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MASTER THESIS

DETERMINING THE GAMBIA'S BIOENERGY AND HYDROGEN PRODUCTION POTENTIAL FROM AGRICULTURAL RESIDUE AND MUNICIPAL SOLID WASTE, IMPLEMENTATION STRATEGIES AND ITS IMPACT ON DEVELOPMENT

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Dedication

This thesis is dedicated to my family most especially my mother for her invaluable support and encouragement throughout my studies.

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Declaration

I declare that this research was undertaken by me and was conducted accurately and ethically and that the conclusions arrived are a true reflection of my findings and that all data generated by me are properly cited.

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List of abbreviations

MSW	Municipal solid waste
OFMSW	Organic fraction of municipal solid waste
AD	Anaerobic digestion
RPR	Residue-to-product ratio
RCR	Residue-to-crop ratio
FAOStats	Food and agriculture organization corporate statistical database
GIS	Geographic information system
GHG	Green house gas

Abstract

To ensure The Gambia meets its long-term energy development goals this thesis investigates implementation strategies to introduce alternative energy sources namely bioenergy and hydrogen production into the energy mix of the country and its development policies. To achieve this, the thesis aims at assessing the country's potential for producing bioenergy and hydrogen from agricultural residue namely: rice, cassava, groundnuts, maize, sorghum, oil palm fruit, seed cotton, millet, and municipal solid waste. The theoretical potential of the organic fraction of municipal solid waste and the crop residue was calculated from the year 2017 to 2038. These results were then used to calculate the biomethane and electricity production potential with the use of Buswell's equation from which using stoichiometry the hydrogen production potential was calculated using steam methane reforming. The technical potential for electricity and hydrogen was then calculated with the use of their respective conversion efficiencies. Using geographic information systems (GIS), the location of a pilot plant was then identified considering the resources the available land area, and its accessibility. The results show that 64.5MW of electricity and 6,228,443.7kmol of hydrogen can be potentially generated in the year 2038. Using these results, a strategy on automated data collection, awareness, and waste-to-energy was designed to fill in the data, management, and infrastructural gaps in The Gambia.

Key words: Municipal Solid Waste, Crop Residue, Theoretical Potential, Technical Potent

Résumé

Afin de s'assurer que la Gambie atteigne ses objectifs de développement énergétique à long terme, cette thèse étudie les stratégies de mise en œuvre pour introduire des sources d'énergie alternatives, à savoir la bioénergie et la production d'hydrogène, dans le mix énergétique du pays et ses politiques de développement. Pour ce faire, la thèse vise à évaluer le potentiel du pays à produire de la bioénergie et de l'hydrogène à partir de résidus agricoles, à savoir : le riz, le manioc, les arachides, le maïs, le sorgho, les fruits du palmier à huile, les graines de coton, le millet, et les déchets solides municipaux. Le potentiel théorique de la fraction organique des déchets solides municipaux et des résidus de culture a été calculé pour la période allant de 2017 à 2038. Ces résultats ont ensuite été utilisés pour calculer le potentiel de production de biométhane et d'électricité à l'aide de l'équation de Buswell, à partir de laquelle, en utilisant la stœchiométrie, le potentiel de production d'hydrogène a été calculé en utilisant le reformage du méthane à la vapeur. Le potentiel technique pour l'électricité et l'hydrogène a ensuite été calculé à l'aide de leurs rendements de conversion respectifs. À l'aide de systèmes d'information géographique (SIG), l'emplacement d'une usine pilote a ensuite été identifié en tenant compte des ressources, de la superficie disponible et de son accessibilité. Les résultats montrent que 64,5 MW d'électricité et 6 228 443,7 kmol d'hydrogène peuvent être potentiellement générés en 2038. Grâce à ces résultats, une stratégie de collecte automatisée de données, de sensibilisation et de valorisation énergétique des déchets a été élaborée pour combler les lacunes en matière de données, de gestion et d'infrastructures en Gambie.

Mots clés : Déchets solides municipaux, résidus de culture, potentiel théorique, potentiel technique

Chapter One

1. Introduction

1.1.Background

1.1.1. Evolution of Development and world energy transition

Over the past century the world's population, development, and technological advancement have continued to grow with an increasing demand for energy and a higher standard of living (King & Van Den Bergh, 2018). This trend commenced during the iron age when humans began making tools and weapons from iron and steel Dani et al., (1992) The Industrial Revolution exploited fossil fuels leading to the growth in carbon emissions which has driven the world into the phenomenon we now know as global warming and climate change. (Child et al., 2018; Gallo et al., 2016; Kraan et al., 2019) Climate change has driven science and research into developing new, clean technologies with low to zero emissions, giving rise to the use of renewable resources.

1.1.2. Africa's energy development and projects

Energy plays a key role in the development of any country, the energy status of a country affects the nation's economy, social activities, infrastructure, and lifestyle. In most African countries electrification is yet to reach 100%, especially in rural areas. In addition, 14% of the total world population of developing countries is found in Sub-Saharan African countries, which accounts for almost 40% of the population without access to electricity (Ajayi, 2013).

However, Africa is a continent blessed with abundant renewable resources and some countries in the continent have started taking advantage of this such as Nigeria, Egypt, Ghana, South Africa, and Kenya to mention a few. In 2021 Kenya introduced a proposed 12MW, grid-connected municipal Waste-To-Energy plant to be located in Kabira, a suburb of Kenya's capital Nairobi. The waste-to-energy project aims at converting three forms of biomass; municipal solid waste (MSW), crop residues, and livestock waste to biogas/fuel ethanol and generating electricity (African Development Bank Group, 2021).

Similarly, Ghana has also implemented a 400KW hybrid waste-to-energy plant in Gyankobaa that is to serve as a pilot project. The plant can handle 50 tons of municipal solid waste per day. Some of the aims of this site are to generate electricity, biogas, fertilizer through composting, green hydrogen, 200KW of solar PV, recycling of plastics through pyrolysis, laboratory analysis, and capacity building in the form of serving as a training center (Africa Energy Portal, 2022).

1.1.3. Overview of The Gambia

The Gambia is a small country located in West Africa along the eastern seaboard of the Atlantic Ocean. According to (IRENA, 2013), the country has a total area of 11570km^2 and it stretches 450km inland along the banks of the Gambia River. The country is bordered on three fronts by Senegal and has a landscape classified under the category of savannah with low hills and a tropical climate. It has an estimated population size of 2.5 million with 176 people per square kilometer making it one of the most densely populated countries in Africa, 57% of the population is concentrated in the urban areas of the country (The World Bank, 2023).

The Gambia's economy is mostly dependent on tourism and agriculture in 2021, its gross domestic product (GDP) was estimated at USD2.078 billion. The agriculture, forestry, and fisheries sectors employ 9.2% of the working population, this excludes a large number of subsistence farmers in The Gambia. Agriculture represents about 24% of the GDP, about 72% of poor households, and 91% of extremely poor rural households. The country serves as a key transit and trade route for Senegal and regional countries (The Gambia 2050 Climate Vision, n.d.).

1.1.4. Emissions and energy status of The Gambia

In 2020, The Gambia's total greenhouse gas (GHG) emissions were at 4,935 GgCO2e and are expected to increase to 6,617 GgCO2e in 2030 if no measures are taken (MCCNR, 2021). The GHG emission estimates show that the transport sector is responsible for 1,026 GgCO2e of the GHG emissions under the energy sector. In 2020, this sub-sector emitted 345 GgCO2e which is projected to increase to 1,026 GgCO2e in 2050. The rise in emissions could be attributed to the increased use of old cars and the poor quality of fuels used. GHG emissions from livestock were at 434 GgCO2e in 2020, which is projected to increase to 1,085 GgCO2e in 2050. The emissions from aggregate sources are estimated at 270 GgCO2e in 2020 and are projected to rise to 674 GgCO2e in 2050. The estimates for forestry stood at 232 GgCO2e in 2020 and a projected value of 578 GgCO2e in 2050. (Change & Resources, 2022) Based on these figures it is evident that The Gambia's emission rates are quite low compared to other parts of the world.

Electricity generation in the country was emitting 241 GgCO2e in 2020 and is estimated to increase to 535 GgCO2e by 2030 this is due to the use of both light and heavy fuels to produce electricity for the country (MCCNR, 2021). The electricity demand was estimated at 1,488 kWh per household per annum in the urban areas whereas for rural households it was estimated at 792 kWh per annum. (Change & Resources, 2022) Furthermore, The Gambia is faced with low access to electricity and insecurity of supply. Electricity access in the Gambia on average is estimated at 60%, mainly in the greater Banjul area, while access in the rural areas is less than 30%; hence, the goal of the Government to achieve universal access to electricity, for 80% of the population nation-wide by 2025.

1.1.5. The Gambia's energy development goals and targets

Electricity generation in the country is entirely dependent on fossil fuel, which is unsustainable and more so, contributes to climate change effects, such as GHG emissions. To avoid such negative externalities to the environment and to gain carbon credits, the government is working on prioritizing renewable energy sources namely: solar PV systems, wind, mini-hydro systems, and biomass, which are more sustainable than fossil fuel.(Change & Resources, 2022; MCCNR, 2021)

To achieve the expected results, and targets, the national and regional renewable energy projects listed below, will be prioritized, and implemented by the government and partners:

I. 150MW Regional Solar PV power plant in Soma (IPP)
II. 20MW Jambur solar PV project
III. 10.5MW NAMA solar PV project

Based on the Ministry of Environment, climate change and adaptation project mapping 2023, the country presently has a total of eight energy and climate change adaptation projects out of which only one project has integrated clean cooking stoves with biogas. As such the country needs to invest in other forms of renewable energy most especially waste-to-energy and green hydrogen projects.

1.1.6. Waste disposal and management in The Gambia

The Gambian waste sector produced a total of 506 GgCO2e in 2020 and is estimated to increase to 1,184 GgCO2e by 2030. (MCCNR, 2021) During a study conducted by the National Environmental Agency in 2014, a total of ninety-five dumpsites were identified across the nation. This is then further classified under the seven respective regions of the country, the volume of waste generated in the respective regions was then determined as follows:

I. Banjul- 4 Dumpsites, volume of 556.9m^3
II. Kanifing Municipality – 16 Dumpsites, volume of14384m^3
III. West Coast region- 20 Dumpsites, volume of 22910m^3
IV. Upper river region- 29 Dumpsites, volume of 13923m^3
V. North Bank Region- 13 Dumpsites, a volume of 9605m^3
VI. Central River region- 12 Dumpsites, a volume of 2448m^3
VII. Lower River Region -4 Dumpsites, a volume of 494.9m^3

Based on this it is clear that the country does not have a standardized landfill. (National Environment Agency, 2014) However, some mitigation measure for this has been identified by the country to improve waste management and reduce emissions. The mitigation measures include reduced dumpsite methane generation, through waste prevention, recycling and banning biodegradable waste from dumpsites, organic waste recovery, increased landfill methane capture and oxidation, waste separation and collection, and improvements at wastewater treatment and compositing facilities (Change & Resources, 2022).

1.2. Problem statement

Lack of alternative energy sources and their impact on circular economy in The Gambia.

1.2.1. The link between alternative energy sources and a circular economy

The circular economy concept helps nations change linear production methods to a cycle wherein, waste that would otherwise be thrown away be reused, recycled, or transformed into a source of energy such as green fuel pellets, biogas, biochar, refuse-derived fuel, heat, and electricity. This encourages efficient and circular use of resources by using waste resources and by-products that are derived locally, thus minimizing the consumption of conventional fuel resources such as fossil fuel and minerals. (Mbazima et al., 2022)

The shift toward a circular economy requires rethinking the supply chains currently used for waste and design policies, business models, investment, and community behavior on less pollutive and efficient activities underpinning our global civilization. As seen in the case of The Gambia most energy projects are currently centered on solar power which brings to question the use of the country's limited space and waste management challenges.

1.3. Objectives

- To assess The Gambia’s bioenergy and hydrogen production potential from crop residue and municipal solid waste.
    - To calculate the country’s generation of municipal solid waste and crop residue per annum.
    - To calculate the biomethane and biohydrogen production potential from the respective feedstocks.
    - To estimate the country’s electricity generation capacity from biomethane.
- Develop implementation strategies to aid the country in achieving its development goals.

1.4.Thesis structure

This thesis has been divided into three main parts based on the three main objectives of the research.

Firstly, this thesis will assess the country's development plans and fill in the missing gaps concerning bioenergy and hydrogen production potential by assessing agricultural residue and municipal solid waste available in the country. Through purpose sampling targeting ministries, municipalities, geographic information system units, and energy regulatory boards of the country to get secondary data on the number of farms and waste disposal sites available in the study site to quantify how much energy the country can produce from the identified feedstock, identify challenges, energy demand and supply.

Followed by designing a detailed step-by-step implementation strategy that will include mapping out a potential pilot plant location through the use of geographic information systems.

