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GREEN HYDROGEN PRODUCTION POTENTIAL FROM THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTE (OFMSW) IN ABUJA, NIGERIA

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DEDICATION

This work is dedicated to my mother, Hajiya Nana Aisha Mohammed who has been my biggest source of motivation throughout this program, May Allah SWT continue to grant her peace and eternal rest in Aljannatul Firdaus, Amin.

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In the name of Allah, the Most Gracious, the Most Merciful. All praise is due to Allah, the Lord of the Universe.

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May Allah's blessings and guidance continue to illuminate my path as I step into new horizons.

DECLARATION

I, Suleiman Aisha Abba, hereby declare that this thesis titled "Green Hydrogen production potential from the Organic Fraction of Municipal Solid Waste in Abuja, Nigeria " and the work presented in it are my original contributions. I affirm that this work has not been previously submitted for any other academic degree, diploma, or certificate. I have properly acknowledged and cited all sources of information, ideas, and data used in this thesis. The content of this thesis is the result of my own research and analysis, and any assistance received during the process has been appropriately acknowledged.

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ABSTRACT

The increasing global demand for clean and sustainable energy sources as a result of climate change has led to growing interest in green hydrogen as a potential solution to reduce carbon emissions and enhance energy security around the world. Several research papers have been published on waste management and waste to energy in Abuja, Nigeria; however, no specific study has focused on the use of Organic Fraction of Municipal Solid Waste (OFMSW) for Hydrogen production in Abuja, Nigeria. In this context, this study explored the production potential of green hydrogen from OFMSW. The methodology of this research involved a comprehensive review of existing literature on green hydrogen production technologies, data on waste generation and population were collected from existing literature, and the Abuja Environmental Protection Board. Additionally, waste- to-energy conversion technologies like Anaerobic digestion and steam reforming were considered due to easy adoption and technology readiness level respectively. The findings of this research revealed that with the current 3.8 million population in Abuja, and 146659.96 tonnes of organic waste generated annually, 7.62 million m^3 of biogas and 1220508.699 kg/year of hydrogen could potentially be generated annually. Similarly, 40.27 TWh of electricity could also be generated annually which surpasses the 29,684 GWh of electricity generated in Nigeria in 2022. Projection of energy potential for 2025, 2030, and 2035 were also calculated and reported in this study. As waste management practice is not efficient in Nigeria, solutions to help achieve an efficient OFMSW to hydrogen conversion were also suggested. The results of this study could stimulate actions from key stakeholders to integrate OFMSW to hydrogen into the city's energy mix and the country's national hydrogen strategy when implemented and contribute to a cleaner energy landscape nationwide.

Keywords: Organic Fraction; Municipal Solid Waste; Green Hydrogen; Abuja; Nigeria

RESUME

La demande mondiale croissante en énergie propre et durable, en raison du changement climatique, a suscité un intérêt croissant pour l'hydrogène vert en tant que solution potentielle pour réduire les émissions de carbone et renforcer la sécurité énergétique dans le monde. Plusieurs articles de recherche ont été publiés sur la gestion des déchets et la valorisation énergétique à Abuja, au Nigeria; cependant, aucune étude spécifique n'a été axée sur l'utilisation des déchets organiques municipaux solides (DOMS) pour la production d'hydrogène à Abuja, au Nigeria. Dans ce contexte, cette étude a exploré le potentiel de production d'hydrogène vert à partir de DOMS. La méthodologie de cette recherche a impliqué une revue complète de la littérature existante sur les technologies de production d'hydrogène vert, les données sur la génération de déchets et la population ont été recueillies à partir de la littérature existante et du Bureau de protection de l'environnement d'Abuja. De plus, les technologies de conversion des déchets en énergie, telles que la digestion anaérobie et le reformage à la vapeur, ont été prises en compte en raison de leur adoption facile et de leur niveau de préparation technologique respectif.

Les résultats de cette recherche ont révélé qu'avec la population actuelle de 3,8 million d'habitants à Abuja et 146 659,96 tonnes de déchets organiques générés chaque année, 7 621 332,081 m^3 de biogaz et 1 220 508,699 kg d'hydrogène pourraient potentiellement être produits annuellement. De même, 40,27 TWh d'électricité pourraient également être générés chaque année, dépassant ainsi les 29 684 GWh d'électricité produits au Nigeria en 2022. Les projections du potentiel énergétique pour 2025, 2030 et 2035 ont également été calculées et rapportées dans cette étude. Étant donné que la gestion des déchets n'est pas efficace au Nigeria, des solutions pour aider à réaliser une conversion efficace des DOMS en hydrogène ont également été suggérées. Les résultats de cette étude pourraient inciter les parties prenantes clés à intégrer les DOMS à l'hydrogène dans le bouquet énergétique de la ville et la stratégie nationale d'hydrogène du pays lorsqu'elle sera mise en œuvre, contribuant ainsi à un paysage énergétique plus propre dans tout le pays.

Mot cles: Fraction Organique; Dechets solides municipaux; Hydrogene vert; Abuja; Nigeria.

LIST OF ABBREVIATIONS

AD: Anaerobic digestion

AEBP: Abuja Environmental protection board

BECCS: Bioenergy with carbon capture and storage

EJ: Exajoules

GHG: Greenhouse gases

IEA: International Energy agency

IPCC: Intergovernmental panel on climate change

MSW: Municipal solid waste

OFMSW: Organic fraction of Municipal solid waste

PEC: Photoelectrochemical

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INTRODUCTION

At the moment, fossil fuels provide a huge proportion of the world's energy needs. Unrestrained usage and exploitation of these nonrenewable resources harm the environment and frequently result in some permanent harm. Studies demonstrate that we have used up half of the oil and other fossil resources taking into consideration the slower rate at which new oil/gas resources are discovered and the steadily rising energy demand (Tashie-Lewis & Nnabuife 2021). Long-term usage of fossil fuels hinders the utilization of renewable energy sources; for every 1% of fossil fuel used, the use of renewable energy decreases by 0.0008% (Somoye et al. 2022). Given the scarcity of resources, a shift to cleaner and greener methods of energy production and consumption is necessary. Deploying renewable energy systems will make it feasible to decarbonize the energy systems, which is necessary to mitigate the consequences of global warming (Ostergaard et al. 2020). The increased usage of renewable technology has accelerated the global energy transition in many regions around the globe (Yue et al. 2021; Lund et al., 2021). In terms of technology, resource evaluation, and system design, renewable energy systems have advanced significantly (Ostergaard et al., 2020; Ostergaard et al., 2020).

The increase in environmental disasters brought on by the release of greenhouse gas, air, and water pollution along with energy and resource scarcity is predicted to increase in the coming decades. This has led to a commitment to advance toward a more sustainable society.

Fossil fuels are mostly used to produce energy and chemicals, which releases CO_2 and other hazardous molecules into the environment (such as volatile organic compounds and nitrogen oxides). According to statistics, the burning of fossil fuels is responsible for 90% of the world's CO2 emissions, which totaled 34 billion tons in 2011 (Arancon et al., 2013) Additionally, because these basic resources are limited, processes that use them as feedstock cannot be sustained, making the security of the supply a huge issue for humanity.

Due to rising population, expanding economy, fast urbanization, and shifting consumer behavior, the world today generates an enormous amount of waste (Cudjoe et al., 2020).

Global production of urban solid waste is predicted to reach 2,200,000 tons and 4,200,000 tons by the years 2025 and 2050, respectively (Gu et al., 2019). The World Bank projects that by 2025, daily global production of solid trash in metropolitan areas will rise from 3,500,000 tons to 6,100,000 tons. Environmentally sustainable municipal solid waste management techniques have become a global challenge as a result of scarce resources (Ramachandra et al., 2018). Due to poor infrastructure, the majority of African cities experience significant problems with urban solid waste collection, disposal, and management (Scarlat et al., 2015).

The increasing accumulation of waste in the environment is a significant problem. Due to the issues brought on by the volume of trash thrown into the environment, the public is now more aware of the problem of waste accumulation. Nonetheless, due to their massive annual output and diversity, these wastes are excellent alternatives to be utilized in high-value applications (Lin et al., 2013).

There are certain drawbacks to using traditional techniques such as landfilling, incineration, and composting for the treatment and management of municipal solid waste (MSW). Waste disposal through landfills causes severe environmental issues, including the uncontrolled release of methane into the atmosphere, a gas with a 20 to 23 times higher global warming potential than carbon dioxide, the production of leachate, which contaminates the soil and groundwater, poisonous odors, and the spread of harmful microorganisms (Matsakas et al., 2016; Matsakas et al., 2015). For instance, more than 95% of food waste between 25% and 70% of MSW) is thought to wind up in landfills, where it releases methane and other Greenhouse gases (GHGs) that have a terrible effect on the climate (calculated to be 125 m^3 of gas per ton of landfilled food waste) (Pham et al. 2015; Melikohlu et al., 2013). In some locations, waste is incinerated to provide heat and energy. Although it is a useful technology, particularly for rural regions, it may cause air pollution [because dioxins and other persistent organic pollutants can be created] and it eliminates the opportunity to recover valuable compounds from trash (Melikohlu et al., 2013; Uckun et al., 2014).

Moreover, incineration has high start-up and ongoing costs (Uckun et al. 2014) and requires specific attention to ensure that the resulting fly ash is handled safely. Organic materials are stabilized during the composting process so that they can be used as an environmentally acceptable fertilizer. However, the composting process must be done correctly; otherwise, composting may cause issues like excessive odors and potential GHG production (Melikohlu et al., 2013).

But, the opportunity to turn wastes into useful fuels and chemicals is a valuable option that has drawn the interest of both the scientific community and the general public. Our earlier research demonstrated that using MSW from regions with considerable Food waste (FW) separation in households resulted in refuse-derived fuels with improved fuel characteristics and decreased POP emissions during combustion (Svensson et al., 2014; Edo et al., 2016).

Although MSW, especially given its abundance, could be a fantastic substrate for upgrading to value products and energy, managing it presents certain difficulties. For instance, the regional and seasonal composition and volumes of MSW exhibit substantial variability, which may, for example, have an impact on the emissions produced during incineration (Phan et al., 2013). The substantial amount of water in them, which makes them susceptible to microbial contaminations, is another difficulty. Because to the fact that microorganisms can contaminate MSW, this could also have an impact on public health.

The higher volumes and weight of MSW due to the high moisture content make drying a crucial step in lowering the cost of transportation. The energy and financial demands of drying and transportation have an impact on the overall process cost. Since that MSW generation occurs in almost all residual areas, there may be a way to minimize drying and long-distance transportation. Low-volume facilities can employ MSW locally in a decentralized system (Pfaltzgraff et al., 2013).

Currently, the world produces 7.7 EJ of hydrogen annually, but that number might increase to 10 EJ by 2050. (Hydrogen Council, 2017). The primary uses are for the manufacturing of ammonia (51%), refined oil (31%), methanol production (10%), and other purposes (8%) (Hydrogen Council, 2017). Also, the H2 market is anticipated to grow soon at a rate of 5-10% per year, mostly as a result of its use in refineries to treat heavy oil fractions and anticipated demand in the transportation sector or as an energy vector. (Levin & Chahine, 2010).

