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MODELLING THE H_2 POTENTIAL AND PRODUCTION FROM MUNICIPAL SOLID WASTE IN CITY OF BISSAU, GUINEA-BISSAU

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by:

Jorge Euclides GONÇALVES

Composition of the Jury:

Jury President: Mianikpo SOGBEDJI, Professor, Université de Lomé - Togo

Examiner/ Judge: Batablinlè LAMBONI, Assistant Professor, Ecole Normale Supérieure -Togo

Major Supervisor: Komi Apélété AMOU, Associate Professor, Université de Lomé-Togo

Co-Supervisor: Satyanarayana NARRA, Professor, University of Rostock – Germany

Jorge Euclides Gonçalves

Modelling the H_2 potential and production from Municipal Solid Waste in City of Bissau, Guinea-Bissau

Lome, 2023

Declaration

I hereby declare that the present master's thesis whose topic modelling the hydrogen potential and production from municipal solid waste in the city of Bissau, Guinea-Bissau has never been the subject of presentation by any person to obtain any academic degree, except with the due citations made throughout the work.

Rostock, August 15, 2023

Jorge Euclides Gonçalves

The Lord is my shepherd, I shall not want. He maketh me to lie down in green pastures: he leadeth me beside the still waters. He restoreth my soul: he leadeth me in the paths of righteousness for his name's sake (Psalm 23:1-3).

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Abstract

The increase in the generation of municipal solid waste is a growing concern in terms of providing them with an adequate final destination. Still, access to energy poses enormous challenges, both social and economic. Energy is currently mostly produced by non-renewable sources, ending up having negative impacts causing various forms of pollution and emitting significant amounts of greenhouse gases. Anaerobic digestion is a biological technology for valuing the organic fraction of municipal solid waste in order to minimize the amount of waste that goes to landfills, minimizing the emission of greenhouse gases, odours from waste and taking advantage of the energy potential. This work serves to determine the hydrogen potential from the organic fraction of waste produced in Bissau and the electricity that can be obtained. The potential for biogas from the same waste was also determined. In Bissau, the production of municipal solid waste is estimated at a total of 316 tons/day, 37% of which is organic, the management of which poses enormous difficulties. On the other hand, the electrification rate is low since only 20% of the population has access to electricity. The methods used are based on consulting bibliographies in order to obtain mathematical expressions through other work already done that allows the respective potential to be determined and the calculations were made in Excel and economic viability was determined. The results show that with the valorisation of organic waste in the city of Bissau for the production of hydrogen, the electricity to be obtained is 0.0458 MWh and for biogas it would be 39.6102 MW with a decrease of approximately 3603452.28 Kg of carbon dioxide equivalent as greenhouse gas. The economic analysis indicates that just generating electricity with biogas will not be profitable, so it is necessary to take other bio products into account.

Key words: Anaerobic digestion, hydrogen potential, Environmental impacts, Electrical energy, Municipal Solid Waste

Résumé

L'augmentation de la production de déchets solides municipaux constitue une préoccupation croissante lorsqu'il s'agit de leur fournir une destination finale adéquate. Pourtant, l'accès à l'énergie pose d'énormes défis, tant sociaux qu'économiques. L'énergie est actuellement produite principalement par des sources non renouvelables, ce qui finit par avoir des impacts négatifs, provoquant diverses formes de pollution et émettant des quantités importantes de gaz à effet de serre. La digestion anaérobie est une technologie biologique permettant de valoriser la fraction organique des déchets solides municipaux afin de minimiser la quantité de déchets envoyés aux décharges, en minimisant les émissions de gaz à effet de serre, les odeurs des déchets et en profitant du potentiel énergétique. Ces travaux servent à déterminer le potentiel hydrogène de la fraction organique des déchets produits à Bissau et l'électricité qui peut être obtenue. Le potentiel de production de biogaz à partir des mêmes déchets a également été déterminé. A Bissau, la production de déchets solides municipaux est estimée au total à 316 tonnes/jour, dont 37% de matières organiques, dont la gestion pose d'énormes difficultés. En revanche, le taux d'électrification est faible puisque seulement 20% de la population a accès à l'électricité. Les méthodes utilisées sont basées sur la consultation de bibliographies afin d'obtenir des expressions mathématiques à travers d'autres travaux déjà réalisés qui permettent de déterminer le potentiel respectif et les calculs ont été effectués sur Excel et la viabilité économique a été déterminée. Les résultats montrent qu'avec la valorisation des déchets organiques dans la ville de Bissau pour la production d'hydrogène, l'électricité à obtenir est de 0,0458 MWh et pour le biogaz elle serait de 39,6102 MW avec une diminution d'environ 3603452,28 Kg d'équivalent dioxyde de carbone. L'analyse économique indique que la seule production d'électricité avec du biogaz ne sera pas rentable, il est donc nécessaire de prendre en compte d'autres bioproduits.

Mots clés : Digestion anaérobie, potentiel hydrogène, impacts environnementaux, énergie électrique, déchets solides municipaux

List of Symbols and Abbreviation

%	Percentage
˚C	Celsius degree
AD	Anaerobic digestion
AFC	Alkaline Fuel Cell
AHP	Annual hydrogen potential
atm	Atmosphere pressure unit
B/ C	Benefit cost ratio
C/N	Ratio between carbon and nitrogen
CH_4	Methane
CMB	Municipality of Bissau (Portuguese acronym- Camara Municipal de Bissau)
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CP	Calorific power
EAGB	Electricity and Water Company of Guinea-Bissau (Portuguese acronym- Electricidade e Aguas da Guiné-Bissau)
FAO	Food and Agriculture Organization of the United Nations

FCI	fixed capital investment
g/ year	Grams per year
GHG	Greenhouse gases
H^+	Ion hydrogen
H_2	Hydrogen
H_{2Den}	Hydrogen density
H_{2LHV}	Lower heating value of hydrogen
H_{2PG}	Power generation from hydrogen gas
H_{2QTY}	Hydrogen gas quantity
H_2S	Hydrogen sulphide
HRT	Hydraulic retention time
HY	Hydrogen yield
INE-GB	National Statistic Institute (Portuguese acronym- Instituto Nacional da Estatistica)
IRR	Internal interest rate
Kg	Kilogram
Kg/ day	Kilograms per day
Kg/ m^3	Kilograms per Cubic Meter
kJ	Kilojoules

kJ/g	Kilojoules per gram
km^2	Kilometer
kWh	kilowatt hour
kWh/m^2	Kilowatt hours per square metre
LCOH	Livelized cost of biogas
LHV	Lower heating value
LVIA	International Association of Lay Volunteers
M	Molar mass
m^2	Meter square
m^3	Cubic meter
m^3/s	Cubic meter per second
MCFC	Molten Carbonate fuel cell
MEIRN	Ministry of Energy, Industry and Natural Resources (Portuguese acronym- Ministério da Energia, Industria e Recursos Naturais)
MJ/kg	Mega joule per Kilogram
MJ/Nm^3	Mega joules per normal cubic meter
mm	Millimetre
MSW	Municipal Solid Waste
MW	Megawatt

NH_3	Ammonia
NOx	Nitrogen oxides
NPV	Net present value
O_2	Oxygen
OC	Operational cost
OFMSW	Organic Fraction of Municipal Solid Waste
PDSDE	Power Distribution System Improvement Project
PEM	Polymer Electrolyte Membrane
pH	Hydrogen potential
PP	Payback period
Sc	Concentration of fraction of organic waste as substrate
SOFC	Solid oxide fuel cells
Sox	Sulphur
TCC	Total capital cost
Ton/ day	Ton per day
TS	Total solids
USCB	United States Census Bureau
V_B	Volume of biogas
VFA	Volatile fatty acids

VOCs	Volatile organic compounds
VS	Volatile solids
WCC	Working Capital cost
WtE	Waste to energy
ω	Fuel cells efficiency

List of tables

List of figure

Table of content

1. Introduction

Energy is essential for the development of any nation, since ancient times, man has always needed to use fire for heating, cooking, electricity or for his own safety. The availability of energy significantly contributes to population growth and development (Caetano et al., 2017), for our life, it is one of the main elements to achieve the economic, social and environmental objectives for the desired sustainable development (Ghiasirad et al., 2020).

The growth of population, technological development increased demand for energy services (Ghiasirad et al., 2020) and increased consumerism have led to a high consumption of resources. Consequently, there is a growing production of waste, and the need to develop an integrated management of municipal solid waste (MSW) (Teixeira et al., 2014). Waste is considered any substance, material, product or any good that is desired being thrown away by its holder (Touré, 2003) but has the nature of producing adverse effects on natural ecosystems (Ngnikam and Tanawa, 2006).

Sanitary landfill and incineration are practices for the treatment of MSW, they cause pollution in the air, soil and water (Ebrahimian et al., 2020). MSW has a large amount of organic fraction that can be transformed into promising sources of alternative energy (Kuznetsova et al., 2019; Nabavi-Pelesaraei et al., 2017a; Nabavi-Pelesaraei et al., 2017b; Nabavi-Pelesaraei et al., 2019). The organic fraction of municipal solid waste (OFMSW) are generally portions in significant quantities of waste with high potential to be used as a raw material for the production of biofuels, such hydrogen and methane through the fermentation process (Lavagnolo, 2018). The bioconversion of OFMSW to biofuels provides a sustainable alternative to both, minimizing the use of fossil-based fuels and sustainable MSW management strategies. However, it can be an opportunity and a challenge. Opportunity because it can positively contribute to the recovery energy potential from waste. Challenge because it can negatively impact the environment and its audience (Peng et al., 2018). Anaerobic digestion (AD) is one of the sustainable technologies that can convert organic fraction of municipal solid waste into the H_2 and biogas (Peng et al., 2018). The extraction of hydrogen from organic waste is sustainable to waste management and to take advantage to generate clean energy (Lovatel, 2016). About 96% of the H_2 produced is based on non-renewable sources, where the most used processes are the reforming of natural gas (48%) and oil (30%), followed by coal gasification (18%). Only 4% of the H_2 produced is obtained from renewable sources (Körner, 2015).

