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Subject/Topic:

H_2 PRODUCTION POTENTIAL BY DARK FERMENTATION OF MSW (MUNICIPAL SOLID WASTE) IN SAO VICENTE ISLAND: TECHNO-ECONOMIC ANALYSIS

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Declaration

I, Danielson Daniel Sousa dos Reis Dias, hereby declare that this thesis, entitled Hydrogen production potential by Dark Fermentation of MSW (municipal solid waste) in Sao Vicente island: Techno-economic analysis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Signed: Danielson Dias

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Abstract (English)

In 2016, global solid waste reached 2.01 billion tons, with projections indicating a substantial increase in the absence of change. For island communities like Sao Vicente, the scarcity of land and sustainable waste management exacerbates the issue, leading to waste dumping and burning. This project proposes a waste-to-energy approach, utilizing dark fermentation to convert the Organic Fraction of Municipal Solid Waste into hydrogen.

The project's initial steps involved waste composition analysis to determine the organic waste volume contributing to hydrogen production. Daily hydrogen and byproduct estimates were then calculated. A cost-benefit analysis was conducted, evaluating annual costs, benefits, and project feasibility using indicators like Net Present Value (NPV), Interest Rate of Return (IRR), Benefit Cost Ratio (B/C), and Payback Period (PP), and lastly a break-even analysis. Additionally, carbon dioxide emissions reduction was estimated using a Greenhouse Gas Emissions Estimation Tool.

The project processes approximately 2.1 tons of organic waste daily, yielding 201.47 m3 of hydrogen, 368.29 kg of CO2, 795.66 kg of acids, and 188.46 kg of slurry. The annual cost falls within the range of similar projects, around $194,266.62 USD.

Revenue is generated through the sale of CO2, slurry, and H2, the last with a levelized cost of $2.64 USD, lower than the market price for biohydrogen production cost. The NPV is positive at $1,381,443.18 USD, IRR at 29%, B/C at 1.5, and PP at 8.19 years, indicating project viability. To break even, 351,773.71 units must be sold within 8 years, including 309,560.87 m3 of hydrogen, 35,177.37 kg of CO2, and 7,035.47 kg of slurry. This approach reduces monthly emissions by 17%, making it environmentally beneficial despite limited hydrogen data availability.

Key words: Dark fermentation, Organic Fraction of Municipal Solid Waste, Hydrogen, Cost-benefit analysis, CO_2 savings.

Abstract (French)

En 2016, les déchets solides mondiaux ont atteint 2,01 milliards de tonnes, avec des projections indiquant une augmentation substantielle en l'absence de changement. Pour les communautés insulaires comme Sao Vicente, la rareté des terres et la gestion durable des déchets exacerbent le problème, entraînant le dépôt et la combustion des déchets. Ce projet propose une approche de valorisation des déchets en énergie, en utilisant la fermentation anaérobie pour convertir la Fraction Organique des Déchets Solides Municipaux en hydrogène.

Les premières étapes du projet ont impliqué une analyse de la composition des déchets pour déterminer le volume de déchets organiques contribuant à la production d'hydrogène. Les estimations quotidiennes d'hydrogène et de sous-produits ont ensuite été calculées. Une analyse coûts-avantages a été réalisée, évaluant les coûts annuels, les avantages et la faisabilité du projet en utilisant des indicateurs tels que la Valeur Nette Actualisée (VNA), le Taux de Rentabilité Interne (TRI), le Ratio Coût-Bénéfice (RCB), la Période de Récupération (PR), et enfin une analyse de seuil de rentabilité. De plus, la réduction des émissions de dioxyde de carbone a été estimée à l'aide d'un outil d'estimation des émissions de gaz à effet de serre.

Le projet traite environ 2,1 tonnes de déchets organiques par jour, produisant 201,47 m^3 d'hydrogène, 368,29 kg de CO2, 795,66 kg d'acides et 188,46 kg de boues. Le coût annuel se situe dans la fourchette de projets similaires, soit environ 194 266,62 dollars américains.