96% of H_2 production technologies are dependent on non-renewable resources, with natural gas reforming (48%) and oil refining (30%) being the two most common processes, followed by coal gasification (18%). Water electrolysis produces only 4% of the H_2 that is produced (International Energy Agency, IEA 2015). Figure 1 and 2 below shows the global consumption of hydrogen and current sources of hydrogen.

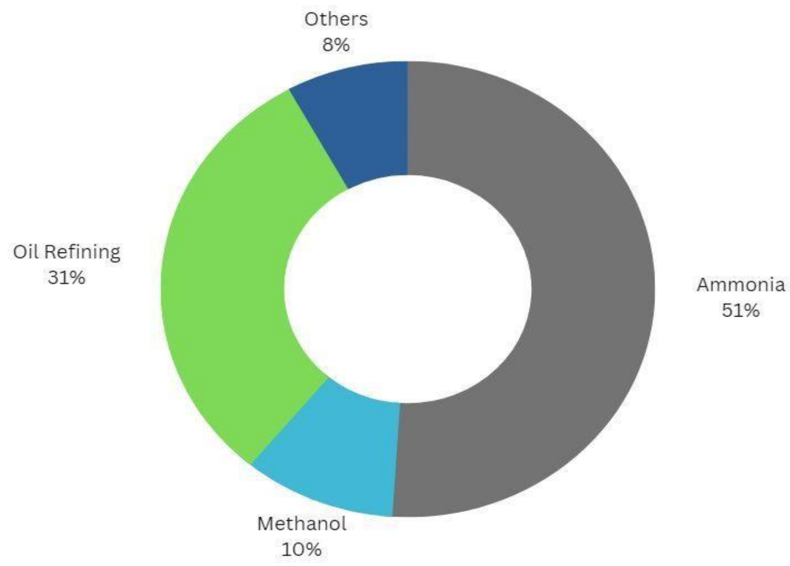

Figure 1: Global Consumption of Hydrogen (Adapted from Hydrogen Council, 2017)

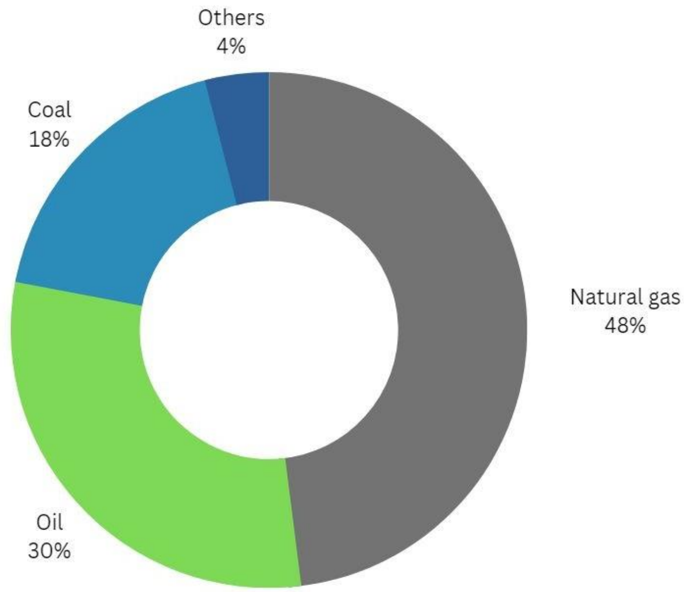

Figure 2: Current sources of hydrogen (Adapted from IEA, 2015)

Since they offer sustainable energy and have lower greenhouse gas emissions, biomass, and hydrogen have received greater attention than other renewable energy sources. A sustainable and clean energy supply relies heavily on renewable energy sources (Gielen et al., 2019; Parra et al., 2019). Hydrogen is abundant in the universe and also has a high energy density per mass. It serves as an alternative energy source in this regard (Kotter et al., 2016). Hydrogen is the lightest and simplest element in the universe, it is also an odorless and colorless gas (Rivkin et al., 2015).

PROBLEM STATEMENT

Nigeria's reliance on fossil fuels has contributed significantly to environmental deterioration and greenhouse gas emissions despite the country's rising energy demand. The organic fraction of municipal solid waste (OFMSW) can be used to produce green hydrogen, which offers a promising alternative as the demand for clean energy sources rises. The possibility of producing green hydrogen from OFMSW in Nigeria has, however, received little attention. Consequently, an analysis of the viability and feasibility of using OFMSW as a source for green hydrogen production in Nigeria is required, taking into account the nation's waste management policies, energy consumption, and economic viability.

OBJECTIVES

- Main Objective:

To propose an alternative and stable source of energy by analyzing the hydrogen production potential from the organic fraction of Municipal solid waste in Nigeria.

Specific Objectives:

- To determine the composition and quantity of the organic fraction in MSW
- To calculate the hydrogen production potential from OFMSW
- To provide recommendations for policy related to green hydrogen production from municipal solid waste.

Significance of the study

The study on the green hydrogen production potential from organic fractions of municipal solid waste in Nigeria is significant for several reasons:

i. Environmental benefits: by offering an environmentally friendly and sustainable method of producing electricity, the study may help Nigeria lower its carbon footprint.

Reducing greenhouse gas emissions and limiting the effects of climate change may be achieved by producing green hydrogen from OFMSW.

ii. Waste management: Nigeria's waste management methods are inadequate, which has led to environmental pollution and challenges to public health. Through the use of OFMSW, this study can highlight the importance of waste management and offer a remedy for efficient waste management procedures.

iii. Energy security: Nigeria's reliance on fossil fuels for energy production has made the nation vulnerable to changes in the price of crude oil around the world. Nigeria could improve its energy security by diversifying its energy sources and lessening its reliance on imported fossil fuels.

iv. Economic benefits: this research can also contribute to the development of new employment opportunities in the waste management and energy industries. Nigeria's energy independence could be increased, its ability to produce green hydrogen from OFMSW increased, and its ability to eventually lower energy costs

Overall, the research on Nigeria's potential for producing green hydrogen from the organic part of municipal solid waste could have considerable social, economic, and environmental benefits, making it an important field of study for the sustainable development of the nation.

CHAPTER 1: LITTERATURE REVIEW

In the future energy system, hydrogen (H_2) is a great secondary energy source and energy carrier (Dutta, 2014). On Earth, hydrogen is the most abundant element however it's typically found in an oxidized state (water). By 2050, 82 Mt of hydrogen will have been produced with annual growth of 5–10% (Saxena et al., 2008). Early in the 16th century, Robert Boyle used the reaction of iron and acid to generate hydrogen gas. Antoine Lavoisier first used the name hydrogen in 1783; it is derived from the Greek words hydro (water) and genes (creator). Its widespread adoption in various spheres of life has the potential to significantly lower GHG emissions. Many primary energy sources, including fossil fuels, renewable energy sources, and wastes, can be used to make hydrogen. Moreover, it can be produced from electricity and efficiently transformed into hydrogen, making electricity and hydrogen two viable choices for secondary energy sources (Wijayanta et al., 2019). With an energy density of 122 MJ/kg, hydrogen is 2.75 times more packed with energy than hydrocarbon fuels. However, due to hydrogen's extremely low volumetric energy density (about 3 Wh/L at atmospheric pressure), hydrogen storage becomes crucial for the efficient transportation and storage of hydrogen. (Aziz et al., 2020). Compression, liquefaction, hydrides, and physical absorption are a few of the storage techniques that have been developed and used to efficiently store and transfer hydrogen (Aziz et al., 2017). In comparison to electricity, hydrogen has a longer shelf life and can be used as a raw ingredient in other processes. To attain high energy security and stability, a mutual conversion of secondary energy sources such as electricity, hydrogen, and heat is essential. Hydrogen can be used for both stationary and mobile applications in the energy sector. Hydrogen can be utilized to generate electricity via fuel cells, co-combustion (mixing with other fuels), and single-fuel combustion. Hydrogen can be used or oxidized to make water, which results in an environmentally friendly application. Moreover, hydrogen is crucial to raising the hydrogen to hydrogen-to-carbon making biofuels from biomass (Kleinert & Bath, 2008). John Bockris first proposed a hydrogen economy in 1970, referring to the distribution of energy in the form of hydrogen rather than hydrocarbon (Mohan and Pandey, 2013).

In terms of technological application, economic performance, and social acceptance, it is also highly anticipated that the hydrogen economy will be able to create a carbon-free energy system. Shortly, it is envisaged that the wider use of biomass and organic solid wastes for the production of hydrogen will enhance and realize the hydrogen economy and encourage energy decentralization and resilience.

Hydrogen (H2) is regarded as another viable substitute for conventional fuels. In addition to being directly used for the generation of electricity using hydrogen fuel cells or other types of fuel cells like SOFC, hydrogen is a green energy source because it only emits water during combustion as opposed to greenhouse gases (Dong et al., 2009; La Licata et al., 2011). It is primarily made from materials derived from fossil fuels (roughly 95% globally) and has a high energy yield (122 kJ/g, 2.75 times higher than that of hydrocarbons) (Dong et al., 2009; Kim et al., 2012; Vijayaraghavan and Mohd, 2006).

1.1. Municipal solid waste

Energy-rich materials found in municipal solid waste include complex waste, plastics, papers, byproducts of wood, and many others. According to the U.S. Energy Information Administration, the US uses 38.5 kg of every 45 kg of municipal solid waste as fuel to produce electricity. Incinerators can reduce the volume of waste by 87% by reducing 907 kg of waste into ashes that weigh between 136 and 272 kg. In a facility for converting municipal waste into energy, also known as trash or rubbish, the waste is incinerated to produce steam, which is subsequently used to produce electricity.

Factors including population density, way of life, and socioeconomic status affect how MSW is made up. While organic waste, such as food waste, makes up a sizeable component of the waste stream in developing nations, MSW in industrialized countries is often made up of a greater proportion of packaging materials and other disposable products. Municipal solid waste differs in composition depending on several variables, including geographic location, population density, and socioeconomic status. However, in general, MSW can be broadly categorized into the following components:

- Organic waste
- Paper and cardboard
- Plastics
- Metal
- Glass
- Textiles
- Other waste

Geographical location, along with other elements like cultural behaviors and waste management policies, can have a substantial impact on the MSW composition. Hence, knowing how MSW is generated is crucial for creating waste management plans that can effectively handle the unique requirements and difficulties of a given area.

1.2. NIGERIA COUNTRY PROFILE

Nigeria is a Sub-Saharan country in the western part of Africa. Three levels of government; the federal, state, and local government rule the nation under the federal system of government. The country has a diversified population and environment (Ebikapade and Baird, 2017).

Nigeria is bordered to the north by Niger, to the east by Chad and Cameroon, to the south by the Gulf of Guinea and the Atlantic Ocean, and to the west by Benin. Nigeria is not only large in an area larger than the U.S. state of Texas but also Africa's most populous country, with a large area of 356,669 sq mi (923,768 sq km) and a population of 222,486,000 (Kirke-Greene et al., 2023).

Nigeria has a diverse geography, with climates ranging from arid to humid equatorial. The country has abundant natural resources, notably large deposits of petroleum and natural gas. The Nigerian economy is one of the largest in Africa. Since the late 1960s, it has been based primarily on the petroleum industry. A series of world oil price increases from 1973 produced rapid economic growth in transportation, construction, manufacturing, and government services (Kirk-Greene et., al 2023). Nigeria has a tropical climate with variable rainy and dry seasons, depending on location. It is hot and wet most of the year in the southeast but dry in the southwest and farther inland. A savanna climate, with marked wet and dry seasons, prevails in the north and west, while a steppe climate with little precipitation is found in the far north. In general, the length of the rainy season decreases from south to north. In the south, the rainy season lasts from March to November, whereas in the far north it lasts only from mid-May to September.

