximum biogas production. Different researchers have established varying RT values for optimum methane and biogas yield from food wastes. (Oliveira, 2015) for example obtained maximum biogas yield from digestion of food waste after a 10 day RT and the highest methane yield after 28 days of the experiment, (Kim et al., 2006) recorded their highest biogas yield at a RT of 10 days and the maximum methane yield was reached two days later.

Therefore, until the first day of gas collection, the amount of feedstock material inside the digester will be;

V_m = FR X RT = $0.9m^3$/day X 15 days = $13.5m^3$ of material.

V_m is also called the Active digester volume of the unit.

5.1.1.3. Feedstock Quality (QT)

Dry matter (DM) content = FD X TS

DM = 450kg X 20% = 90kg of dry matter.

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At a Volatile Solids (VS) content of 40%, QT = VS X DM,

QT = 40% VS X 90kg = 36kgVS/day per 0.9m^3

QT (kgVS/m^3) = 36kgVS / 0.9m^3 = 40kgVS/m^3

40%VS was obtained from the average of the initial VS values obtained from KW1, KW2 and KW3.

5.1.1.4.   Organic loading rate (OLR)

$$OLR = \frac{FR \; X \; QT}{Vm} = \frac{0.9 X 40}{13.5} = 2.67 kgVS/m3$$

However, according to research conducted by (Paritosh et al., 2017), (Xu et al., 2018), (Liu et al., 2017), and (Babaee & Shayegan, 2011b), this is a very high OLR for successful digestion of food waste, recommending OLRs between 1.4 and 22 KgVS/m^3. (Xu et al., 2018) generally encourages operation of food waste digesters at low OLRs as a remedy to system's instability that may result from either the rapid formation and accumulation of volatile fatty acid or ammonia formation from the proteins and lipids inside the digester. (Liu et al., 2017) concluded that under mesophilic digestion of food waste, an OLR of 1.5KgVS/m^3 is optimum for steady methane production, whereas experiments conducted by (Babaee & Shayegan, 2011b) on methane production from vegetable waste concluded that an OLR of 1.4KgVS/m^3 was ideal for the highest and stable methane and biogas yield.

The above recommendations suggest a reducktion in the OLR for the proposed system. This could be reached through either of three steps; (a) Reduction in substrate concentration, (b) improvement in the concentration of the inoculum and (c) increase the alkalinity inside the digester to prevent acidification due to accumulation of VFA. This study assumes that the OLR shall be maintained at 1.5KgVS/m^3 to ensure maximum digester performance.

5.1.1.5.   Expected amount of gas production (G)

In their publication, (Patil & Deshmukh, 2015) conclude that the range of biogas yield from vegetable waste reached by a number of researchers under different conditions was between 0.360 m^3/kg of VS to 0.9 m^3/kg VS added. In this study, the average of the range of biogas yield reported by (Patil & Deshmukh, 2015) is used, which is 0.63 m^3/kg of VS added.

Therefore, G = OLR X V_m X 0.63 m^3/kgVS = 12.76m^3 of gas per day

5.1.1.6.   Total digester unit volume (V_t)

The V_t is a summation of active slurry volume (V_m) and gas storage (holder) volume (V_g).

It is *assumed* that, the ratio of V_m to V_g is 3:1 in a fixed dome anaerobic digester.

Therefore, if V_m represents 75% of V_t, $V_g = 4.5m^3$

$V_t = V_m + V_g = 4.5m^3 + 13.5m^3 = 18m^3$.

5.1.1.7.   Digester dimensions

The most critical dimensions of the digester are its height (H) and diameter (D). The ratio between H and D is usually 2:1 (Kaur et al., 2017) (Ogur & Mbatia, 2013). Therefore, D = 2H. From the mathematical formula of cylinder volume calculation,

$$Vm = \frac{\pi \; X \; H \; X \; D^2}{4} = \frac{\pi \; X \; H \; X \; (2H)^2}{4}$$

$$H = \left(\frac{Vm}{\pi}\right)^{1/3} = \left(\frac{13.5}{3.14}\right)^{\frac{1}{3}}$$

$$H = 1.63m$$

$$D = 2 \; X \; 1.63 = 3.26m$$

Slurry displacement inside the digester is dependent on the schedule of gas usage (Kaur et al., 2017). Displacement is caused by the accumulated gas pressure in the gas holder section which pushes down the slurry, usage of the gas relieves the pressure from the gas allowing the slurry volume to retract back to its original height. From the formulas derived by (Kaur et al., 2017), the d value can be calculated.

