UNIVERSITY OF CAPE COAST

ASSESSMENT OF MARKET WASTE AS FEEDSTOCK FOR BIOGAS DIGESTER IN CAPE COAST - GHANA

BY

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: .... Date: ....

Name: Rhoda Donkor Asiamah

Supervisor's Declaration

I hereby declare that the preparation and presentation of the thesis were supervised per the guidelines on supervision of thesis laid down by the University of Cape Coast.

Supervisor's Signature: .... Date: ....

Name: Dr. Isaac Mbir Bryant

ABSTRACT

With an expanding growth in the world's population, there is an urgency to continually find alternative strategies to foster resourceful and sustainable waste treatment options. The availability and variety of potential feedstocks for biogas generation require reliable knowledge of the waste characteristics and evaluation of specific feedstock types. Even so, not all waste products are suitable for biotransformation. Also, an extensive range of market organic waste is underutilized, resulting in resource waste and other detrimental environmental issues. Consequently, there is an increasing focus on better feedstock utilization and reliability for improved biogas. This research seeks to assess market waste as a potential feedstock for biogas digesters. Using the purposive sampling technique, suitable organic wastes (eleven samples from each market) were weighed from three selected markets (based on proximity and the abundance of food and vegetable vendors) in Cape Coast to determine their abundance and reliability. The findings revealed the average total waste generation per week for each market to be 436.29 kg (Abura), 362.46 kg (Kotokuraba), and 140.64 kg (UCC Science) indicating the abundance of waste for bioconversion in Cape Coast. The waste characteristics showed considerable moisture content ranging from 57.44 % to 91.27 %. The TS with VS concentrations in the waste ranged from 8.73 % - 42.56 % and 0.17 % - 35.06 % respectively. The pH ranged from 3.19 - 6.13 Even though the waste had significant NPK Variation, it was ascertained that the organic fraction of municipal solid waste is typically poor in nutrients. The Cu and Zn determined in the study were 0.98 µg/g to 57.13 µg/g and 25.56 µg/g to 245.07 µg/g respectively. The waste had higher levels of BOD_5 (155.73 mg O_2/L to 731.89 mg O_2/L) and COD (2680 mg O_2/L to 28128) indicating high levels of pollutants in waste. It also had high pathogen contamination in waste samples highlighting a potential environmental and public health risk.

KEYWORDS

Anaerobic digestion

Feedstock

Organic fraction of municipal solid waste

Market waste

Waste (s)

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DEDICATION

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LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
BGA	Brilliant Green Agar
BOD	Biological Oxygen Demand
°C	Degree Celsius
C/N	Carbon: Nitrogen ratio
CFU	Colony Forming Unit
CH_4	Methane
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
Cu	Copper
E. coli	Escherichia coli
EA	Endo Agar
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GWh	Gigawatt-hour
H_2	Hydrogen
H_2S	Hydrogen sulfide
HRT	Hydraulic Retention Time
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	Kilogram
Km^2	Square Kilometer
Ktoe	Kiloton
kWh	Kilowatt-hour

m	Metre
m/s	Minutes per Second
m^3	Cubic metre or metre cube
MC	Moisture Content
mg	Milligram
mL	Milliliter
MSW	Municipal Solid Waste
Mt	Metric Tons
MW	Megawatt
N	Nitrogen
NH_3	Ammonia
OC	Organic Carbon
OFMSW	Organic Fraction of Municipal Solid Waste
OM	Organic Matter
P	Phosphorus
pH	Power of Hydrogen
PV	Photovoltaic
rmp	Revolutions Per Minute
TAN	Total Ammonia Nitrogen
TFC	Total Final Consumption
TS	Total Solids
TWh	Terawatt-hour
VFA	Volatile Fatty Acids
VS	Volatile Solids
WHO	World Health Organization
Zn	Zinc

CHAPTER ONE

INTRODUCTION

Background to the study

With an expanding growth in the world's population, there is an urgency to develop creative and sustainable waste treatment solutions while simultaneously lowering the dependence on fossil fuels (Alqattan et al., 2018). Based on literary sources, municipal solid waste (MSW) constitutes substantial amounts of organic fraction of municipal solid waste (OFMSW), accounting for 46 % of the total, with rates ranging from 64 % in developing nations and 28 % in advanced economies (Hoornweg et al., 2013). Likewise, in Sub-Saharan Africa, the majority of putrescible components (57 %) and other partially biodegradable substances (22 %) are frequently disposed of in uncontrolled landfills or openly burned (UNEP, 2018).

In Ghana, the total amount of MSW generated daily is estimated to be around 12,710 tons, with a daily waste generation per capita of about 0.47 kg/person/day, wherein only 10 % is discarded at designated dumping spots (Miezah et al., 2015). This situation is dangerous owing to the consequences that could arise from the uncontrolled decomposition of OFMSW and indiscriminate waste disposals, such as soil contamination, groundwater contamination, health problems, and potentially hazardous gas emissions (Nanda & Berruti, 2021; Abylkhani et al., 2021; Mozhiarasi et al., 2020; Kumar et al., 2018; Kaza et al., 2018). Despite government and private sector efforts to regulate waste management, challenges persist in several urban centres in Ghana (Douti et al., 2017). Effective solid waste management is essential in tackling the health and environmental crises faced by cities and towns, especially in Sub-Saharan African countries like Ghana (Debrah et al., 2022; Fadhullah et al., 2022).

In this regard, anaerobic digestion (AD) presents a providential alternative for treating OFMSW and a viable remedy to the MSW menace (Cesaro et al., 2019; Fan et al., 2018). AD is a biochemical process that treats organic waste and produces biogas, which can be used as fuel or to generate power and heat simultaneously (Thuppahige et al., 2022; Darimani & Pant, 2019). The AD technology also promotes the sustainability of natural resources when the digestate is utilized as an organically rich fertilizer to replace mineral fertilizers that require fossil energy (Risberg et al., 2016). Additionally, applying circular economy concepts is encouraged by using biogenic residue (market organic wastes) for AD. This also makes waste management easier (Janesch et al., 2021). According to a study market towns produce varying quantities of wastes (Douti et al., 2017). The organic fraction of these wastes from markets has many important components that can be converted to biogas (Morales-polo & Soria, 2019). Additionally, Budiyono et al. (2018) stated that organic wastes like vegetable wastes and agricultural residues are suitable feedstock for biogas production due to their high nutrient content. The table below (Table 1) shows the methane potential of various market wastes as reported by different studies.

Table 1: Methane potential of various market wastes reported by different studies

Waste	Quantity	Methane yield	Reference
Cassava peels	495 t/y	84,217 mg/l	Agyemang et al. (2020)
Yam peels	100 g	327.50 ml	Olanrewaju (2018)
Mango, Orange, apple	10 t	1,075 Nm^3 / day	Mohammed et al. (2017)

Literature shows that the sustainability of AD is determined by the kind of feedstock, operational conditions, biogas utilization pathways, digestate treatment techniques (Agostini et al., 2015), plant scale (Hijazi et al., 2016), and fermentation technology (Czubaszek et al., 2021). This is essential as different feedstock have distinctive merits of biogas generation due to their unique features. While some organic materials can act as the only substrate, others require co-digestion with substrates with supplementary makeup to provide favourable conditions for microbial growth (Mata-Alvarez et al., 2014). In addition to digester type, which is influenced by local weather conditions, among other things, choosing the suitable feedstock is typically based on sustainability, amount, output requirements, availability, and metallic nutrient content (Abubakar, 2022; Hagos et al., 2017). Despite previous studies (Black et al., 2021; Arthur et al., 2021; Bryant, 2019) on biogas and compost production in Ghana, very little literature is currently available on the feedstock potential of OFMSW, especially on market wastes. This research seeks to fill this gap by assessing and quantifying potential feedstock for anaerobic digester. This study will not only give details regarding the market's possibilities for OFMSW but will also help to enhance the country's and continent's sanitary conditions.

Statement of the problem

Solid waste management continues to be among the most ignored aspects of urban growth as the world's population grows (Bong et al., 2016). Hence, an increase in the production and consumption of fruits, vegetables, roots, and tubers results in the accumulation of waste in the Ghanaian markets (Addae et al., 2021). In Ghana, the OFMSW (e.g. food waste, yarn, wood) makes up 61 % of the whole waste produced (Miezah et al., 2015) and about 64 % in Cape Coast, according to the Cape Coast Metropolitan Assembly (2021). However, the underutilization of a variety of these market wastes results in a substantial resource waste and poses multiple environmental and health risks (Abylkhani et al., 2021; Mozhiarasi et al., 2020; Hettiarachchi & Meegoda, 2018). Additionally, issues of leaching and emission of greenhouse gases have been documented (Hettiarachchi et al., 2020).

Despite how convincing the concept of anaerobic digestion is, the practical implementation of AD and using market organic wastes as feedstock is yet to achieve its potential. Even though it suits the overall picture, not all waste products are suitable for biotransformation. Although some previous studies looked at market waste potential, there is still marginal information on the composition and generation trends of market organic wastes and their usage in Ghana, making this an unchartered history (Addae et al., 2021). For instance, Miezah et al. (2017) studied the suitability of biodegradable portion of market and household wastes for biogas and bioethanol production. Also, Addae et al., (2021) studied market waste composition analysis and resource recovery potential. However, their works did not focus on the specific quantities and kinds, of organic wastes (fruits, vegetables, roots and tubers) available on the markets. Again, there is scanty data physicochemical, biological, and microbial properties of market organic wastes. For these reasons, this research focuses on quantifying potential feedstock from three selected markets in Cape Coast to determine its availability for AD while accenting proper waste management practices or strategies. Analyzing the amounts and categories of fruits, vegetables, roots and tuber wastes generated will facilitate a better understanding of how best to implement waste conversion plans.

Significance of the study

The importance of reliable information on both the quantity and composition of feedstock for anaerobic digestion underscores the significance of this study. This research will also produce primary data on the suitability of fruits, vegetables, roots and tuber wastes from the market as raw material for anaerobic digestion in Cape Coast, which may be repeated in other locations in Ghana and Africa. The results will further provide valuable data on quality feedstock, which could yield optimum biogas for households and hygienized digestate for agriculture usage. Again, the data will contribute to formulating sustainable OFMSW management policies in Ghana.

Aim and objectives

General aim

The primary aim of this study is to assess potential feedstock for an anaerobic biogas digester using organic wastes (fruits, vegetables, roots and tuber) from selected markets in Cape Coast, Ghana. The following specific objectives were set to achieve the desired aim:

Specific objectives

Specifically, the research sought to:

1. determine the quantity of organic wastes (fruits, vegetables, roots and tuber) available for AD in three different markets in Cape Coast.
2. determine the physicochemical, biological, and nutrient properties of organic wastes from the three markets.
3. assess the pathogen (*Salmonella spp*. and *E. coli*) concentration of wastes sourced from the three markets.

Hypothesis of the study

The study’s hypotheses were as follows:

1. There will be no significant difference in the quantities of waste sourced from the three different markets.
2. There will be no significant difference in the physicochemical biological, and nutrient properties of wastes from the three markets.
3. There will be no significant difference in the number of microbial colonies in waste samples from the three markets.

CHAPTER TWO

LITERATURE REVIEW

Africa's waste management situation

Africa faces an enormous waste management crisis that requires serious and urgent attention (Bello et al., 2016). This involves all facets of social, economic, and environmental impacts. One of the fundamental issues confronting modern cities and towns is waste collection, treatment, transportation, storage, and final disposal (Kumar & Agrawal, 2020; Godfrey et al., 2019). Given that Africa is the least developed region globally (Bello et al., 2016), its urban population keeps rising steadily (3.5 percent) per annum (UNEP, 2018). Despite the comparatively low amounts of waste generated in the region, poor waste management already affects human and ecological health (Godfrey et al., 2019). If current trends continue, Sub-Saharan Africa will overtake all other regions in total waste generation (UNEP, 2018). Consequently, the area will experience significant socio-economic transformations as its population expands, cities urbanize, and behavioural patterns change. This worsens waste management by adding more pressure to already stressed public and private sector waste services and infrastructure (Godfrey et al., 2019). Scarlat et al. (2015) estimated that 125 million tons of municipal solid waste (MSW) were produced in the region in 2012, with 81 million tons (65 %) coming from Sub-Saharan Africa. This is anticipated to skyrocket to 244 million tons annually by 2025. Nevertheless, with a waste collection rate of just 55% (68 million tons) on average (Scarlat et al., 2015), almost half of all MSW created in Africa is dumped on sidewalks, vacant lots, stormwater drains, and waterways. This causes environmental waste leakage, especially into freshwater and marine ecosystems (Godfrey et al., 2019; Bello et al., 2016).

The fact that an approximated 80 - 90 % of MSW generated in Africa is reclaimable, its beggars' belief that more than 90 % of the continent's waste is still dumped in both unregulated and regulated dumpsites. Only 4% of the region's waste is being recycled, frequently by highly active yet often marginalized informal reclaimers, despite the numerous opportunities that waste presents as a supplementary resource (Godfrey et al., 2019). An estimated 57 % of MSW in the region is organic waste but has been largely ignored. Although it can be easily converted into valuable products like compost and biogas, it remains an unexploited resource. Consequently, there is an increasing trend toward decentralizing organic waste treatment via small-scale anaerobic digestion (UNEP, 2018). This will enhance the country's and the continent's overall sanitary conditions.

Waste management situation in Ghana

Proper solid waste management is a critical concern for socioeconomic and governance reasons, particularly in urbanized areas with high growth and rapid waste generation (UNEP, 2018). Like many Sub-Saharan countries, waste management in Ghana is worrisome. This is a significant issue for the country, particularly in metropolitan areas with substantial economic development, urbanization, and improved standard of living (Lissah et al., 2021; Boateng et al., 2019). Research has shown that the tremendous increase in urban population over the last few decades has created unplanned structural patterns emblematic of uncontrolled urban sprawl (Soobhany, 2019).

In Ghana, the quantity of MSW created daily is around 12,710 tons, with a daily waste generation per capita of about 0.47 kg/person/day, of which only 10% is collected and disposed of at authorized locations (Miezah et al., 2015). Managing solid waste in the country is challenging due to the laborious and often inefficient collection and disposal methods. Urban officials and waste firms are bewildered by the daily waste generated (Douti et al., 2017; Amoah & Kosoe, 2014). Surprisingly, poor waste management standards and a lack of institutional capacity, financing, and policy and strategy guidelines make it impossible to ensure that all waste created in the country is appropriately collected and disposed of. These wastes are either dumped in open dumps, marshes, landfills, and uncontrolled dumps or burnt in the open air in some situations (Doaemo et al., 2021; Abalo et al., 2018).