Finally, this research will determine how the proposed implementation strategy will aid the country in achieving its short-term and long-term energy development goals and targets. The different sectors that would benefit from implementing the strategy and how Senegal could also benefit from the project and strengthen partnerships between the two countries.

Chapter Two

2. Literature review

2.1. Municipal solid waste

Municipal solid waste can be defined as the refuse produced by households, markets, commercial areas, schools, and administrative areas that do not contain hazardous substances that could be obtained from clinical or industrial waste. (Boer et al., 2010) Ideally, waste is segregated at the source of production or collection however, in countries like The Gambia waste is not segregated at the source or the point of disposal. Municipal solid waste can be categorized into both organic and inorganic fractions, it can be further divided into the following: food waste, agricultural waste, wood, animal waste, paper, plastics, latex, fabrics, and dirt.(Hameed et al., 2021) On a global scale, the major fractions of municipal solid waste are comprised of organic (46%), paper (17%), plastics (10%), glass (5%), metals (4%), and other types of waste (18%). Organic waste is considered the highest contributor to municipal solid waste throughout the world, which represents almost 50% of the generated waste. (Zamri et al., 2021a)

2.2.Agricultural residue

Agricultural residue can be categorized as crop residue mainly obtained from farms or gardens. It normally includes rice straw, wheat straw, rice husk, corn stover, stalks and leaves from tomatoes, pepper, coconut shells, sugarcane bagasse, and so forth depending on the region and climatic conditions. They are mostly left on the fields after harvests and used for fodder and landfill material or burnt in many places. These practices can lead to carbon emissions and leaching. (Adhikari et al., 2018) The agricultural residue is mostly inexpensive renewable lignocellulosic fiber resources that can be used as an alternative to woody lignocellulosic biomass. These residues have similar structure, composition, and properties to those of other plant fibers and make them suitable for composite, textile, pulp, and paper applications.(Panthapulakkal & Sain, 2015) These residues can be used for composting and the generation of biogas, biofuels, and green hydrogen.

2.3.Anaerobic digestion

Anaerobic digestion is a biological method that produces biomethane also known as biogas from biomass. During the conversion, it involves four main steps that normally take place in a digester. According to (Kumar et al., 2021; Zamri et al., 2021) the first stage known as hydrolysis is in charge of transforming complex insoluble organic matter into simple soluble molecules through the use of enzymatic hydrolysis microorganisms. This is then followed by the acidogenesis stage. During this phase acid bacteria use both dissolved and bounded oxygen in the solution to degrade the hydrolysis products into short-chained organic acids. Before moving to the third stage called the acetogenesis phase where essential products for methane generation are produced using acetogenic bacteria. During the final stage methanogenesis occurs in which products from the acetogenesis phase namely acetic acid and hydrogen are transformed into biomethane by methanogenic microorganisms. At the end of all the processes involved in AD, the main products produced are biogas and digestate.

2.4.Biohydrogen production pathways

Biohydrogen production can be described as the production of hydrogen through the transformation of biomass. This transformation can be done either biologically or thermochemically. Under the biological methods, the following methods can be utilized: dark fermentation, bio-photolysis, and photo fermentation. On the other hand, for thermochemical methods, the following pathways can be used: pyrolysis, gasification, combustion, and liquefaction.(Nikolaidis & Poullikkas, 2017a)

2.4.1. Biological methods

2.4.1.1. Dark fermentation

Dark fermentation is known as one of the most common and well-understood biological methods for hydrogen production with a net energy ratio of 1.9. In dark fermentation, substrates are converted by anaerobic bacteria that grow in the absence of light. (Łukajtis et al., 2018) It can be used to convert both the organic fraction of municipal solid waste and agricultural residue. Different from anaerobic digestion the main aim of dark fermentation is to produce hydrogen instead of biogas. (Schievano et al., 2016) During dark fermentation several types of bacteria can be used however, Clostridium and Enterobacter are the most commonly used and can use carbohydrates, proteins, and lipids as substrates to produce hydrogen, carbon dioxide, and organic acids, through the acidogenic pathway (Ferreira & Gouveia, n.d.).

2.4.1.2.Bio-photolysis

Bio-photolysis can be classified into two types, direct bio-photolysis where water molecules are split using sunlight as a source of energy with the help of the hydrogenase enzyme that aids in the production of hydrogen without releasing greenhouse gases. The second type is indirect bio-photolysis which is performed by microalgae under anoxic conditions. Under these conditions, microalgae can produce biohydrogen through fermentation or respiration. The indirect method is not continuous as a return of the light period makes the growth photosynthetic and hinders hydrogenase (Ahmed et al., 2021).

2.4.1.3.Photo fermentation

Photo fermentation is described as the fermentation process that utilizes energy from light and organic acids under nitrogen-deficient conditions for the production of hydrogen. Theoretical photo fermentation has a high hydrogen production yield, it also can get hydrogen production from a wide range of substrates including organic acids-rich waste.(Ahmed et al., 2021; Mishra et al., 2019)

2.4.2. Thermochemical methods

Thermochemical methods are pathways that transform biomass with the use of heat and catalysts to produce energy, chemicals, or fuels. The major operating parameters for thermochemical methods are the degree of oxidation, temperature, heating rate, and residence time. (X. Zhang & Brown, n.d.)

2.4.2.1.Pyrolysis

Pyrolysis is a thermal conversion method that occurs in anaerobic conditions within a temperature range of 300 – 900°C with a heating rate that varies largely from less than 0.005°C/s to more than 10,000°C/s. Pyrolysis can be a complete process on its own to produce bio-fuels that can be later reformed to produce hydrogen or be a step-in gasification or combustion. Depending on operating conditions, pyrolysis can be classified as slow, intermediate, fast, or flash pyrolysis. Slow pyrolysis operates at relatively low heating rates, low temperatures, and long residence times with the main product being solid char. Whereas fast pyrolysis occurs under high temperatures where biomass is rapidly heated in the absence of oxygen. As a result, it decomposes to generate mostly vapors and aerosols and some biochar. For biofuel or liquid production, very, low residence time is required to avoid secondary reactions. (Wu et al., 2022; X. Zhang & Brown, n.d.)

2.4.2.2.Gasification

Gasification is a thermochemical technology that transforms biomass or other organic solid wastes into a gaseous product known as syngas. Syngas normally contains H2, CH4, CO, and CO2. By reacting these carbonaceous feedstocks with the gasifying agents such as air, oxygen, steam, or supercritical water (SCW) a temperature range of 500 to 1200°C inside a gasifier. The most commonly used gasifiers include fixed bed gasifiers, fluidized bed gasifiers, and entrained flow gasifiers. (Wu et al., 2022) Gasification can be either an auto-thermal reaction or an allothermal reaction. An auto-thermal reaction can also be known as a direct gasification process where the heat needed is generated internally meaning endothermic. Whereas the allothermal gasification process also known as indirect gasification occurs when the heat required for the reaction to take place is generated externally meaning exothermic. (Book, 2010)

2.4.2.3.Liquefaction

Liquefaction or hydrothermal liquefaction is the conversion of biomass with high moisture content such as wastewater sludge. It can be further described as a depolymerization process to convert wet biomass into bio-oil and bio-chemicals at the temperature range of 250 to 370°C and pressure up to 35 MPa. Compared with the pyrolysis technology, hydrothermal liquefaction produces higher quality and higher yield bio-oil with better physio-chemical properties. It is typically performed in the presence of hot-compressed water, water-alcohol mixed solvents, or other organic solvents in a high-pressure batch reactor or continuous reactor, eliminating the prior drying step for wet feedstock, thereby lowering energy consumption and realizing greater economic benefits. (Wu et al., 2022)

2.5. Sustainable development

Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It can be further divided into four types namely: human sustainability, environmental sustainability, economic sustainability, and social sustainability. (International Institute for Sustainable Development, 2023; Jabareen, 2008)

The Sustainable Development Goals (SDGs), also known as the Global Goals, were founded under the concept of sustainable development it was adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. The sustainable development goals are interlinked as one area will subsequently affect the other this shows that development must be balanced in all four areas. (United Nations Development Program, 2023)

Chapter Three

3. Materials and Methods

3.1. Study site

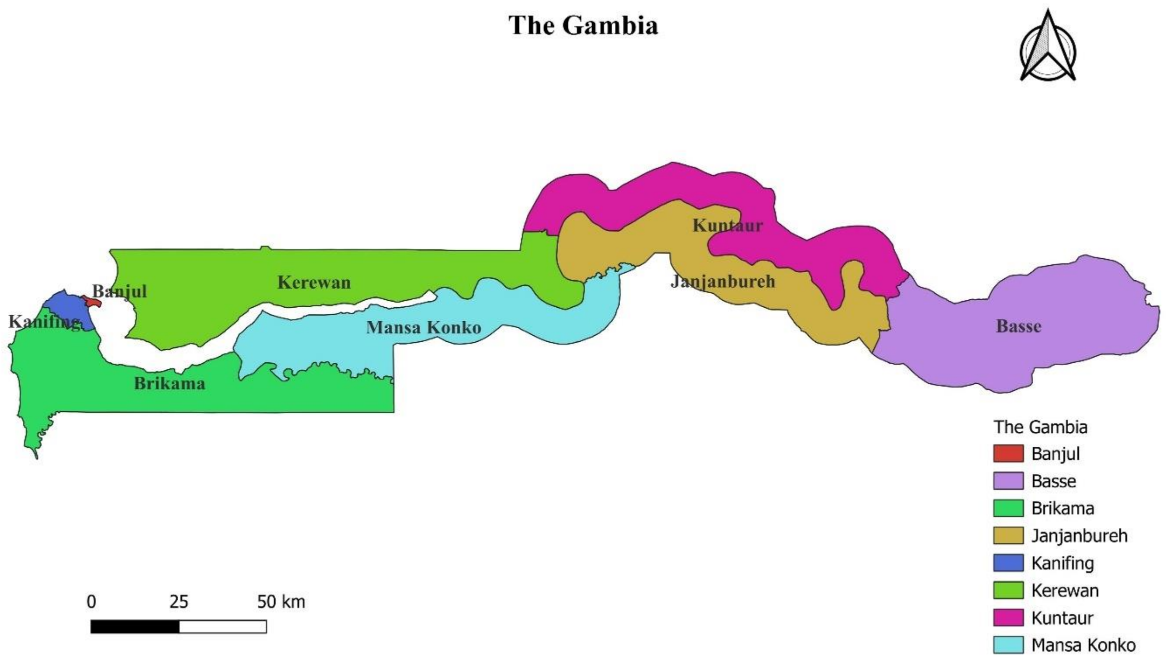

Figure 1 Study site highlighting the eight districts of The Gambia

The Gambia is divided into five administrative regions whose names originate from their position with the River Gambia that runs across the length of the country. The names of the regions are as follows: Central River Region (CRR (North and South)), Lower River Region (LRR), Upper River Region (URR), North Bank Region (NBR), and West Coast Region (WCR). (Change & Resources, 2022) These regions are further divided into eight districts namely Banjul, Brikama, Kanifing, Kerewan, Mansa Konko, Kuntaur, Janjanbureh, and Basse as shown above in Figure 1. This study focuses on municipal solid waste and the crop residue generated by the country as a whole. The Gambia's economy is majorly dependent on agricultural activities and tourism. The agricultural sector contributes 24% of the country's gross domestic product (GDP). (Dibba.B.L & Njie.M, 2021) The agricultural products mainly produced in the country are livestock, crops, and fisheries.

3.2.Feedstock

Crops produced in The Gambia are divided into two categories the first being cash crops which include groundnuts, millet, sorghum, seed cotton, and oil palm fruit. The second category is subsistence crops which include rice, cassava, okra, onions, tomatoes, and other vegetables. Table 1 highlights the fourteen feedstock used to estimate the study site's biogas, biomethane, biohydrogen, and electricity production potential.

Table 1 List of feedstocks used for this research

Selected Feedstock for Research		
Number	**Feedstock**	**Specified Type**
1.	MSW	OFMSW
2.	Rice	Straw
		Husk
3.	Maize (Corn)	Stalks
		Husk
		Cob
4.	Cassava	Stalks
5.	Groundnut (Peanut)	Shells
		Straw
6.	Millet	Stalks
7.	Oil Palm Fruit	Kernel shells
		Fibers
8.	Sorghum	Stalks
9.	Seed Cotton	Stalks

3.3. Methods

The methodology of this research was divided into three main steps namely: secondary data collection and compilation, calculations, and representing results.

3.3.1. Secondary data collection and compilation

To achieve the research objectives the data in table two, three and Four was collected from FAOSTAT (Food and Agriculture Organization Corporate Statistical Database), articles, The Gambia's Ministry of Agriculture, Ministry of Environment, Ministry of Energy, the Kanifing Municipal Council and the Brikama area council.