5.1.2. Biogas utilization

Assuming that utilization of biogas produced daily from the system was to be equally split between cooking and lighting, i.e. 50% to be used in cooking and the other half for lighting, sections 5.1.2.1 and 5.1.2.2 below enumerate the performance in either cases.

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5.1.2.1. Lighting

One cubic meter of biogas has an electric energy potential of about 2 - 2.5KWh (Uddin et al., 2016) (Banks, 2009). Using 50% of the daily biogas production for conversion into electric energy for lighting, available energy is 0.5 X 12.76m^3/day = 6.38 ≈ 6.4m^3/day. Kitchens in parcel 17 area use 40W fluorescent bulbs for lighting. If the lights are to be operated for 10 hours daily, each would consume 40W X 10hrs = 400Wh per day which is equivalent to 0.4 KWh per day.

Electrical energy content in the 6.4m^3 of gas available for lighting everyday = 6.4 X 2.5KWh = 16KWh. This amount of energy can run; 16KWh/0.4KWh = 40 fluorescent bulbs in the kitchen area for 10 hours daily.

5.1.2.2. Cooking.

One cubic meter of biogas has a thermal energy potential of upto 22 MJ (Banks, 2009). Most of the cooking in the AUC kitchens is with gas ovens. With 50% of the biogas energy produced available for cooking, the gas ovens would have; 0.5 X 12.76 = 6.38 m^3 in biogas and 140.36 MJ of thermal energy to complement the daily kitchen cooking needs. Another assumption would be that; if six kitchens in Parcel 17 each employed a gas oven that consumed 1m^3 of gas per hour and operated for only one hour every day, the available biogas for cooking would sufficiently serve the daily gas requirements for the six ovens.

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Sectional view

Plan
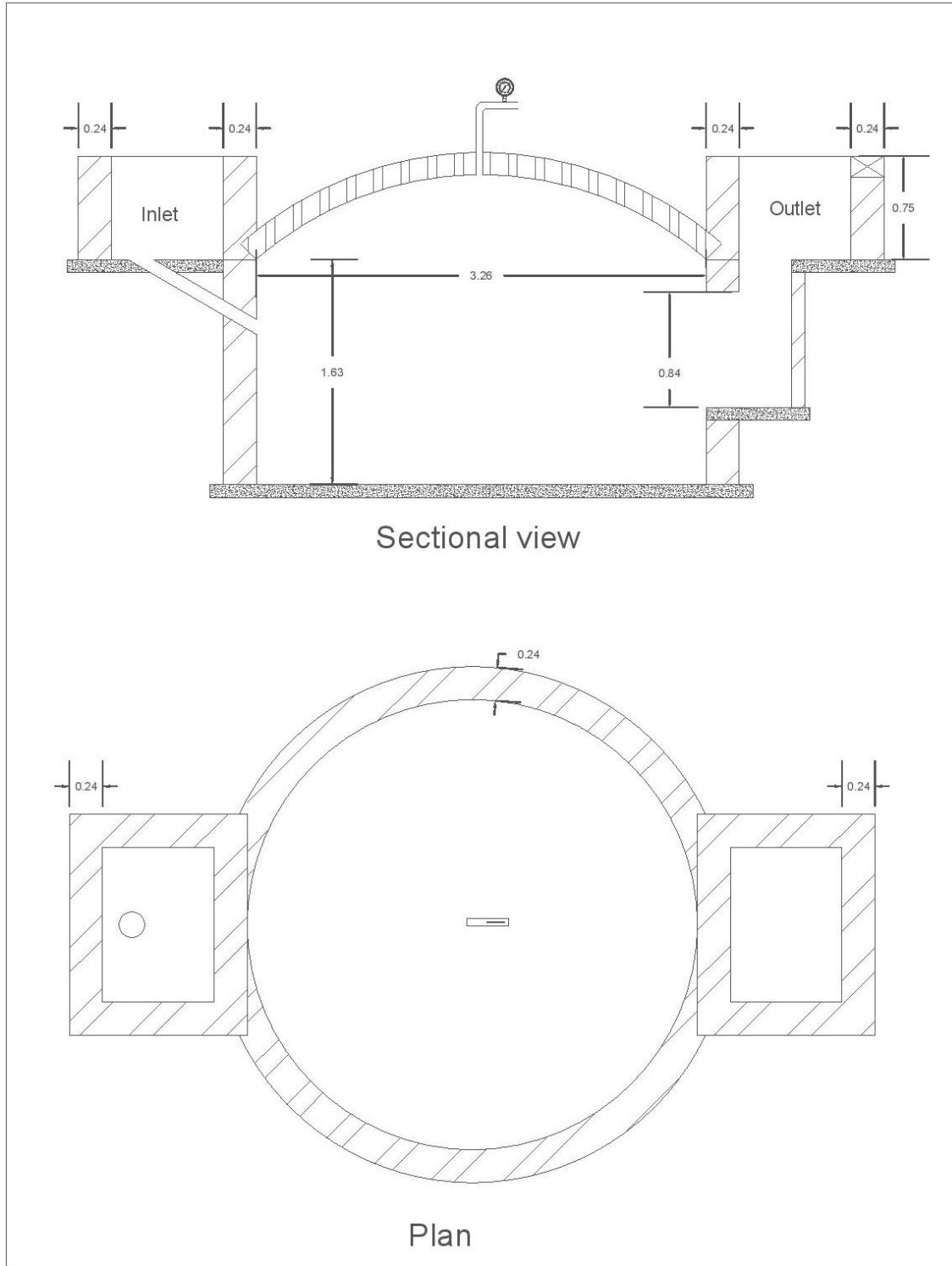
**All measurements are recorded in meters