MSW management is one of the renewable forms of hydrogen production with a view to creating other alternative sources of energy, minimizing the emission of greenhouse gases emitted by the energy sector and in the management of municipal solid waste (Smith et al., 2001). They can be used to generate electricity (Guerrero et al., 2013; Ladislao and Gomez, 2010).

The increase in population contributes significantly to the increase in waste generation. In Africa, the population grew from 294 million in 1960 to 1.0 billion in 2010 and is estimated to increase to 1.4 billion in 2025 and 2.2 billion in 2050 (FAO, 2013) with Municipal solid waste generated are estimated about 125 million tonnes in Africa by 2012 and are expected to double by 2025 with inadequate collection services, only 55% (United Nations Environment Programme (UNEP, 2018). Most of the amount of waste generated in Africa is simply discarded outside, with about 47% in uncontrolled landfills (UNEP, 2018), 9% are burned in the open and 4% are only recycled and/or reused (Lavagnolo and Grossule, 2019).

In West Africa, the population makes up a total of 30% of the population of Africa it is estimated an increased from 69,564,958 in 1950 to 413,340,896 in 2021 and 0.6 billion of population in 2050 (Marcellus and Christian, 2012).

Table 1 West Africa total population estimated (million)

Year	Total		Urban (%)	Rural (%)	Urban	Rural
1980	140		26	74	36	104
1990	184		33	67	61	123
2000	238		39	61	92	146
2010	306		45	55	137	169
2020	383		51	49	195	188
2030	467		57	43	264	203
2040	550		64	36	352	198
2050	626		68	32	428	198

Source: adapted from Badu-Apraku et al (2011)

In Guinea-Bissau, MSW management constitute a serious problem for the environment and public health. The technique used to dispose MSW depend on each citizen's awareness and sensitivity towards the environment. Often the most viable solution is disposal in vacant lots, open burning, clandestine dumps (Falcão, 2022)(Falcão, 2022). The lack of awareness about waste disposal alternatives led to its open burning. On the other hand, the level of poverty and limited legislation and consequent environmental inspection (Lavagnolo and Grossule, 2019).

In Bissau, Capital of Guinea-Bissau the Municipality of Bissau (CMB-acronym in Portuguese), is responsible for the management of municipal solid waste. There is only one deposit declared by the Municipality for the deposit of any type of waste and this is located in a rural area near to Bissau. Waste management essentially consists of limiting its production and valuing the materials it contains in order to ensure its sustainable disposal, from packaging, collection, transport, disposal and final destination (GOMIS, 2018)(Falcão, 2022).

According to the National Institute of Statistics of Guinea-Bissau (INE-GB, 2009) through the last population and housing census, Bissau has a population more than 365,000 thousand inhabitants, which corresponds to approximately 25% of the national population of Guinea-Bissau.

The estimated municipal solid waste is about 316 tons daily generated with a per capita production of 0.6 kg according to studies carried out by the International Association of Lay Volunteers (LVIA, 2016) in the partnership with the Municipality of Bissau with an estimated increase to 394 tons per day by 2025, the organic fraction occupies about 37%, rest of sieve 26%, glass 9% paper/ card 8%, plastic 4%, metals 4%, inert 2%, dangerous 1%, others waste 9%. In the total solid waste generated, less than 30% is collected by the municipality and deposited in the open air landfill near to Bissau, destined for all types of municipal solid waste (LVIA, 2016). In addition to the lack of sustainable management of municipal solid waste, the country has a very low electrification rate, that is, most people do not have access to electricity, about 10% electrification rate at the national level and 20% in Bissau. The power generation installed in the Bissau is made up of a fleet of generators with a capacity of 15 MW produced through a diesel thermal power plant with an overall energy loss rate of 47% due to aging infrastructure, poor quality billing insufficient to meet the demands of 40 MW, a situation that significantly contributes to the marginalization of people (especially women), hinders the promotion of economic activities, undermines competitiveness and hinders the supply of goods and public services (PDSDE, 2018; Guinea-Bissau - Update and Extension of the Country Strategy Paper 2015-2019 to December 2021).

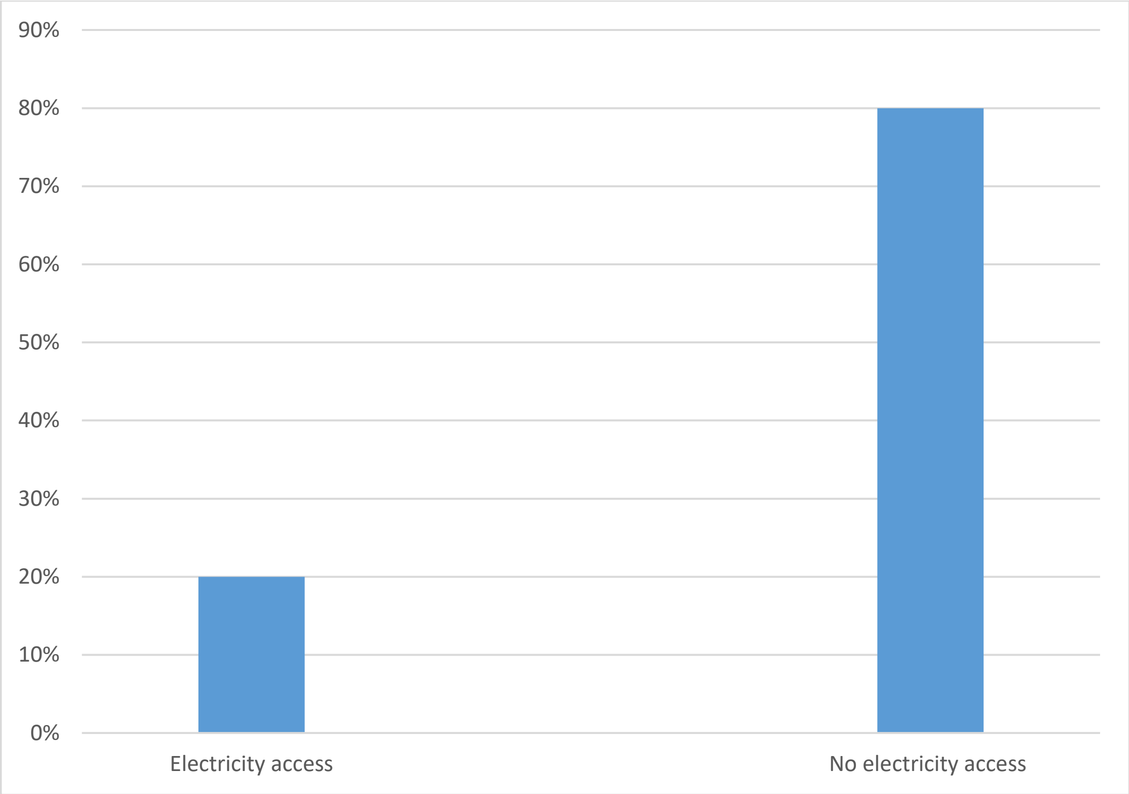

Figure 1 Access of electricity in Bissau

This work aims to model the potential of hydrogen production from the organic fraction of municipal solid waste in Bissau as a way of proposing sustainable solutions through anaerobic digestion.

This dissertation on the model the H_2 potential and production from the organic fraction of municipal solid waste intends to present the current situation of municipal solid waste in Bissau and electricity availability in Bissau, from this work to propose the valorisation of the organic fraction through anaerobic digestion to obtain electricity potential in order to minimize the mismanagement of solid waste and increase alternative sources of energy and consequent number of people with access to electricity. It is divided into 03 chapters, in chapter 01 the state of the knowledge is discussed where reference is made up of major concepts on the subject. Chapter 02 describes all the methodologies used to obtain the results. Chapter 03 reflects the great results obtained throughout the work.

1.2. Objectives

1.2.1. General objective

- Modelling the H_2 potential and production from the municipal solid waste less valorised in Bissau.

1.2.2. Specific objectives

- Know different categories of municipal solid waste daily generated in Bissau;
- Determine the amount of different fractions of municipal solid waste and the amount valorised;
- Estimate the hydrogen potential from organic fraction of municipal solid waste;
- Estimate the biogas potential from the organic fraction of municipal solid waste;
- Determine the electrical energy potential can be generated from de H_2 potential generated.
- Evaluate the economic viability of the project

Chapter II. State of Knowledge

2.1. Waste to energy as a solution for the energy recovery from municipal solid waste

The management of MSW is a challenge in obtaining other commodities, such as recyclable materials (Pereira and Lee, 2016). The decomposition of landfill waste contributes greatly to the formation of greenhouse gases (Smith et al., 2001). They can become opportunities for energy, heat, electricity and fuel (Guerrero et al., 2013; Ladislao and Gomez, 2010). Waste-to-energy (WtE) is an environmentally sustainable solution for recovering energy from waste resources (Moyaa et al., 2017). These technologies are considered biological treatment technologies and thermal treatment technologies (Korai et al., 2017). It is part of Integrated Solid Waste Management Systems not only to produce other by-products, but also to deal with global warming and climate change. It is considered that cities without an effective municipal solid waste management system are also unable to manage the most demanding services, such as electricity, health, education or transport (Moyaa et al., 2017).