According to Abubakar et al. (2022) and Bryant (2019), many illnesses are linked to poor water quality and sanitation, including cholera and typhoid fever. The generation of waste is predicted to proliferate, validating that population influx is prevalent, particularly in Accra and Kumasi, where over 4,000 tons of waste are generated daily (Fagariba & Song, 2016). Meanwhile, Abalo et al. (2018) feel that if waste latent potentials are effectively managed and thoroughly used, they can provide energy, employment, revenue, and a resource for product producers, resulting in a better quality of life for Ghanaians.

There is, without a doubt, a need to evaluate and find alternatives to the current waste management practices. It has been proven through studies conducted in Ghana that the waste produced by the country has the potential to generate energy (Asare et al., 2020; Al-Addous et al., 2018; Gyamfi et al., 2015; Ulrike et al., 2014). Implementing conventional waste treatment technologies is challenging with most African cities' current waste management systems (Godfrey et al., 2019). Community-driven initiatives alongside larger, centralized projects will be necessary (Lissah et al., 2021). Whence conducting this research is essential. It will act as a sustainable waste management approach and help cut greenhouse gas emissions while creating job possibilities.

Solid waste composition in Ghana

Domestic or municipal waste is frequently created from varied sources where varying human interactions are encountered (Abdel-Shafy & Mansour, 2018). According to several studies, households are the prime source of municipal solid waste in developing nations (55-80%), followed by market or commercial areas (10-30%) (Okot-Okumu, 2012; Nagabooshnam, 2011; Nabegu, 2010). These constituents are highly heterogeneous, with varying physical properties depending on their origins (Abdel-Shafy & Mansour, 2018). Bhada-Tata (2012) emphasized that waste composition directly affects collection and disposal. Hence, knowing the waste constituent is crucial for selecting the appropriate treatment solutions. The MSW is typically stated as a composition of organic, paper, plastic, glass, metal, and other components, as depicted in (Table 2) below.

Table 2: Solid waste composition in Ghana

Waste type	Proportions
Organics	61%
Plastics	14%
Inert/Miscellaneous	11%
Papers	5%
Metals	3%
Glasses	3%
Textiles	1%
Leather and rubber	1%

Source: (Miezah et al., 2015)

Organic waste products account for most of the country's waste. Studies by Miezah et al. (2015) suggest that the organic fraction of municipal solid waste (OFMSW) constitutes 61 percent of the total generated waste in Ghana, considerably higher than other waste fractions. Alhassan et al. (2010) reported that indigenous markets in Ghana generate approximately 40 % of the overall waste stream in Ghana’s urban districts, with organic waste accounting for 70 – 80 % of this total. However, it remains largely an untapped resource. The makeup of MSW changes significantly based on economic growth, improved lifestyle, consumerism, and culture (Nguyen et al., 2020; Godfrey et al., 2019; Miezah et al., 2015). Research has found that a high percentage of organic municipal solid waste (OFMSW) has a significant moisture content, which affects waste management, environmental consequences of waste disposal in landfills, and the acceptability of alternative waste treatment technologies (UNEP, 2018). AD treatment of OFMSW can yield a nutrient-rich digestate that can be used as a soil amendment (Karthikeyan et al., 2018;

Paritosh et al., 2018). However, widespread soil, water, and air contamination can arise from OFMSW's unchecked decomposition, which can also contribute to global warming. Therefore, management options aimed at stabilizing OFMSW, especially in developing countries like Ghana, must focus more on sustainable biological processes like AD for treatment efficiency (Mozhiarasi et al., 2020; Roy et al., 2017; Alibardi & Cossu, 2015).

Wastes treatment and energy recovery

The global quest for energy generation alternatives has increased dramatically over the years, resulting in initiatives to raise awareness of the necessity of diversifying energy supply and generation sources (Martens et al., 2021). While fossil fuels can supply this need, they have widespread negative environmental impacts (Hasan et al., 2018). In this situation, producing more sustainable energy while reducing greenhouse gas emissions is possible renewable energy (Callegari et al., 2020). The most common form of energy recovery is anaerobic digestion, which naturally breaks down organic waste into biogas and nutrient-rich fertilizer in the absence of oxygen (Rehman et al., 2019). It is also to transform biogas into other sources of energy such as electricity, heat, or compressed biomethane gas (Kabeyi & Olanrewaju, 2022). Anaerobic digestion is often used to treat wastewater sludge treatment, manage agricultural manure and food waste (Ma et al.,2015). Although current biogas applications focus on energy production, numerous value-added compounds obtained from biogas are expanding the economic and environmental benefits of biogas (Uddin & Wright, 2023).

WtE is a promising alternative energy source with potential economic viability and environmental sustainability (Milbrandt et al., 2018; Baran et al., 2016). However, treating solid waste in an environmentally sound way has been a challenge, especially for third-world countries like Ghana. According to Moharir et al. (2019) alternative waste treatment methods, including WtE, are scarce due to various factors, including insufficient data on waste, legislation, funding, technical innovation, and skilled employees, as documented by Mutz et al. (2017). It is expected that WtE conversion could alleviate the negative environmental impacts of poor waste management. Baran et al., (2016) state that a mandatory recycling program is necessary for sustainable growth and environmentally friendly living. Otherwise, environmental contamination caused by human activity is unavoidable. With Africa's looming waste management crises, creating effective WtE, such as anaerobic digestion-based strategies to improve energy recovery from waste that now goes to landfills, is imperative. This will also help to enhance the country's and the continent's overall hygienic conditions.

Anaerobic digestion process

AD involves the coordinated action of a variety of microorganisms to break down biomass into a gaseous mixture (CH_4, CO_2, H_2O H_2, H_2S, N_2, etc) in the absence of oxygen (Uddin & Wright, 2023; Mutz et al., 2017). In some anaerobic bacteria, oxygen is toxic and its presence threatens the chances of survival (Liu et al., 2024). AD technology is reliable and preferable due to its highly efficient and effective removal of pathogens, odour, decomposition of volatile compounds, and high adherence to numerous national waste management policies (Kiyasudeen et al., 2016). AD technology reduces sludge volume, lowers treatment costs, and recovers renewable energy from biogas (Sibiya et al., 2017).

At the municipal level, AD is gaining traction as a potential option for recuperating energy from waste in the urban context. However, operating biogas plants from diverse MSW presents significant operational, safety, and financial challenges (Mutz et al., 2017). The importance of suitable temperature, pH, and feedstock quality is emphasized for an active and efficient AD process (Uddin et al., 2021; Divya et al., 2015). For the dominance of various methane-forming bacteria strains, the AD process has three primary operational temperature regimes: psychrophilic, mesophilic, and thermophilic (Feng et al., 2021; Ruffino et al., 2020; Didenko et al., 2019). Organic matter decomposition involves a complex process of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, occurring in series and parallel reactions (Nguyen et al., 2019; Uçkun et al., 2016).

Factors affecting anaerobic digestion process

Microbiological, biochemical, and physicochemical processes all involve biological conversion. Moisture, pH, total solid, volatile solid, and C/N ratio among others, are all essential elements to consider when using AD technology (Leung & Wang, 2016; Uçkun et al., 2016). By optimizing these elements the digestion process can be made more efficient depending on the unique feedstock characteristics and its surrounding (Uddin et al., 2021).

Moisture content

The process of organic matter decomposition requires water as a key ingredient, as it facilitates the flow of substrates and nutrients into the microbial niche (Mrosso et al., 2023). Regarding moisture content, the AD process can be grouped into wet and dry AD. Literature showed that dry AD reactor operates at an average of 60-75 % moisture conditions while wet systems operate at 85-90 %. Feedstock with high moisture content tends to decrease digester temperature and limit the efficiency of some endothermic reactions. A maximum of 15 wt % moisture content is often recommended regardless of the feedstock characteristics (Panigrahi & Dubey, 2019; Motta et al., 2018; Hu et al., 2012).

Effects of pH

This crucial parameter has varied implications for the development of microorganisms during anaerobic fermentation. Each kind of bacteria has a different pH range that they prefer. Methanogenesis occurs on the pH scale of 6 to 8.5, with a preferred range of 7.0 to 8.0. (Saraswat et al., 2019; Varjani et al., 2018). Methane generation is hindered when the pH drops below 6.0 or exceeds 8.5, especially during protein and lipid bioconversion (Leung & Wang, 2016). Low pH variations are especially susceptible to methanogens; on the other hand, rising pH may enhance the development of hazardous agents such as excess-free ammonia (Panigrahi & Dubey, 2019). Controlling the pH level to achieve optimum microorganism development offers a possible method to lessen ammonia toxicity in AD resulting from increased free ammonia concentration (Mao et al., 2015). An acidic pH can be neutralized by adding sodium salt, lime, sodium bicarbonate, or sodium hydroxide (Jain et al., 2015). Due to the high cost and limited availability of sodium bicarbonate and sodium hydroxide, lime or sodium salt is recommended in most third-world nations like Ghana (Vögeli et al., 2014; Bryant, 2019).

Total Solids and Volatile solids

Control metrics commonly monitored in biological treatments include total solids (TS) and volatile solids (VS). TS measurement includes total dissolved and suspended solids in the sample. TS is commonly ascertained in an oven via a drying procedure (Peces et al., 2014). The dry matter that often remains after water removal is commonly known as TS (Mauer & Bradley, 2017). Currently, three primary categories of AD technologies have been established based on the TS content of feedstocks: conventional wet (≤ 10% TS), semi-dry (10-20% TS), and modern dry (≥ 20% TS) (Yi et al., 2014). Matheri et al. (2018) and Jain et al. (2015) noticed that an optimized solid-state anaerobic digestion (AD) process could handle more waste in terms of dry mass compared to a liquid AD due to its versatility, robustness, and improved water management tactics. The effectiveness of AD is influenced by the TS content of feedstocks, and variations in this content will result in modifications to the morphology of microorganisms within systems (Yi et al., 2014). Previous research has examined the impact of TS content on AD performance to establish optimal gas generation. Duan et al. (2012) showed that high-solids systems can yield much more volumetric methane than low-solids systems at the same solid retention time in mesophilic anaerobic reactors processing sewage sludge. The results obtained by Abbassi-Guendouz et al. (2012) showed that overall methane output decreased when the TS concentrations increased from 10 % to 25 % in a batch AD of cardboard under mesophilic conditions.

In addition, TS can be further divided into VS and ash. VS is the solidified remnants after evaporation or after filtrates have been dried, weighed, and burned at 550°C (Orhorhoro et al., 2017). However, some volatility may have occurred during the TS measurement (Leung & Wang, 2016). VS can provide an approximate representation of organic content in waste, making it suitable for biological treatments, thus, it can serve as a first step in biodegradation and can also be utilized as a process control parameter (Peces et al., 2014). Research has shown that a decrease in VS is also considered an assessment of digester efficiency (Mei et al., 2016). However, a review by Leung & Wang (2016) indicated that difficulty may arise in precisely distinguishing VS between organic and inorganic matter, as decomposition or volatilization of particular mineral salts causes significant losses. Hence, biochemical oxygen demand and chemical oxygen demand determination could provide reliable measurements of organic matter (Cazaudehore et al., 2019; Leung & Wang, 2016). Table 3 depicts the permissible standard of effluents by the Ghana EPA and WHO/FAO.

Table 3: Standard values of effluent

Parameter	**EPA Ghana limit**	**WHO/FAO limit**
pH	6.5 – 8.9	
Total Coliform (TC) (MPN/100 mL)	400	
BOD_5 (mg/L)	50	30
COD (mg/L)	<250	
E. coli	10	
Cu (ppm)	20	100
Zn (mg/L)	10	

Source: (Owusu-Ansah et al., 2015)

Feedstock categorization for anaerobic digestion

Prioritizing the composition of feedstock is crucial when selecting organic matter that will produce a high amount of biogas (Abubakar, 2022). The availability and supply of feedstock determines the viability of the AD process. The feedstock for anaerobic digestion should be easily biodegradable and devoid of any harmful components that would affect the microorganisms (Uddin & Wright, 2023). The rationale for categorization should be based on geographical, seasonal, and economic implications (Tyagi et al., 2018). The knowledge regarding organic waste is significant for designing proper handling and management techniques for these wastes. AD feedstocks can vary significantly based on their organic fraction, water content, and biodegradability. Organic waste can be categorized into agricultural, municipal, and industrial wastes (Aziz et al., 2019; Atelge et al., 2018). This is further detailed in (Table 4) below.

Table 4: Feedstock classification for anaerobic digestion

Sources	**Various feedstock**
Agriculture	Livestock waste, harvest waste, grass and algae, energy crops, garden waste, and vegetable
Industrial	Food/beverage processing, starch industry, sugar industry, dairy, cosmetic industry, pulp and paper, slaughterhouse
Municipal solid wastes	Households, sewage sludge, schools, restaurants, bars and canteens, garden waste, markets, hotels, hostels

Source: (Abubakar, 2022)

Feedstock type is an important component influencing the sustainability of AD (Agostini et al., 2015). This is essential because different feedstocks have various distinctive characteristics that impact biogas generation (Abubakar, 2022). Certain organic materials may be independent substrates, while others must be co-digested with complementary substrates to provide favourable circumstances for microbial growth (Mata-Alvarez et al., 2014). The organic fraction of municipal solid waste (OFMSW) is a common feedstock for AD and a viable source of biogas production (Abudi et al., 2016). This is because OFMSW exhibits a high heterogeneity with significant compositional, source, and biological structure variations (Paritosh et al., 2018). However, the composition of feedstock differs greatly between anaerobic digesters, presenting a variety of challenges contingent on the feed characteristics and system parameters (Westerholm & Schnürer, 2019). For instance, high-energy substrates such as those high in protein and fat have a high methane potential, but they can periodically cause process disruptions due to the formation of inhibitory compounds (He et al., 2017). Other materials like lignocellulosic materials, which have a lesser risk of process disturbance, might require an unreasonably long time for degradability and extractability (Seruga et al., 2020; Rada et al., 2017).