Figure 5. 2: Sketch of the of digester proposed for use in AD of AUC kitchen waste

5.1.3. Digester construction cost

Table 5- 1: Estimated costs of constructing a biogas digester on AUC campus

Item	Units	Estimated cost/Unit, LE
Excavation in ground other than rock to foundation levels as indicated in drawings, soil investigation report or as directed by the engineer.	m^3	15
Excavation in ground other than rock to foundation levels as indicated in drawings, soil investigation report or as directed by the engineer. (Manual Excavation)	m^2 / 20 cm layer	12
Supply and install Plain concrete with Characteristic strength 200 Kg/cm2 for foundations including formwork, Casting, Curing, Testing and surface finishes according to drawings & specification.	m^3	850
Supply and Install Solid Brick size 25 cm for walls including mortar for bedding and all requirements as per drawings and specifications.	m^3	700
Backfilling with approved selected Excavated soil on layers 250 mm thick. Including compaction to not less than 95% of the maximum dry density of the selected soil.	m^3	30
Supply and application Gravel layer 50:100 mm thick for upper roof.	m^3	150
Reinforced cast-in-place concrete with type I cement, Grade 250 including formwork, steel reinforcement, movement joints, and construction joints, concrete surface repair, water stop wherever necessary and concrete tests all as per drawings and in accordance with specifications	m^3	1500

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Item	Units	Estimated cost/Unit, LE
Supply and apply 2 layers of Waterproofing for foundation by Oxidized Bitumen (bituminous emulsion) for foundation (footings, smells, and backfilling masonry and neck columns) including all necessary preparation works and protection works.	m^2	22
Supply, install and test of Galvanized pipes PN10 (ASTM D3034) for sanitary sewage and Storm drainage networks, the item includes all pipes, fittings, accessories, concrete works, rock soil, backfilling using suitable materials, compaction, dewatering, shoring, removal of excess materials, bedding, non-woven geotextile 300gm/m2 and gravel type A (size 1-2 inches) aggregate surround pipes as per the drawings and technical specifications.	Meter Length	1000
Supply, install and test of uPVC perforated pipes PN10 (ASTM D3034) for sanitary sewage and Storm drainage networks, the item includes all pipes, fittings, accessories, concrete works, rock soil, backfilling using suitable materials, compaction, dewatering, shoring, removal of excess materials, bedding, non-woven geotextile 300gm/m2 and gravel type A (size 1-2 inches) aggregate surround pipes as per the drawings and technical specifications.	Meter length	570
Damp proofing and Waterproofing for Roof, Rate includes light weight concrete with 60 mm thick, water proof membrane 4 mm, metal flashing, mastic sealant, 50 mm screed, 50-100 gravel	m^2	250