Table 2 Crop production t/annum

The Gambia’s Crop Production			
Crop Type	**Year**	**Production t/annum**	**Reference**
Rice	2017	30000	(Food and Agriculture Organization, 2023)
	2018	28000	
	2019	30000	
	2020	40300	
	2021	41900	
Maize (Corn)	2017	31000	(Food and Agriculture Organization, 2023)
	2018	19000	
	2019	31000	
	2020	17000	
	2021	20000	
Cassava	2017	11941.4	(Food and Agriculture Organization, 2023)
	2018	11767.34	
	2019	11941.4	
	2020	11855.76	
	2021	11827.21	
Groundnut (Peanut)	2017	58000	(Food and Agriculture Organization, 2023)
	2018	22000	
	2019	58000	
	2020	36000	
	2021	35000	
Millet	2017	55000	(Food and Agriculture Organization, 2023)
	2018	30000	
	2019	55000	
	2020	43000	
	2021	36000	
Oil Palm Fruit	2017	35076.1	(Food and Agriculture Organization, 2023)
	2018	35075.14	
	2019	35076.1	
	2020	35069.48	
	2021	35070.62	
Sorghum	2017	19000	(Food and Agriculture Organization, 2023)
	2018	9000	
	2019	19000	
	2020	6000	
	2021	6000	
Seed Cotton	2017	545.28	(Food and Agriculture Organization, 2023)
	2018	541.93	
	2019	545.28	
	2020	543.77	
	2021	543.27	

3.3.1.1. Residue to Product Ratio (RPR)

The residue-to-product ratio also referred to as residue-to-crop ratio is a value determined by air-dry conditions (Junfeng et al., 2005) it is a tool used to calculate the theoretical potential of crop residues. (Kemausuor et al., 2014; Singh et al., 2008) Table 3 highlights the RPR values of the selected agricultural feedstock for this research.

Table 3 Residue to product ratio of selected feedstock

Crop Residue	**Residue to Product Ratio (RPR)**	**Reference**
Rice Straw	1.66	(Kemausuor et al., 2014; Seglah et al., 2019)
Rice Husk	0.26	(Kemausuor et al., 2014; Seglah et al., 2019)
Maize Stalks	1.59	(Kemausuor et al., 2014; Seglah et al., 2019)
Maize Husk	0.2	(Kemausuor et al., 2014; Seglah et al., 2019; Simonyan & Fasina, 2013)
Maize Cob	0.29	(Kemausuor et al., 2014; Seglah et al., 2019)
Cassava Stalks	0.06	(Kemausuor et al., 2014)
Groundnut Shells	0.37	(Kemausuor et al., 2014; Seglah et al., 2019)
Groundnut Straw	2.15	(Kemausuor et al., 2014; Seglah et al., 2019)
Millet Stalks	1.83	(Kemausuor et al., 2014; Seglah et al., 2019)
Oil Palm Fruit Kernel Shell	0.07	(Kemausuor et al., 2014)
Oil Palm Fruit Fibers	0.14	(Kemausuor et al., 2014)
Sorghum Stalks	1.99	(Kemausuor et al., 2014; Seglah et al., 2019)
Seed Cotton Stalks	2.755	(Halder et al., 2014)

3.3.1.2. Ultimate and proximate analysis.

The ultimate analysis or elemental analysis is performed to quantify the carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) content of biomass. This analysis is normally conducted with the use of an element analyzer such as the LECO CNS and Model 2400 CHNS-O, Perkin Elmer element analyzers, and the ASTM D 3173-85 OR ASTM D 2243-00 methods. (Cruz et al., 2021; Fonseca et al., 2018; Rathod et al., 2023; Sulaiman et al., 2019) Whereas, the proximate analysis quantifies the moisture content, dry matter, volatile materials, fixed carbon, and ash content in the feedstock. According to (Cruz et al., 2021) to obtain the values of the specified parameters the ASTM E 1617-94 and the ASTM E 1755-01 methods are used.

Table 4 Ultimate and proximate analysis of the selected feedstock

Feedstock	**Ultimate Analysis**					**Moisture Content**	**Dry Matter**	**Reference**
	C	**H**	**O**	**N**	**S**			
Rice Straw	39.65	5.2	37.22	0.92	0.12	11.69%	-	(Biswas et al., 2017; Kaniapan et al., 2022)
Rice Husk	45.2	5.8	47.6	1.02	0.21	10.89%	-	(Biswas et al., 2017; Ndudi Efomahp & Gbabop, 2015)
Maize Stalks	45.33	6.18	46.99	0.52	0.98	6.40%	-	(Y. Zhang et al., 2012)
Maize Husk	38.08	5.44	55.89	0.59	0	8.50%	-	(Waheed et al., 2023)
Maize Cob	46.2	5.42	47.22	0.92	0.24	9.27%	-	(Anukam et al., 2017; Danish et al., 2015)
Cassava Stalks	51.12	6.87	41.34	0.67	<0.1	15.54%	-	(Murugan et al., 2021; Pattiya, 2011; Pattiya & Suttibak, 2012)
Groundnut Shells	50.9	5.15	42.1	0.58	0	9.5%	-	(Rathod et al., 2023)
Groundnut Straw	41.42	5.51	35.21	1.27	0.1	-	93.99%	(Getnet, 2019; Tian et al., 2020)
Millet Stalks	44.4	6	43.8	0.3	0.15	4.9%	-	(Ajikashile et al., 2023; Ouiminga et al., 2012)
Oil Palm Fruit Kernel Shells	48.06	6.38	34.1	1.27	0.09	10.23%	-	(Ninduangdee et al., 2015; Onochie et al., 2017)
Oil Palm Fruit Fiber	42.65	5.48	50.78	1.09	0	11.10%	-	(Onochie et al., 2017; Yahayu et al., 2018)
Sorghum Stalks	46.47	5.69	46.75	1.09	0	6.63%	-	(Mehrvarz et al., 2017)
Seed Cotton Stalks	47.05	5.35	40.77	0.65	0.21	-	92.28%	(Adl et al., 2012; Al Afif et al., n.d.)
OFMSW	47.03	6.75	32.7	2.58	0.52	60%	40%	(Yong et al., 2021)

3.3.2. Calculations

3.3.2.1. Crop residue and municipal solid waste theoretical potentials.

The theoretical potential of crop residues is calculated by multiplying the annual crop production with the residue-to-product ratio as shown in Equation 1.

Equation 1 Theoretical crop residue potential

$$Theoretical\ crop\ residue\ potential\ =\ Annual\ crop\ production\ *\ RPR$$

For this research, the estimation of theoretical crop residue potential was conducted by using the following steps:

Step One:

Determine the annual crop production of the selected feedstock from the literature. Due to unavailable data for years 2022 and 2023, the data in Table 2 and Table 5 was used as a reference to estimate the projected annual crop production for the year 2038.

Step Two:

Calculate the theoretical crop residue potential using equation one and the data in Table 2 and Table 3**.**

Step Three:

The values obtained from step two were then summed up to get the total theoretical crop residue potential for the years 2017 to 2021 and 2038.

Table 5 Conditions required for crop growth, projected temperature, and annual rainfall for the year 2038 for The Gambia

Estimated average temperature 2038	The temperature required for the growth of crop	Estimated annual rainfall 2038	Annual precipitation for crop growth	Crop Type	Reference
19 - 34℃	21 - 37℃	70 -100cm	115 - 300cm	Rice	(Aryal, 2013; Atique-ur-Rehman et al., 2022; Pickson et al., 2022)
19 - 34℃	25 - 28℃	70 -100cm	50 - 100cm	Maize	(*Maize Production Jéan Du Plessis DEPARTMENT: AGRICULTURE REPUBLIC OF SOUTH AFRICA*, n.d.)
19 - 34℃	25 - 30℃	70 - 100cm	100 - 300cm	Cassava	(Villamayor, n.d.)
19 - 34℃	20 - 30℃	70 - 100cm	45 - 125cm	Groundnuts	(Cilliers, n.d.)
19 - 34℃	26 - 29℃	70 - 100cm	50 - 90cm	Millet	(*Cultivation of Millets (Finger Millet and Kodo Millet)*, n.d.)
19 - 34℃	20 - 40℃	70 - 100cm	125 - 200cm	Oil palm fruit	(Unjan et al., 2017)
19 - 34℃	20 - 30℃	70 - 100cm	45 - 65cm	Sorghum	(*Sorghum Production*, n.d.)
19 - 34℃	21 - 37℃	70 - 100cm	85 - 110cm	Seed cotton	(Dai et al., 2017)

The theoretical potential of municipal solid waste is calculated by multiplying the annual production of municipal solid waste with the organic fraction of municipal solid waste percentage of the study site, as shown in Equation 3.

Equation 2 Annual municipal solid waste production

$$Annual\ MSW\ production\ =\ Population * Per\ capita\ generation * Number\ of\ days\ in\ the\ year$$

Equation 3 Municipal solid waste theoretical potential

$$MSW\ Theoretical\ potential =\ OFMSW * MSW$$

To obtain the municipal solid waste theoretical potential for this research the following steps were taken:

Step One:

To calculate the country's generation of municipal solid waste for each of the specified years, equation two was used by multiplying the population value by each corresponding year with the per capita generation of that particular year and the number of days in the year. The values for the population size and per capita generation of MSW are highlighted in Table 6.

Step Two:

To obtain the theoretical potential of municipal solid waste the estimated municipal waste generation was multiplied by the percentage of the organic fraction of municipal solid waste for each respective year. The percentage of the OFMSW is shown in Table 6.

Table 6 The Gambia's population projections and per capita generation of municipal solid waste

Year	**Population**	**Per capita generation of MSW**	**OFMSW**	**Reference**
2017	2.21	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2018	2.28	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2019	2.34	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2020	2.42	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2021	2.49	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2022	2.56	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2023	2.63	0.53	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2028	3.01	0.6	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2033	3.42	0.6	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)
2038	3.84	0.6	0.5	(Sanneh et al., 2011; United Nations department of economics and social affairs population division, 2022)

To obtain the total theoretical potential of all the feedstocks equation four was used by simply summing up the MSW theoretical potential with the crop residue theoretical potential, this was done for each of the respective years.

Equation 4 Total theoretical potential

$$Total\,Theoretical\,potential = MSW + Crop\,residue$$

3.3.2.2. Theoretical Buswell's equation

The theoretical Buswell's equation shown below Equation 5 was introduced in 1952 and is used to estimate the biogas potential of a given feedstock from anaerobic digestion. The values required while using the equation are the carbon, oxygen, hydrogen, nitrogen, and sulfur composition (ultimate analysis) of the specified biomass. To estimate the methane potential a combination of Buswell's equation with the carbon content of the biodegraded material. (Addae et al., 2021; Aragon-Briceño et al., 2022; Banks, n.d.)

Equation 5 Buswell's equation

$$\begin{aligned} CcHhOoNnSs &+ 1/4(4c - h - 2o + 3n + 2s)\,H2O \\ &\rightarrow 1/8(4c - h + 2o + 3n + 2s)\,CO2 + 1/8(4c + h - 2o - 3n - 2s)\,CH4 \\ &+ nNH3 + sH2S \end{aligned}$$

To calculate the methane and energy yield the steps below were followed with data from Table 4.

Step One: Theoretical biogas composition

This was calculated with the use of Equation 5 and Equation 6.

- To get the coefficient of carbon dioxide and methane, the elemental value from the ultimate analysis of a specific feedstock was divided by its corresponding atomic mass.
- The values obtained at this stage were then used in Buswell's equation to get the earlier-mentioned coefficients.
- The methane percentage of the biogas was then determined by dividing the methane coefficient by the sum of the methane and carbon dioxide coefficient as shown in Equation 6.
- This value was then subtracted from one hundred to get the carbon dioxide percentage.

Equation 6 Methane percentage

$$CH4\,/\,(CH4 + CO2) = \%CH4$$

Step Two: Methane yield

- The theoretical potential of each of the chosen feedstock was converted from tones to kilograms.
- The converted values were used to determine the theoretical potential dry matter and moisture content by multiplying the specified moisture percentage in Table 4 with its respective theoretical potential. The same process was followed for the dry matter content.
- The carbon percentage was calculated by multiplying the elemental value from the ultimate analysis by its corresponding atomic mass the values for each of the elements were then summed up. The value for carbon was then divided by the summed-up value and multiplied by one hundred to get the carbon percentage.
- Calculate the weight of carbon of the feedstock by multiplying the carbon percentage with the dry matter content of the feedstock's theoretical potential.
- Calculate the weight of carbon converted to biogas first, assuming the percentage of biodegraded carbon as 70%. This percentage is multiplied by the weight of carbon to get the weight of carbon converted to biogas.
- Determine the weight of methane carbon by multiplying the methane percentage of biogas with the weight of carbon converted to biogas.
- According to (Banks, n.d.) 1mol of methane is equal to 16g of methane.
- To calculate the weight of methane, 16g of methane is divided by the atomic mass of carbon which is then multiplied by the weight of methane carbon to get the weight of methane in kilograms before it is later converted to grams.
- According to (Banks, n.d.) 1mol of gas at standard temperature and pressure (STP) is equal to 22.4 liters and 16g of methane is equivalent to 22.4 liters.
- To calculate the volume of methane in cubic meter the weight of methane in grams obtained earlier is then divided by 16 to get methane in mols. The methane in mols is then multiplied by 22.4 to get the volume of methane in liters, this value is then converted to cubic meter.
- The weight of methane was then converted to metric tons by dividing the value of methane in kilograms by one thousand.