Feedstock and resources for biogas in Ghana

Numerous organic resources in Ghana qualify as feedstock for biogas and compost production. The agricultural sector, which includes food crops, livestock, fisheries, cocoa, and forestry, is the economy's backbone (Danso-Abbeam & Baiyegunhi, 2020; Mensah, 2019). Documentation by Awafo & Agyemang (2020) saw the existence of two main classes of biomass feedstock in the country. According to them, the first category comprises farmland, animal manure, and agricultural waste. The second includes MSW and organic waste from industry (food and feed) sectors. This includes essential agro-industries that have very high biomass feedstock potential such as processed cassava waste, rice leftovers, palm oil residue, fruit processing waste, and shea cakes (Awafo & Agyemang, 2020). Nonetheless, there are variances within these categories, for example, regarding what types of agricultural residues are encompassed and what kinds of kitchen waste are included (Ammenberg et al., 2017).

Microbial composition of OFMSW in Ghana

Food waste contributes the most faecal coliforms (80.62 %) for all potential sources. Several leafy vegetables (lettuce, cabbage, and spring onions) in the Ghanaian market contain significant total coliforms, faecal coliforms, and various strains of helminth population, regardless of the irrigation water supply (Amoah et al., 2007). Ascaris lumbricoides, *Hymenolepis diminuta, Trichuris trichuriasis, Fasciola hepatica, and hookworm* were some examples of helminth populations discovered on the vegetables. *Strongyloides stercoralis* (abundant in the samples) and *nauplius larvae* were also discovered. *A. lumbricoides* was found in approximately 85% of all infected crops, posing severe health risks to Ghanaians due to their high infectious dosage relative to their host (Amoah et al., 2007).

Studies by Feglo & Sakyi (2012) detected *Staphylococcus aureus*, *Bacillus species,* and *Klebsiella pneumoniae* in numerous ready-to-eat foods in Ghana’s Kumasi metropolis. The samples also contained the bacteria *Enterobacter cloacae*, *Enterobacter skazki*, *Staphylococcus aureus* (which causes the production of heat-resistant toxins in food), *Escherichia coli* (a sign of faecal contamination), and *Pseudomonas aeruginosa*. Some of the microorganisms in these foods would eventually end up in landfill leachates (after the leftovers are trashed), which will percolate and infiltrate into surface and underground water bodies once the waste is trashed without any pre-treatment. These pathogens suggest faecal contamination and poor sanitary conditions (Bryant, 2019). Regarding industrial ecology, the challenges associated with tackling OFMSW must be tackled vigorously due to its negative environmental impact and subsequent threat to human health. Although OFMSW is touted as a potential alternative fertilizer, its direct integration into agricultural soils without prior treatment may have negative consequences due to the production of various chemically decomposing compounds, which might impede root growth (Soobhany et al., 2017). Fortunately, AD at a thermophilic temperature of 54 ℃ is reported to eliminate pathogens (Seruga et al., 2020).

CHAPTER THREE

MATERIALS AND METHOD

Area of the Study

Cape Coast is a coastal city, the administrative capital of the Central Region, and one of Ghana's most historically significant and fastest-growing cities (Ghana Statistical Service, 2013). The Metropolis is bordered to the south by the Gulf of Guinea, west by Komenda Edina Eguafo Abrem municipality, east by Abura Asebu Kwamankese district, and north by Twifu Heman Lower Denkyira district. Cape Coast is approximately 122 square kilometres and lies between longitude 1° 15'W and latitude 5° 06'N (Ghana Statistical Service, 2013). The vegetation is primarily shrubs, grasses, and a few scattered trees (Ghana Statistical Service, 2021). The landscape in the Metropolis's northern parts is mainly low-lying and ideal for crop cultivation (Ghana Statistical Service, 2013). Due to this, some residents are into skilled agriculture, which resulted in the sale of more fresh and organic food products in the local market over the last decade (Ghana Statistical Service, 2013).

The city of Cape Coast, the core of Ghana's tourism industry, is facing serious difficulty with solid waste management (SMW). The growing issue here is about increased waste volumes and institutional failure to appropriately treat them (Gyimah et al., 2019). Uncollected solid waste, marine litter, and indiscriminate dumping pose a major threat to the tourism industry in Cape Coast, threatening the local economy and its growth (CCMA, 2020). The Metropolis generated approximately 60,225 tonnes of solid waste in 2014, with an estimated population of 220,000 and a waste generation rate of 165 tonnes per day (CCMA, 2015). By 2040, the projected population and solid waste generation are predicted to triple to 486,573 and 133,199 tonnes, respectively, if the current trend continues (CCMA, 2015). The Metropolis has two primary market centres: Kotokuraba and Abura. However, other market centres like Efutu, Kakumdo, Nstin, and UCC Science markets exist. Organic wastes containing fresh fruits, primarily from markets and families, account for most of the city's municipal solid wastes (CCMA, 2020). Meanwhile, unless the waste is properly managed, waste can adversely impact the ecosystem and public health (Siddiqua et al., 2022). Therefore, Cape Coast needs a well-defined management mechanism for SMW. As a result, conducting this research is imperative not only to analyze possible feedstock for biogas production but also to treat market wastes and enhance the city's sanitary conditions. *Figure* 1 is a map of Cape Coast showing the three markets in red considered for this study.

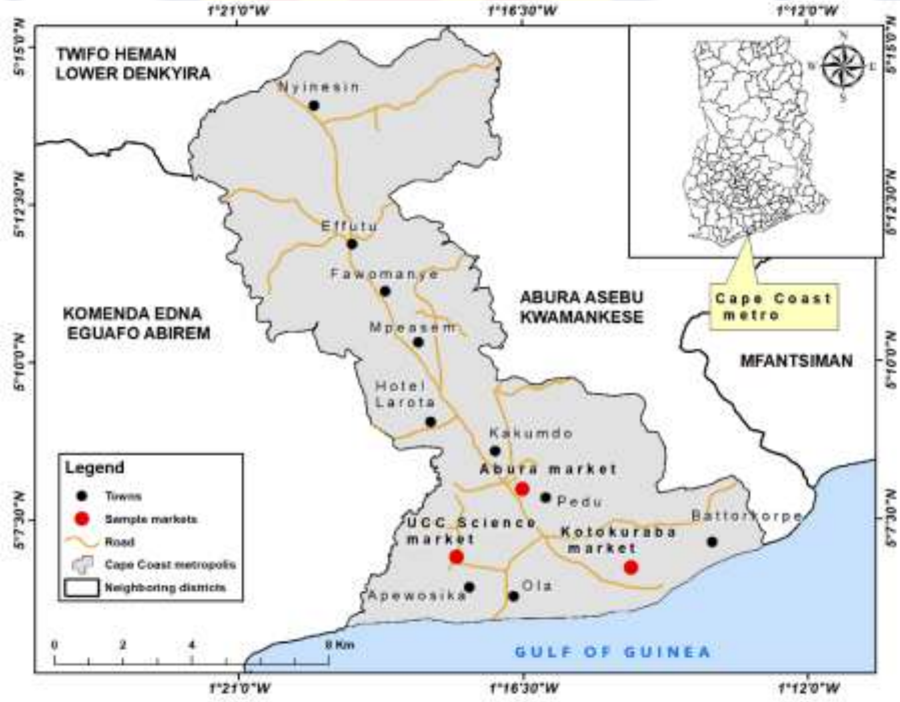

Figure 1: **Map of the study area (Researcher's Construct, 2021)**

Research design

A purposive sampling strategy was used in this study. The rationale for this type of technique for the study is that according to Palinkas et al. (2015) and Robinson, (2014), purposive sampling involves an iterative process of identifying and selecting information-rich cases linked to the phenomenon of interest as opposed to starting with a predefined sampling frame as utilized in qualitative and mixed methodologies. The selection process consists of themes, concepts, and indicators through observation and reflection (Schutt, 2018). Schutt (2018) emphasized the significance of each sampling element's distinct position relative to the research endeavour. To this end, researchers often employ purposeful sampling to select informants based on their specific knowledge and experience, focusing on empirical inquiry.

Target population

A target audience is the population of interest to the researcher. It is the population from which a researcher would like to answer the research questions. The target audience for this study was the vegetable, fruit, root and tuber vendors in Abura, Kotokuraba, and UCC Science markets in Cape Coast, Central Region of Ghana.

Statistical tools

All statistical analyses were done using one–way ANOVA (in randomized blocks) and Excel.

Selection of market waste samples

Eleven different samples of fruits, vegetables, root and tuber wastes were sourced from each of the three different locations (Abura, Kotokuraba, and UCC Science markets). These samples were chosen based on their availability on the markets, decomposition characteristics, and abundance. Fruits, vegetables, roots, and tuber waste above 1 kilogram on the markets were sourced. generation. Fruits, vegetables, roots, and tuber waste above 1 kilogram on the markets were ideal for selection.

Collection and quantification of market wastes

Market wastes were collected from Abura, Kotokuraba, and UCC Science markets in Cape Coast, Ghana, from April to June 2021. The wastes collected from each market were weighed using a mechanical clock hanging scale with a hook (Model no.: GS-006, Gromy Industry Co., Ltd. Hangzhou, Zhejiang, China), and the values were recorded in kilograms (Kg). *Figure 2* shows a picture of the researcher weighing some waste samples during market waste quantification.

***Figure 2:* Picture of the researcher weighing some waste samples during market quantification (Field photograph, 2021).**

Physical segregation and observation of collected waste components were used to determine waste material composition. The wastes were divided into three categories: (a) vegetable wastes, which included wastes from okra, onion, kontomire, cabbage leaves, carrot leaves, and spring onion (b) fruit wastes from oranges, banana, watermelon, lemon, pineapple, and pawpaw (c) root and tuber and sucker wastes from cassava, yam, sweet potato, and plantain.

Forty-four samples of market waste were collected in one month (for each market), thus eleven different samples in a week and homogenized into 11 distinct samples per market. Throughout the study period, the amount of solid waste samples collected per sampling was approximately 3 Kg. The samples were taken to the A.G. Carson Technology Laboratory, UCC, and stored in a fridge at 4 °C. The formula below was used to calculate the weekly average generation of market waste.

$$AVM = \frac{\text{total quantity of wastes generated per month}}{\text{number of weeks in a month}} \qquad (1)$$

Where:

AVM = average monthly generation of wastes (Kg)

Preparation of waste samples for laboratory analysis

Waste residues were pre-treated by cutting and grounding using La Italia by Renesola ABS powerful blender (Model: food processor, Rate power: 1000W, 220-240VAC ~ 50/60Hz, MRP: Rs: 11990/-, Renesola India) to a size of good quality that may be handled in the laboratory for further investigation. A fraction of the samples were dried, processed through a 1-mm screen, and stored in airtight sampling bags. *Figure 3* shows a picture of the researcher preparing waste samples for further laboratory analyses.

Figure 3: **Picture of the researcher preparing waste samples for further laboratory analysis in the A.G Carson Technology Laboratory, UCC (Laboratory photograph, 2021).**

Moisture content determination

Exactly 5 g of solid sample (each sample) was weighed using A&D Galaxy Analytical Balance, 252 g/0.1mg (Model: HR-250AZ, 1756 Automation Parkway, San Jose, CA 95131, USA), and placed into porcelain crucibles and oven (Memmert Beschickung/ Loading- Modell 100 – 800; Memmert GmbH, 91107 Schwabach, Germany) dried at 105 °C for 24 hours. To achieve even heat dispersion, the crucibles containing the sample were distributed over the base of the oven. After that, heated samples were cooled in a desiccator and reweighed to determine the mass of the dry sample. After cooling down, the samples were weighed again. This was measured following the APHA/AWWA/WEF, (2012) standard methods. The moisture content was determined using the following formula:

$$M = \frac{(w-d)}{w} * 100 \qquad (2)$$

Where:

M = wet mass moisture content, %

w= initial mass of sample as delivered, Kg

d = mass of the sample after drying, Kg

Total solids and volatile solids determination

The weights of dried crucibles were recorded as R1 using an A&D Galaxy Analytical Balance, 252 g/0.1mg (Model HR-250AZ, 1756 Automation Parkway, San Jose, CA 95131, USA). The analytical balance weighed each waste sample (about 40 g) from the three markets, and the weight was recorded as R2. The samples were dried overnight at 105°C in the oven (Memmert Beschickung / Loading-Model 100 – 800, Memmert GmbH). The samples were taken from the crucibles and chilled in a desiccator. The weight of each cooled sample was recorded as R3 once it was weighed.

The weighted crucibles and the dried samples were placed in a muffle furnace (Carbolite AAF/3, 1100 °C, S/N. 21-201189, UK) and burned to ashes for two hours at 550 °C. Crucibles and ashes were taken out after two hours, cooled in a desiccator, and reweighed as R4. The difference in dry weight between solid waste and residue weight after fire was used to calculate the weight of VS. The percentages of TS and VS were calculated as follows (APHA/AWWA/WEF, 2012):

$$TS\,\% = \frac{R3-R1}{R2} * 100 \qquad (3)$$

Where:

$R1$ = weight of dried crucible (g)

$R2$ = weight of the sample (g)

$R3$ = weight of (crucible + sample) after 105 °C (g)

$$VS\ \% = \frac{mass\ of\ sample - mass\ of\ sample\ after\ ignition}{Mass\ of\ sample} * 100 \qquad (4)$$

Determination of organic carbon using modified Walkley – Black (partial oxidation) method

About 1 g of each solid waste sample was weighed using Mettler Toledo analytical balance (Model: PG203 -S, 1900 Polaris Pkwy Columbus, OH 43240-4035, United States) into a labelled 100 ml conical flask. The sample was wholly wet or dissolved in about 10 ml of 5 % potassium dichromate. The flask was then filled with 20 mL sulphuric acid from a fast burette, stirred gently for a minute, then set aside for 30 minutes. After 30 minutes, 50 ml 0.4 % barium chloride was added to the content and stirred to ensure thorough mixing. The mixture was centrifuged using Gallenkamp (made in England) laboratory centrifuge for 10 minutes at 3000 rpm.