2.2. Biological treatment technologies

Biological conversion involve the use of microorganisms and their enzymes to decompose the organic fraction of MSW for conversion of bio hydrogen. Biological conversion feedstock should be prepared considering organic content, dry solids, volatile solids, moisture, micronutrients and macronutrients for microorganisms without any contaminants such as pesticides, insecticides, disinfectants , antibiotics, pharmaceuticals. Biological processes have great benefits in the production of hydrogen, being a renewable alternative and using waste as substrates (Martinez-Pérez et al., 2007).

For the production of hydrogen through biological methods, there are three ways: bio photolysis, photo fermentation and anaerobic digestion. Bio photolysis occurs through solar energy and its transformation into chemical energy, followed by the decomposition of the water molecule and subsequent protonation of the H^+ ion, thus generating the hydrogen molecule (Pandey et al., 2013). Photo fermentation occurs with the help of photosynthetic bacteria, which also use light energy to produce hydrogen, but use organic acids such as butyric and acetic as substrate (Hallenbeck and Benemann, 2002). The process of anaerobic digestion, the substrate for acid genic bacteria is the carbohydrate that they convert into organic acids, CO_2 and H_2 (Loubette and Junker, 2006; Ren et al., 2009).

Bio photolysis and photo fermentation have constraints because they depend on light and have a low rate of hydrogen production. While anaerobic digestion is favourable due to its non-dependence on light energy (Chong, et al., 2012) and presents high yield compared to other methods (Das et al., 2008).

2.2.1. Anaerobic digestion process

Anaerobic digestion (AD) encompasses several biochemical reactions where organic matter with the help of bacteria are broken down through a gaseous mixture (CH_4, CO_2, H_2, H_2S, etc.) without the presence of oxygen. Anaerobic digestion is a process that takes place in a closed vessel. After the anaerobic digestion, there are always residual solids and organic matter called digestate in liquid and solid form in the container. These digestates have important nutrients that can replace the use of fertilizers in agricultural applications that favor plants (Uddin and Wright, 2021).

These, in turn, attack the structure of the complex organic compounds contained in the waste, converting it to biogas, which corresponds to a gaseous mixture consisting essentially of methane (55% to 75%) and carbon dioxide (25% to 45%), (Fernandes, 2013; Junior, 2013; Santos, 2013; Zhang et al., 2014). For biogas, its end can be for heat and electricity generation (Uddin and Wright, 2021).

Anaerobic digestion is mostly used for methane conversion. It can also be used to obtain hydrogen, for which it is necessary to take some measures to suppress the methanogenesis phase. The production of hydrogen occurs in the conversion of substrates into carboxylic acids. In anaerobic digestion, hydrogen is the co-product during the substrate conversion phase into carboxylic acids (Nissilä et al., 2011).

The biodegradation process consists of four distinct phases called: hydrolysis, acidogenesis, acetogenesis and methanogenesis, (Hagos et al., 2016; Sagula, 2012; Yu et al., 2014; Zhang et al., 2014; Steinmetz, 2016).

In the first phase, hydrolysis is the first step in the process of anaerobic digestion occurs in which macromolecules such as cellulose, starch, proteins, and lipids are broken down by fermenting bacteria into simple monomer units like glucose, fatty acids and amino acids that have greater solubility (Chiu et al., 2013; Hagos et al., 2016). This reaction takes place as follows:

$$C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2 \qquad (1)$$

In the second phase, acidogenesis, the results of the first phase reaction (hydrolysis) are decomposed by acidogenic bacteria into short-chain volatile fatty acids (VFA), such as: acetic acid, propionic acid, formic acid, acid lactic; equally converted into alcohol (ethanol, methanol), into ketones (glycerol and acetone) (Sagula, 2012; Santos, 2013) along with the generation of by-products (NH_3, CO_2 and H_2S, etc.). It is a process that must be well controlled because it occurs quickly, thus containing the risk of accumulation of VFA in the digester resulting in toxicity (Uddin and Wright, 2021). The chemical sequences that occur are as follows:

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \qquad (2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \qquad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \qquad (4)$$

In the third phase called acetogenesis, the products of acidogenesis and the fatty acid chain are hydrolyzed into acetate, CO_2 and H_2 (Santos, 2013; Zhang et al., 2014). In the acetogenesis stage, bacteria are not thermodynamically spontaneous if the H_2 partial pressure is greater than 10-4 atm. This pressure is reduced with methanogenic bacteria consuming the hydrogen produced (Uddin and Wright, 2021). The following equations illustrate the acetogenesis step:

$$CH_3CH_2COO- + 3H_2O \leftrightarrow CH_3COO- + H+HCO_3- + 3H_2 \qquad (5)$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \qquad (6)$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO- + 3H_2 + H+ \qquad (7)$$

Methanogenesis: it is the last phase of anaerobic digestion where methane production occurs through all the products of the preceding phases. At this stage, bacteria cannot survive in the presence of oxygen, which makes it extremely anaerobic.

Acetate (CH_3COOH) and hydrogen (H_2) are converted into CO_2 and CH_4 by groups of acetophilic and hydrogenophilic bacteria. Acetophilic bacteria convert acetate to CH_4 and CO_2, while hydrogenophilic bacteria convert H_2 and CO_2 to CH_4 (Uddin and Wright, 2021). The reactions in this step are as follows:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (8)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (9)$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (10)$$

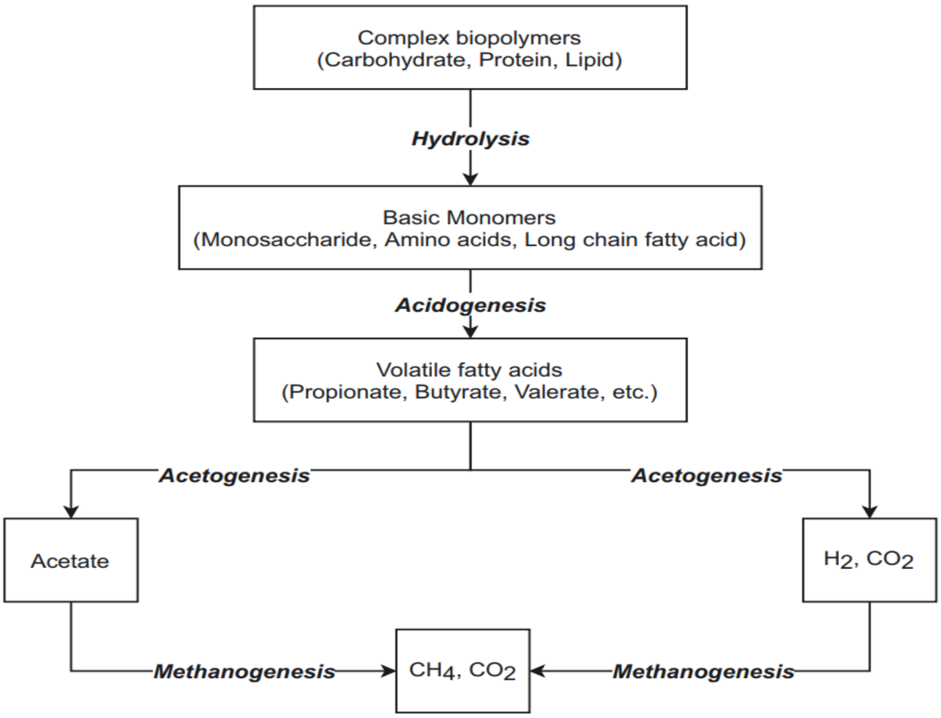

Figure 2 Anaerobic digestion (AD) of organic fraction of municipal solid waste (Source: Wright and Uddin, 2021)

On the contrary, MSW containing recalcitrant organic components (e.g. waste paper, packaging boxes and cardboard) and non-biodegradable organics (e.g. plastics, rubber, polymers and tires) are better suited for thermochemical conversion technologies (Nanda and Berruti, 2021).

There are different critical parameters that affect the operating conditions of anaerobic bacteria, among them temperature, C/N ratio, hydraulic retention time (HRT), pH, organic load rate (OLR) (Wright and Uddin, 2021).