Step Three: Energy value of methane

- Based on (Banks, n.d.)1m^3 of methane is equal to 36MJ (megajoules) and 1kWh is equivalent to 3.6MJ and 1m^3 of methane is equal to 10kWh.
- The energy value of methane for each of the chosen feedstock was determined by multiplying the volume of methane in cubic meters by ten to get it in kilo-watt hour.
- This was then converted to MWh with the use of Equation 7**.**

Equation 7 kWh to MWh conversion equation

$$MWh = kWh * 10\hat{} - 3$$

Equation 8 MWh to MW conversion equation

$$MW = MWh/h$$

3.3.2.3. Hydrogen production potential from steam methane reforming with the use of stichometry.

Steam methane reforming is an endothermic reaction that converts methane to hydrogen with the aid of steam. To determine the theoretical hydrogen potential of selected feedstocks theoretical methane potential is a branch of chemistry known as stichometry that involves the use of reactants and products in a chemical reaction to derive the quantity of the element needed in this case hydrogen. Equation 9 obtained from (Shahhosseini et al., 2018; Yokota et al., 2012) was used to estimate the hydrogen potential of the selected feedstocks for this research.

Equation 9 Steam methane reforming

$$CH4 + H2O = CO + 3H2\, \Delta Ho = 206\, kJ/mol$$

Based on (Nikolaidis & Poullikkas, 2017b; Yin & Wang, 2022) 1mol of methane will give 3 moles of hydrogen gas stoichiometrically. Equation 10, Equation 11, and Equation 12 were then used to calculate the hydrogen theoretical potential.

Equation 10 Molar mass of methane

$$Molar\ mass\ of\ methane = 12 + 4 = 16\, kg/kmol$$

Equation 11 Amount of methane

$$Amount\ of\ methane = m/M = y/16 = x\, kmol$$

Equation 12 Amount of hydrogen

$$Amount\ of\ hydrogen = x * 3 = z\, kmol$$

3.3.2.4. Technical potential

The technical potential for energy generation and hydrogen production was calculated to determine the achievable production quantity. To do this the conversion efficiencies for electricity from methane which is 85% and the conversion efficiency of hydrogen through steam methane reforming which ranges from 65% to 75% were obtained (De Souza et al., 2014; La Picirelli de Souza et al., 2021). The conversion efficiency percentage of energy was multiplied by the theoretical energy potential for each corresponding year. The same process was followed to calculate the technical potential for hydrogen as shown in Equation 13.

Equation 13 Technical potential

$$Technical\ potential = Theoretical\ potential * Conversion\ efficency\ percentage$$

3.3.3. Representing results with QGIS

QGIS is an application used to design geographical maps. This research was used to represent the study site area and locate a potential pilot plant location based on the resources available and the land area such as former sand mining sites. The following steps were followed while designing the map.

- Download the shapefile of the country.
- On the QGIS application, the calculated data for the MSW generation per district was merged with the shape file data in the form of a vector.
- The districts were then labeled and color-coded with the darkest color corresponding to the district with the highest generation of MSW.
- The location of the pilot plant was selected and the scale, legend, and compass were added to the designed map.

Chapter Four

4. Results

4.1. Theoretical Potential

4.1.1. Theoretical crop residue potential

Shown below in Figure 2 the total theoretical crop residue potential for each of the respective years as seen in Table 7 to Table 12 shows that the years 2017 and 2019 had the highest theoretical crop residue potential due to the high production yield as compared to 2018 which had a lower potential due to flooding that occurred during July and August in The Gambia. Although the theoretical crop residue potential for the years 2020 (303660.0t/annum) and 2021(297639.2t/annum) were much better than that of 2018 (231094.8t/annum). However, compared to the year 2019 which had a potential of 416284.7t/annum it was significantly lower, this reduction in yield could be attributed to the COVID-19 pandemic that had a severe impact on the country’s agricultural activities. Assuming the absence of natural disasters and pandemics the estimation for the year 2038 was conducted with the aid of data in Table 5, this helped to prove that when exposed to the required growth conditions the country's theoretical crop residue potential would increase steadily.

Table 7 Theoretical crop residue potential for the year 2017

2017 Theoretical crop residue potential				
Crop Type	**Production /annum in tons**	**Residue type**	**RCR**	**Residue/tons**
Rice	30000	Straw	1.66	49800
		Husks	0.26	7800
Maize (Corn)	31000	Stalks	1.59	49290
		Husks	0.2	6200
		Cobs	0.29	8990
Cassava	11941.4	Stalks	0.06	716.484
Groundnuts	58000	Shells	0.37	21460
		Straw	2.15	124700
Millet	55000	Stalks	1.83	100650
Oil palm fruit	35076.1	Kernel shells	0.07	2455.327
		Fiber	0.14	4910.654
Sorghum	19000	Stalks	1.99	37810
Seed Cotton	545.28	Stalks	2.755	1502.2464
Total	**240562.78**			**416284.7114**

Table 8 Theoretical crop residue potential for the year 2018

2018 Theoretical crop residue potential				
Crop Type	**Production /annum in tons**	**Residue type**	**RCR**	**Residue/tons**
Rice	28000	Straw	1.66	46480
		Husks	0.26	7280
Maize (Corn)	19000	Stalks	1.59	30210
		Husks	0.2	3800
		Cobs	0.29	5510
Cassava	11767.34	Stalks	0.06	706.0404
Groundnuts	22000	Shells	0.37	8140
		Straw	2.15	47300
Millet	30000	Stalks	1.83	54900
Oil palm fruit	35075.14	Kernel shells	0.07	2455.2598
		Fiber	0.14	4910.5196
Sorghum	9000	Stalks	1.99	17910
Seed Cotton	541.93	Stalks	2.755	1493.01715
Total	**74617.07**			**231094.837**

Table 9 Theoretical crop residue potential for the year 2019

2019 Theoretical crop residue potential				
Crop Type	**Production /annum in tons**	**Residue type**	**RCR**	**Residue/tons**
Rice	30000	Straw	1.66	49800
		Husks	0.26	7800
Maize (Corn)	31000	Stalks	1.59	49290
		Husks	0.2	6200
		Cobs	0.29	8990
Cassava	11941.4	Stalks	0.06	716.484
Groundnuts	58000	Shells	0.37	21460
		Straw	2.15	124700
Millet	55000	Stalks	1.83	100650
Oil palm fruit	35076.1	Kernel shells	0.07	2455.327
		Fiber	0.14	4910.654
Sorghum	19000	Stalks	1.99	37810
Seed Cotton	545.28	Stalks	2.755	1502.2464
Total	**240562.78**			**416284.7114**

Table 10 Theoretical crop residue potential for the year 2020

2020 Theoretical crop residue potential				
Crop Type	**Production /annum in tons**	**Residue type**	**RCR**	**Residue/tons**
Rice	40300	Straw	1.66	66898
		Husks	0.26	10478
Maize (Corn)	17000	Stalks	1.59	27030
		Husks	0.2	3400
		Cobs	0.29	4930
Cassava	11855.76	Stalks	0.06	711.3456
Groundnuts	36000	Shells	0.37	13320
		Straw	2.15	77400
Millet	43000	Stalks	1.83	78690
Oil palm fruit	35069.48	Kernel shells	0.07	2454.8636
		Fiber	0.14	4909.7272
Sorghum	6000	Stalks	1.99	11940
Seed Cotton	543.77	Stalks	2.755	1498.08635
Total	**189769.01**			**303660.0228**

Table 11 Theoretical crop residue potential for the year 2021

2021 Theoretical crop residue potential				
Crop Type	**Production /annum in tons**	**Residue type**	**RCR**	**Residue/tons**
Rice	41900	Straw	1.66	69554
		Husks	0.26	10894
Maize (Corn)	20000	Stalks	1.59	31800
		Husks	0.2	4000
		Cobs	0.29	5800
Cassava	11827.21	Stalks	0.06	709.6326
Groundnuts	35000	Shells	0.37	12950
		Straw	2.15	75250
Millet	36000	Stalks	1.83	65880
Oil palm fruit	35070.62	Kernel shells	0.07	2454.9434
		Fiber	0.14	4909.8868
Sorghum	6000	Stalks	1.99	11940
Seed Cotton	543.27	Stalks	2.755	1496.70885
Total	**186341.1**			**297639.1717**

Table 12 Theoretical crop residue potential for the year 2038

2038 Theoretical crop residue potential				
Crop Type	**Production /annum in tons**	**Residue type**	**RCR**	**Residue/tons**
Rice	44900	Straw	1.66	74534
		Husks	0.26	11674
Maize (Corn)	23000	Stalks	1.59	36570
		Husks	0.2	4600
		Cobs	0.29	6670
Cassava	14827.27	Stalks	0.06	889.6362
Groundnuts	38000	Shells	0.37	14060
		Straw	2.15	81700
Millet	39000	Stalks	1.83	71370
Oil palm fruit	38070.62	Kernel shells	0.07	2664.9434
		Fiber	0.14	5329.8868
Sorghum	9000	Stalks	1.99	17910
Seed Cotton	543.27	Stalks	2.755	1496.70885
Total	**207341.16**		13.365	**329469.1753**

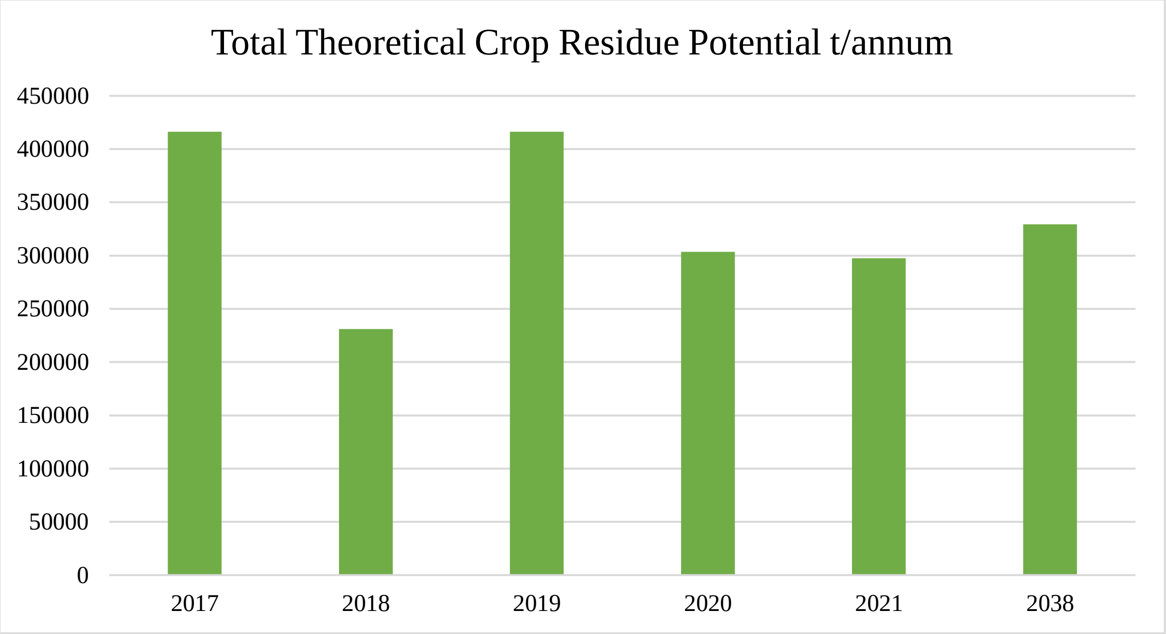

Figure 2 The total theoretical crop residue potential per year

4.1.2. Municipal solid waste theoretical potential

Unlike the theoretical crop potential shown above in Figure 2, the municipal solid waste theoretical potential represented in Figure 3 shows a steady yearly increase in municipal solid waste theoretical potential, this trend is due to the increase in population size and the per capita generation of the country. Based on this trend in addition to that of the crop residue potential, Figure 4 shows that the country has an estimated total theoretical potential of 329889.7t/annum.