A colorimeter cuvette was filled with an aliquot of the clear supernatant solution. Each standard and sample's absorbance were measured and recorded. The concentrations of each unknown and blank solution were determined. The organic carbon (OC) was calculated based on the formula (APHA/AWWA/WEF, 2012):

$$OC\ \% = \frac{value\ \ for\ corrected\ concentration * 0.1}{weight\ of\ sample * 0.74} * 100 \qquad (5)$$

pH Measurement

The solid samples' pH was evaluated using a Mettler Toledo FiveEasy pH/mV bench meter according to conventional procedures (Model F20, SRN: B930002355, Mettler-Toledo GmbH, lm Lancher 44, 8806 Greifensee, Switzerland). To around 20 g of solid waste sample, precisely 50 ml of distilled water was added. The amalgam was gently swirled for 10 minutes, then left to sit for 30 minutes before being agitated again for 2 minutes. The pH of the supernatant liquid was then determined.

Measurement of biochemical oxygen demand (BOD_5) using Winkler Azide modification titrimetric method

Exactly 500 ml of each waste sample (blended and strained) was filled into eleven BOD_5 amber bottles containing magnetic stirrers. A blank was created by weighing the same amount of distilled water. Each vial containing the sample and water received around 1 mL $MnCl_2$. Following that, 3 mL of alkali-iodide azide reagent was added. Before the bottles were snugly closed, five pellets of NaOH (an absorbing agent) were placed in each perforated rubber septum. Then, 3.0 ml concentrated H_2SO_4 was put in each bottle and re-capped. 200 ml of each sample was titrated to achieve the initial oxygen concentration.

In a BOD_5 digital equipment (VELP scientific, Model FTC 120, cooled incubator, Italy), each bottle holding the produced sample (300 ml) was incubated at 20 °C for five days. Each mixture was swirled to consume oxygen to attain a saturation limit using the magnetic stirrers in the bottles. The researcher is seen in Figure 4 preparing several waste samples for BOD_5 incubation. As a result of the procedure, carbon dioxide was created, but it was absorbed by the NaOH pellets in the septum. After five days of incubation, oxygen concentrations in the samples and the blank were measured by titration to calculate the BOD_5 values at 20 ℃ as:

$BOD_5. 20\ ℃$

$$= (Initial\ concentration\ of\ oxygen\ in\ the\ sample - Final\ concentration\ of\ oxygen\ in\ the\ sample) * Dilution\ factor \qquad (6)$$

The values of the BOD_5 were recorded based on the positions of the sample bottles in the BOD_5 equipment cell chamber and the average BOD_5 was calculated for the effluent. *Figure 4* shows a photo of the researcher preparing market waste samples for BOD_5 incubation.

***Figure 4:* Photo of the researcher preparing waste samples for BOD_5 incubation in the Water and Sanitation laboratory, UCC (Laboratory photograph, 2021).**

Measurement of chemical oxygen demand (COD) using Closed Reflux, Titrimetric method

The waste sample (2.5 mL) was dispensed into digestion tubes (borosilicate culture tubes) containing potassium dichromate ($K_2Cr_2O_7$) digestion solution and concentrated sulphuric acid (H_2SO_4). An equal quantity of distilled water was also measured and used as a blank. The cuvettes containing the mixed sample were tightly capped and placed in a block digester (Lovibond – tintometer, Model RD 125, S/N: 0715/000321, made in Germany), preheated at 150 °C and reflux for two hours. After two hours, the samples and blank were cooled to room temperature and titrated. 0.05 – 0.10 mL Ferroin indicator was added and rapidly swirled while titrating with standard 0.10 M ferrous ammonium sulphate (FAS) (Matthews, 2014). The endpoint was an abrupt shift in colour from blue-green to reddish brown.

COD of market waste was calculated as follows:

$$\text{COD as mg } O_2/L = \frac{(B-A) * M * 8000}{mL\ sample} \qquad (7)$$

Where:

B = mL FAS used for sample

A = mL FAS used for blank

M = molarity of FAS

8000 = milliequivalent weight of oxygen * 1000 mL/L

Test for microbial parameters - Pour Plate Method

All test tubes, petri dishes, and pipette tips were sterilized in an autoclave (Hand wheel pressure steam sterilizer, Model: YRO5670, Kalstein, France). Solid waste samples from the various markets were homogenized, blended with distilled water, and strained for inoculation. 1.0 µL of the waste sample was serially diluted to achieve 10^{10} dilutions and dispensed onto the media. At 20 - 22 °C, samples were infected on Brilliant Green Agar (BGA) and Endo Agar (EA). The BGA selective medium was used for *Salmonella spp*. while for *Escherichia coli*, the EA selective medium was utilized. Positive and negative (sterile agar) controls were used for the two strains to monitor each inoculum. Each of the presumptive colonies of *E. coli* and

Salmonella spp. were counted. The microbial count was computed using the formula below.

$$\text{CFU/ml} = \frac{number\ of\ counts * df}{volume\ of\ sample} \qquad (8)$$

Where

CFU = colony Forming Unit

df = dilution factor

Endo-selective/differential media preparation (agar)

The manufacturer's instructions were followed for preparing the endo-selective medium. 12.45g Endo powder was measured into 50 mL of distilled water (41.5 g in 1000 ml distilled water), agitated gently to obtain a homogenous mixture, and ensured the pH was 7.5 ± 0.2 (25 °C). The mixture was autoclaved for 15 minutes at 15 lbs pressure (121 °C) in a vertical pressure steam sterilizer (Model LS-50HJ, 16L-1623, AC 220V, 50Hz/ 3 KW) to ensure all the powder had dissolved. It was cooled to 50 °C after 15 minutes. The media was poured into various sterilized petri dishes in a controlled environment and then hardened for around 30 minutes. The firm agar was kept in a secure location without light exposure. *E. coli* displayed golden green on endo agar (EA), but *Salmonella spp.* They appeared pale pink or pinkish white on EA.

Preparation of selective media with Brilliant Green agar (modified)

According to the manufacturer's instructions, brilliant green powder (modified) was made. 15.81 g of bright green (modified) powder was measured into 300 ml of distilled water (52.7 g in 1 L of distilled water), gently spun to obtain a homogenous mixture, and the pH was checked at room temperature to be 6.9 ± 0.2. It was heated in a water bath (Digital generalpurpose water bath, Model: WB-11, Interlab, New Zealand) at 100 °C for 40 minutes to ensure the powder had dissolved entirely, without autoclaving. It was cooled to a temperature of 50 °C after 40 minutes. *Salmonella spp. and E. coli* growth on EA and BGA media, as shown in *Figure 5*. The media was dispensed into various sterilized petri plates and allowed to solidify for about 30 minutes in a fume room, working under sterile conditions. The firm agar was kept in a secure location without light exposure. On BGA, *Salmonella spp.* was pink, *while E. coli* was yellow.

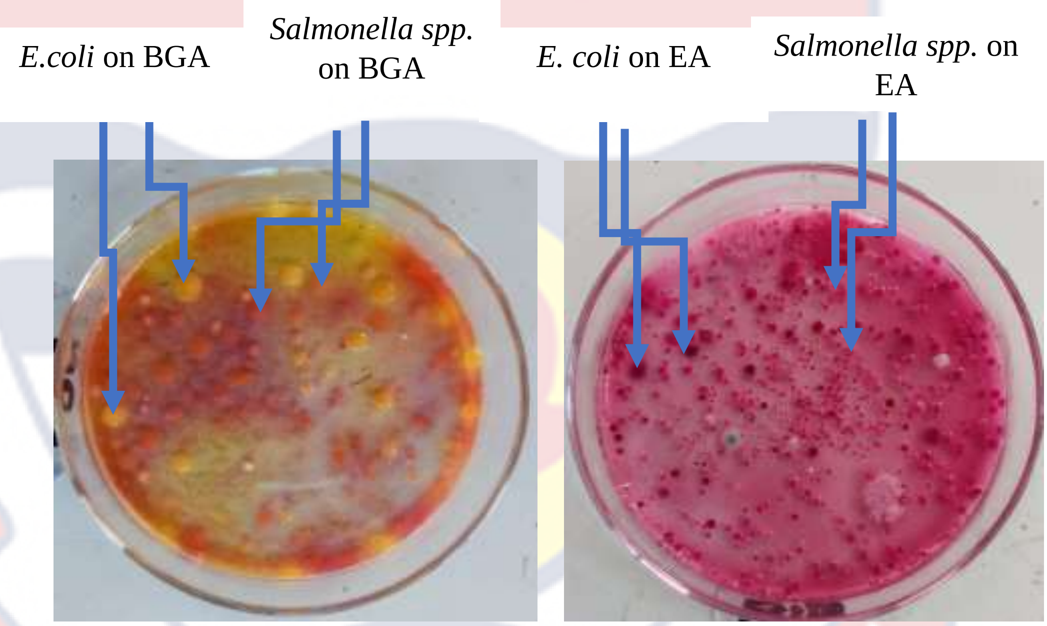

Figure 5: **Growth of Salmonella spp. and E. coli on EA and BGA media (Laboratory photograph, 2021*)***

Sample solution preparation for N, P, K, Cu, and Zn Determination

Preparing solution samples for elemental analyses involves an oxidation process, which is required to remove organic materials via acid oxidation before performing a complete fundamental analysis.

Digestion of sulphuric acid and hydrogen peroxide

350 mL of hydrogen peroxide (H_2O_2), 0.42 g of selenium powder, 14 g of lithium sulphate, and 420 mL sulphuric acid (H_2SO_4) made up the digestion combination. 0.10 g to 0.20 g of oven-dried ground sample was measured into a 100 mL Kjedahl flask, followed by 4.4 mL of mixed digestion reagent and the samples were digested for two hours at 360 °C. In the same way, blank digestions were carried out. The digests were quantitatively placed into 100 mL volumetric flasks and built up to volume after digestion.

Distillation for total nitrogen determination (Micro-Kjedahl method)

A steam distillation apparatus was set up, and steam was passed through it for approximately 30 minutes. After 30 minutes, a 100 mL conical flask containing 5 mL of boric acid indicator solution was placed beneath the condenser of the distillation apparatus. Through a trap funnel, 12 mL of alkali mixture was added to the reaction chamber along with an aliquot of the sample digestate, and distillation commenced. About 25 mL of the distillate was taken and titrated against M/140 hydrochloric acid (HCl) from green to the indicator's initial red-wine hue. The procedure was repeated with distilled water as a blank, and the blank's titre value was deducted from the sample's titre value, yielding the % nitrogen calculation as given below:

$$N\,\% = \frac{(S-B) * solutiion\ volume\ (ml)}{100 * aliquot\ (ml) * sample\ weight\ (g)} \qquad (9)$$

Where:

S = Sample titre value (ml)

B = Blank titre value (ml)

Determination of Phosphorus (P) using the ascorbic acid method

Colour-forming reagent and P standard solutions were prepared for the procedure. Reagents A and B were used to make the colour-producing reagent. 12 g ammonium molybdate in 20 mL distilled water, 0.2908 g antimony sodium tartrate in 100 mL distilled water, and 2.5 mL sulphuric acid were used to make Reagent A. The three solutions were combined in a 2 L volumetric flask, and distilled water was added to make up the volume. 1.56 g of ascorbic acid was dissolved in 200 mL of reagent A to make reagent B. Working standards of P with concentrations of 0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 g P/mL were set in 25 mL volumetric flasks using a stock solution of 100 gP/mL.

Each digested sample had a 2 mL aliquot pipetted into a 25 mL volumetric flask. A 2 mL aliquot of the blank digest was pipetted into each working standard to provide the samples and standards with an identical background solution. After adding 10 mL of distilled water to the standards and samples, 4 mL of reagent B was added, and their contents were diluted to 25 mL with distilled water and swirled. The criteria and samples were measured using a spectrophotometer (Thermo Fisher Scientific, Model: Genesys 20, 4001/4, SN: 3SGP144001, 168 Third Avenue Waltham, MA USA), at a wavelength of 882 nm after it was left to stand for 15 minutes for the colour to develop. Their concentrations and absorbance were used to create a calibration curve. Based on the calculations below, the concentrations of the sample solutions were extrapolated from the standard curve:

$$Concentration\ of\ PO4 - P\ \left(\frac{\mu \mathrm{gP}}{mL}\right)$$

$$= \frac{Concentration\ of\ PO4 - P\ in\ sample * Dilution\ factor}{Weight\ of\ sample} \qquad (10)$$

(Adepetu et al., 2000).

Potassium (K) determination

A flame photometer (Jenway, Model: PFP7, S/N: 76300, Cole-Parmer Ltd. Stone, staffs, ST 15 OSA, UK) measured potassium in the digested samples. Working standards of K were developed in the following concentrations: 0, 2,4,6,8, and 10 g/mL. Individually, the operational standards and sample solutions were inhaled into the flame photometer, and their emissions (readings) were recorded. The concentrations and emissions of the working standards were used to create a calibration curve. Based on the equations below, the concentrations of the sample solutions were extrapolated from the standard curve using their emissions:

$$\mu gK/g = \frac{Concentration * solution\ volume}{Sample\ weight} \qquad (11)$$

(Adepetu et al., 2000).

Using an atomic absorption spectrophotometer, copper and zinc concentrations were determined.

Standard solutions of 1, 2, and 5 g/mL of Cu and Zn were created based on the results (APHA/AWWA/WEF, 2012). The atomic absorption spectrophotometer (AAs) (Thermo Fisher Scientific, Model: Genesys 20, 4001/4, SN: 3SGP144001, produced in the USA) was used to aspirate the standard solutions, and the calibration curves were drawn on the AAS. The concentrations of the sample solutions were estimated as they were aspirated, as given in the formulae below:

$$Concentration\ of\ Cu\left(\frac{\mu gP}{mL}\right)$$

$$= \frac{Concentration\ of\ Cu\ in\ sample * volume\ of\ solution}{weight\ of\ sample} \qquad (12)$$

$$Concentration\ of\ Zn\left(\frac{\mu gP}{mL}\right)$$

$$= \frac{Concentration\ of\ Zn\ in\ sample * volume\ of\ solution}{weight\ of\ sample} \qquad (13)$$

CHAPTER FOUR

RESULTS

Availability of market wastes for biogas production

Table 5 compares the market weekly average generation of wastes from the three markets to determine their availability for biogas. There was a significant difference between waste generated in the Abura market and the other markets in weeks 2, 3, and 4. There was a progressive increase in weeks 1 to 3 recording a value of 84.82 kg, 111.0 kg, and 132.91 kg respectively, then a minor fall in week 4 giving a value of 108.18 kg, and concluding in the greatest total waste of 436.29 kg. Abura market consistently generated the highest amount of organic waste each week. In addition, Abura's waste generated was significantly higher than Kotokuraba and UCC Science ($p < 0.006$).