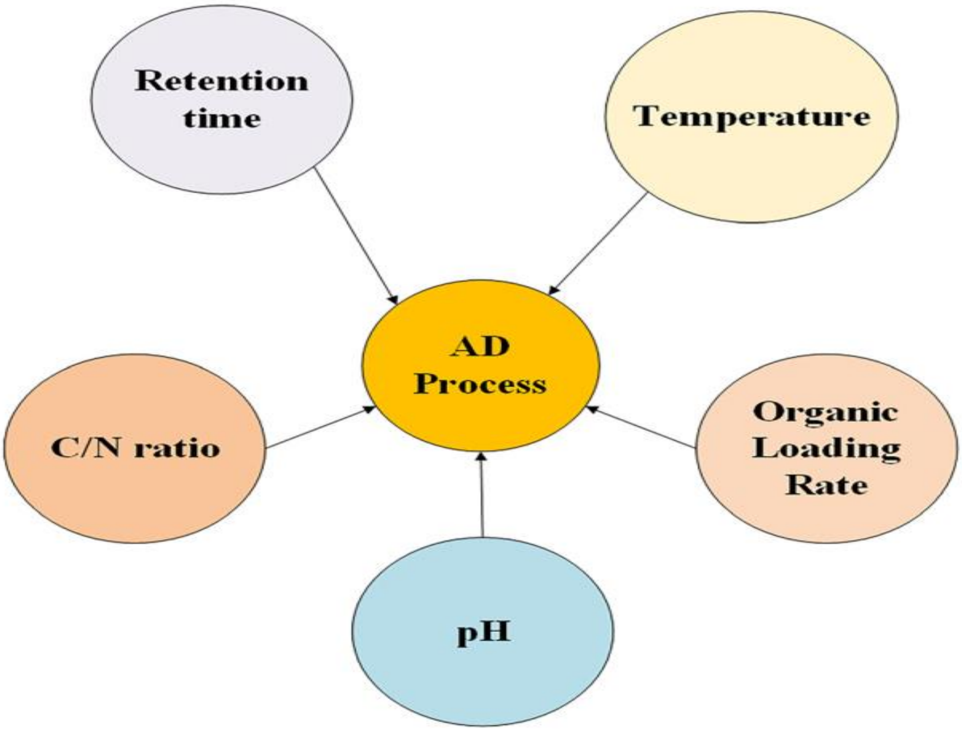

Figure 3 Anaerobic digestion process parameters

2.2.1.1. Temperature

The temperature ranges are widely accepted as the most favourable temperature for the maximum performance of anaerobic bacteria. A digestion temperature ranging from 55–60 °C is defined as thermophilic digestion. Thermophilic digestion requires additional energy (heat) input but provides a higher biogas production rate. However, the process is often unstable. A thermophilic temperature increases the feed degradation rate leading to a shorter hydraulic retention time (HRT). It also generates a high-quality digestate with fewer pathogens (Wright and Uddin, 2021). Mesophilic digestion occurs within the 35–40 °C temperature range. Most of the commercial digesters operate at the mesophilic range. Mesophilic digestion produces less biogas than thermophilic digestion (Wright and Uddin, 2021).

2.2.1.2. Carbon/ nitrogen ratio (C/N)

Carbon (C) is the necessary energy source for microorganisms, and they need a certain amount of nitrogen (N) for their metabolism. The optimal ratio between C/N ranges from 20 to 30 in most cases. Less than this means that there is a high concentration of N that turns into excess ammonia. Excess ammonia produces higher digester alkalinity and inhibits the digestion process, resulting in lower biogas yield (Wright and Uddin, 2021). On the other hand, a high C/N ratio means a deficiency of N in the substrate. Microorganisms will consume the N and there will not be enough to their metabolism (Wright and Uddin, 2021).

2.2.1.3. Hydraulic Retention Time (HRT)

HRT is the average time the substrate resides in the digester. It is recommended that the substrate remain long enough to ensure maximum conversion of organic materials into biogas (Wright and Uddin, 2021).

2.2.1.4. pH

The pH is the concentration of H_2 (hydrogen) in a solution. Most organisms function at neutral pH. Methanogens perform best at pH around seven. Hydrolytic bacteria perform best with pH between 5.5 and 6.5. For acidogenic bacteria, the higher pH ranges are more tolerant. It is a challenge to maintain the ideal pH for all microorganisms in the same digester (Wright and Uddin, 2021).

2.3. Hydrogen: production and application

Hydrogen is the chemical element with a single proton, an electron and no neutron considered the lightest chemical. In molecular form it will present as diatomic gas (Cruz, 2010). It is a gas with the highest amount of energy per unit mass compared to any other substance. Its main advantages are the fact that it has a high mass density compared to other fuels, it is non-toxic (Wang et al., 2016).

The development of other alternative sources of energy is extremely important to reduce the use of fossil fuels, H_2 is an ideal fuel gas because it is not polluting and therefore serves to minimize greenhouse gas (GHG) emissions (Wang et al., 2016). During its combustion, the only residue generated is water, which is why it is considered clean energy. Its energy content is approximately 3 times greater than that of fossil fuels derived from petroleum, it contains a calorific value of 122 kJ/g at 25°C and 1 atm (Kadpan and Kargi, 2006) methane with 55.5 kJ/g, gasoline with 48 kJ/g and diesel with 45 kJ/g (Abe et al., 2019), whose density of hydrogen gas is extremely low: 0.09 kg/m^3 (Kadpan and Kargi, 2006).

H_2 needs to be extracted from other components, either from non-renewable sources through the reform of natural gas, methane, although it has negative consequences for the environment since it contributes significantly to production of greenhouse gases (Jong, 2009).

Hydrogen can be obtained from water electrolysis, petroleum reform, biomass gasification and by biological methods (Parizzi, 2008). The extraction of hydrogen by biological methods through anaerobic digestion of organic waste is sustainable in nature and generates clean energy (Lovatel, 2016). Anaerobic digestion is a viable alternative, as it converts organic waste even with liquid content to hydrogen (Han et al., 2016), it does not require a high amount of energy to obtain the final products (Lovatel, 2016).

2.4. Fuel cells

Hydrogen is a versatile energy carrier that serves to supply energy demands. It could play a particularly important role in the future, replacing imported fuels and petroleum products. The fuel cell is an energy conversion device that can efficiently capture and use hydrogen energy. (Department of Energy EERE, 2010). Fuel cells it is one of the engine used to produce energy using hydrogen and oxygen as inputs for the conversion of chemical energy into electricity through electrochemical reactions with water and heat as by-products (Revankar and Majumdar, 2014; Saikia et al 2018). Fuel cells are considered different from batteries since they need a continuous source of fuel and oxygen to sustain the reaction, while batteries do not, for batteries the chemical energy comes from metals and their ions (Khurmi, 2014). Fuel cells continuously produce electricity as long as fuel is supplied along with oxygen (Ajanovic and Hass, 2018; Hames et al., 2018). The electrochemical half reaction and overall that represents the indirect combustion of hydrogen in fuel cell are:

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (11)

Cathode reaction: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (12)

Overall raction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (13)

2.4.1. Why Fuel Cells?

Fuel cells are pollution-free, but they can also be more than twice as efficient as traditional combustion technologies. A power plant based on conventional combustion normally generates electricity with efficiencies of 33-35%, while fuel cell systems can generate electricity with efficiencies of up to 60%. The gasoline engine in a conventional car is less than 20% efficient at converting the chemical energy of gasoline (Department of Energy EERE, 2010).

2.4.2. Working Principle

There are different types of fuel cells, all of them are composed of anode, cathode and electrolyte which facilitates positively charged hydrogen ions to move to both sides. At the anode, there is always a catalyst with the function of helping the fuels in the oxidation reactions that generate positively charged hydrogen ions and negatively charged electrons gasoline (Department of Energy EERE, 2010).

In fuel cells, fuel undergoes an electrochemical oxidation reaction and is transformed into a hydrogen ion or proton by releasing electrons at the anode. Charged ions or protons are transported through the ion-conducting but electronically insulating electrolytic material from the anode side to the cathode side (Revankar and Majumdar, 2014).

At the cathode, oxygen undergoes an electrochemical reduction reaction combining with incoming protons and electrons, producing water. Electrons flow through the electrically conductive electrodes and external load circuit, resulting in electricity and doing electrical work. The two electrochemical half-reactions and the general reactions that represent the indirect combustions of hydrogen in the fuel cell (Revankar and Majumdar, 2014). In addition to electricity, fuel cells produce water, heat, and, depending on the fuel source, very small amounts of nitrogen dioxide and other emissions. The energy efficiency of a fuel cell is generally between 40 and 60% (Department of Energy EERE, 2010).

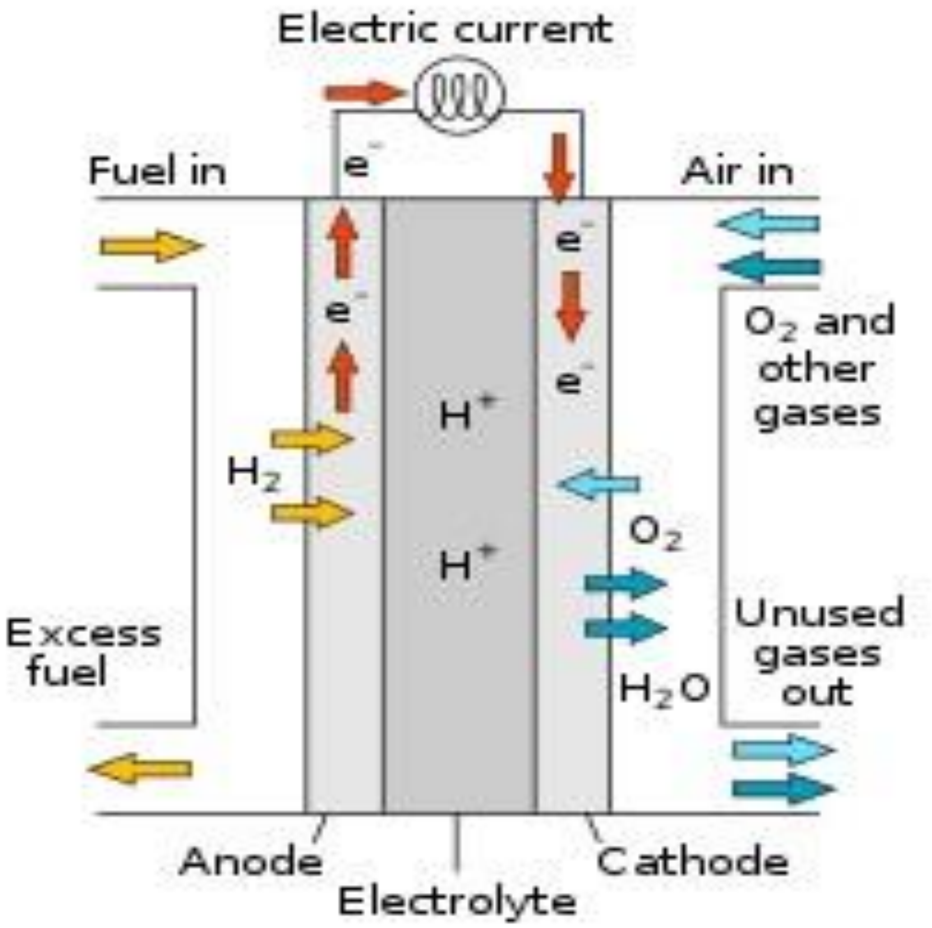

Figure 4 Working principle of fuel cells (Source: Ota, 2014)