Table 13 Municipal solid waste theoretical potential

Total Theoretical Municipal Solid Waste Potential						
Year	**Population**	**Per capita generation of MSW**	**No. of days in the year**	**MSW tons/annum**	**OFMSW**	**MSW Theoretical Potential t/annum**
2017	2.21	0.53	365	427.5245	0.5	213.76225
2018	2.28	0.53	365	441.066	0.5	220.533
2019	2.34	0.53	365	452.673	0.5	226.3365
2020	2.42	0.53	365	468.149	0.5	234.0745
2021	2.49	0.53	365	481.6905	0.5	240.84525
2022	2.56	0.53	365	495.232	0.5	247.616
2023	2.63	0.53	365	508.7735	0.5	254.38675
2028	3.01	0.6	365	659.19	0.5	329.595
2033	3.42	0.6	365	748.98	0.5	374.49
2038	3.84	0.6	365	840.96	0.5	420.48

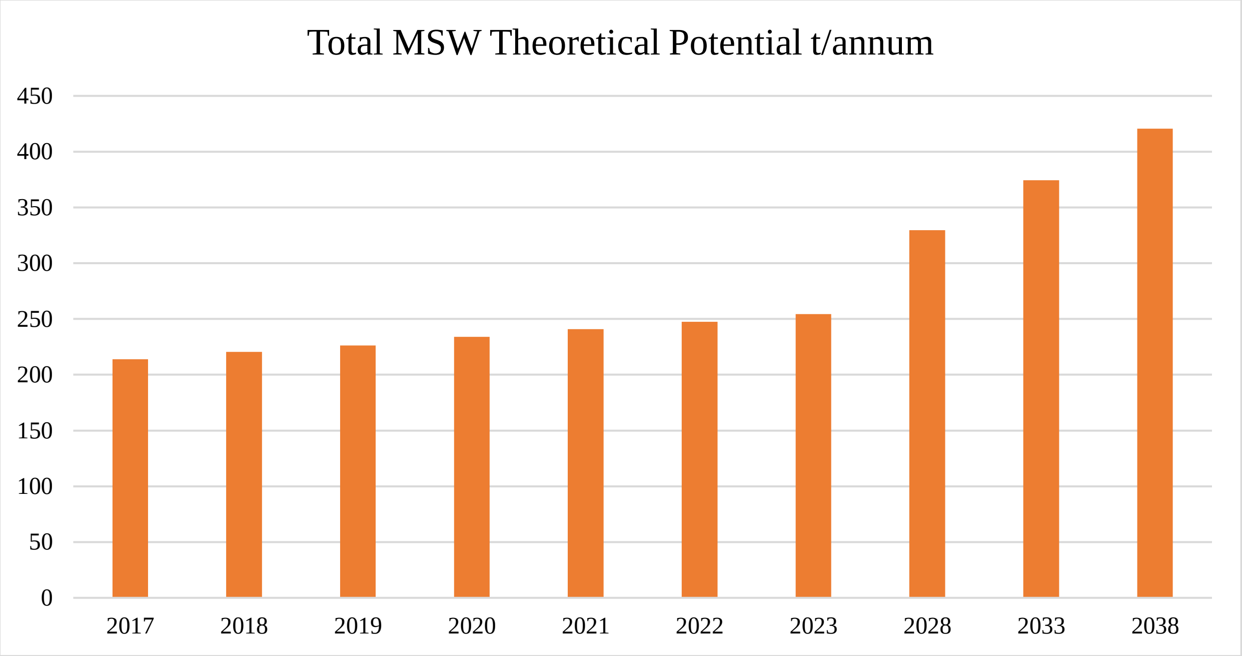

Figure 3 The total theoretical potential of municipal solid waste

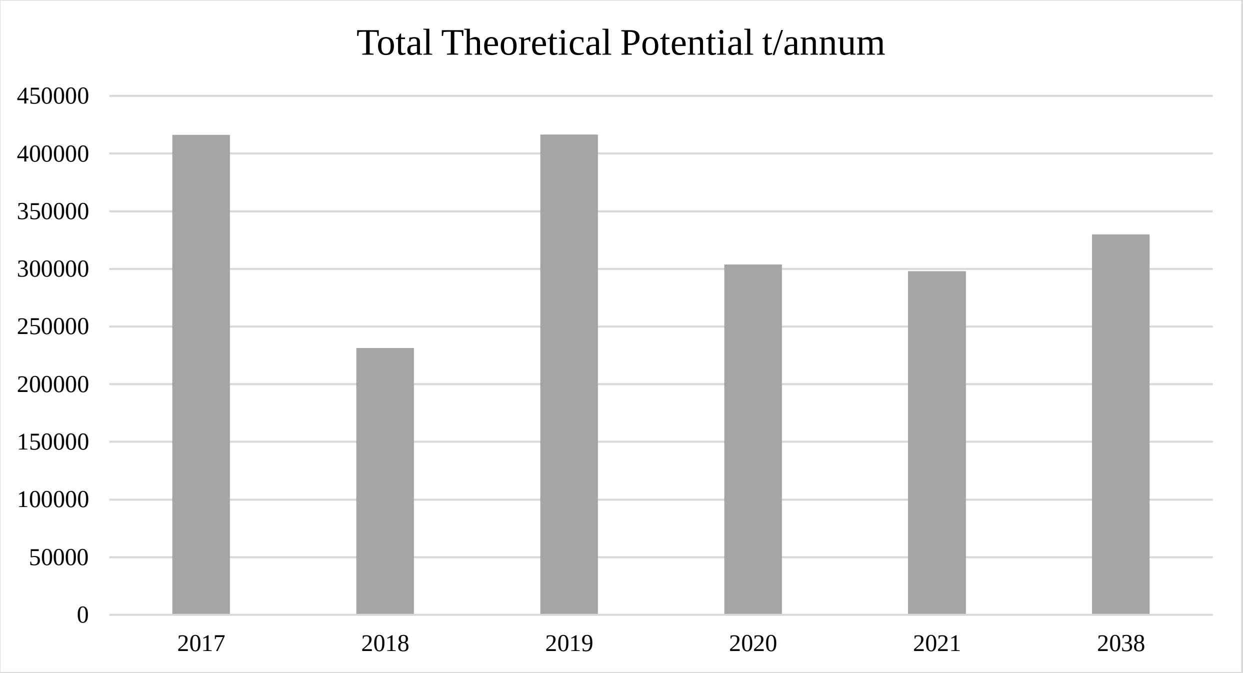

Figure 4 Total theoretical potential per year

4.2. Theoretical methane potential

The results represented in Figure 5 show that the residues from the cash crops namely groundnuts, millet, sorghum, and maize have higher methane production potentials as compared to the subsistence crops. It also shows that the organic fraction of municipal solid waste has the lowest theoretical methane production potential.

In the years 2017, 2018, 2019, 2020 and 2021 results for methane from groundnut residues which had the highest potential were: 30,836mt/annum, 11,696.6mt/annum, 30,836.6mt/annum, 19139.9mt/annum, and 18608.3mt/annum respectively. The projected methane production for groundnuts in the year 2038 is 20,203.3mt/annum.

In contrast, methane produced from the OFMSW results showed that it has the lowest potential when compared to crop residue, its results for years 2017, 2018, 2019, 2020, 2021, and 2038 were: 22.1mt/annum, 22.8mt/annum, 23.4mt/annum, 24.2mt/annum, 24.9mt/annum, and 43.5mt/annum respectively.

Although crop residues on their own have a good potential for methane production a more desirable output would be combining the OFMSW and crop residues for production. The results of the total combined feedstock for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 62,102.7mt/annum, 34,129.4mt/annum, 70,039.9mt/annum, 44,485.7mt/annum, 42,492.7mt/annum, and 47,455mt/annum respectively.

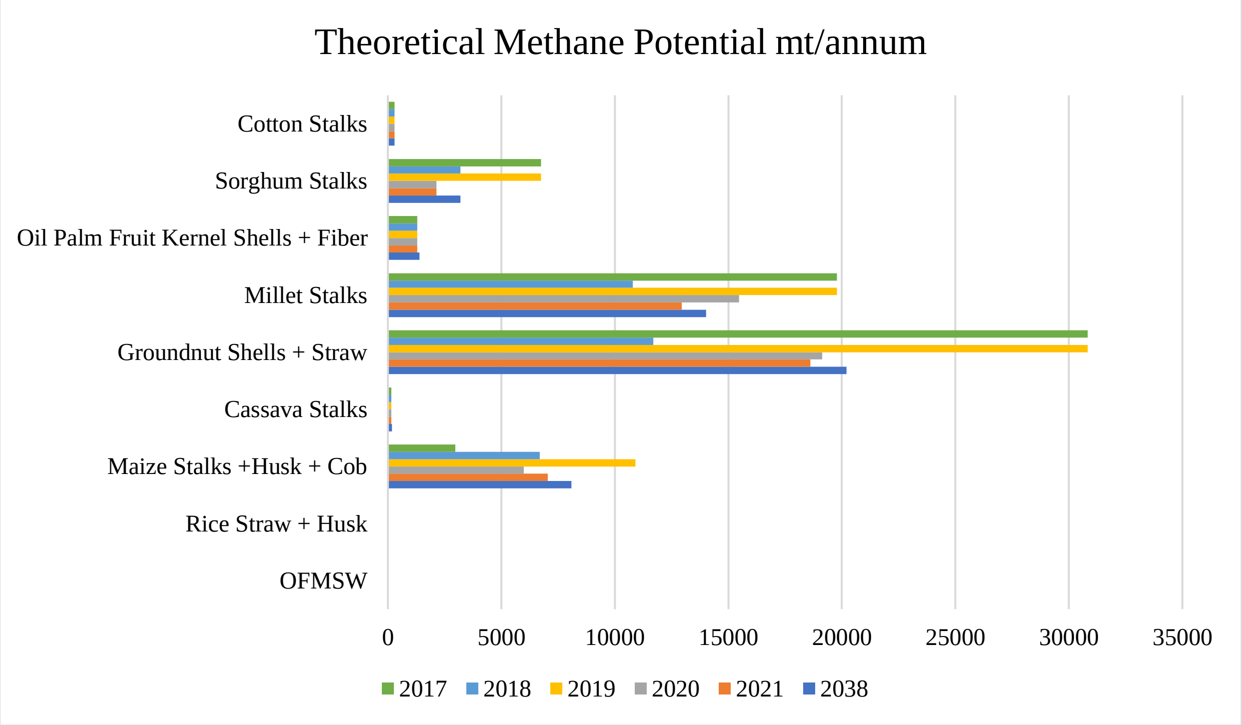

Figure 5 Total theoretical methane potential

4.3. Theoretical and technical energy potential

Similarly, the results represented in Figure 6 show that the residues from the cash crops namely groundnuts, millet, sorghum, and maize have higher energy production potentials from methane as compared to the subsistence crops. It also shows that the organic fraction of municipal solid waste has the lowest theoretical energy potential.

In the years 2017, 2018, 2019, 2020, 2021, and 2038 results for energy production from groundnut residues which had the highest potential were: 431711.8MWh, 163752.8MWh, 431711.8MWh, 267959.1MWh, 260515.8MWh, and 282845.7MWh respectively.

On the other hand, the energy produced from the OFMSW results showed that it has the lowest potential when compared to crop residue, its results for years 2017, 2018, 2019, 2020, 2021, and 2038 were: 309.8MWh, 319.6MWh, 328MWh, 339.2MWh, 349.4MWh, and 609.4MWh respectively.

Although crop residues on their own have a good potential for energy production a more desirable output would be combining the OFMSW and crop residues for production. The results of the total combined feedstock for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 869437.6MWh, 477811.1MWh, 980558.1MWh, 622799.2MWh, 594898.1MWh, and 664367.3MWh respectively.