Marked differences exist between north and south, not only in the n physical landscape, climate, and vegetation but also in the social organization, religion, literacy, and agricultural practices of the people. These differences form the basis of the division of Nigeria into three geographic regions: the south, or Guinea coastlands; the central region; and the north, or Nigerian Sudan (Kirke-Greene et al., 2023). Figure 3 below shows the map of Nigeria, showing the 36 states and the federal capital territory.

Figure 3: Map of Nigeria showing the 36 states

1.3. MUNICIPAL SOLID WASTE MANAGEMENT IN NIGERIA

Municipal solid waste is a nonhazardous material that needs to be collected and transported to a facility for processing or disposal. Rubbish and garbage are included in waste. Garbage is primarily highly putrescible food waste or yard waste that can decompose, but rubbish is primarily dry materials that can't easily disintegrate, such as glass, paper, cloth, or wood. Several types of trash can be recycled, and some communities compost trash, yard waste, and other waste on a big scale (Britannica, 2023)

Economic and technological improvements have led to an increase in stakeholders' responsiveness to MSW management as one of the key study areas in developed nations (Joshi and Ahmed, 2016) However, when it comes to MSW management, developing nations confront several common issues, such as zero or inadequate recycling strategies and activities, restricted or ineffective handling of hazardous waste, etc. These issues include poor and inefficient service coverage and operation (Purity et al., 2016). To ensure a sustainable environment, MSW management is a crucial requirement (Njoroge et al., 2014) and it entails the collection, transportation, and final disposal. A crucial factor in MSW management is the nature of the waste, which determines the technology required for waste processing and/or disposal (Nabegu and Mustapha, 2014).

Nigeria faces the issues of a poor waste management system and an insufficient electrical supply, just like many developing nations. This results from the nation having a roughly 200 million-person estimated population, producing 32 million tonnes of MSW annually (0.43 kg/person/day), and only having a 20–40% formal waste collection rate (Sowunmi, 2019)

In Nigeria, waste is typically thrown into drainage channels, open pits that are nearby, flowing gutters, and roadside ditches (Babayemi and Dauda, 2009; Onwughara et al., 2010). In the majority of Nigeria's urban cities, the careless disposal of municipal waste has become a common practice. As opposed to big towns, municipal solid waste is handled in rural villages in smaller quantities and is typically burned, composted, fed to animals, or dumped at landfills. Waste is managed in Nigeria through the processes of storage, collection, transportation, and disposal at landfills. Figure 4 below shows the existing municipal solid waste management flowchart in Nigeria.

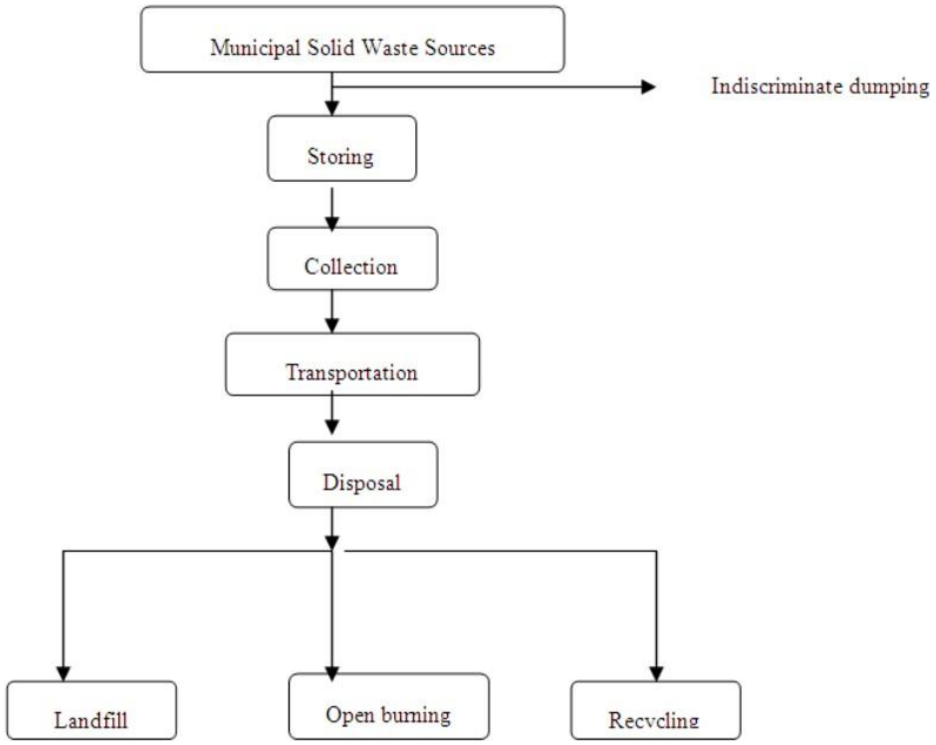

Figure 4: Existing municipal solid waste management flowchart for Nigeria (Beatrice and Jussi, 2020).

There are various methods for disposing of municipal solid waste, but the most popular ones are landfilling, burning, composting anaerobic digestion, and recycling (Ogwueleka, 2009).

Although at the moment open dumping, landfilling, and open burning are the most widely used methods in Nigeria for managing municipal waste, incineration is rarely used. In Nigerian hospitals, where medical waste is burnt on a very small scale, incinerating municipal waste is a cost-effective option that is rarely used (Olanrewaju and Ilemobade, 2009).

Landfilling is the easiest and least expensive way to dispose of trash. Although landfills have a significant negative influence on the environment, this impact could be reduced if sanitary measures are followed and waste reduction is promoted. In 2007, 49% of England's methane emissions came from landfills (Burney et al., 2011).

Moreover, recycling, an environmentally friendly choice, is not properly utilized. In Nigeria, there are no official recycling industries. Scavengers who acquire old junk from people and visit both legal and illegal dump sites in search of materials that can be reused and repurposed informally recycle waste. The production of municipal solid waste is continuously rising from sources like households, businesses, and educational institutions. Municipal waste generators in Nigeria include residential, business, industrial, agricultural, and institutional facilities, among others. In urban and rural locations, as well as between states, there are differences in the quantity and composition of trash produced. The amount of waste produced is strongly associated with population, socioeconomic class, and urbanization level (Igbinomwanhia, 2011; Adeoye et al., 2011; Adewole, 2009).

1.4. HYDROGEN PRODUCTION TECHNOLOGIES

Hydrogen is a versatile and clean-burning fuel that has the potential to play a significant role in the transition to a sustainable energy future. It can be produced using a variety of methods. Each hydrogen production technology has its advantages and disadvantages and the choice of hydrogen production technology depends on several factors, including the type and availability of feedstocks, the desired level of purity, the scale of production, and the environmental impact of the process (Jonas, 2023)

Steam Methane Reforming: A method of producing hydrogen that accounts for around 95% of the hydrogen produced worldwide is steam methane reforming (SMR). It includes producing hydrogen and carbon monoxide from the reaction of natural gas, methane, or other hydrocarbons with high-temperature steam in the presence of a catalyst. The water-gas shift reaction is then used to further react the carbon monoxide with steam, resulting in the production of further hydrogen and carbon dioxide. Synthesis gas, often known as syngas, is the resultant gas mixture (EERE, 2023). As a technique for producing hydrogen, SMR provides several benefits, including high efficiency, low capital and, operating costs, and the accessibility of feedstocks. It can also produce a significant amount of hydrogen and is simple to connect to the current natural gas infrastructure. SMR has several downsides including the process's significant production of greenhouse gases like carbon dioxide. The availability of fossil fuels, which are non-renewable resources, is also a requirement for SMR. High temperatures and pressures, which can be costly and energy-intensive, are also necessary for the manufacturing of SMR. Because of its great efficiency and low cost, SMR continues to be a popular way of producing hydrogen despite its shortcomings. To make SMR a more sustainable alternative for producing hydrogen, scientists are working hard to develop carbon capture and storage technologies that will lower the greenhouse gas emissions that are linked with it (A.M et al., 2022).

Electrolysis: Another typical technique for producing hydrogen is electrolysis, which involves using an electrical current to split water molecules into hydrogen and oxygen. This approach is compatible with a variety of electricity sources, including clean energy from the sun and wind.

Through the process of electrolysis, water is broken down into its constituent parts. The hydrogen and oxygen that make up each water molecule are disassembled by the electric current. The hydrogen gas is then gathered and cleaned so that it can be used as fuel (EERE, 2022).

Hydrogen can also be produced on a small-scale using electrolysis, for use in fuel cells for portable electronics, for example. Electrolysis has certain disadvantages as well. It is currently more expensive than SMR and other hydrogen production techniques, mainly because the process requires a lot of electricity, which is expensive. It also needs a lot of water, which can be a constraint in areas with a shortage of water. To make electrolysis a more attractive option for producing hydrogen on a wide scale, researchers are aiming to increase its efficiency and lower its cost. Future improvements in renewable energy technologies, such as the creation of more effective solar and wind energy systems, are also anticipated to make electrolysis a more viable and affordable method of hydrogen production.

Coal Gasification: In the process, coal is transformed into a gas mixture that contains carbon dioxide, hydrogen gas, and carbon monoxide. A gas mixture is created when coal is heated with steam and oxygen present. This mixture is then separated, and the hydrogen gas is purified. In China, coal gasification is a substantial source of hydrogen gas, but it is a process that uses a lot of energy and emits a lot of carbon dioxide.

Biomass Gasification: In the process, organic material like wood, agricultural waste, or municipal solid waste is transformed into a gas mixture that contains carbon dioxide, hydrogen gas, and carbon monoxide. The biomass is heated in the presence of oxygen and steam during the process, resulting in a gas mixture that is then separated, and the hydrogen gas is purified. A sustainable technique of producing hydrogen via biomass gasification can lower greenhouse gas emissions and provide a source of renewable energy (EERE, 2022).

Photoelectrochemical (PEC) water splitting: is a method of hydrogen production that involves splitting water into hydrogen and oxygen using solar energy. The process involves using a semiconductor material that absorbs sunlight and generates electrons. The generated electrons then react with water molecules, producing hydrogen gas and oxygen gas. PEC water splitting is a promising method of hydrogen production that can be powered by renewable energy sources (Kumar et al., 2022).