Item	Units	Estimated cost/Unit, LE
layer, as per drawings, specifications and approved sample.		
(Internal Walls) Cement plaster applied directly on surfaces of concrete or masonry including metal beads, metal reveals and other fixing accessories all in accordance with the specifications	m^2	55
Manual labor	All above items include workmanship	If labor costs / Around 20,000.00 EGP
Technical fee (consultant)		2.5 % from total construction cost

5.1.4. Biogas appliances costs

Table 5- 2: Estimated costs of biogas appliances to utilize produced biogas

Item	Amount	Estimated cost, LE
Biogas generator	01	12,000
Gas flow meter	01	1,000
Pressure regulator	02	1,000
Desulfurizer	01	350
Food waste shredder	01	12,000
Gas storage balloon	02	3,500
	Total cost	29,850 LE

5.2. Benefits to AUC

In addition to the merits of anaerobic digestion listed in chapter 2.3, AUC as a global university committed to sustainable development and more specifically environmental conservation has a lot more to benefit from anaerobic digestion. The range of benefits cuts across the societal, economic and environmental scopes of sustainability. Summarized in figure 5.3 are benefits of an anaerobic digestion initiative to AUC.

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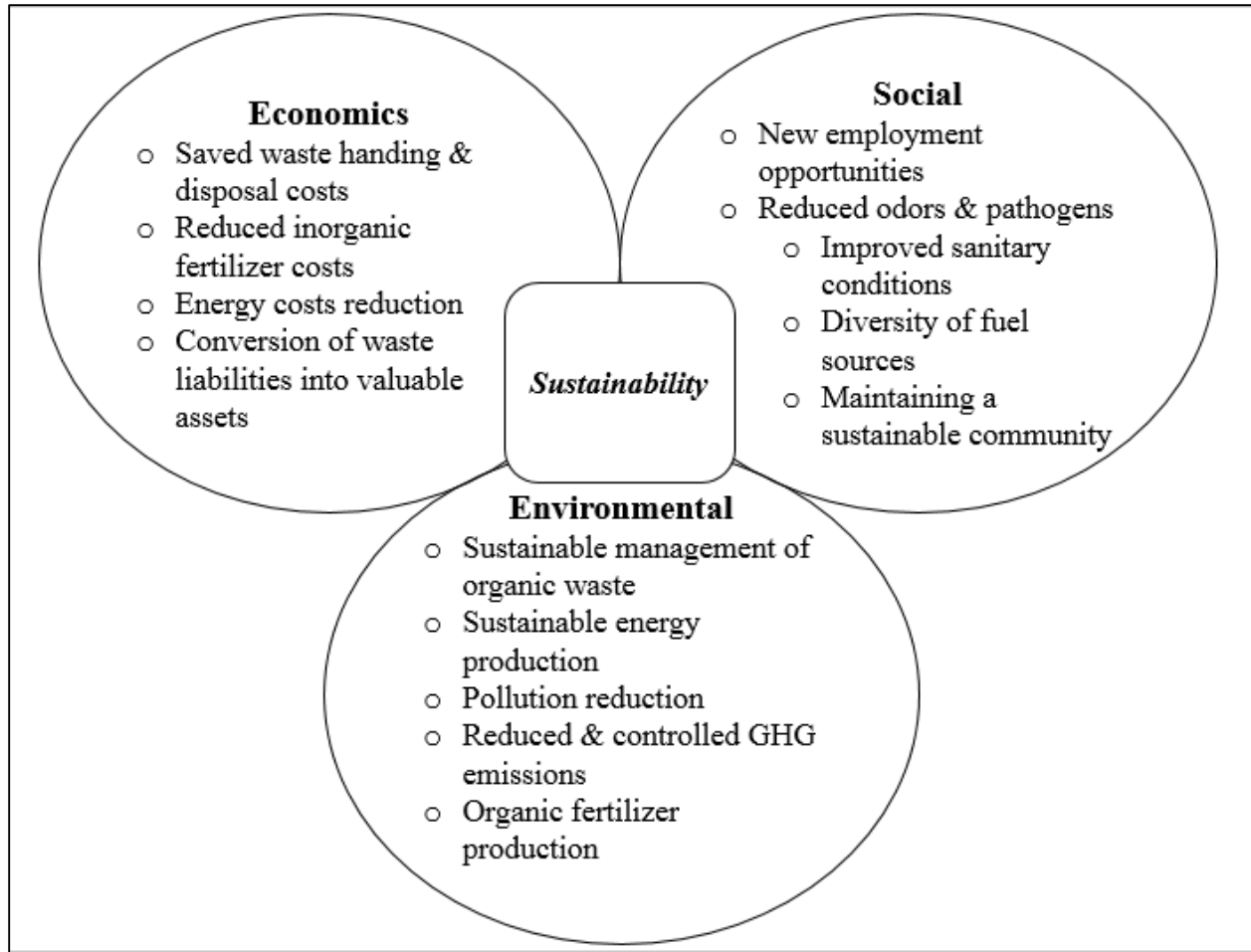
Figure 5. 3: Sustainability benefits of anaerobic digestion of AUC's kitchen waste