2.4.3. Different types of fuel cells

Table 2 Different types of fuel cells

Fuel Cell	Efficiency	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	• 60% transportation • 35%stationary	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	• 60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO 2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	• 40%	• Distributed generation	• Higher temperature • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	• 45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	• 60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

The methodology applied for the present work is essentially based on the application of mathematical formulas to obtain the potential of hydrogen, biogas, the potential for production of electrical energy and greenhouse gases that can be minimized with the valorisation of the organic fraction of municipal solid waste in the city of Bissau in light of work already carried out by other authors. The municipal solid waste data obtained was through a study carried out by LVIA in 2016 in partnership with the municipal council of Bissau It should be noted that among all the possible methods, this was considered the most appropriate for obtaining the desired results due to the scarcity of data on waste generation in the city of Bissau. The following chapter is the methodology that describes how the results were obtained.

Chapter III. Material and methods

3.1. Description of study area

The study area for the present work is the city of Bissau, Capital of Guinea-Bissau. Bissau is a Capital and largest city of Republic of Guinea-Bissau with a surface area of 77 km^2 having the population of 364,000 inhabitants comprises 25.19% of the total population of the country. It is located on the estuary of the River Geba, on the Atlantic coast (INE-GB, 2009). In (2015) population was 492.004 of people (LVIA, 2016).

Figure 5 Study area, Bissau

Source: http://www.ezilon.com/maps/africa/guinea-bissau-maps.html

3.2. Data collection

To carry out this work, data were collected through available national data and secondary data. National data includes those from the National Statistics Institute of Guinea-Bissau (INE-GB), studies carried out by the Association of Lay Catholics (LVIA, 2016) in partnership with the Bissau city council. In addition to national data, it was also collected through other academic work carried out.

The main purpose of data from academic work is to find different formulas that allow all the necessary calculations to be made to obtain the necessary potential. Calculations were made using Excel.

In addition to obtaining the formulas, academic work was essential to understand the situation of municipal solid waste management in Bissau, from its packaging to its final destination.

The academic works were obtained through online research on Google Scholar, articles published in different newspapers whose priority time frame is in the last 5 years.

Online searches were most often conditioned using key search words such as: "solid waste management, anaerobic digestion, potential for hydrogen production, city of Bissau, urban solid waste, etc.

In case of difficulty in obtaining data based on recent articles, some articles that were more than 5 years old were used.

As a result, which allowed, through anaerobic digestion, to determine the potential of hydrogen and biogas in Bissau and power generation capacity. The environmental assessment was also taken into account to minimize the emission of greenhouse gases (GHG) through waste in garbage per ton to allow estimating the GHG emitted by waste produced in Bissau and what amount can be minimized with the valorisation of the organic fraction of urban solid waste in Bissau.

During data collection, several limitations were encountered, the work carried out in this domain in the study area is limited, which makes it difficult to obtain data.

3.3. Data analysis

After data collection, they were analysed with the purpose of responding to the previously proposed objectives in the study area, in this particular case the city of Bissau.

3.3.1. Properties of the municipal solid waste

The properties of municipal solid waste in Bissau were obtained through studies carried out by International Association of Lay Volunteers (LVIA, 2016) in partnership with the municipality of Bissau, where the compositions of municipal solid waste, the amount daily generated, per capita generation and the fraction occupied by organic waste in the total waste were described.

3.3.2. **Management of municipal solid waste in Bissau**

In Bissau, the Municipality of Bissau is responsible for the management of municipal solid waste generated, whose collection services are generally limited to the main blocks or districts of the city centre. There is only one deposit declared by the Municipality for the deposit of any type of waste and this is located in a rural area close to the capital (Franco, 2022). There are two main stages of urban solid waste collection, the first is the door-to-door collection from different dwellings to informal deposit points on the main roads, which is carried out directly by residents or by local community organizations. The second collection is carried out periodically by the Municipality from informal deposit points to the landfill (Marcellus and Christian, 2012). In the dump, there are men, women and even children to take advantage of the recyclable waste, all of them being exposed to serious health risks, because of the burning of waste, contact with hazardous and biomedical waste, infections, so on (Marcellus and Christian, 2012).

Most urban areas in Bissau have a high population density, lack of urbanization and difficult access due to poor road conditions and especially in the rainy season. The reason why the Bissau city council's collection services are centred on the main streets, leaving the first collection at the initiative of the residents and local associations (Marcellus and Christian, 2012).

Figure 6 Safim garbage dump (Source: Bissau, online 2021)

Waste used

The used waste contributes to reducing the amount that goes to the landfill, on the other hand, minimizing the pressure on natural resources for the manufacture of other materials and consequent reduction of adverse environmental effects. There is no adequate management system for municipal solid waste in Bissau (Franco 2022). Still according to Franco (2022), different types of solid waste are valorised through the following techniques:

Plastic and glass waste

Plastic and glass waste are highly valued by the population. They are used as storage containers for products such as: palm oil, olive oil, lemon juice, among other products that can be divided into small volumes and sold. These types of garbage can be purchased from garbage collectors or even purchased in nearby bars. It is very common to use plastic bottles for water storage due to scarcity. These containers are still used to store some traditional Guinea-Bissau drinks, for example cashew wine (Franco, 2022).

Metal waste

Metallic waste, namely soda and beer cans, are used to make pots and some kitchen utensils by melting at high temperatures, they are also melted to form a pot, it is also possible to make stoves, dustpans, suitcases and other frequently used objects from ferrous waste. These are the most used recycling techniques for this type of metal (Franco, 2022).

Waste of paper

Paper and cardboard are used to protect reused bottles, smoke fish, and light firewood and charcoal, they are also used as a shelter to sleep (Franco, 2022).

Organic waste

Organic waste serves as food for some domestic animals, fuel for coal, serves to make traditional brooms, even with this use, the amount of organic waste valued is very insignificant (Franco, 2022).

Determination of the amount of waste generated in Bissau

The total of municipal solid waste was obtained from the daily total of solid waste identified by LVIA, (2016). The daily total of municipal solid waste which allowed the determination of the annual amount of municipal solid waste through the following mathematical expressions:

$$MSW = Daily * 365 \qquad (14)$$

Where: MSW is annual municipal solid waste generated in tons; daily is the amount of municipal solid waste generated per day; 365 is the number of day per year;

Amount of organic fraction of municipal solid waste (OFMSW)

The organic fraction of municipal solid waste (OFMSW) according to LVIA, (2016) represents 37% of total urban solid waste. Based on the previous formula, it was possible to determine the annual total of the organic fraction of municipal solid waste in ton through the following mathematical expression:

$$OFMSW = MSW * 0.37 \qquad (15)$$

Where: OFMSW is organic fraction of municipal solid waste in ton; MSW is total municipal solid waste; 0.37 percentage of organic fraction of municipal solid waste in decimal form;

3.3.3. Hydrogen potential from organic fraction of Municipal solid waste

Kapdan and Kargi, (2006) considered that organic waste contains a high content of carbohydrates that serve as important raw materials for the production of hydrogen from biological methods. For Valdez-Vazquez et al., (2009) the hydrogen potential can be obtained through different ways, in the case of hydrogen potential from organic waste, the yield must first be determined through the following mathematical expression:

$$HY = 0.316\ Sc^{-0.44} \qquad (16)$$

Where: HY is hydrogen Yield (m^3/ year); *Sc* = concentration of fraction of organic waste as substrate (g/ year).

From the hydrogen yield according to the Valdez-Vazquez et al., (2009), the hydrogen potential is calculated through the following:

$$AHP = MSW * \delta_{OFMSW} * \delta_{TS} * \delta_{VS} * HY \qquad (17)$$

Where: AHP is annual hydrogen potential (m^3/year); MSW is the municipal solid wastes (kg/year); δ_{OFMSW} is the percentage of organic fraction of municipal solid waste in decimal form; δ_{TS} is the percentage of total solids in decimal; δ_{VS} is the percentage of volatile solids in decimal form; HY is hydrogen yield (m^3/year).