Biological water splitting is a method of hydrogen production that mimics the process of photosynthesis in plants. The process involves using bacteria or algae to convert water into hydrogen gas and oxygen gas. The bacteria or algae are genetically engineered to produce hydrogen gas using sunlight, which can be collected and purified. Biological water splitting is a sustainable method of hydrogen production that has the potential to be powered by renewable energy sources (EERE, 2022)

1.5. CHALLENGES IN HYDROGEN PRODUCTION TECHNOLOGIES

Despite the potential benefits of hydrogen production technologies, several challenges need to be overcome to enable their widespread adoption. Some of the major challenges include:

- Many hydrogen production technologies are currently more expensive than traditional fossil fuel-based technologies. This is due in part to the high cost of the equipment and materials required for hydrogen production, as well as the relatively low economies of scale in the industry.
- Hydrogen production technologies often require large amounts of energy to produce hydrogen, leading to high energy losses and reduced overall efficiency.
- The current infrastructure for hydrogen production, storage, and distribution is underdeveloped, which limits the ability of hydrogen to be used on a large scale.
- Hydrogen is a highly flammable gas, which presents safety challenges for its storage and transport.
- While hydrogen is often touted as a clean and sustainable fuel source, its production can still result in greenhouse gas emissions if not produced using renewable energy sources or carbon capture technologies

Hydrogen production technologies have the potential to play a significant role in the transition to a sustainable energy future. The adoption of hydrogen fuel cells in the transportation sector is increasing, and the development of new hydrogen production technologies is ongoing. The use of renewable energy sources to power hydrogen production technologies is also increasing, reducing carbon emissions and making hydrogen gas a more sustainable alternative to traditional fossil fuels While hydrogen production technologies are still in the early stages of development, there is growing interest in the industry and a significant amount of investment going into research and development. As costs continue to come down and efficiency improves, hydrogen could become a more viable and attractive alternative to traditional fossil fuel-based technologies.

There are also significant challenges that need to be addressed to enable the widespread adoption of hydrogen production technologies. These include cost, energy efficiency, infrastructure, safety, greenhouse gas emissions, and resource availability. Addressing these challenges will require continued investment and collaboration across industry, government, and academia.

1.6. HYDROGEN PRODUCTION POTENTIAL

Bioenergy with carbon capture and storage (BECCS) is considered by the Intergovernmental Panel on Climate Change (IPCC) as a vital technology that is crucial to attempts to decrease greenhouse gas (GHG) emissions (Fajardy and Mac, 2019). In this regard, municipal solid waste (MSW) is a promising renewable energy source due to its abundance of organic matter (Kuznetsova et al., 2019; Nebavi-Peleseraei et al., 2017; Nebavi-Peleseraei et al., 2017; Nebavi-Peleseraei et al., 2019). Also, as the rate of urbanization around the world has risen over the past few decades, its annual production has been increasing rapidly. In 2050, the World Bank projected that there would be an increase in MSW output from 2.01 billion tonnes to 3.40 billion. According to statistics, 46% of MSW is organic waste (Tyagi et al., 2018). It is important to note that over half of the MSW produced worldwide comes from the organic portion of municipal solid waste. Yet, managing OFMSW involves both chance and risk; improper management could have a harmful influence on both the environment and public health (Peng et al., 2020).

1.7. FEASIBILITY STUDIES

To assess the viability of producing hydrogen in Nigeria from municipal solid waste, a number several including economic, environmental, and social ones, must be taken into account. The cost of the technology, the price of the feedstock, and the potential revenue from the sale of hydrogen are all economic considerations. The project's effect on the quality of the air and water, as well as the potential for greenhouse gas emissions, are environmental factors. Stakeholder involvement, public approval, and the potential for employment development are examples of social considerations.

1.8. FRAMEWORK FOR IMPLEMENTATION

A thorough framework is required to achieve green hydrogen production from the organic part of municipal solid waste in Nigeria. The infrastructure, rules, and regulations required to support the project should be included in this framework. For instance, rules and regulations that encourage the development of renewable energy sources are needed, as well as investments in infrastructure for garbage collection and recycling.

1.9. CONCLUSION

Nigeria's potential for producing hydrogen from municipal solid waste is a huge opportunity for the development of renewable energy. Several studies have evaluated the potential for hydrogen production from municipal solid waste using a variety of technologies. Studies on the generation of hydrogen from MSW gasification are few in the literature at the moment, particularly in Nigeria but the benefits are enormous. Hydrogen production from organic waste surpasses conventional waste treatment in numerous ways. Firstly, it generates clean energy from carbon-rich waste, unlike incineration or landfilling which emit pollutants. This process yields carbon-neutral hydrogen, mitigating greenhouse gas emissions. Additionally, it transforms waste into a valuable resource, reducing landfill use and fostering energy independence, it also provides opportunity for job creation and economic development if this hydrogen is exported. Organic waste-based hydrogen production stands as an environmentally superior and economically beneficial alternative to conventional waste treatment, addressing energy and waste challenges while promoting a greener future in Nigeria.

CHAPTER 2: METHODOLOGY

2.1. INTRODUCTION

This chapter deals with the materials and methods used during the course of this study to establish the desired aim and objectives.

2.2. RESEARCH DESIGN

To ensure the desired goals and objectives, a mixed method type of research was carried out because this study is concerned with using existing data from the literature, reports from concerned government agencies, and calculations to determine the current hydrogen production potential, future projections, and strategies to achieve better efficiency in terms of conversion of organic waste to hydrogen. The process of determining the green hydrogen production potential from the OFMSW in Abuja involves knowledge of the study area's population, MSW generation capacity, the amount of OFMSW, the technology of choice, and its efficiency. The population is one of the major factors that determine the amount of waste generated in a city.

2.3. STUDY AREA

Abuja is the capital city of Nigeria. It is subdivided into six area councils for administrative purposes; these include Abuja municipal area council, Bwari, Kuje, Gwagwalada, Abaji, and Kwali. It was formed in 1976 and is situated north of the confluence of rivers Benue and Niger, between latitudes 7◦25′ N and 9◦ 20′N and longitudes 5◦ 45′E and 7◦ 39′E. Abuja occupies a land area of 7,753.85 km2 with an estimated population of 3,324,000 in 2020 (National Population Commission Nigeria,2014; United Nations Fund for Population Activities-UNFPA, 2015; Aderoju and Guerner, 2020). It has two main seasons in a year, in common with the climate of Nigeria as a whole; the dry and wet (rainy) seasons. The dry season is normally between November and March which constitutes months of lowest rainfall and humidity, while the wet or rainy season is from April to October, with the highest mean rainfall of ∼119 mm in August and mean humidity of 58% (Aderoju et al., 2018). The population of Abuja is projected to exceed 5.8 million by 2026, based on a 2001 population of 1,724,205 (National Population Commission Nigeria, 2014). This, therefore, poses serious environmental and socio-economic challenges to the city, including MSW management. Abuja has a central government institution responsible for solid waste management in the city known as the Abuja

Environmental Protection Board (AEPB). The Board’s solid waste management portfolio has the following components: City cleaning, street sweeping, litter control, solid waste collection and transfer, and vegetation control (Ezeah, 2010) F.C.T has waste landfill sites located in all the area councils including those located at Mpape, Gosa, Ajata, Karshi, and Kubwa to serve the municipal area. The Mpape dumpsite which was opened in 1989 was closed in 2005 due to complaints of odour and air pollution. It panned 16 hectares with a waste depth of about 15-30 meters at the time of closure (Rogoff, 2019). Ajata dumpsite was opened in 1999 while the Kubwa dumpsite which was opened in 2004 has been forced to close in 2005 due to odor and random fire outbreaks.

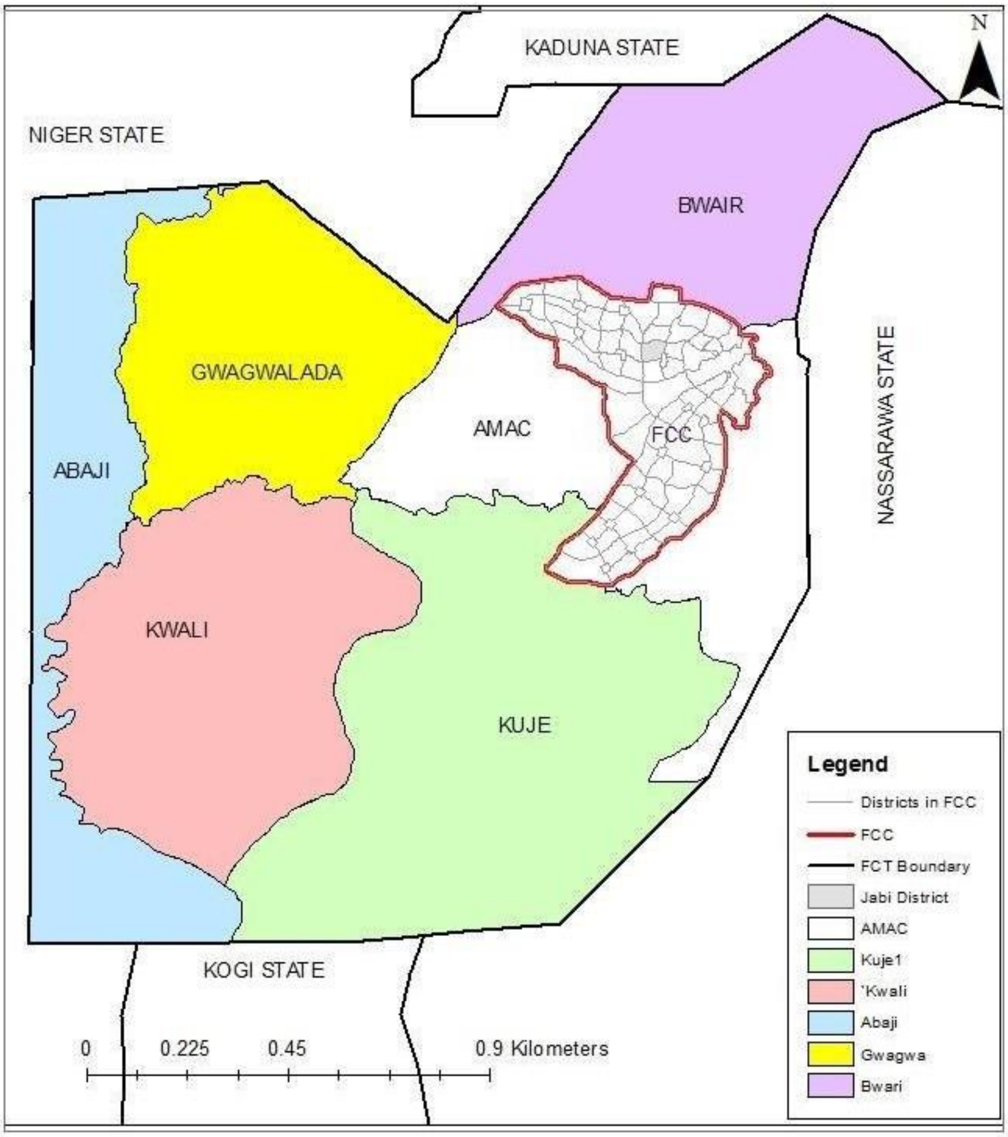

Figure 5: Map of Abuja showing the 6 area councils (AGIS 2016)

2.4. Population data in Abuja

In 2023, the current population of Abuja is estimated to be 3.8 million and is expected to reach 6.07 million by the year 2035 as shown in figure 6. In 1950, the population of Abuja was 18,977. Abuja has grown by 187,617 in the last year, which represents a 5.14% annual change. These population estimates and projections come from the latest revision of the UN World Urbanization Prospects. These estimates represent the Urban agglomeration of Abuja, which typically includes Abuja's population in addition to adjacent suburban areas (World population review, 2023).