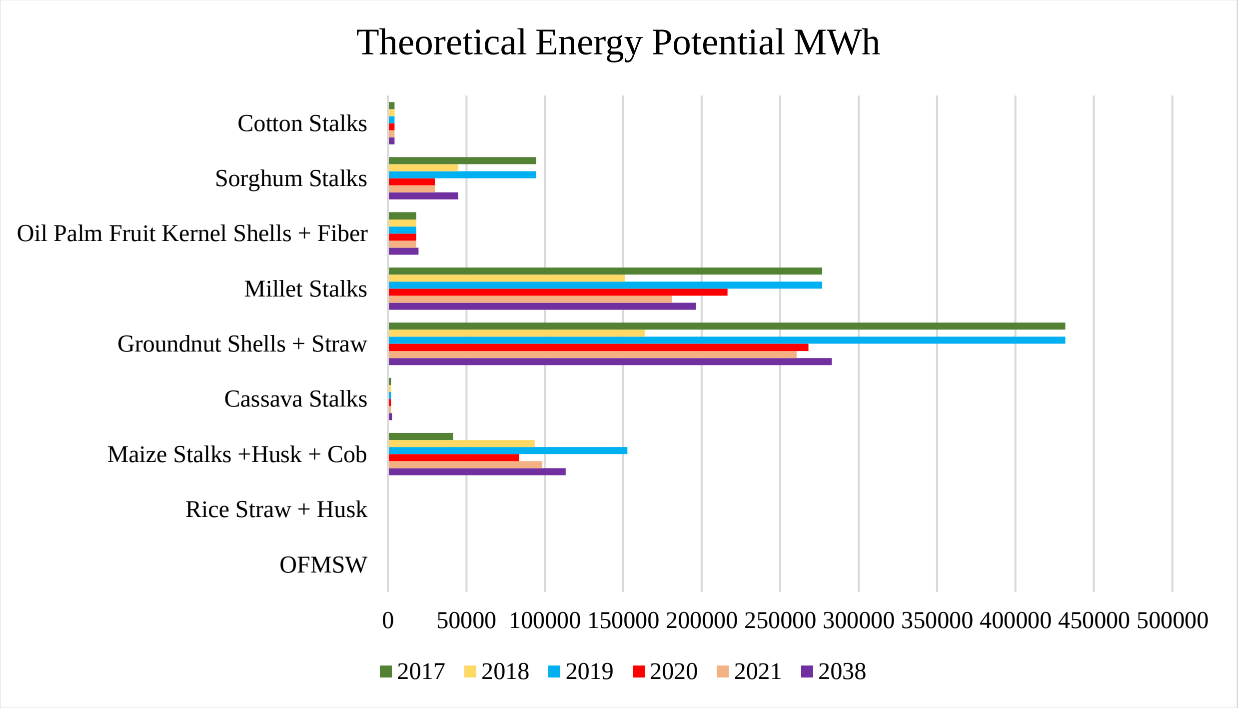

Figure 6 Total theoretical energy potential

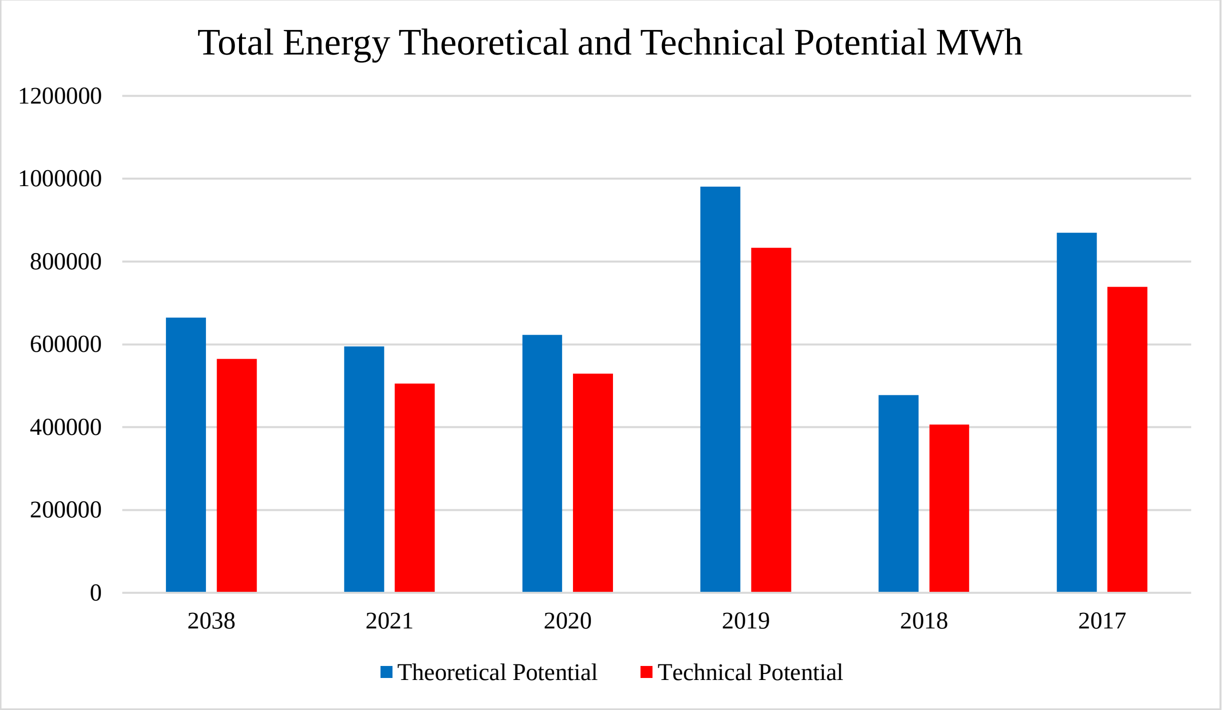

Figure 7 Total energy theoretical potential compared to the technical potential

As shown above in Figure 7 the technical potential represented in red proves that when all the feedstocks are summed up the actual achievable capacity for the country to produce electricity from the feedstocks for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 739022MWh, 406139.5MWh, 833474.4MWh, 529379.3MWh, 505663.4MWh, and 564712.2MWh.

Based on the feedstocks analyzed for this thesis the country could potentially implement a waste-to-energy plant with an actual achievable capacity of 64.5MW for electricity generation.

4.4. Theoretical and technical hydrogen production potential

As seen in the results for methane and energy production potentials the results represented in Figure 8 show that the residues from the cash crops namely groundnuts, millet, sorghum, and maize have higher hydrogen production potentials as compared to the subsistence crops. It also shows that the organic fraction of municipal solid waste has the lowest theoretical hydrogen potential.

In the years 2017, 2018, 2019, 2020, 2021, and 2038 results for hydrogen production from groundnut residues which had the highest potential were: 5,781,855.1kmol, 2,193,117.4kmol, 5,781,855.1kmol, 3,588,737.6kmol, 3,489,050.5kmol, and 3,788,111.9kmol.

In contrast, hydrogen produced from the OFMSW results showed that it has the lowest potential when compared to crop residue, its results for years 2017, 2018, 2019, 2020, 2021, and 2038 were: 4,148.9kmol, 4,280.3kmol, 4,393kmol, 4,543.1kmol, 4,674.6kmol, and 8,161.1kmol respectively.

Although crop residues on their own have a good potential for energy production a more desirable output would be combining the OFMSW and crop residues for production. The results of the total combined feedstock for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 11,644,254kmol, 6,399,256.1kmol, 13,132,474.2kmol, 8,410,60.2kmol, 7,967,385.5kmol, and 8,897,776.7kmol respectively.

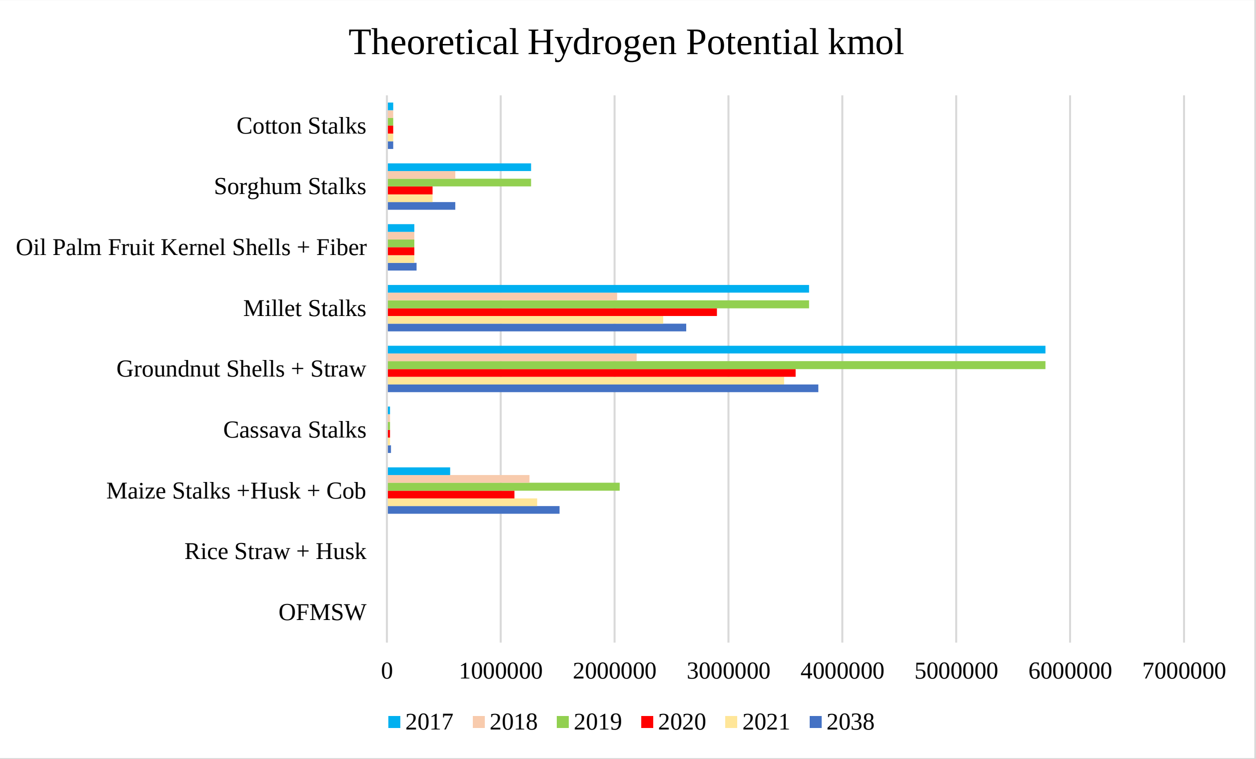

Figure 8 Total theoretical hydrogen potential

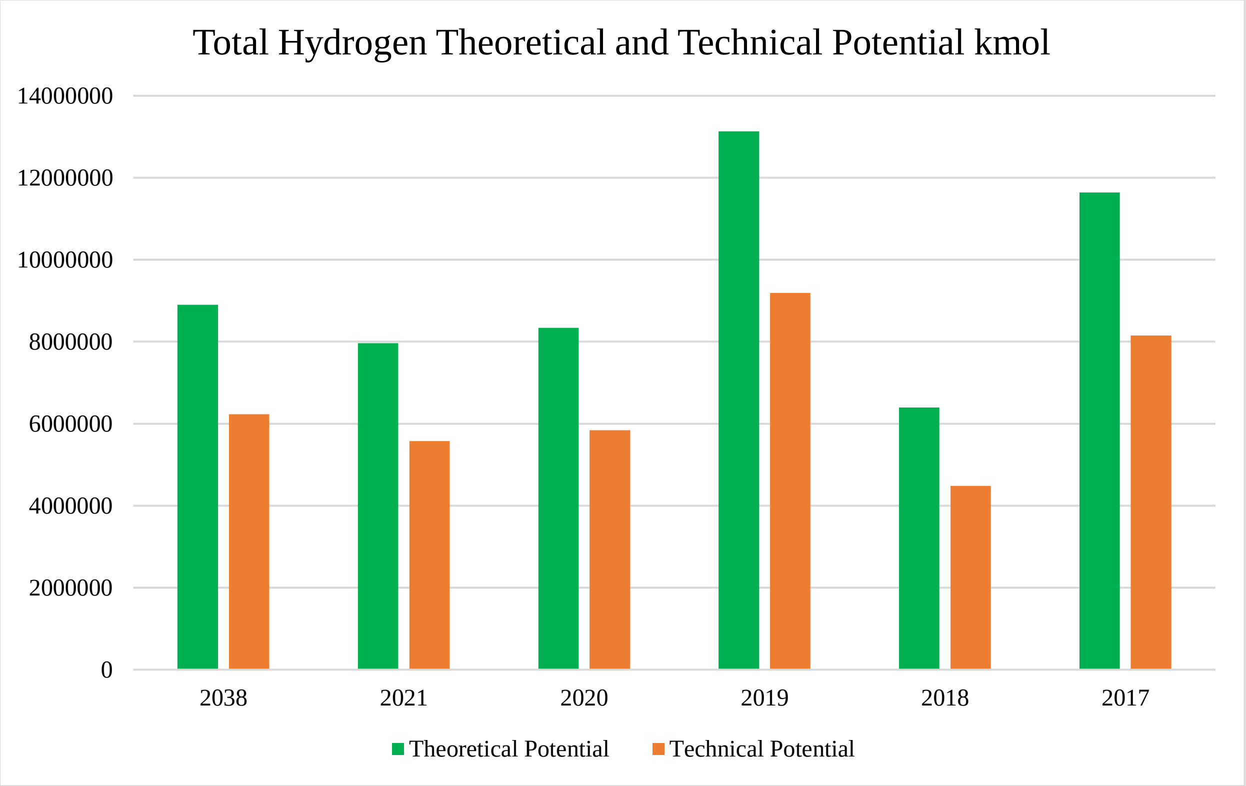

Figure 9 Total hydrogen theoretical potential compared to the total technical potential

Figure 9 compares the results for the theoretical potential to that of the technical potential for hydrogen although the theoretical potential is more than the technical potential for each of the years the country still has a good hydrogen production capacity based on the chosen feedstock for this research.

The technical hydrogen potential for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 8,150,977.8kmol, 4,479,479.3kmol, 9,192,731.9kmol, 5,838,742.2kmol, 5,577,169.9kmol, and 6,228,443.7kmol respectively.

Chapter Five

Discussion

5.1. Pilot waste-to-energy plant based on technical energy and hydrogen potential results

Based on the results obtained from Figure 7 and Figure 9 clearly show that The Gambia has the potential to produce both electricity of 64.5MW and hydrogen of 6,228,443.7kmol from the organic fraction of municipal solid waste although based on the method of calculation used a pilot plant can choose to produce only electricity and later produce hydrogen based on the market demand and what the country needs at the time but not the two products at the time. Moreover, this will aid the country in achieving its 2050 long-term development goal of achieving 100% electrification. However, to fully utilize the country's potential waste from livestock and aquatic life the country should be included.