According to Reinhart, (2004) the total solid waste corresponds to 30% and volatile solids with approximately 27.5%.

Estimation of power generation potential of hydrogen

The generation of electricity is one of the many ways in which hydrogen can be harnessed (Sarrias-Mena, 2015). The potential electricity generated from hydrogen gas is expressed in kWh. According to Afi Seglah et al, (2023), the estimate of electricity generation from hydrogen gas can be obtained from the following mathematical expression:

$$H_{2PG} = \omega \times H_{2LHV} \times Den_{H2} \times H_{2QTY} \qquad (18)$$

Where: H_{2PG} is power generation from hydrogen gas; ω is fuel cells efficiency (60%); H_{2LHV} is lower heating value of hydrogen that correspond 33.3 kWh/kg (Platzer and Sarigul-Klijn, 2021); Den_{H2} is hydrogen density that correspond 0.09 Kg/m^3 (Ayodele et al, 2019); H_{2QTY} is the hydrogen gas quantity.

3.3.4. Biogas production potential

The production of biogas from organic waste through anaerobic digestion is essentially methane with 53% and carbon dioxide with 47%. And electricity generation relies mostly on methane from organic waste to feed the digester. Therefore, methane is determined using the Bushwell equation (Amoo and Fagbenle, 2013; Ogunjuyigbe et al., 2017).

$$C_cH_hO_oN_nS_s + 1/4(4c - h - 2o + 3n + 2s)H_2O \rightarrow 1/8(4c - h + 2o + 3n + 2s)CO_2 + 1/8(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S \qquad (19)$$

Table 3 Ultimate analysis of MSW

Chemical element	C	H_2	O_2	N	S
Ultimate value	450	2050	950	12	01
Molar mass (M)	12	01	16	14	32
Partial Total	5400	2050	15200	168	32
Total Ultimate value	22850				

Source: adapted from Cudjoe et al, (2020)

The amount of carbon in organic waste

% of Carbon= Ultimate Value of Carbon/ Total Ultimate Value

Mass of methane that can be produced from the digester can be estimated as (Ogunjuyigbe et al., 2017):

CH_4 (Kg)= [π_{3*} 16/ (Mol_c*t) + (Mol_H* r) + (Mol_O*m +Mol_N)] * 1000 (20)

The total solid of OFMSW is 30%, moisture content is 70%

Volume of methane (m^3/ton) can be determined as:

$CH_{4(V)}$ = CH_4 (kg)/ 0.717 (Kg/m^3) (21)

Where 0.717(kg/m^3) is the density of methane; CH4 (v) is the volume of methane (Ogunjuyigbe et al., 2017).

Power generation potential from biogas

According to Ayodele et al., (2018) the electricity potential is determined through the methane produced in the digesters with the following mathematical expression.

PG (kWh) = V_B (m^3) × CP (kWh/m^3) (22)

Where is PG (kWh) power generation of biogas expressed in kWh; CP (kWh/m^3) calorific power of biogas is 6.9 kWh/m^3.

3.3.5. Determination of greenhouse gases can be avoided

GHG emission in MSW of city with a net contribution 781.05 Kg CO_2-eq. per tonne of landfill (Verma and Borongam, 2022), if organic waste is valued through the production of hydrogen, the amount of greenhouse gases will be reduced through the amount that goes to landfill.

Based on this, the amount of GHG emitted per total of municipal solid waste produced in Bissau was determined the following mathematical expression:

$$GHG\ (Kg\ CO_2\ eq) = MSW * 781.05 \quad (23)$$

Where: GHG (Kg CO_2 eq) is greenhouse gases to Kg of CO_2 equivalent; MSW is total annual of municipal solid waste (tonne/ year).

Then, the total amount that can be avoided with the valorisation of the organic fraction of municipal solid waste (OFMSW) was determined through the following mathematical expression:

$$GHG\ (Kg\ CO_2\ eq) = OFMSW * 781.05 \quad (24)$$

Where OFMSW is organic fraction of municipal solid waste.

3.4. Economic analysis

To carry out the economic feasibility study, the cost-benefit analysis must be taken into account, which is essentially based on the following parameters: net present value (NPV), internal interest rate (IRR), benefit cost ratio (B/C) and payback period (PP). This techno-economic analysis is based on bibliographic sources and assumptions were also made.

Total capital cost (TCC)

For total capital costs, two categories were considered, fixed capital investment (FCI) and Working Capital cost (WCC). The FCI can be divided into equipment, whether direct or indirect costs. All estimates were made in the CFA currency as it is the currency used in the country, in this case Guinea-Bissau.

$$TCC = FCI + WCC \quad (25)$$

Where: TCC is the total capital cost; WCC is working capital cost that it is estimated 6.1% of the total fixed cost (Lam et al., 2014).

Operational cost (OC)

According to Yun et al., (2018) the operating cost is estimated to be 25% of the capital cost. The cost of maintenance is 6% of the FCI (Peters et al., 2003). To Kannah et al., (2021) around 50% goes to administrative costs including salaries, insurance, and other fees. The inflation rate was also taken into consideration to determine the operating cost throughout the life cycle, which is approximately 7.80% (CIA World 2020).

Cost during the project lifetime

The project life cycle was estimated for a period of 20 years. The discount rate in Guinea Bissau according to CIA World (2020) is 4.25.

$PV= \sum Ct/ (1+i)^t$ (26)

Benefit

The benefit is derived from biogas.

Biogas selling

The sales price was possible to calculate according to the biogas potential estimate previously determined.

LCOH (livelized cost of biogas) = discounted CO/ quantity of biogas produced (over lifetime of the project)

Biogas selling tariff

Selling tariff= LCOH + profit margin (27)

The profit margin was assumed and added to the LCOH in order to obtain the selling tariff.

Net present value (NPV)

$NPV= \sum C_t/ (1+i)^t - \sum B_t/ (1+i)^t$ (28)

Where: I is the discount rate; t is the number of years

The revenue estimate was based on the 20-year lifetime of the project.

Internal rate of return (IRR)

The internal rate of return serves to determine the economic viability of the project.

Benefit cost ratio (B/ C)

This is considered an important indicator to determine the profitability of a given project, the following conditions are taken into account:~

B/C >1-> the project can be implemented and there is profit

B/C<1-> is not economically profitable

BCR= disc cash in flow/ disc cash out flow

Payback period (PP)

The implementation of a project requires a loan, therefore it is necessary to estimate the year the owner needs to settle the debt.

PP= initial investment/ ave annual castflow

Where: Initial investment- TCI plus the operational cost in year in zero; Cashflow- the difference between the discounted benefit and cost. These indicators greatly facilitate decision-making.

Chapter IV. Results and discussion

Results and discussion

The results and discussion section necessarily involves presenting the calculations made up to determine the amount of organic fraction of municipal solid waste produced in the city of Bissau, the potential of hydrogen, and the potential of biogas, techno economic analysis. Power generation can be obtained from hydrogen gas and from biogas, greenhouse gases can also be minimized by valuing the organic fraction of municipal solid waste as well.

4.1. Amount of organic fraction of municipal solid waste

According to studies carried out by the International Association of Lay Volunteers (LVIA, 2016) in partnership with the Municipality of Bissau, in Bissau about 316 tons of municipal solid waste generated daily with a per capita production of 0.6 kg MSW/inhabitant day, with an estimated increase to 394 tons per day by 2025. The waste generated in Bissau are different categories: organic waste 37%, paper 8%, plastic waste 4%, metals 4%, hazardous waste 1% rest of sieve 26%, inert 2%, others 9% and less than 30% are collected by Municipality of Bissau and 70% follow an uncertain destination.

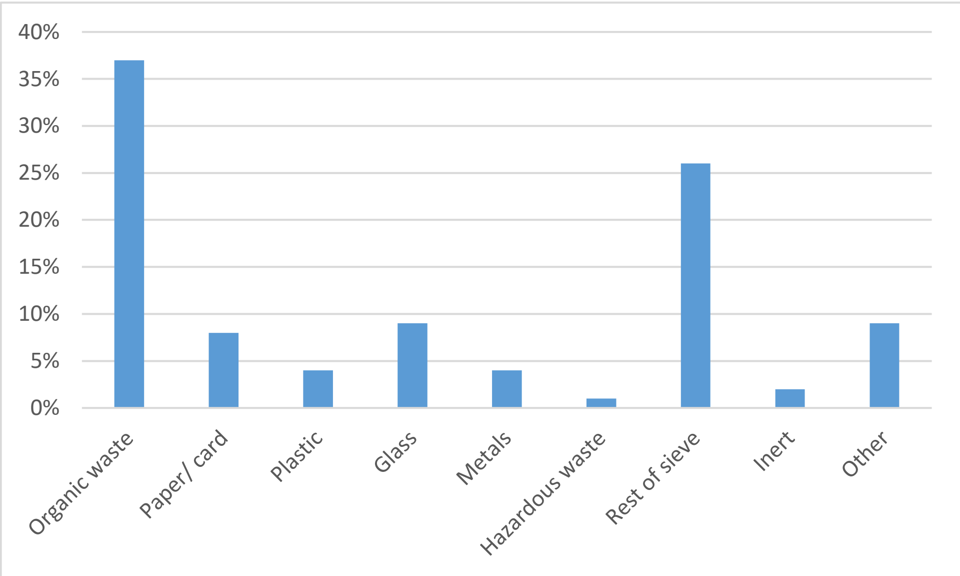

Figure 7 Waste composition in Bissau

Source: adapted from LVIA, 2016

4.2. Waste used in Bissau

In the total of municipal solid waste produced, there are some that are used for different purposes, so that most of the waste used constitute the metal fraction and the least used are organic waste.