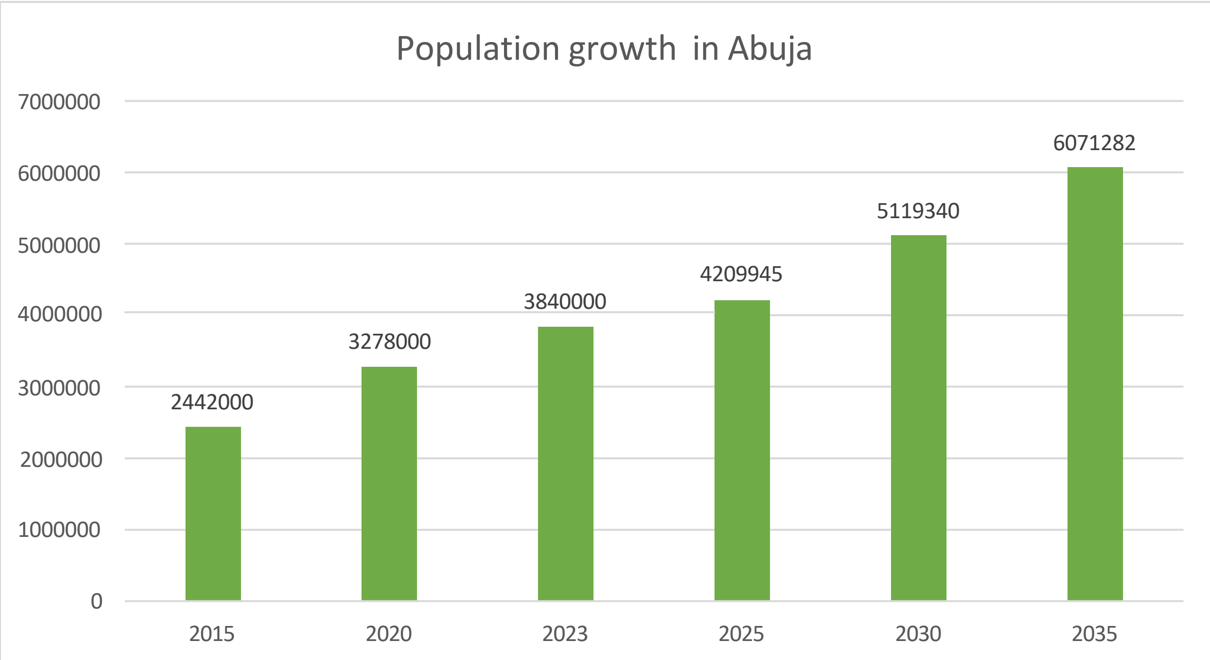

Figure 6: Data on population in Abuja (Adapted from World population review, 2023)

2.5. Waste generation in Abuja

Data from 2000 to 2020 indicates that Abuja city has an average solid waste generation of about 1.51×10^5 t y^{-1}, out of which the organic content constitutes 47% which is also predominant (AEPB, 2020). Therefore, there is a large potential for energy generation from these wastes. The component of the organic fraction of MSW found in Abuja includes waste from food such as vegetable waste, kitchen waste, fruit skin, leaves, and manure which is shown in the figure 8.

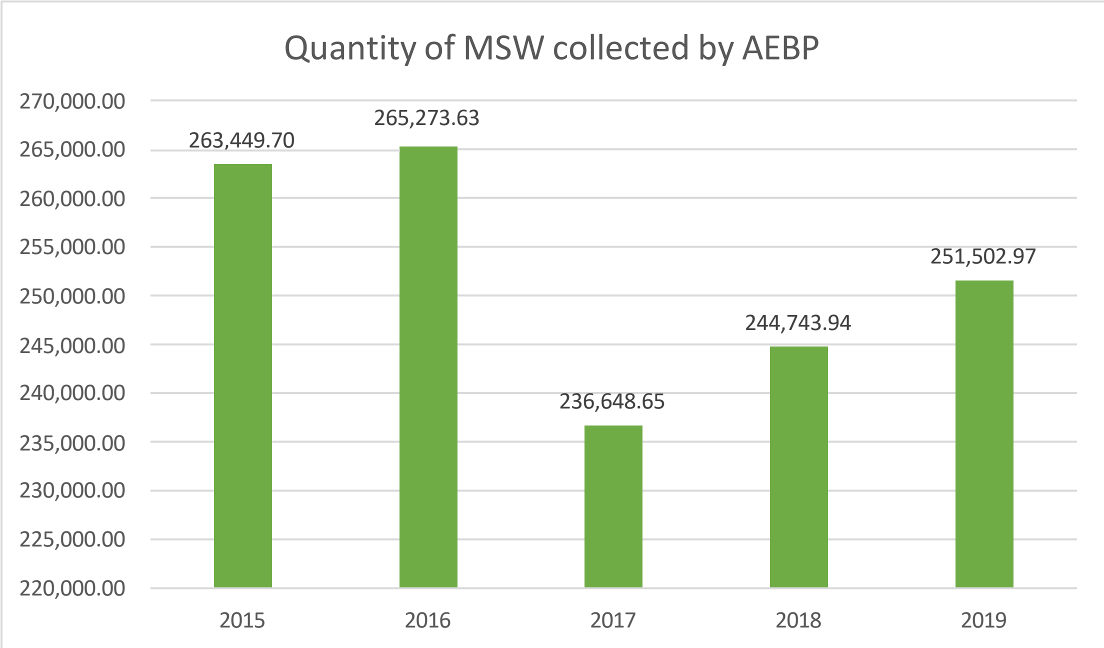

Figure 7: Quantity of MSW collected by AEBP (Adapted from AEBP, 2020)

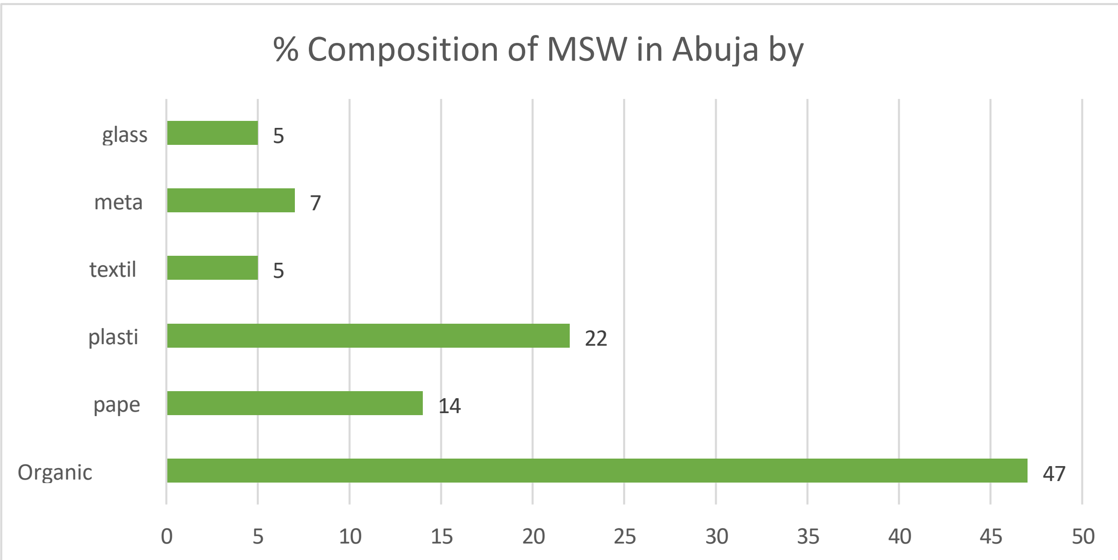

Figure 8: Composition of MSW in Abuja (Adapted from AEBP,2020)

In 2019, it was recorded that 251 thousand tons of waste was generated by 3.095 million people; therefore, this information can be used to predict the amount of waste that can be generated in subsequent years since the population size is known. For example, in 2020, the population is 3.27 million people in Abuja, if 251 thousand tons of waste is generated by 3.095 million people in 2019, how many tons can be generated by 3.27 million people?

The amount of OFMSW for each year was also calculated by multiplying the annual MSW generated by 0.47 to get the exact amount of organic fraction since the waste contained 47% organic fraction.

2.6. BUSWELL'S THEORETICAL BIOGAS PRODUCTION

Anaerobic digestion, shown in figure 9 is a process through which bacteria break down organic matter—such as animal manure, wastewater biosolids, and food wastes in the absence of oxygen. Anaerobic digestion for biogas production takes place in a sealed vessel called a reactor, which is designed and constructed in various shapes and sizes specific to the site and feedstock conditions. These reactors contain complex microbial communities that break down (or digest) the waste and produce resultant biogas and digestate (the solid and liquid material end-products of the AD process) which is discharged from the digester (EPA,2023).

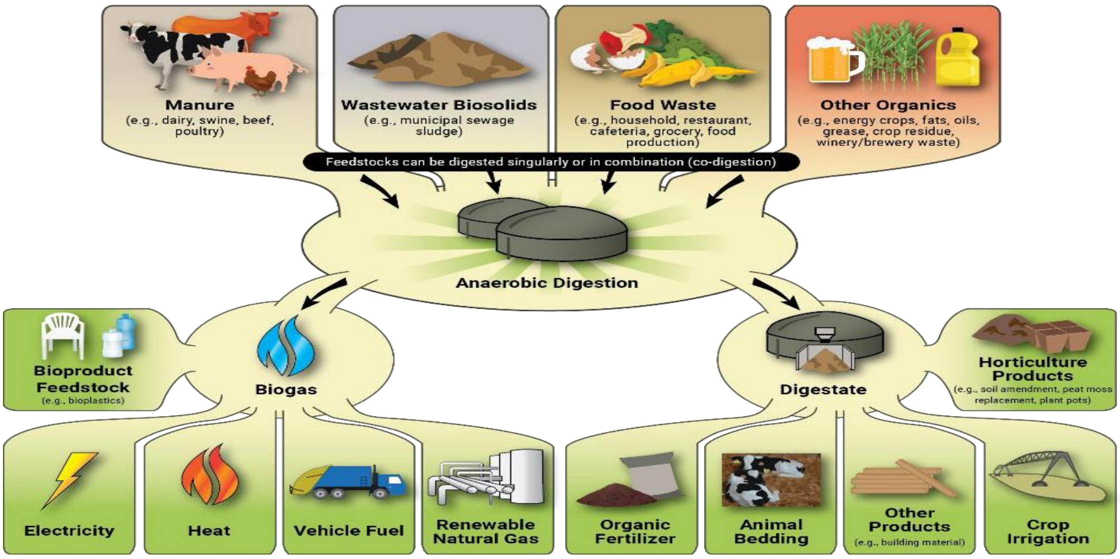

Figure 9: Biogas production via Anaerobic digestion (EPA,2023)

Buswell created an equation in 1952 to estimate the products from the anaerobic breakdown of a generic organic material of chemical composition CcHhOoNnSs. Boyle's modified Buswell equation was used to determine the theoretical biogas and methane potential at standard conditions (0°C, 1 atm) as shown in the equation 1below.

$$C_cH_hO_oN_nS_s + 1/4(4c - h - 2o + 3n + 2s)H_2O =$$
$$1/8(4c - h + 2o + 3n + 2s)CO_2 + 1/8(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2 \quad (1)$$

C – Carbon, H – Hydrogen, O – Oxygen, N – Nitrogen, S – Sulfur, H_2O – Water, CH_4 – Methane, CO_2 – carbon dioxide, NH3 – Ammonia, H_2S – Hydrogen Sulfide.