Kotokuraba market generated moderate amounts of organic waste each week. Kotokuraba generated significantly less waste than Abura but more than UCC Science. The waste generated a progressive climb from week 1 to 3 and declined in week 4, recording 69.64 kg, 86.82 kg, 112.91 kg, and 93.09 kg respectively, and gave a total waste of 362.46 kg. In all weeks, Kotokuraba's waste generation differs significantly from UCC Science ($p < 0.001$), but not significantly from Abura in Weeks 2 – 4. In Week 1, Kotokuraba produced substantially less garbage than Abura, but more than UCC Science.

UCC Science market constantly generated the least amount of organic waste each week. Waste generated in the UCC Science market was much lower than that of the Abura and Kotokuraba markets in all weeks, with P values less than 0.001. there was a decline in waste generated from week 1 to 3 and a slight increase in week 4, scoring a value of 39.91kg 34.73 kg, 30.45 kg, and 35.55 kg.

Table 5: Comparison of market weekly average generation of organic wastes

Market	**Week 1 (Kg)**	**Week 2 (Kg)**	**Week 3 (Kg)**	**Week 4 (Kg)**	**Total (Kg)**
Abura	84.82 a	111.00 b	132.91 b	108.18 b	436.29
Kotokuraba	69.64 b	86.82 b	112.91 b	93.09 b	362.46
UCC Science	39.91 a	34.73 a	30.45 a	35.55 a	140.64
p-value	0.006	0.001	0.018	0.008	0.033
L.s.d	25.87	37.14	71.9	45.54	217.45

*NB: Numbers are mean values. Different alphabet within each column indicates significance at $p < 0.001$.

Comparing the weekly average quantities of organic waste generated from the three markets observed some significant figures. From Table 6 below, cabbage leaves and carrot leaves usually generated the most waste, especially in Week 3, when carrot leaves were at 254.33 kg and cabbage leaves were at 225.33 kg. In comparison, lemon, onion, and spring onion produced the least waste, with lemons contributing as little as 6.67 kg in week 1.

In week 1, there was no significant difference between spring onion, cassava, okra, pineapple peels and also carrot leaves, cabbage leaves, ripe plantain peels, and yam waste. Also, there was no significant difference between onion and lemon. Week 1 showed no significant differences in the waste generated. However, in week 2 significant differences were observed. There was no significant difference between spring onion, onion, cassava, okra lemon, and pineapple peels. Again, there was no significant difference between carrot leaves, cabbage leaves, ripe plantain peels, yam waste, and kontomire.

Table 6: Comparison of weekly average generation of organic waste

Waste sample	**Week 1 (Kg)**	**Week 2 (Kg)**	**Week 3 (Kg)**	**Week 4 (Kg)**
Spring onion	20.00 ab	25.00 a	17.33 a	19.67 a
Onion	9.33 a	26.00 a	13.67 a	12.00 a
Cassava	37.67 ab	39.00 a	67.33 a	53.67 ab
Okra	23.67 ab	24.00 a	18.33 a	13.33 a
Carrot leaves	114.33 c	157.67 b	254.33 c	170.33 cd
Cabbage leaves	151.00 c	196.00 b	225.33 bc	221.33 d
Ripe plantain peels	128.00 c	130.67 b	114.00 ab	127.33 bc
Yam waste	131.33 c	145.33 b	212.67 bc	167.67 cd
Lemon	6.67 a	29.00 a	9.67 a	8.00 a
Kontomire	61.67 b	51.33 b	47.33 a	53.33 ab
Pineapple peels	29.00 ab	28.67 a	35.00 a	23.67 a
Total	712.67	846.67	1014.99	870.33
p-value	<.001	<.001	0.004	<.001
L.s.d	51.77	73.66	140.3	86.09

*NB: Numbers are mean values. Different alphabet within each column indicates significance at $p < 0.001$.

Furthermore, week 3 observed a slightly significant difference in the waste generated. There was no significant difference from spring onion, onion, cassava, okra, lemon, kontomire, and pineapple peels, and cabbage leaves and yam waste indicated no significant variation. Also, week 4 indicated significant variation. Spring onion, onion, okra, lemon, and pineapple peels show no significant variation. There was no significant difference in cassava, and kontomire. The total waste increased from week 1 (712.67 kg) to week 3 (1014.99 kg), indicating an increase, before falling slightly in week 4 (870.33 kg). The p values (<0.001 and 0.004) show statistically significant differences in waste production among samples, showing they are not connected to random chance.

Also, the UCC Science market generated other food wastes that were not available in the other two markets. In Table 7 UCC Science market generated the highest organic waste from watermelon peels (89.75 kg), followed by sweet potatoes (74.75 kg). Orange and pawpaw peels produce substantial quantities of garbage (36.75 kg and 34.50 kg, respectively), whilst banana peels yield the least (17.75 kg). There were statistically significant differences (p < 0.001).

Table 7: Average generation of other organic wastes from the UCC Science market

Waste sample	Market quantity (Kg)
Sweet potato	74.75 c
Watermelon peels	89.75 d
Orange peels	36.75 b
Pawpaw peels	34.50 b
Banana peels	17.75 a
p-value	<.001
L.s.d	13.39

*NB: Numbers are mean values. Different alphabet within each column indicates significance at p < 0.001.

Characteristics of potential feedstock for biogas

Different parameters influence the performance of anaerobic digesters and compost plants at different levels. Some of the parameters analyzed in this study include total solid (TS), volatile solid (VS), moisture content (MC), pH, COD, and BOD, among others. From Table 8 the moisture content across different waste samples varied significantly, which has important implications for biogas production.

High moisture content is essential as it facilitates microbial activity. Generally, the MC ranged between 57.44 % to 91.27 % across the three markets. Onion waste and cabbage leaves exhibited the highest moisture content, with 90.54 % and 91.27 % respectively, making them highly beneficial for biogas production. In contrast, cassava waste and yam waste had relatively lower moisture content, at 66.47 % and 62.36 % respectively. This lower moisture content may necessitate the addition of water to optimize biogas production.

Table 8: Physicochemical qualities of market organic waste

	Moisture content (MC %)			Total solids (TS %)		
Waste sample	**AM**	**KM**	**SM**	**AM**	**KM**	**SM**
Spring onion	83.58 k	84.51 lm	0.00 a	16.42 o	15.49 m	0.00 a
Onion waste	90.54 st	90.21 qrs	0.00 a	9.46 de	9.80 fg	0.00 a
Cassava waste	66.47 e	61.56 c	0.00 a	33.53 t	38.44 v	0.00 a
Okra waste	85.39 n	85.91 o	0.00 a	14.61 k	14.09 j	0.00 a
Carrot leaves	85.45 no	87.02 p	82.12 i	14.55 k	12.98 i	17.89 p
Cabbage leaves	90.38 rst	89.82 q	91.27 u	9.63 ef	10.18 h	8.73c
Ripe plantain peels	84.86 m	84.07 l	84.63 m	15.14 l	15.926	15.38 lm
Yam waste	62.36 d	57.44 b	62.05 d	37.64 u	42.56 w	37.95 u
Lemon	75.55 f	76.51 g	77.17 h	24.45 s	24.76 s	22.83 r
Kontomire	90.72 t	92.07 v	90.01 qr	9.28 d	7.93b	9.99 gh
Pineapple peels	81.77 i	82.86 j	84.43 lm	18.24 q	18.32 q	15.57
p-value	<.001	<.001	<.001	<.001	<.001	<.001
L.s.d	0.2798	0.01461	0.4847	0.1915	0.1000	0.3317

*NB: Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at p < 0.001. AM= Abura market, KM = Kotokuraba market, SM = UCC Science market.

The TS content in the waste samples also varied significantly, ranging from 8.73 % - 42.56 % throughout the markets. High TS percentages were observed in yam waste from Kotokuraba (42.56 %) and cassava waste from Kotokuraba (38.44 %) (Table 8). Also, onion waste from Abura and cabbage leaves from UCC Science exhibited low TS percentages at 9.46 % and 8.73 % respectively. The total solids content is inversely related to moisture content, with high TS indicating more organic material per unit mass.

Volatile solids (VS) are important indicators of the organic matter available for microbial digestion, which is essential for biogas generation. Generally, almost all waste samples from all the markets recorded low VS with ranges between 0.17 % - 35.06 % across all markets. On the contrary, ripe plantain peels and yam waste from the UCC Science market demonstrated high VS percentages of 13.40 % and 35.06 % respectively, (Table 9) indicating significant potential for biogas production. Lemon and cabbage leaves, on the other hand, showed lower VS percentages in some samples, which varied significantly across the different market locations.

Table 9: Volatile solids component of market wastes

	Volatile solids (VS %)		
Waste sample	**Abura**	**Kotokuraba**	**UCC Science**
Spring onion	1.12 de	1.20 e	0.00 a
Onion waste	1.07 cde	1.59 f	0.00 a
Cassava waste	5.8 2 i	5.17 h	0.00 a
Okra waste	1.28 e	1.17 de	0.00 a
Carrot leaves	0.94 bcd	1.14 de	13.22 lm
Cabbage leaves	0.78 b	0.77 b	6.58 j
Ripe plantain peels	13.40 m	13.35 m	13.11 l
Yam waste	7.88 k	3.60 g	35.06 p
Lemon	0.17 a	0.17 a	0.85 bc
Kontomire	0.86 bc	0.86 bc	7.96 k
Pineapple peels	1.61 f	1.563 f	14.58 n
p- value	<.001	<.001	<.001
L.s.d	0.1340	0.0700	0.2321

*NB: Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at $p < 0.001$.

The table below compares the pH levels of various market waste from the Abura, Kotokuraba, and UCC Science markets ranging from 3.19 to 6.13. There were significant differences in pH values ($p < 0.001$) between marketplaces. Some wastes, such as ripe plantain peels, have a stable pH across markets (4.35), whereas others, such as cassava and yam wastes, vary significantly. However, certain wastes, including spring onion, onion, cassava okra, and lemon, were not available at the UCC Science Market (Table 10).

Table 10: Comparison of pH of market wastes

Waste sample	Abura market	Kotokuraba market	UCC Science market
Spring Onion	4.75 g	4.81 h	0.00 a
Onion waste	4.07 c	4.11 d	0.00 a
Cassava waste	4.73 fg	5.12 k	0.00 a
Okra waste	4.72 f	4.74 fg	0.00 a
Carrot leaves	5.20 lm	5.19 l	5.23 no
Cabbage leaves	5.22 mn	5.27 p	5.25 op
Ripe plantain peels	4.35 r	4.35 r	4.35 r
Yam waste	5.13 k	5.18 l	6.13 q
lemon	3.19 b	3.19b	0.00 a
Kontomire	4.95 ij	4.94 i	4.97 j
Pineapple peels	4.35 e	4.34 de	4.35 e
p- value	<.001	<.001	<.001
L.s.d	0.01525	0.00796	0.02642

*NB: Numbers are mean values, (0) = not available on the market. Different alphabet within each column indicates significance at $p < 0.001$.

The analysis also explored the nutrient composition of the market wastes, focusing on organic matter (OM), organic carbon (OC), nitrogen (N), phosphorus (P), and potassium (K). Pineapple peels (UCC Science) and lemon (UCC Science) showed high organic matter percentages, at 99.02 % and 98.02

% respectively. OM ranged from 71.23 % - 99.02 % across the markets. Spring onion samples from Abura and Kotokuraba had lower OM percentages, 78.00 % and 71.23% respectively, (Table 11). Organic carbon ranged from 31.43 % - 57.43 % throughout the markets. High OC percentages were observed in pineapple peels from UCC Science (57.43 %) and kontomire from UCC Science (56.83 %), while spring onion from Abura and Kotokuraba had lower OC percentages of 45.24 % and 41.31 % respectively (Table 11). The pH values across the markets were lower than the permissible limits set by the Ghana EPA (Table 3).

Table 11: Organic matter and organic carbon component of market wastes

	Organic matter (OM %)			Organic carbon (OC %)		
Waste	**AM**	**KM**	**SM**	**AM**	**KM**	**SM**
Spring onion	78.00 c	71.23 b	0.00 a	45.24 d	41.31 c	0.00 a
Onion waste	87.17 g	92.53 i	0.00 a	50.56 i	53.67 k	0.00 a
Cassava waste	95.56 mn	96.01 mno	0.00 a	55.43 mn	55.69 no	0.00 a
Okra waste	84.46 f	90.25 h	0.00 a	48.99 h	52.35 j	0.00 a
Carrot leaves	78.98 d	79.26 d	95.33 lm	45.81 e	45.97 e	55.29 m
Cabbage leaves	77.74 c	82.776	97.85r	45.09 d	48.01 f	56.76 rs
Ripe plantain peels	86.61 g	95.73 mn	97.73 qr	50.23 i	57.09 st	56.69 qr
Yam waste	96.46 op	96.18 no	97.11 pq	55.95 op	55.79 no	56.33 no
Lemon	93.71 j	94.02 jk	98.02 r	54.36 l	31.43 b	56.85 rs
Kontomire	83.47 e	92.20 i	97.97 r	48.41 g	47.68 f	56.83 rs
Pineapple peels	94.07 jk	94.64 kl	99.02 s	54.56 l	55.56 mno	57.43 t
p- value	<.001	<.001	<.001	<.001	<.001	<.001
L.s.d	0.2028	0.1059	0.3512	0.2276	0.1188	0.3942

*NB: Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at p < 0.001. AM= Abura market, KM = Kotokuraba market, SM = UCC Science market.

The nitrogen and phosphorus content also varied across the waste samples, ranging between 0.49 % - 4.26 % and 911 µg/g – 6322 µg/g. Kontomire from UCC Science and Kotokuraba had high nitrogen percentages of 4.26 % and 3.91 % respectively, and cabbage leaves from Abura had 3.69 %. On the lower end, cassava waste from Abura had a nitrogen percentage of 0.49 %. Also, Phosphorus content ranged from phosphorus content was highest in kontomire from UCC Science (6322 µg/g) and okra waste from Kotokuraba (6196 µg/g), while lemon from Abura had the lowest phosphorus content at 911 µg/g (Table 12).