The Gambia produces approximately 7,000t/annum of oyster (Macfadyen et al., 2023), and since oyster shells contain a high percentage of $CaCO_3$ (Calcium carbonate) when used in an anaerobic digester it can reduce acidity and improve anaerobic dark fermentation, increase hydrogen and methane yields. (Andrade et al., 2020; Notodarmojo et al., 2021). Not only can oyster shells help increase production yields of hydrogen and methane for the country but they can also be used to produce catalysts that can be exported to add to the economy of the country.

Considering the results and the above-mentioned factors the country has a strong potential to produce methane, electricity, hydrogen, and other products if a pilot plant is implemented. This will aid the country in achieving its development goals by increasing the GDP, and standard of living and reduce migration as it will open job opportunities both in rural and urban centers. Due to the country’s strategic location next to the Atlantic Ocean on its western borders export of other products such as catalysts to other countries can be easily achievable.

To select an ideal location for the pilot plant the following factors were considered:

- The district that generates the highest amount of MSW is shown in Figure 10.
- Former mining sites that are no longer operational namely Kartong and Kachuma shown in Figure 11 could be used as a location to build the mining site. Mining sites were considered to avoid competition with fertile land that can be used for agriculture and urbanization as the country is still developing, mining sites in the country are also close to water bodies and are far from residential areas and factories making it an ideal location to avoid fire incidents and to increase methods of transportation of waste and products either by land or sea.
- The country's Sandika market and the largest slaughterhouse in the country are also located in Brikama. This is also ideal as waste from the market and slaughterhouse can be easily transported to the potential site.
- Brikama has easy access to The River Gambia and the Banjul port. This could facilitate the trade of products between the two countries.

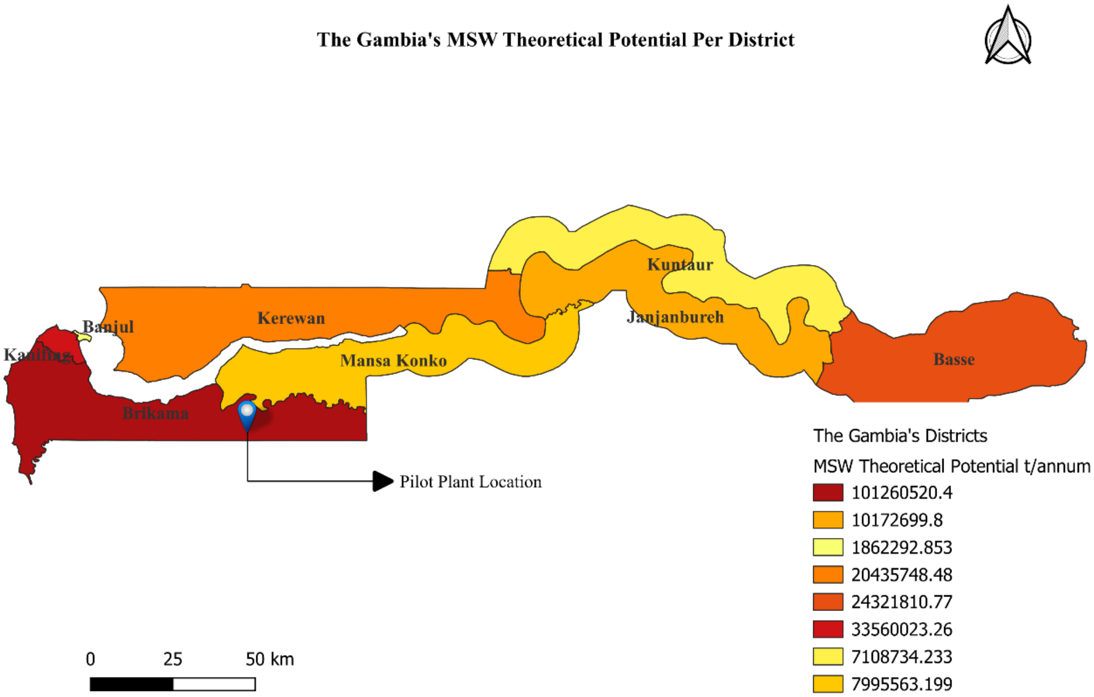

Figure 10 Municipal solid waste potential across the eight districts for the year 2013 and location for a pilot plant(Reused with permission and modified after National Environment Agency, 2014)

Figure 10 represents The Gambia’s eight districts with the darkest color representing the area with the highest MSW generation. It also highlights the suggested location for a pilot plant. The calculations represented in Figure 10 are explained in Table 14 the calculations shown in this table were unable to be conducted for the other years as demographic sensors for the districts haven’t been conducted since 2013.

Table 14 MSW Generation per region 2013 calculation results

2013 MSW Generation per District						
Districts	**Population**	**Per capita generation of MSW**	**No. of days in the year**	**MSW tons/annum**	**OFMSW**	**MSW Theoretical Potential t/annum**
Banjul	31054	0.53	365	6007396.3	0.31	1862292.853
Kanifing	377134	0.53	365	72956572.3	0.46	33560023.26
Brikama	688744	0.53	365	133237526.8	0.76	101260520.4
Mansakonko	81042	0.53	365	15677574.9	0.51	7995563.199
Kerewan	220080	0.53	365	42574476	0.48	20435748.48
Kuntaur	96703	0.53	365	18707195.35	0.38	7108734.233
Janjanbureh	125204	0.53	365	24220713.8	0.42	10172699.8
Basse	237220	0.53	365	45890209	0.53	24321810.77
Total	**1857181**			**359271664.5**		**206717393**

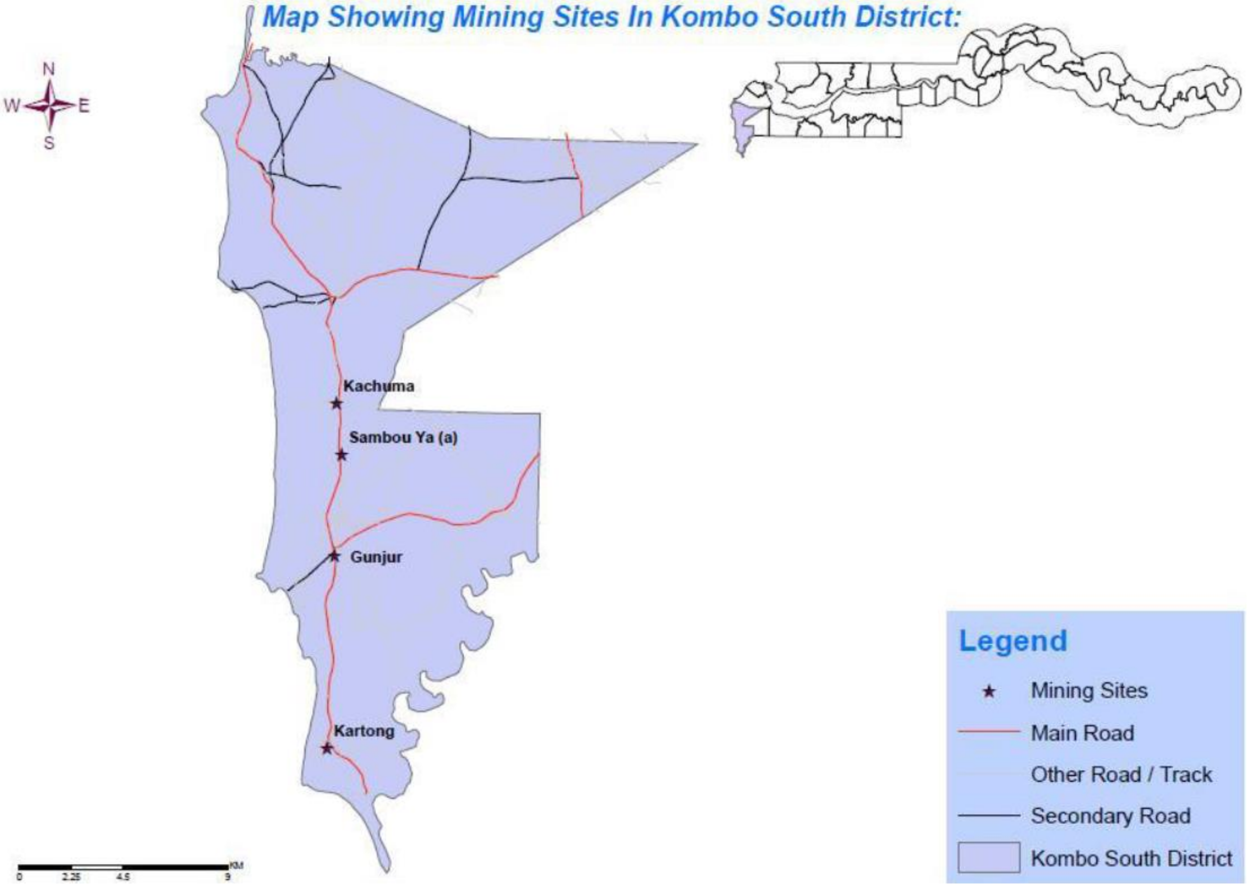

Figure 11 Mining sites in the Brikama district

5.2. Gaps

During the research, the following gaps were identified:

- Data on types and quantity of crops produced yearly and seasonally.
- Use of crop residue and disposal of unwanted residue.
- Geographic information system (GIS) location of gardens and land area planted on.
- Number of dumpsites and the quantity of municipal solid waste generated yearly.
- Composition of The Gambia’s municipal solid waste.
- Ultimate and proximate analysis of crops produced and municipal solid waste in The Gambia.
- The residue-to-crop ratio of crops produced in The Gambia.

These gaps were further categorized into three main gaps which are as follows:

- No proper management and monitoring of crop residue and MSW.
- Lack of awareness of waste management and its energy value.
- Lack of systems and proper infrastructure for the conversion of waste to valuable goods and resources.

5.3. Implementation strategies

The implementation strategies shown below were developed as solutions for the identified gaps mentioned above.

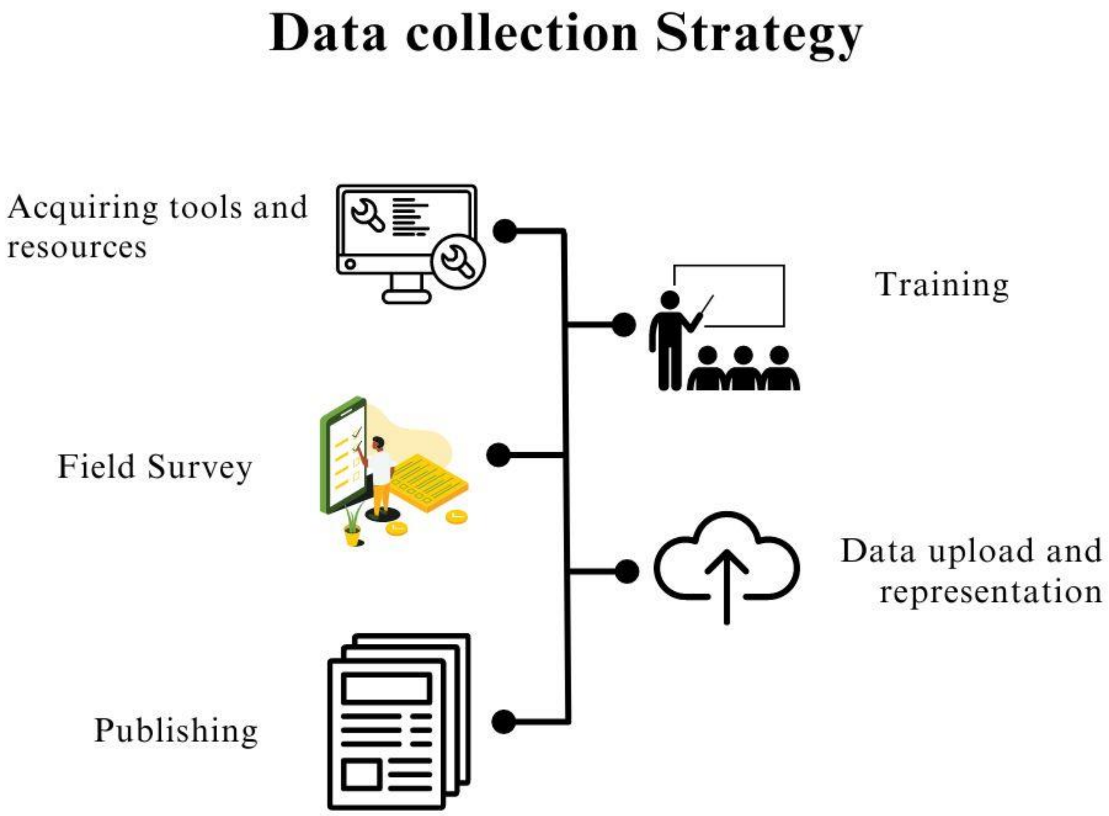

Figure 12 Automated data collection strategy illustration

The data collection strategy has the potential to be implemented within a span of one to two years if the below points are considered.