The carbon content of a feedstock in combination with the Buswell equation was used to estimate the methane production, and 70% of biodegradable municipal solid waste is assumed as the proportion of the material degraded in the process to produce.

53% of CH4 and 47% of CO2. The carbon content was calculated by dividing the ultimate value of carbon by the total ultimate value of the feedstock.

The total solid of 35% and the Volatile solid of 70% were also taken into account in the theoretical biogas calculation.

2.7. STEAM METHANE REFORMING

Steam reforming converts methane into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst (www.nyserda.org) which is shown in figure 10.

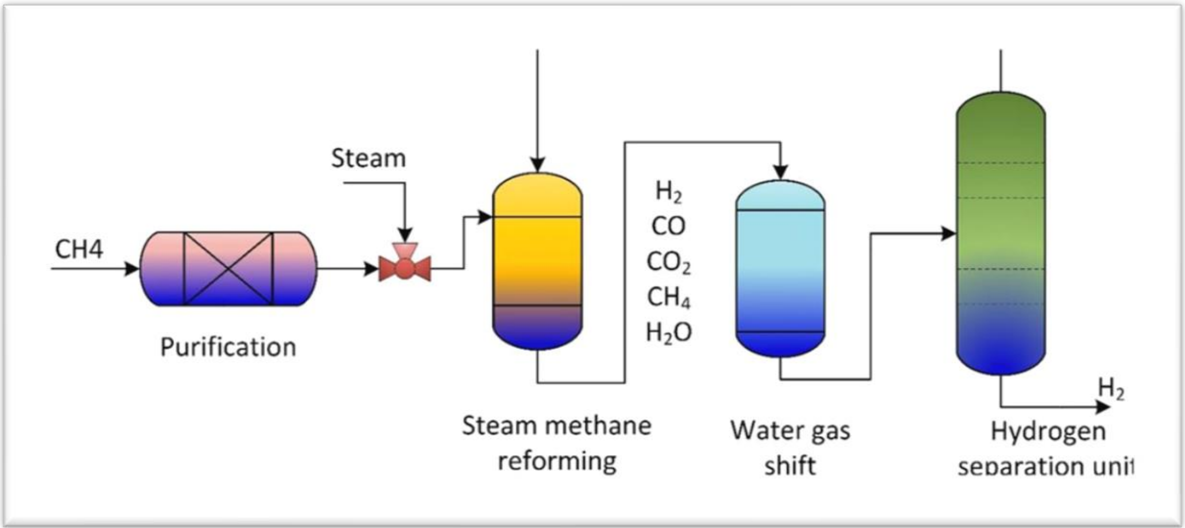

Figure 10: Steam reforming technology set up

Steam reforming is one of the major technologies used in hydrogen production worldwide and the feedstocks include Natural gas (Methane) from fossil fuel and OFMSW. In steam reforming, Methane reacts with steam to produce CO and H_2 primarily, CO_2 and solid carbon are also formed as secondary by-products as shown in the equation 2.

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad \Delta H_{SR} = 206 \text{ kJ/mol} \qquad (2)$$

This process requires a heterogeneous catalyst and is highly endothermal. Thermodynamic studies have shown that the reaction is favorable at high temperatures between 500-900 to obtain a high methane conversion (Linde, n.d.)

The theoretical amount of methane from the Buswell equation was used to calculate the amount of hydrogen that can be produced the efficiency of the steam reforming process was also considered in this calculation which was about 65% to 75%, among the highest of current commercially available production methods.

2.8. ELECTRICITY GENERATION POTENTIAL

The Electricity generation potential of Hydrogen can be calculated by multiplying the energy content of hydrogen by the mass of hydrogen obtained. The formula used in this calculation is stated in equation 3.

$$EL = QH2 * LHV \qquad (3)$$

Where;
E_L: Electrical energy in kWh
Q_{H2}: Quantity of Hydrogen in Kg
LHV: Lower heating value of H_2 (33kWh/Kg of Hydrogen)

This formula was used to calculate the electricity generation potential for the years 2015, 2023, 2025, 2030, and 2035.

2.9. JUSTIFICATION OF METHODOLOGY

The production of bioenergy from anaerobic digestion (AD) is a promising alternative to climate change mitigation and is considered a viable treatment technology for waste management (Pantaleo et al., 2013) Biogas systems protect the environment by recycling organic waste into clean energy and manure to enrich the soil while reducing global emissions. There is an urgent need to manage organic waste which forms a high percentage of Municipal solid waste and this is one of the major benefits of biogas systems because they can help displace fossil fuels. Combining all of these benefits, carbon emissions can be reduced, soils can also be enriched with organic fertilizer, and reliable baseload renewable energy can be produced. (American Biogas Council)
Steam reforming is a widely used technology in the industry today. Hydrogen is produced by this method in large centralized plants for several applications. Steam reforming technology offers an efficient, cost-competitive, and widely used process for hydrogen production and also provides near and mid-term energy security and environmental benefits. This process also has

a high efficiency of up to 75% which makes it an interesting option amongst the current commercially available technology. It is a mature technology and the cheapest method of Hydrogen production with a technology readiness level (TRL) of 9 which is very important to begin the transition to a hydrogen economy because it already accounts for 48% of the global hydrogen production **(**WRI India**)**

CHAPTER 3: RESULTS AND DISCUSSION

3.1. POPULATION TREND

Data obtained from the world population review for the past, current, and projected annual population in Abuja shows a consistent increase in the population trend since 2015, and this number is projected to increase up to three times in 2035. The population of a particular location is a major factor that influences the rate and type of waste that can be generated and these wastes can be valorized to meet energy demands, and the size of the population makes Abuja is good location for waste-to-energy conversion technologies. Figure 11 shows the population trend from 2015 to 3035 with a steady increase.

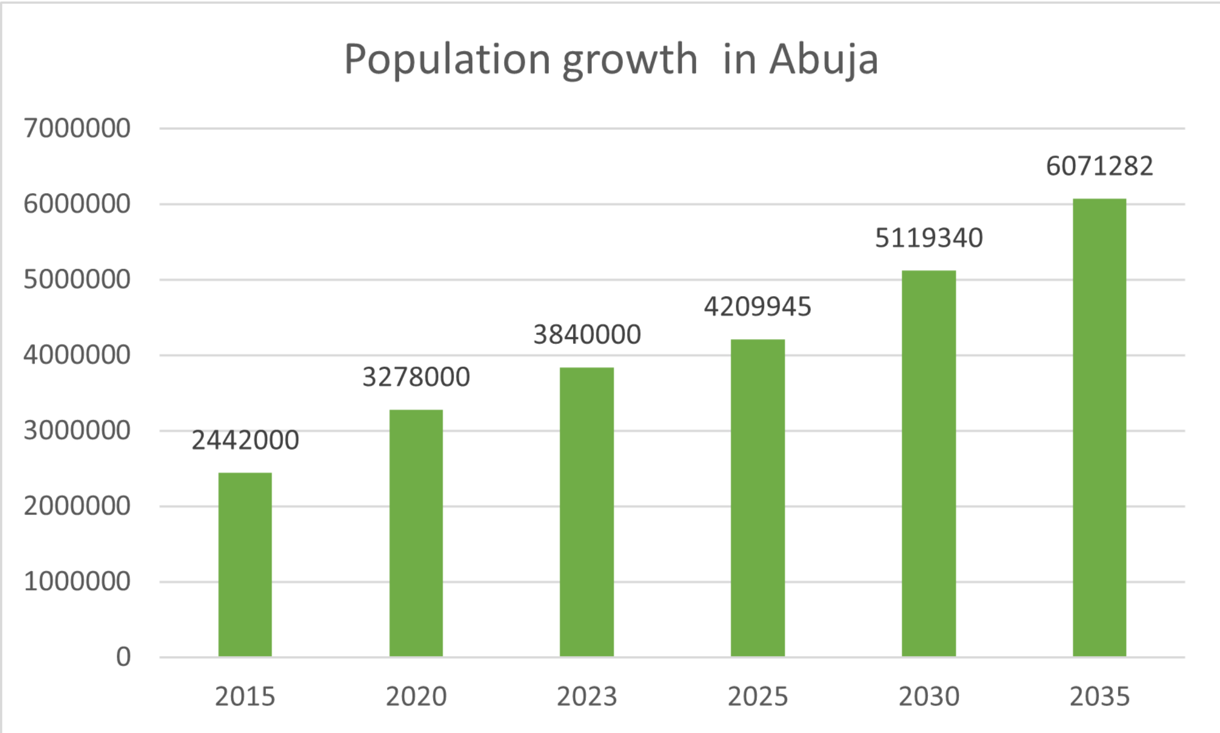

Figure 11: **Population growth in Abuja (Adapted from world population review)**

3.2. WASTE TREND

Data obtained from the Abuja Environmental Protection Board for the average annual quantity of MSW collected in Abuja is shown in Figure below. Excluding the outlier years of 2020 due to COVID-19, the data show a consistently increasing trend in solid waste generation. The total organic waste generated in 2015 was 263,449 tonnes amongst which 123,821 tonnes of it was organic. From this data, the waste generated for 2023 was calculated to be 312,000 tonnes and 146,659 tonnes of this waste is organic. It was also calculated that the waste generation capacity in Abuja will reach 493,358 tonnes with an organic fraction of 231,878 tonnes, which is twice the amount obtained in 2015. Figure 12 shows the amount of municipal waste generated for 5 different years and the amount of organic fraction which is 47% of the total waste.

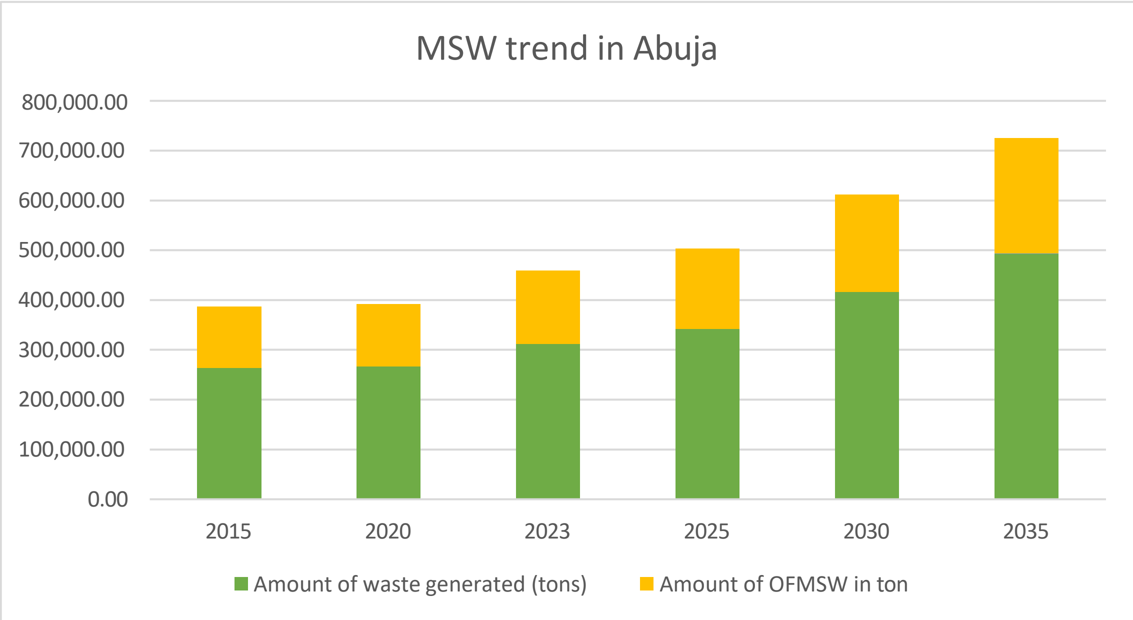

Figure 12: MSW Trend in Abuja

3.3. BIOGAS POTENTIAL

The figure 13 shows the calculated biogas production trend for the years 2015,2023,2025,20230 and 2035. The daily biogas production potential for each year was also calculated and reported. The result also revealed the high biogas potential in Abuja due to the high amount of MSW obtained yearly in Abuja. There is also a steady increase in the production potential trend from 2015 to 2035 as shown in figure 13.