Table 12: Nutrient composition of market organic waste

	Nitrogen (N %)			Phosphorus (P µg/g)		
Waste sample	**AM**	**KM**	**SM**	**AM**	**KM**	**SM**
Spring onion	1.999 m	2.71 p	0.00 a	2897 gh	3474 m	0 a
Onion waste	2.02 m	2.61 o	0.00 a	3267 kl	3382	0 a
Cassava waste	0.49 b	0.64 c	0.00 a	1164 cd	1551 e	0 a
Okra waste	2.74 p	2.20 n	0.00 a	5250 q	6196 t	0 a
Carrot leaves	1.65 j	1.93 lm	1.58 ij	3159 ij	2825 gh	4317 o
Cabbage leaves	3.69 r	3.29 q	3.65 r	6146 t	3612 m	5470 r
Ripe plantain peels	1.88 l	1.5 i	1.76 k	2735 fg	2725 fg	2971 hi
Yam waste	1.49 hi	1.46 h	0.98 e	1647 e	1248 cd	2590 f
Lemon	1.49 hi	1.19 fg	1.23 g	911 b	913 b	5713 s
Kontomire	3.86 s	3.91 s	4.26 t	4014 n	4955 p	6322 t
Pineapple peels	0.74 d	0.82 d	1.12 f	1151 c	1182 cd	1350 d
P value	<.001	<.001	<.001	<.001	<.001	<.001
L.s.d	0.05291	0.02763	0.09165	112.0	58.5	193.9

*NB: Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at p < 0.001. AM= Abura market, KM = Kotokuraba market, SM = UCC Science market.

Moreover, the potassium content showed significant variations (6126 µg/g to 17596 µg/g) across markets, with kontomire from Kotokuraba and Abura having the highest levels at 17596 µg/g and 16001 µg/g respectively. Ripe plantain peels from Abura also had high potassium content at 15284 µg/g. Similarly, lemon from Abura had the lowest potassium content at 7497 µg/g (Table 13).

Table 13: Potassium composition of market waste

	Potassium (K µg/g)		
Waste sample	**Abura**	**Kotokuraba**	**UCC Science**
Spring onion	6597 cd	10123.	0 a
Onion waste	7513 g	6126 b	0 a
Cassava waste	6500 cd	6442 c	0 a
Okra waste	9924.	9740 j	0 a
Carrot leaves	12217 n	12383 n	11080 l
Cabbage leaves	9792	11079 l	11587 m
Ripe plantain peels	15284 q	14109 o	9410 i
Yam waste	6467.	6671 de	6219 b
Lemon	7497 g	7452 g	8944 h
Kontomire	16001 r	17596 s	14739 p
Pineapple peels	6866 ef	6892 f	7417 g
p- value	<.001	<.001	<.001
L.s.d	127.7	66.7	221.2

*NB: Numbers are mean values, (0) = not available on the market. Different alphabet within each column indicates significance at $p < 0.001$.

Table 14 compares copper (0.98 µg/g to 57.13 µg/g) and Zinc (25.56 µg/g to 245.07 µg/g) concentrations in market wastes from Abura, Kotokuraba, and UCC Science markets, revealing substantial differences ($p < 0.001$). In spring onion waste, Copper (Cu) and Zinc (Zn) levels were present in the Abura market and Kotokuraba market but absent in the Science market. Cu levels were higher in the Kotokuraba market (10.89 µg/g) than in the Abura market (9.27 µg/g), with zero in the UCC Science market. Zn levels were similar in Abura market (73.63 µg/g) and Kotokuraba market (73.83 µg/g), but absent in the UCC Science market. Cu levels in cassava waste were slightly higher in the Abura market (19.18 µg/g) than in the Kotokuraba market (18.64 µg/g), but absent in the UCC Science market. The Cu levels in okra waste are similar in Abura market (13.11 µg/g) and Kotokuraba market

(13.86 µg/g). Carrot leaves had similar Cu levels across markets, but greater Zn levels in the Abura market (206.05 µg/g) and Kotokuraba market (205.3 µg/g) than in the UCC Science market (131.33 µg/g). Cabbage leaves had consistent Cu levels across the Abura market (56.44 µg/g), Kotokuraba market (57.13 µg/g), and SM (57.09), but Zn levels vary greatly, with AM having the lowest (25.56) and SM having the highest (52.40). Ripe plantain peels contain stable Cu values, whereas the highest Zn levels were found in the morning. Cu levels in yam waste increase from AM (9.74) to SM (15.96), with SM having the greatest Zn concentration

(165.2). Pineapple peels had the highest Cu in the Kotokuraba market (53.08 µg/g) and the lowest Cu in the UCC Science market (45.77), but the highest Zn in the Kotokuraba market (177.35 µg/g) and the lowest in UCC Science market (109.6 µg/g) (Table 14). The substantial P value implies considerable variability in metal concentrations between markets, necessitating specialized waste management solutions. Except for cabbage leaves and pineapple peels, the Cu and Zn values were below permissible standards of the Ghana EPA and WHO (Table 3).

Table 14: Copper and Zinc concentration in market wastes

	Copper (Cu µg/g)			Zinc (Zn µg/g)		
Waste sample	**AM**	**KM**	**SM**	**AM**	**KM**	**SM**
Spring Onion	9.27 d	10.89 ef	0.00 a	73.63 bcdef	73.83 bcdef	0.00 a
Onion waste	1.74 b	0.98 ab	0.00 a	115.63 defg	96.77 cdefg	0.00 a
Cassava waste	19.18	18.64 i	0.00 a	69.45abcdef	69.46 abcdef	0.00 a
Okra waste	13.11 g	13.86 g	0.00 a	203.1 hi	238.6 i	0.00 a
Carrot leaves	13.43 g	11.31 f	11.08 f	206.05 hi	205.3 hi	131.33 fg
Cabbage leaves	56.44 m	57.13 m	57.09 m	25.56 ab	39.82 abc	52.40 ab
Ripe plantain peels	4.95 c	4.94 bc	4.95 c	245.07 i	234.20 hi	207.83 hi
Yam waste	9.74 de	12.90 g	15.96 h	120.57 defg	103.84 cdefg	165.2g gh
lemon	10.49 def	10.48 def	0.00 a	55.32 abcde	55.31 abcde	0.00. a
Kontomire	15.18 h	15.59 h	15.83 h	73.60 bcdef	85.04 bcdef	94.47 bcdef
Pineapple peels	50.65 k	53.08 l	45.77 j	125.14 efg	177.35 defg	109.6 cdefg
p- value	<.001	<.001	<.001	<.001	<.001	<.001
L.s.d	0.7201	0.3761	1.2473	40.81	21.31	70.69

*NB: *Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at $p < 0.001$. AM= Abura market, KM = Kotokuraba market, SM = UCC Science market.

Table 15 compares pH, Cu, and Zn levels in waste samples from the UCC Science market, indicating substantial variances (P < 0.001). Sweet potato waste had a pH of 5.637, significant Cu (66.63 µg/g), and no Zn data. Watermelon peels exhibited the greatest pH (6.093), Zn (141.9 µg/g), but low Cu content (11.92 µg/g). Orange peels had the lowest pH (3.337), with moderate Cu (14.63 µg/g) and Zn (91.6 µg/g). The Zn levels in pawpaw and banana peels were similar (185.7 µg/g), but banana peels had more Cu (93.73 µg/g).

Table 15: pH, Cu, and Zn composition of other waste from the UCC Science market

Waste sample	pH	Cu (µg/g)	Zn (µg/g)
Sweet potato	5.637 d	66.63 c	146.9 b
Watermelon peels	6.093 e	11.92 b	141.9 b
Orange peels	3.337 a	14.63 b	91.6 a
Pawpaw peels	4.863 b	8.52 a	185.7 c
Banana peels	5.143 c	93.73 d	185.a c
p- value	<.001	<.001	<.002
L.s.d	0.03904	2.721	37. 14

*NB: Numbers are mean values. Different alphabet within each column indicates significance at p < 0.001.

Generally, the BOD and COD across the markets varied between 155.73 mg O_2/L to 731.89 mg O_2/L and 2680 mg O_2/L to 28128 mg O_2/L respectively. The highest BOD_5 values were observed in kontomire and carrot leaves, highlighting the presence of more organics in the wastes. For

Kontomire, the BOD_5 values were 710.82 mg O_2/L in Abura, 731.89 mg O_2/L in Kotokuraba, and 268.80 mg O_2/L at UCC Science. Similarly, for carrot leaves, the BOD_5 values were 637.98 mg O_2/L in Abura, 607.24 mg O_2/L in Kotokuraba, and 518.73 mg O_2/L at UCC Science (Table 16). These high BOD values in kontomire and carrot leaves signify a high amount of biodegradable organic matter. On the other hand, the highest COD values were observed in ripe plantain peels and kontomire. For ripe plantain peels, the COD values were 28128 mg O_2/L in Abura, 14853 mg O_2/L in Kotokuraba, and 17280 mg O_2/L at UCC Science. For kontomire, the COD values were 13126 mg O_2/L in Abura, 17280 mg O_2/L in Kotokuraba, and 4200 mg O_2/L at UCC Science (Table 16). These high COD values, especially in ripe plantain peels and kontomire, indicate a large number of oxidizable pollutants, suggesting a low potential for biogas production as these wastes contain substantial amounts of inorganic materials. The average BOD_5 and COD concentrations in the waste samples were higher than the BOD_5 and COD required by the Ghana EPA and WHO (Table 3).

Table 16: Comparison of biological components of market waste

	BOD (mg O_2/L)			COD (mg O_2/L)		
Waste sample	**AM**	**KM**	**SM**	**AM**	**KM**	**SM**
Spring onion	650.09 n	650.16 n	0.00 a	15002 ef	11520 de	0 a
Onion	640.45 mn	633.42 m	0.00 a	24378 g	23040 g	0 a
Cassava	568.27 j	567.06 j	0.00 a	-	-	0 a
Okra	462.18 g	464.40 g	0.00 a	5620 bc	5947 bc	0 a
Carrot leaves	637.98 mn	607.24 l	518.73 h	7501 c	17280 f	2680 ab
Cabbage leaves	669.97 o	668.31 o	569.80 jk	11251 d	11520 de	2680 ab
Ripe plantain peels	540.67 i	540.67 i	733.30 q	28128 h	14853 def	17280 f
Yam waste	582.01 k	582.01 k	522.33 h	-	-	-
Lemon	251.60 d	251.60 d	0.00	26253 gh	17280 f	0.
Kontomire	710.82 p	731.89 q	268.80 e	13126 de	17280 f	4200 bc
Pineapple peels	155.73 b	160.11 bc	169.67 c	15002 ef	11520 de	13440 de
p- value	<.001	<.001	<.001	<.001	<.001	<.001
L.s.d	7.653	3.997	13.256	2134.5	1232.4	3697.1

*NB: Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at p < 0.001. AM= Abura market, KM = Kotokuraba market, SM = UCC Science market.

The non-familiar wastes generated from the UCC Science market recorded significant values of BOD and COD (Table 17). Sweet potato and banana peels, both from UCC Science, exhibited high BOD values of 536.4 mg O_2/L and 435.0 mg O_2/L respectively, indicating a substantial organic load suitable for biogas generation. On the lower end, pawpaw peels from UCC Science had a BOD of 151.0 mg O_2/L. Similarly, high COD values were recorded for sweet potato (14720 mg O_2/L) and banana peels (17280 mg O_2/L) from UCC Science, further highlighting the presence of high oxidable pollutants in the wastes. However, watermelon peels from UCC Science had the lowest COD value of 7040 mg O_2/L. Again, these values exceed the Ghana EPA permissible limits for BOD_5 and COD.

Table 17: Biological concentrations of other wastes from the UCC Science market

Waste sample	**BOD (mg O_2/L)**	**COD (mg O_2/L)**
Sweet potato	536.4 e	14720 b
Watermelon peels	183.9 b	7040 a
Orange peels	451.4 d	5760 a
Pawpaw peels	151.0 a	8320 a
Banana peels	435.0 c	17280 b
p- value	<.001	<.001
L.s.d	2.858	4657.3

*NB: Numbers are mean values, (0) = not available on the market. Different alphabet within each column indicates significance at $p < 0.001$.

Pathogen concentration of potential feedstock for biogas

The application of organic waste products to arable lands depends largely on the quality of digestate, especially as pathogens could enter the human food chain through this approach (Brochier et al., 2012; Bryant, 2019). Consequently, the concentrations of *Salmonella spp* and *Escherichia coli* in market waste samples were assessed using Endo Agar (EA) and Brilliant Green Agar (BGA) media. Significantly high means of bacterial counts were observed in waste samples from Abura, Kotokuraba, and UCC Science markets (Tables 18, 19, and 20). Table 18 below shows the coliform count of waste samples from the Abura market.

Table 18: Pathogen concentrations of waste samples from the Abura market

Treatments	**Brilliant Green Agar**		**Endo Agar**	
	***Salmonella spp* (CFU/mL)**	***Escherichia coli* (CFU/mL)**	***Salmonella spp (CFU/mL)***	***Escherichia coli* (CFU/mL)**
Spring Onion	2.4×10^{10}	1.7×10^{10}	1.8×10^{10}	2.8×10^{10}
Onion waste	1.9×10^{10}	1.3×10^{10}	1.6×10^{10}	2.1×10^{10}
Cassava waste	2.2×10^{10}	1.2	0	0
Okra waste	1.6×10^{10}	1×10^{10}	1.3×10^{10}	2×10^{10}
Carrot leaves	2.2×10^{10}	1.3×10^{10}	1.5×10^{10}	2.1×10^{10}
Cabbage leaves	2.7×10^{10}	1.6×10^{10}	1.4×10^{10}	2.4×10^{10}
Ripe plantain peels	1.2×10^{10}	1×10^{10}	1×10^{10}	1.1×10^{10}
Yam waste	1.3×10^{10}	0	1×10^{10}	1×10^{10}
lemon	2.5×10^{10}	1.5×10^{10}	1.7×10^{10}	2.9×10^{10}
Kontomire	2.1×10^{10}	1.2×10^{10}	1.1×10^{10}	1.2×10^{10}
Pineapple peels	3.6×10^{10}	1.4×10^{10}	2.4×10^{10}	3×10^{10}

*NB: Numbers are mean values.

From the table above, the concentrations of *Salmonella spp* on BGA ranged from 1.2×10^{10} CFU/mL to 3.6×10^{10} CFU/mL with pineapple peels having the highest bacteria count. Also, the concentrations of *Escherichia coli* on BGA ranged from 1.0×10^{10} CFU/mL to 1.7×10^{10} CFU/mL with spring onions having the highest bacterial count. Comparatively, the growth of *Escherichia coli* in the waste samples was a little higher than it was in BGA as its concentrations ranged from 1×10^{10} CFU/mL to 3×10^{10} CFU/mL with yam waste and pineapple peels recording the lowest and highest counts respectively.