As AUC struggles to remain true to its goals of decreasing the University's carbon footprint, promoting environmental research and education, implementing recycling programs and raising public awareness, anaerobic digestion of kitchen waste comes in handy. Employing a greenhouse gas calculator available on https://watchmywaste.com.au/food-waste-greenhouse-gas-calculator/, the 450kg of kitchen waste generated on campus daily emit 855 Kg CO_2-e. On a four months semester basis where only a 22 days/month waste generation is considered, emissions from kitchen waste alone would amount to over 75 MT CO_2-e, which is over 4% of the CO_2 emissions from the combustion of natural gas for on campus domestic and lab purposes in the University's 2016 academic year alone (AUC, 2017). Extrapolating the amount of KW production to the end of an academic year, AUC pumps a tremendous load of CO_2 into the atmosphere by falling short of a sustainable KW management strategy. The conversion of this

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seemingly invaluable waste into a sustainable source of energy would therefore offset a great deal of CO_2 emissions from AUC's account.

In the 2016 academic year, the university consumed 32,308,600KWh of electricity and 847,272 m^3 of natural gas to meet its electrical and heating needs (AUC, 2017). With this very huge amount of energy consumption, an energy offset of a couple of bulbs and gas ovens may not seem of tangible significance. However, the significance lies in the nature of energy. Biogas being a sustainable form of energy with a high environmental pollution mitigative potential should be afforded a more attentive audience if the University is to honor its commitment to sustainable development.

To maintain the University's elegant landscape through the 2016 academic year, 6.28 metric tons and 2105 liters of solid and liquid synthetic fertilizers respectively had to be injected into the soil. The two forms of synthetic fertilizers combined emitted 9.2 MT CO_2e into the atmosphere (AUC, 2017). On the other hand, CO_2 emissions from the 150 metric tons of organic fertilizers (both locally produced and purchased compost) applied alongside the synthetic fertilizers only totaled to 4.5 MTCO$_2$e (AUC, 2017). Comparing emissions potential of inorganic and organic fertilizers, there is a significant difference in favor of inorganics. The use of organic fertilizers therefore offsets an enormous amount of CO_2 emissions. Anaerobic digestion is not alien to production of organic fertilizers itself. The slurry at the end of the AD process as discussed earlier is a good source of pathogen free organic fertilizers, whose application in addition to the locally produced compost will not only contribute to CO_2 emissions reductions but also aid to reduce the amount spent on procuring extra compost.

5.3. SWOT analysis for the project

Despite the attractiveness of the venture, to create grounds for fair decision making into whether the path is worth taking, this study took the extra step to conduct a strength, weakness, opportunities and threats (SWOT) analysis about on campus anaerobic digestion. The results of a brainstorming process are shown in table 5-3 below.