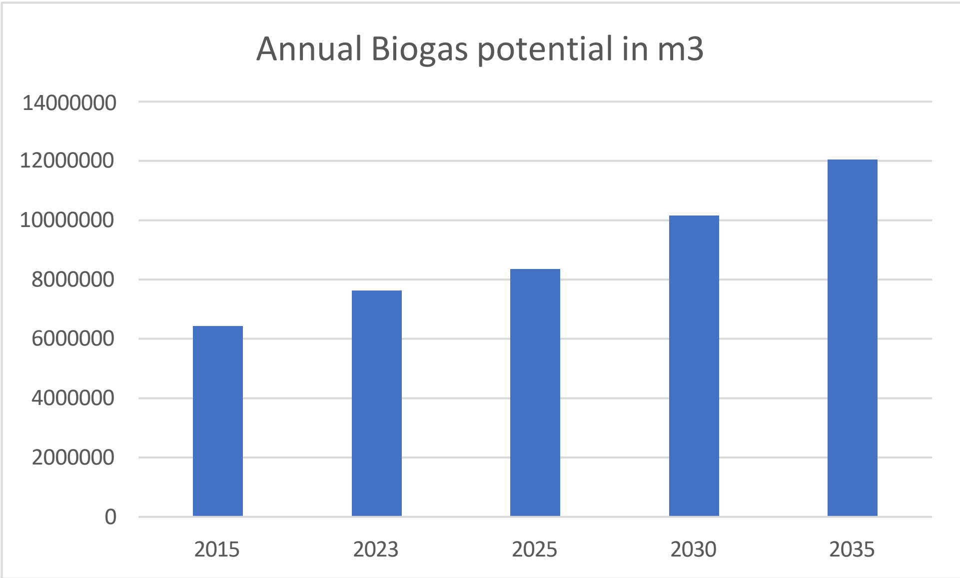

Figure 13: Biogas production trend in Abuja from OFMSW

3.4. H_2 POTENTIAL

The methane obtained from the theoretical biogas calculation for each year was used to calculate the hydrogen production potential in Abuja. The results of hydrogen potential were obtained in kilograms and meter cubes as shown in figure 14 and 15. The hydrogen yield result showed constant growth from 2015 to 2035.

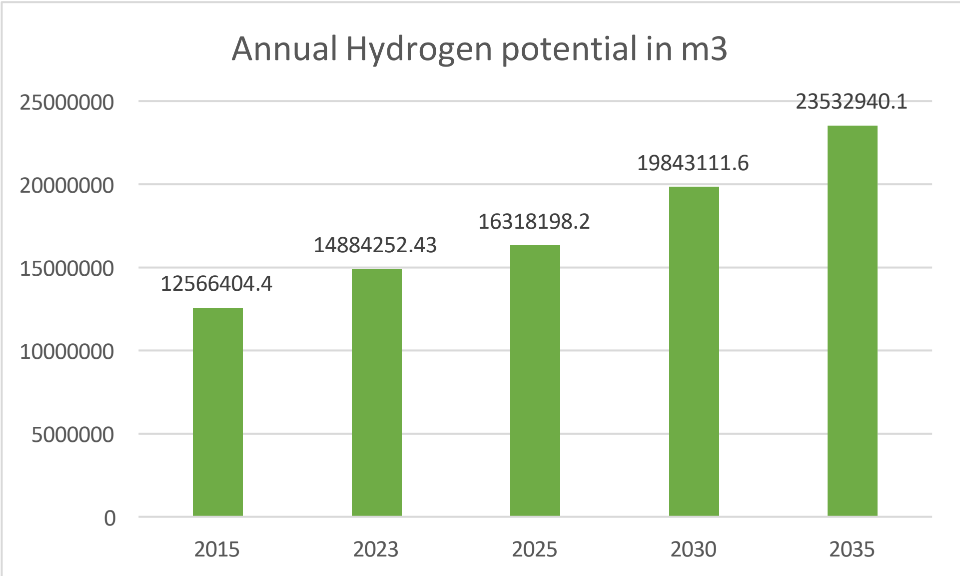

Figure 14: Hydrogen potential in Abuja (m^3)

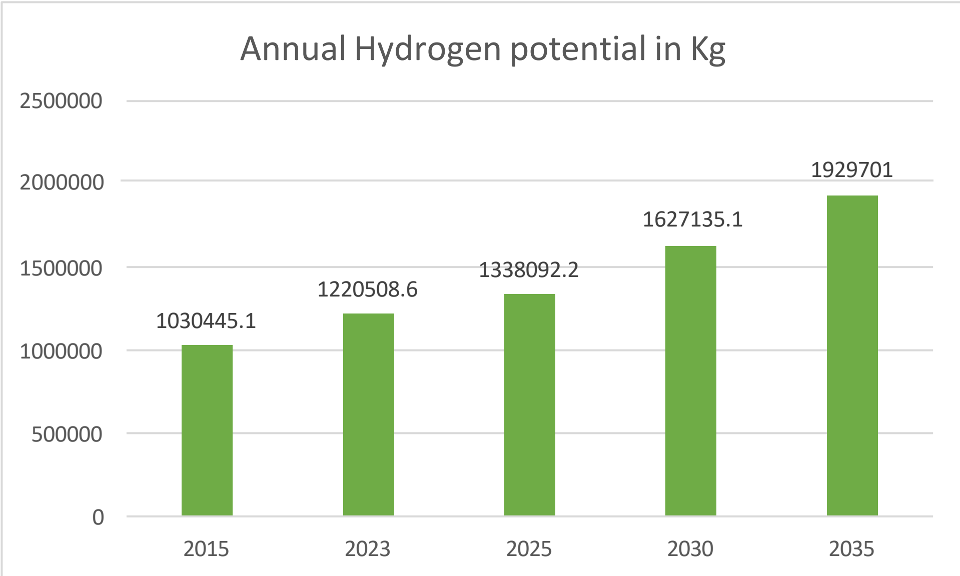

Figure 15: Hydrogen potential in Abuja (kg)

3.5. ELECTRICITY POTENTIAL

The data below shows the electricity generation potential from OFMSW in Abuja and this revealed that there is a great potential for green hydrogen to be a major source of electricity as opposed to natural which is replenishable. In 2023, the result showed 40.2 TWh of electricity can be generated from hydrogen in Abuja which is far greater than the 29,684 GWh that was produced in the country as a whole in 2022.

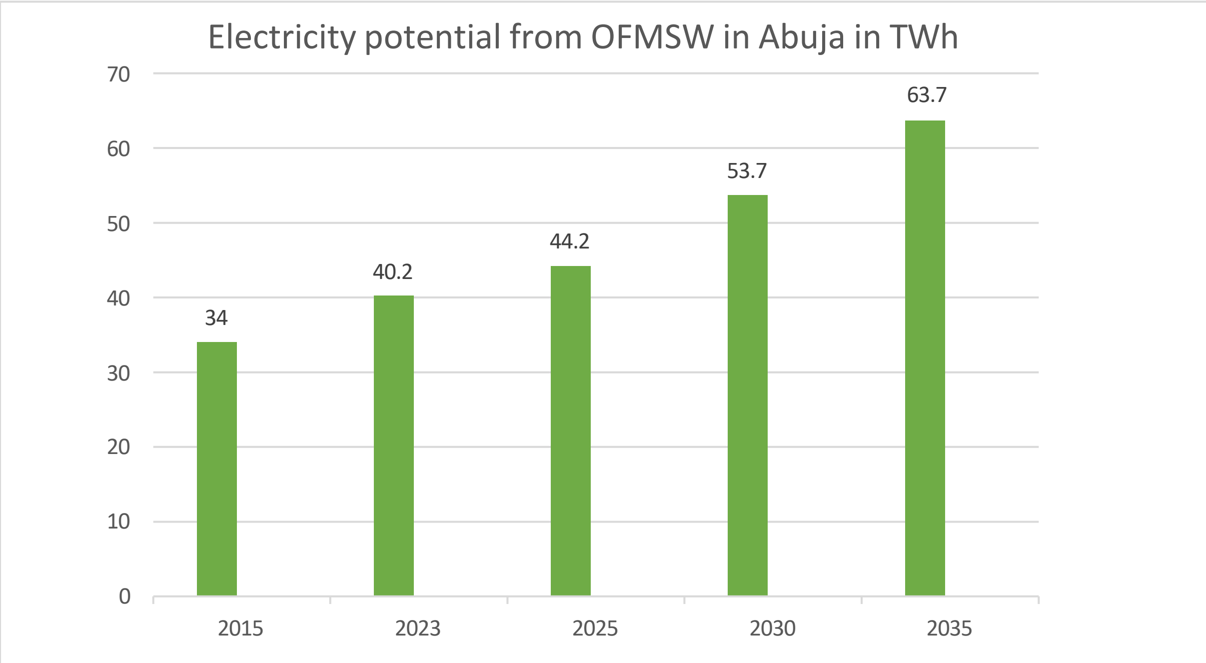

Figure 16**:** Electricity potential from OFMSW in Abuja

Electricity Production data of Nigeria is updated quarterly averaging at 6,962 GWh from Mar 2005 to Sep 2022. The data reached an all-time high of 9,936 GWh in Sep 2015 and a record low of 3,247 GWh in Jun 2009. The graph below shows the electricity generation in Nigeria in GWh for the last five years. The production increased from 31,256 GWh in 2018 to 36,400 GWh in 2021, however, a decrease was observed last year to 29,684 GWh due to various factors (CEIC Data 2022).