Table 19 shows high pathogen concentrations in waste samples sourced from the Kotokuraba market. The concentrations of *Salmonella spp* on BGA were a little higher than it was on EA ranging from 1.0×10^{10} CFU/mL to 3.2×10^{10} CFU/mL with ripe plantain peels and yam waste recording the lowest and pineapple peels recording the highest counts correspondingly. Similarly, the concentrations of *Escherichia coli* in the waste samples on EA increased slightly more than they were recorded in BGA with concentration values from 1×10^{10} CFU/mL to 2.8×10^{10} CFU/mL of which the highest count was associated with cabbage leaves and ripe plantain peels recorded the least.

Table 19: Pathogen concentrations of waste samples from the Kotokuraba market

	Brilliant Green Agar		**Endo Agar**	
Treatments	***Salmonella spp*** **(CFU/mL)**	***Escherichia coli*** **(CFU/mL)**	***Salmonella spp*** **(CFU/mL)**	***Escherichia coli*** ***(CFU/mL)***
Spring Onion	2.0×10^{10}	1×10^{10}	1.4×10^{10}	2.3×10^{10}
Onion	1.7×10^{10}	1×10^{10}	1.2×10^{10}	2×10^{10}
Cassava waste	2×10^{10}	0	1×10^{10}	0
Okra waste	1.3×10^{10}	1×10^{10}	1×10^{10}	1.7×10^{10}
Carrot leaves	2.2×10^{10}	1.1×10^{10}	1.4×10^{10}	2×10^{10}
Cabbage leaves	2.5×10^{10}	1.4×10^{10}	1.8×10^{10}	2.8×10^{10}
Ripe plantain peels	1×10^{10}	1×10^{10}	1.2×10^{10}	1×10^{10}
Yam waste	1×10^{10}	0	1×10^{10}	0
Lemon waste	2×10^{10}	1×10^{10}	1.1×10^{10}	2×10^{10}
Kontomire	2.1×10^{10}	1.1×10^{10}	1.4×10^{10}	2×10^{10}
Pineapple peels	3.2×10^{10}	1.3×10^{10}	1.3×10^{10}	2.4×10^{10}

*NB: Numbers are mean values.

UCC Science market exhibited high values bacteria concentration. The measured concentrations of *Salmonella spp* in waste samples on BGA ranged from 1×10^{10} CFU/mL to 4.1×10^{10} CFU/mL, slightly higher than they were observed in EA. The mean viable counts were higher for pineapple waste and orange peels and lower for ripe plantain peels and yam peels. The growth of *Escherichia coli* on the EA in the waste samples was a little higher than it was in BGA as its concentrations ranged from 1×10^{10} CFU/mL to 4.3×10^{10} CFU/mL (Table 20). The measured concentrations of pathogens in waste samples from all three markets exceeded the permissible limit (400 CFU/100 mL) defined by the Ghana EPA (Table 3).

Table 20: Pathogen concentrations of waste samples from the UCC Science market

Treatments	**Brilliant Green Agar**		**Endo Agar**	
	Salmonella spp **(CFU/mL)**	***Escherichia coli*** **(CFU/mL)**	***Salmonella spp*** **(CFU/mL)**	***Escherichia coli*** **(CFU/mL)**
Carrot leaves	2.1×10^{10}	1×10^{10}	1.3×10^{10}	2.3×10^{10}
Cabbage leaves	2.5×10^{10}	1.5×10^{10}	1.4×10^{10}	2.0×10^{10}
Ripe Plantain peels	1×10^{10}	1×10^{10}	1.1×10^{10}	1×10^{10}
Yam peels	1×10^{10}	0	0	0
Kontomire	2×10^{10}	1.4×10^{10}	1.3×10^{10}	1.7×10^{10}
Pineapple waste	4.1×10^{10}	2.8×10^{10}	3.5×10^{10}	3.9×10^{10}
Sweet potato peels	2.4×10^{10}	1.4	2.5×10^{10}	1.8×10^{10}
Watermelon peels	2×10^{10}	2.2×10^{10}	2×10^{10}	2.6×10^{10}
Orange peels	4.1×10^{10}	1×10^{10}	1.6×10^{10}	4.3×10^{10}
Pawpaw peels	2.5×10^{10}	2×10^{10}	1×10^{10}	4×10^{10}
Banana peels	4×10^{10}	1×10^{10}	3×10^{10}	2×10^{10}

*NB: Numbers are mean values

CHAPTER FIVE

DISCUSSION

Availability of market wastes for biogas production

Market waste generation comparison

The comparison of the markets' weekly average generation of organic waste in the present study (Table 5) reveals considerable disparities in waste creation across the markets studied. Abura market consistently generated the most organic waste per week, accumulating 436.29 kg, much more than Kotokuraba (362.46 kg) and UCC Science (140.64 kg). These results were consistent with the research on waste generation in urban marketplaces, where higher waste volumes are frequently associated with larger market sizes and increased consumer activity (Lissah et al. 2021; Godfrey et al. 2019). The study findings also corroborate with Vilariño et al. (2017) who attributed this reason to numerous phases, including harvesting, transportation, storage, marketing, and processing. Edwiges et al. (2018) appends that fruit and vegetable waste is prevalent in wholesale fresh food marketplaces.

There was a gradual increase in waste from weeks 1 to 3 in the Abura market, followed by a modest decrease in week 4, indicates an increase in market activity in the middle of the observation period. This pattern could be attributed to market-specific factors such as a greater trade day or higher market patronage during certain weeks. In contrast, the UCC Science market produced consistently little waste, indicating a smaller market size or lower customer engagement. Another reason for the observation could be the metropolitans' nearness to communities serving as food baskets. This may also be due to the market's broad range of goods and services (Addae et al., 2021). The large disparities in waste development among markets highlight the importance of market-specific waste management solutions, as addressed by Godfrey et al. (2019) and UNEP (2018).

Organic waste composition

A complete review of the weekly average generation of market organic waste (Table 6) shows that cabbage leaves and carrot leaves were the most significant contributors to organic waste, particularly in Week 3, where they generated 254.33 kg and 225.33 kg, respectively. This high amount of waste from green leafy vegetables and fruits could be attributed to their high perishability and huge volume of moisture, which is consistent with findings from Miezah et al. (2015), who discovered a high organic content in municipal solid waste (61 %). Zia et al. (2022) and Arhoun et al. (2019) reported similar findings in their studies. On the other hand, commodities such as lemon, onion, and spring onion created the least waste, with lemon contributing as low as 6.67 kg in week 1. The decreased waste generated from such commodities may reflect their extended shelf life or lower total market volume. Market wastes used reflect the wastes used in previous studies for biogas generation (Gunaseelan, 2004; Scaglione et al., 2008; Olanrewaju, 2018; Nweke & Nwabanne, 2021; Zia et al., 2022). The large differences in waste production between different types of organic waste underscore the necessity of understanding waste composition for successful waste management (Bhada-Tata, 2012; Okot-Okumu, 2012).

Other organic waste from the UCC Science market

Unlike the two other markets, the UCC Science market generated other unique kinds of waste that were not available in the other markets.

Watermelon peels (89.75 kg) and sweet potatoes (74.75 kg) were the top organic waste sources in the UCC Science market, with statistically significant differences ($p < 0.001$) (see Table 7). This observation confirms the works of Abdel-Shafy & Mansour (2018) who claimed that the content of waste changes greatly depending on the source, which in this case is most likely impacted by the types of things sold in this market. This clearly shows that the production and composition of market waste organics differ significantly depending on seasons, geographic location, cultural variety, lifestyle, and collection time (Girotto et al., 2015; Tyagi et al., 2018). Banana peels generated the least waste (17.75 kg), which could indicate either a lower banana consumption rate in this market or better usage techniques by vendors and consumers. The large differences in waste generation between all kinds of organic waste in the UCC Science market highlight the need for developed waste management systems that take into account the individual waste types prevalent in each market (Nguyen et al. 2020; Miezah et al. 2015).

Potential feedstock characteristic for biogas generation

The physical and chemical parameters of feedstock are crucial in the design of anaerobic digesters and compost plants because they influence methane generation and process stability. The digester efficacy and the quantity of biogas produced depend on moisture content (MC), pH, volatile solids, nutrient quantity, particle size, and biodegradability of the feedstock (Ebunilo et al., 2015). The highly significant variations in waste characteristics can be attributed to several factors, including the type of waste, environmental conditions, and market-specific handling practices (Vilariño et al., 2017).

MC is a critical parameter that influences the biodegradation rate of organic waste. High moisture content typically indicates a higher potential for microbial activity and decomposition (Zhao et al., 2013). In this study, the moisture content MC (57.44 % - 91.27 %) was relatively higher than the outcome of household waste reported by Ohene Adu & Lohmueller (2012). This according to Addae et al. (2021) could be explained by the greater quantities of food, fruit, and vegetable waste available in market waste, composed of water, compared to household waste made up of cooked food. Onion waste and cabbage leaves exhibited the highest moisture content, making them highly beneficial for biogas production, as they facilitate the flow of nutrients and substrates toward the microbial niche (Mrosso et al., 2023; Uddin & Wright, 2022). Also, the highest moisture content obtained in this study was different from the results obtained by Patil & Deshmukh (2015) who investigated the biogas yield of potato and onion market waste. However, the moisture content obtained in their work was similar to the moisture content of spring onion obtained in the present study. Contrarily, the results on yam waste, cassava waste, and plantain peels were lower than the results observed by Makinde & Odokuma (2015) in a comparative study of the biogas potential of yam and plantain peels.

Interestingly, the high MC of market waste samples indicates their susceptibility to microbial breakdown, owing to the large volumes of root and tuber, fruit, and vegetable wastes. According to Charlottenburg & Rosenheim (2015), AD is most suited for organic waste with a high MC, especially food waste. Qu et al. (2009) reported high methane quantities when MC was 80 % in typical Chinese and French municipal solid waste. Further results demonstrated a higher methane and biogas output feasibility when water content increased (Abbassi-Guendouz et al., 2012; Mustafa et al., 2016; Lalak et al., 2016). Rocamora et al. (2020) believe that decreased moisture content is a reason for gas and liquid diffusion problems as well as the buildup of inhibitors. Nonetheless, Rahman et al. (2020) also detailed that although moisture is required for microbial activity, excessive moisture reduces porosity and oxygen supply, resulting in an anaerobic decomposition and release of offensive odour.

Total solids and volatile solids concentrations in potential feedstock

The total solids (TS) content of the samples revealed an inverse relationship with moisture content (He et al., 2013). Findings from the study revealed yam waste from Kotokuraba and cassava waste from Kotokuraba had high TS percentages, while onion waste from Abura and cabbage leaves from UCC Science exhibited low TS percentages. This may be attributed to the high MC in the market waste samples. Thenabadu et al. (2014) also reported similar findings among food and vegetable wastes in market waste characterization. Interestingly, the findings from this study do not agree with the findings reported by Aliyu (2017) who studied the biogas potential of kitchen waste. However, the present findings agrees with the values reported by Deressa et al. (2015) but also disagree with the TS reported by Bryant (2019). According to some reports, biogas yield rate and yield potential rise with increased TS concentration (Maamri & Amrani, 2014). Sathish et al. (2019) buttressed this claim. Their results noticed maximum biogas yield from rice husk at 20 % TS concentration. This was explained by the higher volume of biogas produced due to the high organic loading and the readily biodegradable components consumed by microbes. Although some waste samples recorded low TS values, Dhar et al. (2016) are of the view that food waste is considerably more readily degradable and has more calories per dry mass despite having a low TS and many soluble organic materials.

Similarly, VS (0.17 % - 35.06 %) was relatively lower than market waste (22.55 % - 85.9 %) in Kumasi (Addae et al., 2021). The variation in results could be linked to the homogenization of different waste samples and the consideration of seasonal variations in waste composition analysis by Addae et al. (2021). Ripe plantain peels and yam waste demonstrated high VS percentages indicating significant potential for biogas production (Zia, Ahmed, & Kumar, 2020). However, the study results were lower than the VS (0.7 % - 9.9 %) of black water reported by Bryant (2019). The high VS content in ripe plantain peels and yam waste highlights their suitability as feedstock for biogas digesters, especially from markets like Abura and UCC Science, where these wastes are abundant. However, Yavini et al. (2014) cautioned that high biogas yield may not automatically be occasioned by high VS content as there is the existence of insufficient VS of lignin material (Yavini et al., 2014).

VS and TS provide helpful information on the amount of biogas that will be produced and the efficacy of the anaerobic process (Mrosso et al., 2023). Thus, A change in TS will alter the microbial morphology of AD systems (Orhorhoro et al., 2017). Thus, the role of both parameters must be understood to ensure process efficiency.

pH concentration of market waste

pH is the most sensitive environmental parameter in monitoring and managing AD because it can speed up or slow the fungal development and biodegradation process (Gupta & Pathak, 2020). According to research, bacteria that produce methane thrive best in neutral to alkaline environments, thus, in an optimum pH range between 6.8 to 9 (Owusu-Ansah et al., 2015). In other words, process efficiency is ensured when the pH value is maintained at an optimal range (Sathish et al., 2019). However, in the present study, pH range of 3.19 to 6.13 was relatively lower than the pH of wastewater documented by Ma et al. (2020) and yam and cassava by (Olanrewaju, 2018). In contrast, the results were comparable to the initial pH values of organic waste observed by Akpan et al. (2019) indicating the acidic nature of market waste samples. This could be attributable to a high lactic acid bacteria and ammonia concentration, contingent on the raw materials and the trend of degradation (Sundberg et al., 2011; Sundberg et al., 2013; Varma et al., 2015). Widyarani et al. (2018) and Thenabadu et al. (2014) agreed that acidic or lower pH can hamper the growth of methanogenic bacteria and reduce biogas yield. This was again confirmed by Widyarani et al. (2018), who studied the influence of pH on biogas production. Latif et al. (2017) detected a drop in methane production as pH was decreased, with an 88 % reduction at pH 5.5, due to the accumulation of VFAs, especially propionic and butyric acids, leaving a more significant amount of organic matter undegraded (Veluchamy et al., 2019). For optimum value yield of present market wastes, literature suggests that requisite buffer capacity is more important than altering the pH of waste samples (Awasthi et al., 2016). The relationship between the system's buffering capacity and bicarbonate concentration can be used to predict process stability and efficiency (Rajput & Sheikh, 2019).