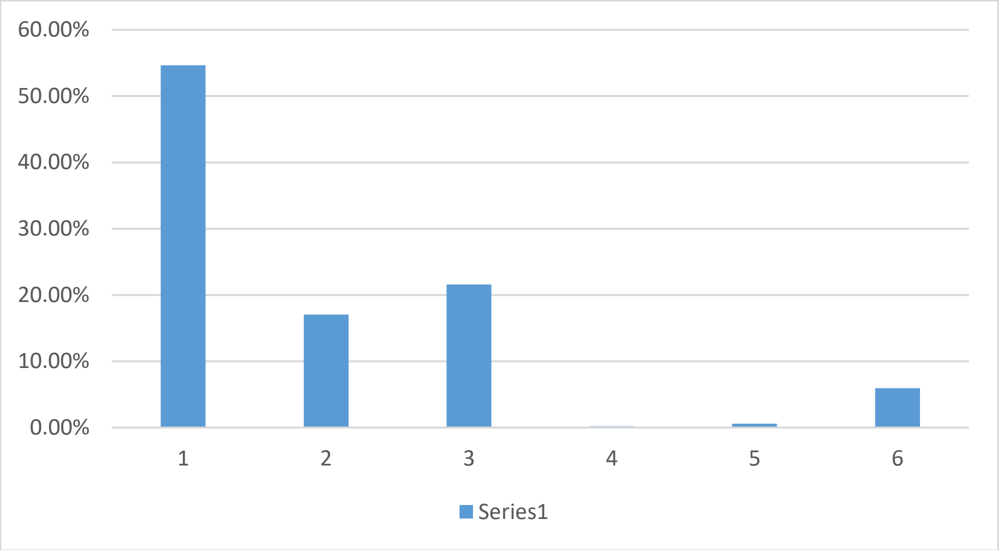

Figure 8 Waste used in Bissau

Source: adapted from LVIA, 2016

4.3. Hydrogen potential

The hydrogen potential is obtained through the anaerobic digestion of organic fraction of municipal solid waste. Where the yield of hydrogen is first determined and with that, it allowed to determine its annual potential as follows.

Table 4 Components to determine the hydrogen potential

Components	Unit	Percentage
MSW	kg/ year	
OFMSW	δ	0.37
TS	δ	0.3
VS	δ	0.27
HY	m^3/year	

Where: MSW- municipal solid waste; OFMSW- organic fraction of municipal solid waste; TS- total solid: VS- volatile solid; HY- hydrogen yield; δ is the decimal form;

The total municipal solid waste was estimated based on the daily total generated by tons, which is 316 tons and converted into kilograms, with organic waste accounting for 37%. The yield of hydrogen is obtained through the organic fraction as a substrate obtained in grams and converted into m^3 raised to the exponent (-0.44) multiplied with 0.316 of the formula.

Table 5 Annual hydrogen potential (AHP)

MSW (kg/year)	δ_{OMSW}	δ_{TS}	δ_{VS}	HY	HP(m^3/ year)
$11534*10^4$	0.37	0.3	0.275	0.0029	10210.41

The table represents the hydrogen potential in m^3 obtained per year estimation of hydrogen as a function of total municipal solid waste and the rate of production of the organic fraction of municipal solid waste. The annual hydrogen potential can be estimated in daily terms by dividing by 365 (number of days per year), the daily estimate would be 27.97 m^3/ day.

4.3.1. **Estimation of power generation from hydrogen**

The electrical energy potential of 1 kg of hydrogen is taken into account, which is 33.3 kWh of electricity that can be generated. The total amount of hydrogen obtained from the organic fraction of municipal solid waste is 2.29 Kg and considering the efficiency of the fuel cell, which is 60%, the total amount of electricity that can be obtained is 45.8 Kwh.

Table 6 Power generation potential

Den_{H2} (Kg/m^3)	H_{2QTY} (Kg)	Electricity (Kwh)	Fuel cell efficiency (ω)	H_{2PG} (Kwh)
0.09	2.29	76.38	0.6	45.8

The annual hydrogen potential obtained is converted into a daily estimate. Thus, based on the daily estimate of hydrogen potential, it is converted from liquid form (m^3) to gas (Kg) through its density. The potential electricity generated from hydrogen gas is expressed in kWh.

4.4. GHG emission can be reduced from municipal solid waste

Greenhouse gases emitted by municipal waste soils when deposited in landfills.

Table 7 GHG from Municipal Solid Waste

GHG (Kg CO_2-eq/ ton of MSW)	MSW in Bissau (ton/ year)	GHG (Kg CO_2 eq)
781.05	115340	90086307

The table represents the amount of greenhouse gases emitted through municipal solid waste in landfills. 1 ton of municipal solid waste is capable of emitting 781.05 Kg of CO_2-eq. Therefore, in the city of Bissau a total municipal solid waste produced are 115340 ton/ year, which corresponds to about 90086307 Kg of CO_2-eq.

4.4.1. Greenhouse gases emitted by organic waste in Bissau

Greenhouse gases emitted by organic fraction of municipal solid waste soils when deposited in landfills.

Table 8 GHG from organic fraction of MSW

GHG (Kg CO_2-eq/ ton of MSW)	O_{MSW} in Bissau (ton/ year)	GHG (Kg CO_2 eq)
781.05	4613.6	3603452.28

The table shows the amount of greenhouse gases capable of preventing their emission by valuing the organic fraction of urban solid waste.

4.5. Biogas potential from Organic fraction in Bissau

The potential of biogas is obtained through the potential of the organic fraction of municipal solid waste of Bissau through anaerobic digestion.

Of the total municipal solid waste produced, only 30% is total solid with the potential to produce biogas and 70% is moisture content.

Table 9 Organic fraction for the biogas potential

OFMSW (Kg/ year)	TS (%)	Total (Kg)
42675800	0.3	12802740

The table shows that in the total organic fraction of solid organic waste produced annually in Bissau, the amount of 30% corresponding to the total solid with potential for biogas production was determined.

Table 10 % of carbon in organic waste

Ultimate value of carbon	5400
Total ultimate value	22850
% of Carbon	0.236323851

The table reflects the percentage of carbon in urban solid organic waste.

Table 11 Amount of carbon in waste

% of Carbon	0.236323851
Total solid	12802740
Amount of carbon in waste	3025592.823

The table serves to determine the amount of carbon existing in solid urban waste according to Bissau's potential for generating the organic fraction of solid urban waste.

Table 12 The 70% of carbon useful to biogas potential

Amount of carbon in waste	% of carbon useful	Total
3025592.823	0.7	2117914.976

The table determines that in the total amount of existing carbon, only 70% are useful for biogas production.

Table 13 Weight of CH_4-C

Amount of useful carbon	2117914.976
CH_4 (%)	0.53
Total (Kg)	1122494.937

In this table, the amount of CH_4-C was determined.

Table 14 Weight of CH_4

Weight of CH_4-C	1,122,494.937
Molar mass (CH_4)	16
Molar mass (C)	12
Total (Kg)	1,496,659.916

The potential of the biogas in Kg.

Table 15 Biogas potential in m^3

m^3/ year	m^3/ day
2095323.883	5740.61338

This table shows that the amount of biogas obtained per kg is converted into m^3 per year and the daily amount estimated

4.5.1. Estimation of power generation from biogas

Table 16 Power generation potential from biogas

Calorific power (Kwh/m^3)	V (m^3)	Electricity (Kwh)
6.9	5740.61	39,610.2

The table reflects the potential to produce electricity through biogas in Bissau

4.6. Economic analysis

The assessment of the economic viability of a project is based on cost-benefit analysis.

4.6.1. Total capital cost

The total cost of capital is divided into investment in fixed capital (direct and indirect) and working capital. The cost of capital, investment in fixed capital and working capital were 671,538662.67 CFA, 583,092,410.98 CFA and 35,568,637.07 CFA. When we consider bank loan inflation of 7.80%, which is used to make the cost projection. And the specifications can be found in the table below:

Table 17 Total capital cost

	Direct cost	Percentage of TCC	Cost
Fixed capital investment	Purchased equipment installed	30%	186,884,600.00 CFA
	Instrumentation and control installed	7%	47,007,706.39 CFA
	Piping installed	6%	40,292,319.76 CFA
	Buildings (including services)	5%	33,576,933.13 CFA
	Yard improvement	2%	13,430,773.25 CFA
	Indirect cost		
	Service facilities installed	12%	80,584,639.52 CFA
	Engineering and Supervision	7%	47,007,706.39 CFA
	Construction	8%	53,723,093.01 CFA
	Legal and Contractor fees	4%	26,861,546.51 CFA
	Project contingencies	8%	53,723,093.01 CFA

FCI		89%	583,092,410.98 CFA
Electricity generation			52,877,614.63 CFA
Working capital cost			35,568,637.07 CFA
Total capital cost	FCI+WC		671,538,662.67 CFA

The production of biogas through anaerobic digestion involves costs associated with direct operation, such as purchased equipment, building and yard. and this cost is not directly related to the daily operation of the facility, such as engineering and supervisory services. All the costs were defined based on the percentage of the total capital cost. The total cost was estimated based on the amount of potential biogas coming from the organic fraction of urban solid waste generated daily in Bissau. It is important to highlight that the costs were obtained based on assumptions.