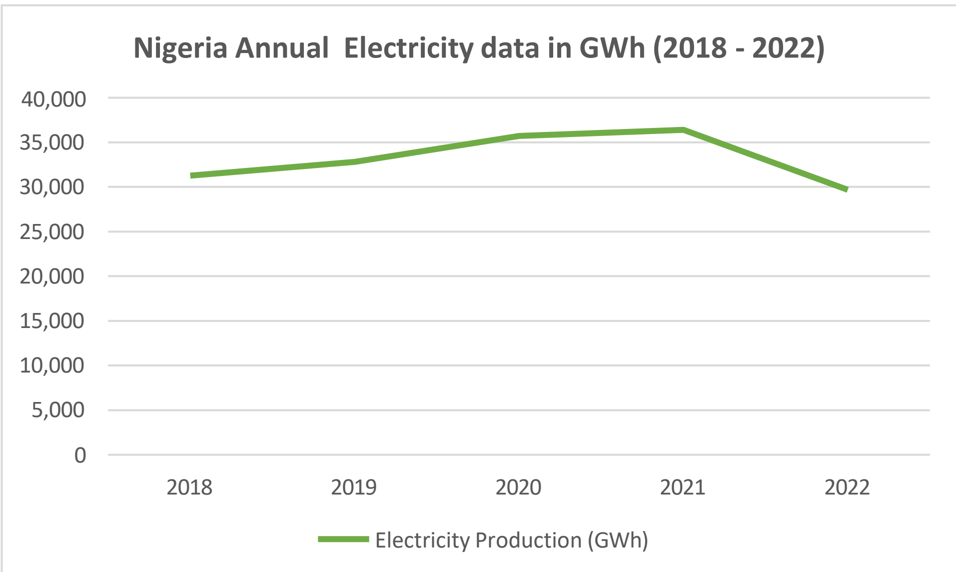

Figure 17: Nigeria Annual electricity data in GWh (Adapted from CEIC Data)

The reasons for this decrease in production were associated with low rainfall which affected the hydropower plants, shortage of gas supply to the power thermal gas plants, and also the fire at the Egbin power plant (Ogheneruona and Nnaemeka, 2022). The major source of electricity in Nigeria is natural gas which makes up 70.5 % of the mix followed by hydropower with 27.3% and this explains why when the two major sources were affected in 2022, there was a decrease in electricity generation.

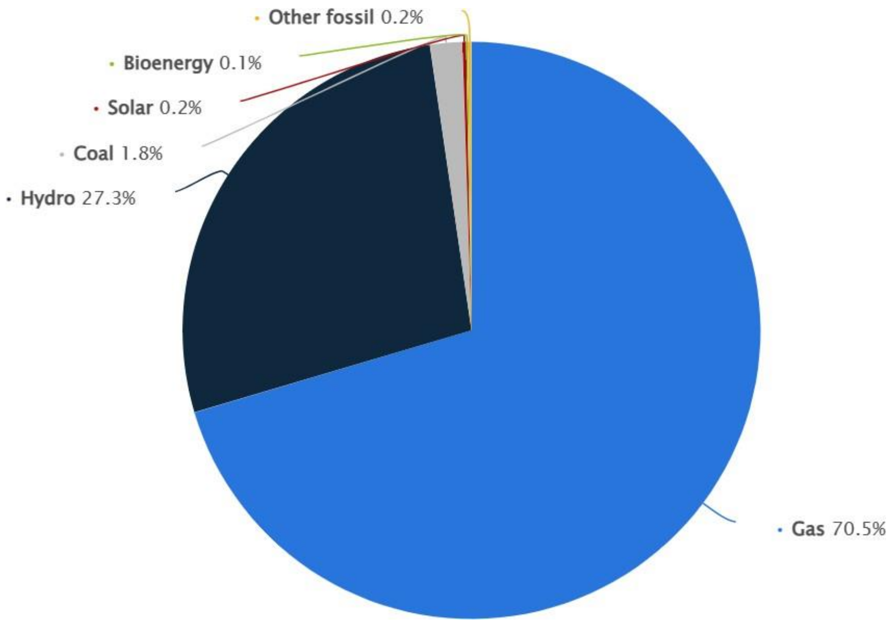

Figure 18: Distribution of electricity generation in Nigeria (Stastitica, 2023)

3.6. SUMMARY OF RESULT

The table 1 shows the biogas, hydrogen, and electricity potential from OFMSW in Abuja for five different years. The biogas and hydrogen potential from OFMSW is gradually increasing over the years and this is due to the increasing population and waste generation annually. The electricity potential is increasing as well and this is largely influenced by the increase in hydrogen potential which can be used to generate this electricity. The increasing trends suggest that as waste management and segregation continues to increase over time, the energy potential from OFMSW will also increase, so it is important to put laws and strategies in place in order to maximize the full potentials of OFMSW for energy generation.

Year	Annual n Biogas Potential in m3	Annual Hydrogen potential in Kg	Annual Hydrogen potential in m3	Electricity potential in TWh/year
2015	6434501.3	1030445.1	12566404.4	34
2023	7621332	1220508.6	14884252.43	40.2
2025	8355569.6	1338092.2	16318198.2	44.2
2030	10160465.8	162735.1	19843111.6	53.7
2035	12049805.8	1929701	23532940.1	63.7

Table 1: Summary of Energy potential from OFMSW for different years.

3.7. RECOMMENDATION TO ENABLE INCREASED CONVERSION OF OFMSW TO H_2 IN ABUJA.

Problem:

The segregation of waste is very poor in Abuja, Nigeria. MSW which includes food items, plastics, glass, nylon, metal, and others are usually disposed of together (Elum et al., 2017; Adewuyi, 2020) The Abuja MSW system is characterized by inefficient collection methods, inadequate coverage of the collection points, and inappropriate disposal systems (Ogwueleka, 2009).

Recommendation:

- The AEBP can encourage residents to sort out their waste by providing waste sorting bins and placing them in strategic areas around residential areas, this would make it easier for individuals to remember to take action
- The AEBP should partner with media personnel such as Radio and social media to advocate the benefits of waste sorting.

Figure 19: Different waste sorting bins (Adapted from Ktanya and yummy via Canva 2023).

Problem: Poor collection efficiency is another barrier to the waste to energy (WtE) framework in Nigeria. Only 41% of the MSW generated in Nigeria is collected. Bad road networks and inadequate truck maintenance are some of the factors causing the low level of waste collection (Somorin et al., 2017).

Figure 20: A photo of a bad road network in Abuja, Nigeria (Oasis Magazine,2017).

Recommendation:

- Government should ensure a good road network around residential areas to allow the smooth operation of waste collection
- Build waste-to-energy facilities closer to areas like this where it is difficult to get this waste out.
- The AEBP can improve the poor collection by procurement of more waste collection trucks and employment of sufficient staff
- Provide incentives to existing waste collectors to enable them to expand the areas they cover and provide training for people willing to venture into waste collection as a private entity.

Other recommendations:

- The AEBP can partner with AEDC and waste-to-energy industries to see how the price of electricity can be subsidized by incorporating Electricity generated from OFMSW into the grid in addition to the existing Natural gas.

- The environmental and conservation department in NABDA produces biogas for research and strategy development purposes, The AEBP can partner with them to train individuals in biogas production from OFMSW as most trainings are usually on plastic processing.
- Partnership with the Hydrogen Diplomacy office in Abuja is also crucial to see how hydrogen production from OFMSW can be incorporated into the Nigerian hydrogen value chain.

3.8. CONSTRAINTS ATTACHED TO WASTE-TO-HYDROGEN PLANT

Building a waste-to-hydrogen plant in Abuja Nigeria, like any other waste to energy plant project, comes with a range of potential constraints and challenges that need to be carefully considered during the feasibility assessment, and some of the key constraints includes:

- Financing: Securing the necessary funding for such a project can be a major hurdle. Convincing investors, securing loans, or obtaining grants for a waste-to-hydrogen plant may be difficult due to the perceived risks or uncertainties related to hydrogen and its safety.

- Feedstock Availability: The consistent and reliable supply of waste feedstock (e.g., The organic fraction of municipal solid waste) is essential. In most regions in Abuja, waste collection, sorting and management systems are inadequate.

- Environmental Concerns: Addressing environmental concerns and ensuring that the waste-to-hydrogen process doesn't negatively impact local ecosystems and communities is essential. This may require advanced pollution control and waste management measures.

- Market Viability: Assessing the demand for hydrogen in Nigeria or potential export markets is important for project sustainability. Identifying potential customers and securing long-term off-take agreements can be challenging.

- Social Acceptance: Social acceptance plays a crucial role in the success of any waste-to-hydrogen project. Building community support and addressing any concerns or opposition from local communities is important. Proactive engagement with stakeholders can help mitigate potential conflicts because the knowledge of green hydrogen technology is relatively low in Abuja, Nigeria.

3.9. PERSPECTIVE FOR THE FUTURE

A waste-to-hydrogen project in Nigeria can bring several significant benefits to the country, including environmental, economic, and social advantages.

- Clean Energy Production: The project generates hydrogen, a clean and versatile energy carrier. This can contribute to reducing greenhouse gas emissions and air pollution, thus improving air quality and public health.

- Waste Management: The project helps address Nigeria's waste management challenges by converting municipal solid waste into a valuable energy resource. This can reduce the amount of waste sent to landfills and mitigate environmental pollution.

- Energy Independence: By producing hydrogen locally from waste, Nigeria can reduce its dependence on imported fossil fuels, increasing energy security and resilience.

- Job Creation: The construction and operation of the waste-to-hydrogen plant create job opportunities in engineering, operations, maintenance, and support services, contributing to employment and economic growth.

- Technological Advancement: The project encourages the development and adoption of advanced waste-to-energy technologies and expertise within Nigeria, fostering innovation and technological progress.

- Renewable Hydrogen: If renewable energy sources like solar or wind power the hydrogen production process, it can contribute to Nigeria's transition to a more sustainable and renewable energy mix.

- Hydrogen Export Potential: Nigeria can potentially export hydrogen to international markets, especially if it produces hydrogen efficiently and at a competitive cost. This can create additional revenue streams for the country.

- Climate Mitigation: By reducing methane emissions from decomposing waste, the project helps mitigate climate change, as methane is a potent greenhouse gas.

- Improved Public Health: Reducing landfilling and associated pollution can lead to improved public health outcomes, as it reduces the risks of disease transmission and exposure to hazardous substances.

To maximize these benefits, it's essential for the waste-to-hydrogen project to be well-planned, efficiently executed, and operated in an environmentally responsible and socially sustainable manner. Additionally, collaboration among government agencies, private sector partners, and local communities is crucial to ensuring the project's success and positive impact on Nigeria's economy and environment.

CONCLUSION

The research explored the potential of green hydrogen production from OFMSW in Abuja, Nigeria, and the objective was to propose an alternative and stable source of energy other than fossil fuels. From the calculations, data available, and projections, it was evident that green hydrogen from OFMSW can play a crucial role in meeting the energy demands of Nigeria as a whole, and help reduce the emissions of greenhouse gases.

This research showed that MSW Contained a high amount of organic fraction which can be converted to hydrogen via anaerobic digestion and steam reforming. The results of this research revealed that with the current 3.8 million population in Abuja, and 146659.96 tonnes of organic waste generated annually, 7.62 million m3 of biogas and 12 million kg /year of hydrogen could potentially be generated annually, similarly, 40.27 TWh of electricity could also be generated annually which surpasses the 29,684 GWh of electricity generated in Nigeria in 2022, and in 2035, up to 12 million m3 of biogas, 23 million kg of hydrogen and 63 TWh of electricity can be potentially generated. Integrating the production of hydrogen from OFMSW will help solve the problems of poor waste management, landfill methane emissions, and polluted air which causes illness among residents. However, despite the huge potential, some gaps need to be filled to achieve a high waste-to-hydrogen conversion and all stakeholders need to be involved to make this happen. Joint efforts from policymakers, waste management authorities, and renewable energy stakeholders will be crucial to realizing this potential and ensuring the successful integration of green hydrogen from waste into the hydrogen value chain and energy mix.

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