Organic matter and organic carbon concentrations in potential feedstock

Organic matter (OM) has a significant function in the ecosystem (Hamilton, 2012). Results of the present study indicated substantial OM (71.23 % - 99.02 %) and OC (31.43 % - 57.43 %), which imply potential bioconversion into methane (Fernández-Domínguez et al., 2020; Vinardell et al., 2021) and generation of nutrient-rich by-products (Fernandez-Bayo et al., 2018; Guo et al., 2018). However, OC in the existing study was higher (43 %) than the carbon value in market waste reported by Addae et al. (2021) owing to the presence of organic and inorganic wastes in Addae et al. (2021). Ayeleru et al.(2018), found carbon (45.32 %) of city waste in Johannesburg which was higher than the OC in the current study. Pineapple peels from UCC Science and lemon from UCC Science showed high OM percentages. In contrast, spring onion samples from Abura and Kotokuraba had lower OM percentages. Study findings on OM and OC were generally quite similar to the findings reported by Jiménez & García (1992) and Navarro et al. (1993) in a preliminary on the relationship between OM and OC of municipal solid waste (MSW). The high OC and OM values are attributable to the presence of a high concentration of vegetables, mainly carbohydrates in market waste (Addae et al., 2021). Thus, the feedstock typology is critical to understanding the ultimate OM and OC quality of digestates (Rocamora et al., 2020). Also, this variation highlights the importance of selecting wastes with high organic content to optimize biogas production processes. (Singh et al., 2022) found that waste with higher organic carbon content is beneficial for improving soil health and fertility.

OC supports soil structure, retention and availability of moisture, retention and turnover of nutrients, degradation of pollutants, and carbon sequestration (Jalalipour et al., 2020). As a result, when waste with a high OC is balanced with nitrogen, it produces more methane (Peterson, 2017). Based on this common trend, the results of the present study indicate a viable potential for biogas production. Notably, AD of organic matter is a more delicate balance than aerobic digestions due to the biological intricacies of sequential phases in bio-methanation, making digester instability a typical concern. To avoid instabilities, it is critical to understand and regulate the environmental and physicochemical elements that influence the entire anaerobic digestion process (Fisgativa et al., 2016).

Mineral composition of potential feedstock for biogas

Nutrient availability in digestate (Logan & Visvanathan, 2019) is one of the key abiotic elements influencing plant growth (Razaq et al., 2017; Jalalipour et al., 2020). The study results (0.49% - 4.26%) were higher than the N value (1.4 %) reported by Addae et al. (2021) and 0.45 % of kitchen waste by He et al. (2021). Also, the results were higher than the N values (0.3 – 3 %) of organics as recognized by Romero-Cedillo et al. (2017) who acknowledged that the organic fraction of MSW (OFMSW) is typically poor in nutrients. Yu et al. (2022) remarked that high nitrogen content in compost improves its fertilizing value. Phosphorus varied from 911 µg/g to 6322 µg/g, and much lower than the values of market waste recorded by Addae et al. (2021) and in MSW by Romero-Cedillo et al. (2017). Phosphorus is a critical nutrient for plant growth and development. Goldan et al. (2023) mentioned that phosphorus-rich digestates can enhance soil phosphorus availability. The potassium (K) content ranged between (6126 µg/g to 17596 µg/g) and was lower than the potassium content of household waste obtained by He et al. (2021) and MSW by Akpan et al.(2019). The variation in the results could be linked to wastes from different origins, which may have different nutrient compositions (Li et al., 2016). Even though previous studies established that the OFMSW is typically poor in nutrients, Huo et al. (2023) established that organic wastes with high potassium content can significantly benefit soil potassium levels when used as compost.

High pollutants may be found in organic waste, including copper (Cu) and zinc (Zn) (Belon et al., 2012). Remarkably, Cu and Zn concentrations of market wastes ranging from 0.98 µg/g to 57.13 µg/g and 25.56 µg/g to 245.07 µg/g respectively, were relatively lower than the results of animal waste reported by Matheri et al. (2016). Bozym et al. (2015) also recorded Cu and Zn values of fruit wastes higher than the findings of the present study. According to them, high Cu and Zn concentrations can inhibit methane formation and process efficiency. Excluding cabbage and pineapple peels where Cu levels were high, concentrations of Cu and Zn in the remaining market wastes were below the recommended standard and could enhance biogas and healthy digestate production. Even so, the putrefaction of organic materials during anaerobic digestion can result in a decrease in the overall mass of organic waste and a proportional rise in the concentration of trace elements (Marcato et al., 2008). Therefore, monitoring trace element concentrations in digestates and characterizing their chemical forms is crucial for understanding their mobility, bioavailability, and ecotoxicity (Smith, 2009; He et al., 2005)

Biological composition of potential feedstock for biogas

Fruit, vegetable, root, and tuber wastes typically contain significant levels of suspended particles, as well as high BOD_5 and COD content (Kosseva, 2011), consisting of undesirable elements such as harmful organic and inorganic contaminants (Nath & Debnath, 2022). Results of the present revealed substantial BOD_5 (155.73 mg O_2/L to 731.89 mg O_2/L) and COD (2680 mg O_2/L to 28128 mg O_2/L) concentrations in waste samples which were lower than the results obtained in food waste and blackwater effluent by (Bryant, 2019). In comparison, the results were relatively higher than the findings in food wastewater obtained by Ma et al. (2020). Abura, Kotokuraba, and UCC Science markets recorded high COD and BOD_5 concentrations. However, the average BOD_5 and COD concentrations were observed to be higher than the threshold limits defined by the Ghana EPA and WHO, indicating high levels of pollutants in wastes. These high values could be explained by Karlsson et al. (2011). Based on their report, high organic matter load and total suspended solids can result in high BOD and COD. Daud et al. (2018) claim that waste with high BOD levels (greater than 300 mg. L^{-1}) can be handled effectively via the anaerobic approach. In contrast, organic matter with low BOD (less than 300 mg. L^{-1}) can be handled effectively by employing the aerobic method. Thus, considering the high content of organic matter in the prospective feedstock samples collected, the AD strategy ought to be regarded as the primary mode of treatment for efficient BOD and COD removal (Kawai et al., 2016; Arifan et al., 2021).

Pathogen concentration of potential feedstock

Most fruits and vegetables sold in the Ghanaian markets are highly contaminated with microorganisms, particularly bacteria (Adetunde et al., 2015; Amoah, 2015; Abakari et al., 2018). This contamination could be attributed to cultivation practices such as contaminated water irrigation, animal waste manure application, and post-harvest management procedures (Amoah, 2014; Gil et al., 2015; Smith et al., 2019). Interestingly, the mean counts for market waste were higher in the Abura market than in Kotokuraba but slightly similar to the UCC Science market, whereas fruit wastes from the UCC Science market were the most contaminated. Yafetto et al., (2019) in a primary study revealed that vegetable wastes from the Abura market are more highly contaminated with bacteria than those from the Kotokuraba market. This could be attributed to the source of vegetables, transportation, and market conditions. Most bacteria contaminations reported for fruit and vegetable wastes in the present study are similar to findings previously reported by (Topal et al., 2016; Yafetto et al., 2019; Fidelis Akpan et al., 2019). Also, the bacteria contamination of wastes observed in this study is comparable to those noted for beef and chevon by Yafetto et al., (2019).

Analogous research carried out in other countries to evaluate the microbiological quality of vegetables, fruits, roots, and tuber revealed the presence of bacteria also reported in this study (Kłapeć et al., 2016; Kuan et al., 2017; Verma et al., 2018; Elenwo et al., 2019; Possas et al., 2021; Muhie, 2022). Interestingly, Sadeghi et al. (2022) and Seruga et al. (2020) reported that poorly treated and untreated MSW entail enteric pathogens (*Salmonella spp. and E. coli*) that are likely to pose a danger to humans and the environment. In the view of Yafetto et al. (2019) consuming contaminated food can result in hospitalization or possibly death. The agricultural use of municipal solid waste (MSW) digestates boots soil fertility and output, yet there is concern regarding microbial quality (Logan & Visvanathan, 2019). According to Mitscherlich & Marth (2012), *Salmonella* can thrive for an extended duration, for instance, in slurry for more than 77 days, with growth in varying temperatures from 6 to 47 ^{O}C. also, Wang et al. (1996) claimed that *E. coli* can thrive for up to ten (10) weeks and produce verotoxins during this period. This calls for proper waste treatment and digestate hygienization. Seruga et al. (2020) detailed that notwithstanding the type of digestate utilized for AD, efficient elimination of pathogen risk is indispensable even when there is a high pathogen concentration. Although AD is the most suitable approach for treating pathogen-contaminated organic waste, its merits can be annulled due to improper treatment of feedstock and digestate (Khoshnevisan et al., 2018). Recontamination might occur if storage conditions encourage bacterial regrowth (Seruga et al., 2020).

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

Conclusion

In conclusion, analysis of market waste revealed significant variations across markets. The study determined the availability of fruit, vegetables, root and tuber wastes from three different markets (Abura, Kotokuraba, and UCC Science) in Cape Coast. The prominent components were okra, onion, kontomire, cabbage leaves, carrot leaves, spring onion, cassava, yam, plantain peelings, lemon, and pineapple. However, the study also discovered other kinds of waste (sweet potato, orange peels, pawpaw peels, banana peels, and watermelon rinds) from the UCC Science market only. The comparison of the market's weekly average generation of organic waste revealed considerable disparities in waste creation across the markets studied. Abura market consistently generated the most organic waste per week, accumulating 436.29 kg, much more than Kotokuraba (362.46 kg) and UCC Science (140.64 kg). Also, comparing the weekly average generation of waste, the total waste increased from week 1 (712.67 kg) and week 2 (846.67 kg) to week 3 (1014.99 kg), indicating an increase, before falling slightly in week 4 (870.33 kg). Ripe plantain peels, cabbage leaves, carrot leaves, and yam wastes consistently generated the most waste, highlighting their abundance for biogas production. The large numbers of fruits, vegetables, roots, and tuber wastes indicate a future possibility for recycling initiatives and sustainability in Cape Coast.

The physicochemical, biological, and nutrient analysis of the market waste showcased substantial variation in moisture content ranging from (57.44

% to 91.27 %) indicating their susceptibility to microbial breakdown. The TS with VS concentrations in the waste ranged from 8.73 % - 42.56 % and 0.17 % - 35.06 % respectively. The pH was relatively low, ranging from 3.19 - 6.13 an indication of the high acidity of market waste. This suggests the need for buffering. The study findings also revealed high P 0.001 levels of OM (71.23 % - 99.02 %) and OC (31.43 % - 57.43 %) implying that market waste digestate could serve agricultural purposes. The N, P, and K concentrations were very low throughout the markets. With ranges N (0.49% - 4.26%), P (911 µg/g to 6322 µg/g) and K (6126 µg/g to 17596 µg/g). Cu (0.98 µg/g to 57.13 µg/g) and Zn (25.56 µg/g to 245.07 µg/g) concentrations confirmed the suitability of market waste as potential feedstock for biogas. Furthermore, BOD_5 and COD concentrations were found to be relatively high, ranging from 155.73 mg O_2/L to 731.89 mg O_2/L and 2680 mg O_2/L to 28128 mg O_2/L respectively, indicating the presence of high pollutants. The study further observed high pathogen contamination of market waste, indicating significant environmental and public health risks.

Based on the waste characteristics assessed, the UCC Science market emerged as particularly advantageous for biogas production. Wastes such as pineapple peels and kontomire exhibited high moisture content and volatile solids, which are essential for efficient anaerobic digestion and biogas yield. Additionally, these wastes have significant nutrient levels, including N, P, and K. However, the UCC Science market presents challenges that require careful management. Monitoring pathogen levels is essential due to potential health risks associated with untreated waste. Ensuring thorough pre-treatment processes can mitigate these risks, enhancing the safety and efficiency of biogas production.

In contrast, the Abura market faces specific challenges that may affect biogas production efficiency. Some wastes, such as spring onions and cassava, exhibited lower organic matter and nutrient content. This limitation suggests a potential need for supplementation with higher-quality feedstock or additional nutrients to optimize biogas yields effectively. Also, the Abura market poses threats related to higher pathogen concentrations in the waste. This situation is true for the Kotokuraba market. Addressing these concerns through rigorous pre-treatment measures is essential to mitigate health risks during biogas production operations.

Recommendation

The following recommendations were based on improving feedstock quality and quantity for biogas production in Cape Coast, Ghana.

i. Pilot studies should be carried out to assess the methane potential of the market waste in this study.
ii. Future studies should include other markets in Cape Coast for a broader scope.
iii. In later research, various methods for estimating the organic fraction of market food waste (vegetable, fruits, roots and tuber), such as sorting procedures, should be used to check for consistency and accuracy in data.
iv. Quantification of other market waste organics, such as paper waste, as a more comprehensive source of feedstock should be included in future studies.

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APPENDIX

Appendix 1: Supplementary data on other wastes from UCC Science market

Waste	MC %	TS %	V S %	OM %	OC %	N (µg/g)	P (µg/g)	K (µg/g)
Sweet potato	74.80 a	25.20 b	21.45 e	96.25 a	55.83	1.23 a	3315 b	8180 a
Watermelon rinds	94.12 e	5.5 a	4.85 b	98.80 e	57.31 d	2.64 c	3809 c	16667 e
Orange peels	77.17 b	22.83 d	20.85 d	98.02 d	56.85 b	1.23 a	5713 e	8944 b
Pawpaw peels	90.10 d	9.90 b	8.85 e	98.95 e	57.40 e	2.89 d	5229 d	9985 c
Banana peels	88.07 c	11.93 d	10.35 c	98.42 c	57.09 c	1.55 b	2725 a	14109 d
p-value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
L.s.d	0.40591	0.17602	0.34881	0.12722	0.07380	0.0976	174.0	426.9

*Numbers are mean values, (0) = not available on the market, %=percent. Different alphabet within each column indicates significance at $p < 0.001$.

Appendix 2: More Images from the Laboratory Work

Appendix 3: Schematic diagram showing the setup for the Kjeldahl method