4.6.2. Purchased equipment

The equipment was defined in accordance with the previous flowchart and the costs were estimated jointly in CFA.

Table 18 Purchased equipment to set up the facility

Equipment	**FCFA**
Preatreatment system	186,884,600.00 CFA
Biodugestor system	
Purification system	
electricity production system	

The purchased equipment was defined as a factor of 30% of total cost.

4.6.3. Operation cost (OC)

The operational cost for the first year of the project was estimated taking into the consideration the rate of inflation and lifetime of the project that is 20 years.

Table 19 Operational of the project

	Fixed costs	Description	Factor	Cost
Operational cost	Overhead facility	Insurance, taxes, adm salaries	51%*(FCI+LC)	38,796,846.76 CFA
	Maintenance and repairs		7% of FCI	40,816,468.77 CFA
	Labor cost	1 engineer, 4 operators	21% of OC	35,255,779.79 CFA
	Variable costs			
	Utilities	Water, electricity, inoculum		37,905,950.43 CFA
	Laboratory charges		9% of OC	15,109,619.91 CFA
Total				167,884,665.67 CFA

The annual production cost was estimated to be 25% of the total capital cost. Annual indirect cost are around 23% of the operational cost, this cost arbitrates administrative issues (Peters, 2003).

4.6.4. Costs and benefits

Lifetime cost of the project

The discount rate is around 4.45%, with the life time estimated for 20 years.

Table 20 Life time of the project

	Year	Costs	Present Value
Discounted total cost	0	839,423,328.34 CFA	839,423,328.34 CFA
	1	216,548,306.66 CFA	207,720,198.23 CFA
	2	230,664,720.89 CFA	212,240,885.52 CFA
	3	245,882,215.42 CFA	217,019,583.96 CFA
	4	262,286,674.54 CFA	222,060,836.90 CFA
	5	279,970,681.46 CFA	227,369,515.40 CFA
	6	299,034,040.92 CFA	232,950,822.25 CFA
	7	319,584,342.42 CFA	238,810,296.60 CFA
	8	341,737,567.44 CFA	244,953,818.85 CFA
	9	365,618,744.01 CFA	251,387,616.11 CFA
	10	391,362,652.35 CFA	258,118,267.96 CFA
	11	419,114,585.54 CFA	265,152,712.82 CFA
	12	449,031,169.52 CFA	272,498,254.59 CFA
	13	481,281,247.05 CFA	280,162,569.90 CFA
	14	516,046,830.63 CFA	288,153,715.67 CFA
	15	553,524,129.73 CFA	296,480,137.30 CFA
	16	593,924,658.16 CFA	305,150,677.18 CFA
	17	637,476,427.80 CFA	314,174,583.75 CFA
	18	684,425,235.48 CFA	323,561,521.11 CFA
	19	735,036,050.16 CFA	333,321,579.01 CFA
Total			5,830,710,921.46 CFA
Average			283,868,161.54 CFA

4.6.5. **Lifetime benefits of the project**

Biogas selling

The revenue obtained from the biogas selling throughout the project lifetime is expressed below, where the total amount of biogas produced yearly was multiplied by selling tariff

Table 21 Benefits of the project

	Year	Revenue	Present value	
Discounted total revenue	0	6,115,410,921.46 CFA	6,115,410,921.46 CFA	5,275,987,593.12 CFA
	1	6,115,410,921.46 CFA	5,866,101,603.32 CFA	5,658,381,405.08 CFA
	2	6,115,410,921.46 CFA	5,626,955,974.40 CFA	5,414,715,088.89 CFA
	3	6,115,410,921.46 CFA	5,397,559,687.68 CFA	5,180,540,103.72 CFA
	4	6,115,410,921.46 CFA	5,177,515,287.94 CFA	4,955,454,451.04 CFA
	5	6,115,410,921.46 CFA	4,966,441,523.20 CFA	4,739,072,007.80 CFA
	6	6,115,410,921.46 CFA	4,763,972,684.13 CFA	4,531,021,861.87 CFA
	7	6,115,410,921.46 CFA	4,569,757,970.39 CFA	4,330,947,673.79 CFA
	8	6,115,410,921.46 CFA	4,383,460,882.87 CFA	4,138,507,064.01 CFA
	9	6,115,410,921.46 CFA	4,204,758,640.64 CFA	3,953,371,024.53 CFA
	10	6,115,410,921.46 CFA	4,033,341,621.72 CFA	3,775,223,353.76 CFA
	11	6,115,410,921.46 CFA	3,868,912,826.59 CFA	3,603,760,113.77 CFA
	12	6,115,410,921.46 CFA	3,711,187,363.63 CFA	3,438,689,109.04 CFA
	13	6,115,410,921.46 CFA	3,559,891,955.52 CFA	3,279,729,385.62 CFA
	14	6,115,410,921.46 CFA	3,414,764,465.73 CFA	3,126,610,750.05 CFA
	15	6,115,410,921.46 CFA	3,275,553,444.34 CFA	2,979,073,307.04 CFA
	16	6,115,410,921.46 CFA	3,142,017,692.42 CFA	2,836,867,015.24 CFA
	17	6,115,410,921.46 CFA	3,013,925,844.04 CFA	2,699,751,260.29 CFA
	18	6,115,410,921.46 CFA	2,891,055,965.51 CFA	2,567,494,444.40 CFA
	19	6,115,410,921.46 CFA	2,773,195,170.75 CFA	2,439,873,591.75 CFA
Total			84,755,781,526.26 CFA	3,946,253,530.24 CFA
Annual revenue			4,644,002,227.28 CFA	

4.6.6. Total benefits

The total revenue from the project is obtain from the benefits of electricity.

Table 22 Total average revenue of the project

Benefits	**Selling tariff**	**Unit**
Electricity	21,480.19 CFA	CFA/MWh
Total		

4.6.7. The cost benefit indicators, analysis

Economic analysis is carried out based on 4 main indicators. The NPV, IRR, B/C and PP.

Table 23 Indicator of the cost benefits analysis

Cost Benefit parameters	Value	Unit
NPV	78925070604.81	CFA
IRR	#NOMBRE!	%
B/C	14.53609734	
PP	0.21	years

The table shows that biogas production alone will not be profitable for the project in economic terms

4.7. Contribution of the waste recovery rate on access to electricity in Bissau

The current installed capacity in Bissau is 15 MW different from the energy needed to supply the demands of the city of Bissau which is 40 MW. With the valorization of the organic fraction of municipal solid waste generated in Bissau for the production of hydrogen and consequent electricity, the power generation will be 45.8 Kwh which corresponds to 0.045 MW. Biogas has more capacity to produce electricity through anaerobic digestion of the organic fraction of urban solid waste with 39,610.2 Kwh which corresponds to 39.6102 MW.

5. Conclusion

Different forms of energy are essential for Man from the most remote pasts to the present day as they are used for heating, cooking, electricity or for his own safety. With technological development accompanied by accelerated population growth, it causes more consumption of natural resources and more production of municipal solid waste and a growing need for diversification of energy sources.

In Bissau, one of the options for the final destination of municipal solid waste is its disposal in landfills, which causes different forms of pollution from air, soil, water and compromises the health of the population. In addition to inadequate management of urban solid waste, Bissau faces difficulties in accessing electricity, where only 20% of the population has electricity, most do not.

The present is to model the potential of hydrogen production from municipal solid waste in the city of Bissau with the purpose of recovering the energy from waste in order to promote its valorisation, decrease the amount of waste that goes to rubbish, reducing the amount of greenhouse gases emitted through municipal solid waste in the city of Bissau.

The work serves to determine the potential of the city of Bissau to hydrogen and biogas production from organic fraction of municipal solid waste, despite being the most produced, constitutes a portion of the less valorized and then to determine how much electrical energy can be obtained. The methods used to obtain the results are through the secondary data through the work that have been done by the other authors using the different categories of solid waste produced in Bissau. Therefore, for organic waste, an annual hydrogen production potential of 10210.4 m^3 per year is obtained, corresponding to 27.9 m^3 that can be produced daily, obtained the total available electrical energy of 45.8 Kwh.

Therefore, the amount of organic waste generated impacts on the quantity of hydrogen can be produced and consequently low electrical energy potential can be obtained. Biogas has a potential energy the 39,610.2 Kwh which corresponds to 39.6102 MW which contributed significantly to minimizing the population's lack of access to electricity.

The electricity required for the city of Bissau is approximately 40 MW, but the installed capacity is 15 MW.

The energy recovering from municipal solid waste will contribute significantly to reducing the amount of waste that goes to landfills, minimizing the environmental problems arising from the poor management of waste and the consequent increase in the rate of access to electricity, promoting, and the essential factor for the development.

6. Recommendation

Based on the present work, it can be highlighted that it is extremely important to value municipal solid waste with the purpose of taking advantage on their energy potential for the benefit of the population by generating energy and, on the other hand, minimizing the negative impacts on the environment caused by the poor management of municipal solid waste in Guinea-Bissau in general and in the capital Bissau in particular, that is why it is recommended the applicability of waste recovery through biogas since it has enormous benefits. It also recommends that the future work to suggest other alternatives for the valorization of different fraction of municipal solid waste such as environmental and energy benefits. It is recommended to implement the valorization of municipal solid waste for energy recovery and serves as alternative sources of energy.

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