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Table 5- 3: A SWOT analysis for AD of AUC kitchen waste

Strengths	Weaknesses
1. Biogas is a sustainable energy source	1. High initial investment costs
2. AD solves the organic waste disposal problem	2. Not enough space available for waste collection in the kitchens
3. Availability of space to establish the facility	3. Limited awareness about AD among food vendors
4. Organic waste from other on-campus sources could as well be digested	4. Individual food vendors handle their wastes differently
5. KW can be easily digestible with help of a starter	5. Lack of a designated place for organic waste collection and sorting
6. No need for extra waste collection and transportation infrastructure	6. Absence of a clearly documented strategy for organic waste management
7. AD would reduce AUC's carbon footprint	7. Limited collaboration between offices regulating food, campus services and sustainability
8. Low operation and maintenance costs	
9. University is responsible for waste collection on campus	8. Hard to justify the financial viability of the project
10. Kitchen services are overseen by the university's food services office	9. The need to establish special required pipes and systems for utilizing the biogas
11. Presence of a campus sustainability office	10. Need for special safety inspections and/or permits
	11. Process requires biological starter none of which is readily available on campus
	12. Inefficiency of the at-the-source waste separation system currently in place
	13. Biogas can only be used in limited applications
	14. Methane use has to be controlled to reduce emissions into the atmosphere

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Opportunities	Threats
1. AUC's dedication to a reduction in its carbon footprint	1. Composting of landscape waste
2. Presence of a sustainable environment research institute on campus	2. Existence of an on-campus central utility power generation plant
3. Organic wastes from the landscape and other departments can be used as co-substrates	3. Absence of a clear guideline for KW waste collection channels
4. Existence of at-the-source waste separation infrastructure on campus	4. Contracted waste disposal services
5. No special governmental permits required for the establishment of small scale plants	5. Fatalities linked to gas leaks
	6. Unfavorable weather conditions
	7. Difficulty in acquiring loans from banks for AD as the field is considered risky
6. In some cases natural gas infrastructure can use biogas without any prior modifications	8. Upscaling of the digester is difficult
7. Biogas production and energy conversion is a well-developed technology	9. Organic fertilizer application requires extra effort, skills and precaution
8. Existence of avenues to utilize all intended AD products	10. Inconsistence in amount of waste – dependent on student population

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Chapter 6

Conclusions and Recommendations

6.1. Conclusions

In the current study, anaerobic digestion was investigated as a sustainable strategy to managing organic waste from kitchens on the AUC New Cairo campus. The experiments were carried out in two phases with different substrates - phase I utilized market vegetable waste, animal and chicken manure whereas phase II relied exclusively on AUC kitchen waste inoculated with different starters. Four setups were prepared in the first phase of the experiment; 100% animal manure(A), 100% chicken manure (B), animal manure mixed with chicken manure in ratio 1:1 (C) and animal manure mixed with kitchen (market vegetable) waste in a ratio of 1:4 (D). Mesophilic AD of these substrates for 9 weeks accumulated 285.33L, 300.54L, 329.95L and 0L of biogas respectively. Average composition of methane in biogas produced from digesters A, B and C was 43.54%, 52.59% and 45.58% respectively.

In the second experimental phase, AUC kitchen waste (KW) – a mixture of vegetable and fruit waste, was the sole AD substrate. Three setups KW1, KW2 and KW3 with equal amounts of KW were prepared, each inoculated with a different starter. KW1 was inoculated with digested animal manure (AM) from digester A, KW2 with digester chicken manure (CM) from digester B whereas KW3 was inoculated with Chinese bokashi, a form of effective microorganisms. Inoculation with digested CM showed superior biogas yield accumulating 498.64L of biogas at the end of the six weeks' psychrophilic digestion period. KW2 was followed by KW3 in biogas yield producing 284.58L. Least biogas accumulation was in KW1 with only 65.54L at the end of the digestion process. Average methane yield was 25.55%, 40.33% and 41.63% in KW1, KW2 and KW3 respectively. Considering its yield of the highest biogas with a considerable methane composition, the use of digested CM as the starter in AD of AUC KW would be considered most suitable under psychrophilic conditions.

In addition to the biological feasibility of AD of AUC kitchen waste, the process is also both technically and economically feasible for AUC. On campus biogas production comes in handy

with a multitude of benefits satisfying the three pillars of sustainability. Through their applications, the potential in use of AD products to offset CO_2 emissions stands out. For example, AD of KW produced in a four-month semester would intercept an equivalent of over 4% of the CO_2 emissions from the combustion of natural gas for on campus domestic and lab purposes from being pumped into the vulnerable atmosphere.