Acquiring tools and resources:

- Purchase and design of automated data collection software e.g. Fast field
- Purchase of laboratory equipment and reagents.
- Employment of field workers, laboratory staff, data managers, and software developers. (Farmers and waste collectors can be hired to obtain correct data from the field and promote social acceptance).
- Purchase of tablets and computers.

Training:

- Training staff on the utilization of data collection tools.

- Training field workers on conducting surveys using the local languages.

Field survey:

- Data collection on types of crops harvested per month and their respective quantity.
- Sample collection.

Data upload and representation:

- Collected data laboratory results to be uploaded onto the software.
- Uploaded data are to be analyzed and interpreted with the use of tables and graphs.

Publishing:

- Analyzed data published on the official website.
- Publishing articles yearly based on the analyzed data.

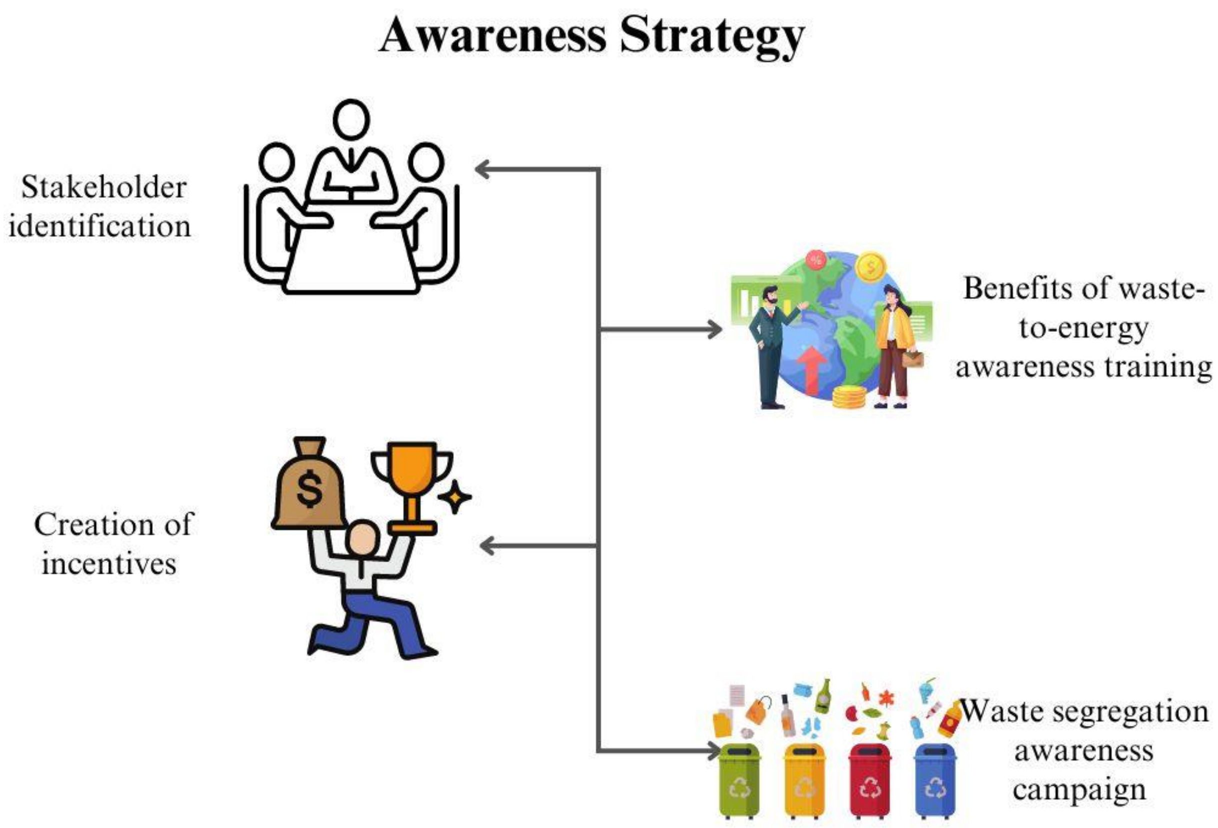

Figure 13 Awareness strategy illustration

Stakeholder identification: The identified stakeholders from the Ministry of Energy shown below will be in charge of implementing the strategy shown in Figure 13.

- Ministry of Petroleum and Energy
- Department of Community Development
- The Association of Non-Governmental Organizations in the Gambia (TANGO)
- All Gambia Forestry Platform
- Gambia Bureau of Statistics (GBoS) -
- National Agricultural Research Institute (NARI)
- National Environment Agency (NEA)
- Gambia National Water and Electricity Company
- MBOLO Association (deals with renewable)
- Civil Society and Community-based organizations
- Department of Forestry (DoF)
- United Nations Development Programme (UNDP)
- Ministry of Agriculture (MoA)
- Ministry of Finance & Economic Affairs
- Action Aid, The Gambia
- Department of Parks and Wildlife Management (DPWM)
- The National Coordinating Organization for Farmers Associations Gambia (NACOFAG)
- National Disaster Management Agency (NDMA)
- Rural Integrated Climate Adaptation and Resilience Building Project (RICAR)
- Environment and Resilience Development Project (ERDP)- support in cook stoves
- NAMA Facility Project
- Gambia Inclusive and Resilient Agricultural Value Chain Development Project (GIRAV)
- Rice Value Chain Development Project (RVCDP)
- Ministry of Lands and Regional Government
- Governors’ office
- Village Development Committee
- Ward Development Committees
- Area Councils
- School of Agriculture and Environment Sciences, University of The Gambia
- Ministry of Finance & Economic Affairs
- Ministry of Women's Affairs, Children, and Social Welfare
- Ministry of Youths and Sports

- National Disaster Management Agency
- National Youth Council
- University of the Gambia, WASCAL Programme
- United Nations Environment Programs
- Influencers and entertainers such as Jizzile, ST, and Attack.

Benefits of waste-to-energy, awareness training:

- Reduced greenhouse gas emissions.
- Added value to farm produce and increased income for farmers.
- Added electricity supply.
- Economic development.
- Reduction in rural-urban migration and illegal migration.

Creation of incentives:

- Subsidies on products produced from recycling.
- Reduced tax on businesses that contribute to the supply chain.
- Yearly awards can be given to institutions that practice waste segregation and use products from renewable sources.

Waste segregation awareness training:

- Training on waste segregation at source is to be done at schools, social media, and television. With the use of songs or movies in the local languages for easier comprehension and social acceptance.

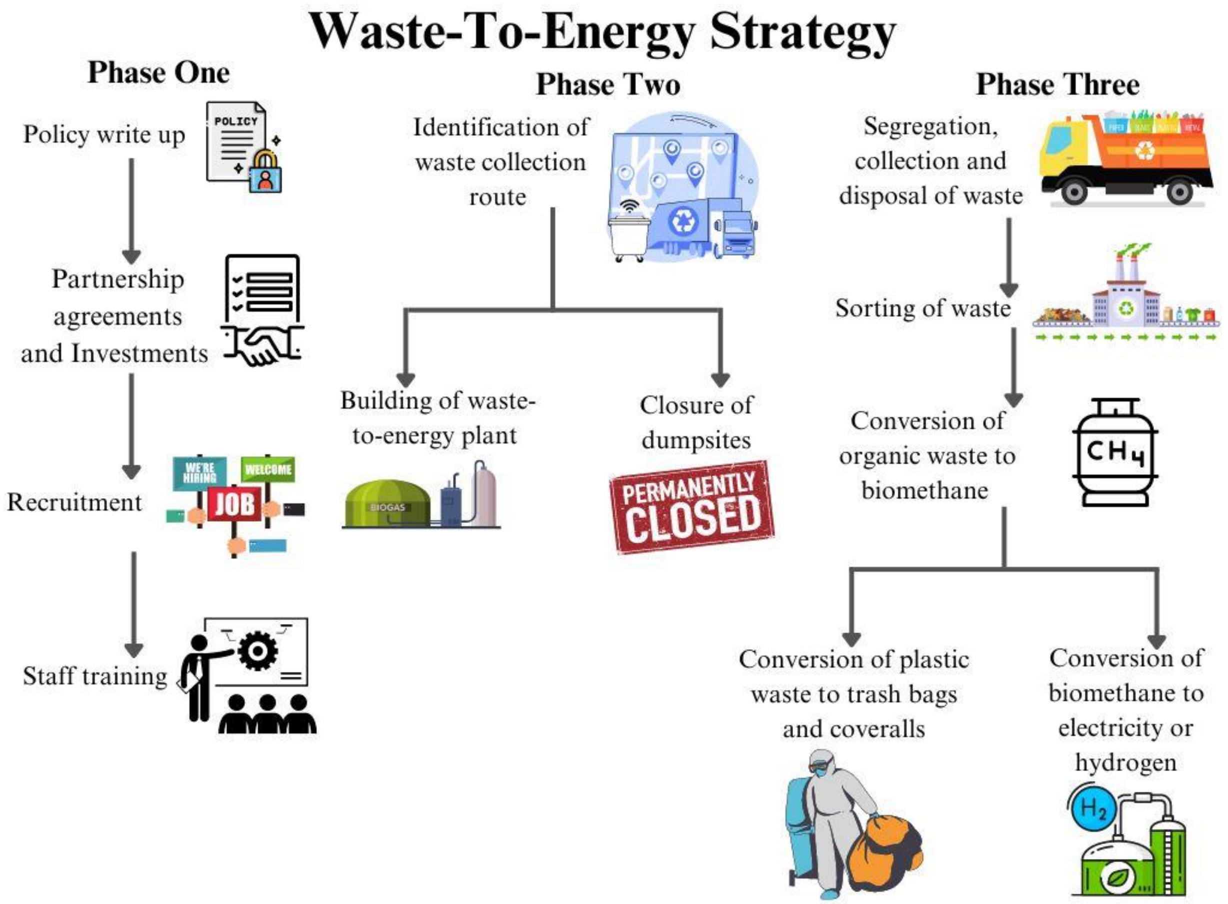

Figure 14 Three-phase waste-to-energy strategy illustration

Phase one of the waste-to-energy strategy can be implemented from the years 2024 to 2027. This phase involves the following:

- Partnerships in the form of a memorandum of understanding between private waste collection companies and the government and founders.
- Training of farmers on how to separate and store crop residue that can be potentially used for energy generation and also on how to make compost.
- Training of waste collectors on GIS tools and the use of swipers and other types of equipment needed for transporting waste to the proposed plant in phase two.
- Feasibility studies on the proposed plant in phase two.

Phase two can be implemented from the years 2027 to 2030 and it involves the following:

- Using geographic information systems to identify an efficient waste collection route.
- Connecting the proposed plant to the grid lines.
- Identification of distribution methods of products generated from the proposed plant.

- Purchase of sweepers, waste collection trucks, and community bins with color codes used for training in the awareness strategy.

Phase three of this strategy can be implemented between the years 2030 to 2038 it involves the following:

- Electricity generation and supply to the grid.
- Plastic waste is to be converted into valuable resources such as trash bags, biohazard bags, coveralls, and gloves.
- Valuable products generated from the plant can be sold within the country and exported to neighboring countries.

Chapter Six

6. Conclusion and outlook

The major objective of this thesis is to determine if The Gambia has the potential to produce hydrogen and bioenergy sources from the generated municipal solid waste and crop residue. The theoretical potential of the organic fraction of municipal solid waste and the crop residue is calculated from the year 2017 to 2038. These results are then used to calculate the biomethane and electricity production potential with the use of Buswell's equation from which using stoichiometry the hydrogen production potential is calculated using steam methane reforming. The technical potential for electricity and hydrogen is then calculated with the use of their respective conversion efficiencies.

As shown in Figure 7 and Figure 9 for the target year of 2038 the country can potentially produce 64.5MW of electricity or 6,228,443.7kmol of hydrogen.

Although these results are positive not all agricultural residues have been studied due to unavailable data. To solve these issues three strategies namely: automated data collection, awareness, and waste-to-energy strategies are developed. These strategies explain ways the country can have adequate data for research and achieve its 2050 long-term development goals.

As the data used for analysis for this research is secondary it posed a major limitation in the study because climatic conditions and soil content vary by location, therefore, for future research samples from The Gambia should be collected to obtain results specific to the country.

Another major limitation of the work was the time given to conduct this research which did not make it possible to conduct economic analysis for this research. However, due to this further research on this topic should be conducted to include livestock and aquatic life of the country. The research can be further expanded to research catalyst generation from oyster shells and the production of ammonia from the digestate.

Furthermore, a business case can also be derived from this research based on the strategies mentioned above. In addition, if the strategies are further developed and the economic analysis is also conducted the government of The Gambia could be approached to implement these strategies to help achieve its development goals and create a circular economy.

Chapter Seven

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