A SWOT analysis of the project revealed the many strengths and opportunities making the project such an attractive venture for university sustainability. Although the venture is not without weaknesses and threats, integration of an anaerobic digestion facility into the existent campus waste management architecture stands imperative. Close collaboration of the University's offices overseeing food services, campus sustainability, landscape, and facilities and operation with technical help from the Center for Sustainable Development and the Research Institute for a Sustainable Environment is the key to making the project a possibility.

6.2. Recommendations

Basing on the results and establishments of this study, it is recommended to incorporate anaerobic digestion into AUC's sustainable waste management programs. Sensitization of the kitchens on campus should be prioritized to achieve a considerable degree of sorted organic waste and performance of the overall anaerobic digestion strategy. It is also recommended that a fourth waste category be introduced in addition to the existing at-the-source waste separation categories to have food waste from secondary sources accounted for.

Since all food vendors on campus are under contracts, it is recommended that their adherence to some of the University values such as sustainability and research be stressed to create a healthy atmosphere for their mandatory collaboration in on campus research projects. It is imperative to promote the necessary awareness of merits of waste recycling among all stake holders for the many efforts undertaken in this direction to bear fruit.

This research has been conducted with the aim of providing supporting information about anaerobic digestion as a strategy for recycling kitchen and food waste in general. However, to provide stronger supporting information for the concerned stakeholders, there is need to conduct

research into the feasibility and viability of other recycling methods for kitchen waste such as composting.

In light of research, this study aimed at setting stage for applied research in the field anaerobic digestion. However, experiments on AUC's kitchen waste were only carried out under psychrophilic conditions. Therefore, research under mesophilic and thermophilic conditions is recommended to reach conclusive data about the most viable conditions for optimum results from the project. In the current study, priority was given to biogas yield and its quality as opposed to slurry and its quality. Therefore, further research dedicated to the slurry, its quality, applications and sustainability impacts is also recommended.

Active involvement and/or collaboration of the different organs dedicated to sustainable development and food chain management on campus is also highly required. In their respective capacities, the Center for Sustainable Development, the Sustainability and Food Services Offices, and the Research Institute for a Sustainable Environment have vital roles to play in diverting the 450kg of food waste per day from landfills and significantly cutting back on the associated environmental risks as is the case currently. Involvement could be but not limited to research, ensuring food-vendor adherence to waste management policies, and technical support among others.

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Appendix

Table 4- 7: Weekly and cumulative biogas production during anaerobic digestion of AM, CM and mixture of AM and CM.

Digestion period (weeks)	L_b / Digester / week (liters)			Cumulative L_b / digester (liters)		
	A	B	C	A	B	C
1	34.48	00.49	32.74	34.48	00.49	32.74
2	18.67	18.91	35.43	53.15	19.40	68.17
3	24.66	37.32	37.15	77.81	56.72	105.32
4	35.32	46.75	46.20	113.13	103.47	151.52
5	44.62	49.24	50.46	157.75	152.71	201.98
6	41.23	36.97	43.60	198.98	189.68	245.58
7	28.50	32.83	31.91	227.48	222.51	277.49
8	25.00	28.80	21.79	252.48	251.31	299.28
9	18.06	25.40	17.36	270.54	276.71	316.64
10	14.79	23.83	13.31	285.33	300.54	329.95

L_b – Volume of biogas produced,

Table 4- 8: Biogas chemical composition during experimental phase I

Digester	Digestion period (weeks)	CH_4%	CO_2%	Other gases %
A	4	21.50	59.15	15.30
	7	45.66	35.14	19.20
	10	63.55	23.27	13.18
B	4	19.30	48.12	32.58
	7	56.52	39.01	04.47
	10	81.94	06.15	11.92
C	4	25.55	42.22	36.28
	7	42.68	31.66	25.66
	10	68.50	27.11	04.39

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Table 4- 9: Results from the chemical analysis of biogas in phase II experiment

Digester	Digestion period (days)	CH_4 (%)	CO_2 (%)	Other gases (%)
KW1	2	Nil	96.067	3.933
	12	53.603	43.196	3.201
	20	15.042	78.875	6.083
	40	08.001	81.428	10.571
KW2	2	Nil	96.594	3.406
	12	62.148	33.839	4.013
	20	48.610	46.161	5.229
	40	10.237	82.422	7.341
KW3	2	Nil	94.076	5.924
	12	49.822	45.367	4.811
	20	39.049	56.449	4.502
	40	36.008	58.165	5.827