Les revenus sont générés grâce à la vente de CO_2, de boues et d'H_2, ce dernier ayant un coût nivelé de 2,64 USD, inférieur au prix du marché de la production de biohydrogène. La VNA est positive à hauteur de 1 381 443,18 dollars américains, le TRI à 29 %, le RCB à 1,5 et la PR à 8,19 ans, indiquant la viabilité du projet. Pour atteindre le point mort, 351 773,71 unités doivent être vendues dans les 8 ans, y compris 309 560,87 m3 d'hydrogène, 35 177,37 kg de CO_2 et 7 035,47 kg de boues. Cette approche réduit les émissions mensuelles de 17%, ce qui en fait un avantage environnemental malgré la disponibilité limitée de données sur l'hydrogène.

Mots clés : Fermentation Noire, Fraction organique des déchets solides municipaux, hydrogène, analyse coûts-avantages, économies de CO_2.

Acronyms and Abbreviations

Anaerobic Digestion	(AD)	33
Atlantic, Indian Ocean, Mediterranean, and South China Sea region	(AIMS)	14
Benefit Cost ratio	(B/C)	34
Biohydrogen	(bioH2)	30
Bundesministerium für Bildung und Forschung	(BMBF)	iv
Cape Verde	(CV)	13
Carbon dioxide	(CO2)	17
Chemical Oxygen Demand	(COD)	25
Continuous Stirred Tank Reactor	(CSTR)	32
daily hydrogen volume	VH-	40
Dark Fermentation	(DF)	15
Doctoral Research in Program in Climate Change and Energy	(DRP-CCE)	iv
Federal Ministry of Education and Research	(FMER)	iv
feed flow rate	Q	39
Fixed capital investment	(FCI)	33
Fixed Capital Investment	(FCI)	40
Graduates Studies Program	(GSP)	iv
Green House Gases	GHG	13
Homoacetogenic Bacteria	(HAB)	27
Hydraulic Retention Time	(HRT)	31
Hydrogen gas	(H2)	18
Hydrogen Partial Pressure	(HPP)	30
Industrial Waste	(IW)	28
Institute for Energy and Environmental Research	(IEER)	35
Internal Rate of Return	(IRR)	34
International Master program in Energy and Green Hydrogen	(IMP-EGH)	iv
Lactic Acid Bacteria	(LAB)	27
Levelized Cost of Hydrogen	(LCOH)	33
Medical Waste	(MW)	28
methane	(CH4)	14
Municipal Solid Waste	(MSW)	13
Municipal Solid Waste Management	(MSWM)	21
National Agency for Water and Sanitation	(NAWS)	14
National Strategic Plan for Prevention and Waste Management	(NSPPWM)	37
Net Present Value	(NPV)	34
Nitrous Oxide	(NO2)	17
Operational costs	(OC)	40
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Organic Fraction of Municipal Solid Waste	(OFMSW)	18
Payback period	(PP)	34
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Small Island Development States		

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Introduction

Climate change is a critical issue that poses a severe threat to the environment and human wellbeing due mostly to the anthropogenic emissions of Green House Gases (GHG), from the combustion of fossil fuel (Santos, 2020). However, in addition to the emissions from fossil fuel burning, waste generation and management also contribute to this problem, as the global population continues to grow waste generation is increasing at an alarming rate.

According to the World Bank Group (2021), the global waste generation per capita per day is 0.74 Kg, with some countries producing up to 4.54 Kg per capita per day (The World Bank, 2021). The global waste generation in 2016 was estimated to be a little over 2 billion tons, and it is projected to reach 3.40 billion tons by 2050, under a business-as-usual scenario (Rebellón, 2017).

Considering that several of the Sustainable Development Goals (SDGs) are directly or indirectly related to waste management, a suitable approach toward waste generation and management is crucial to mitigate the effects of climate change around the world and contribute to achieving these goals.

Globally the Municipal Solid Waste (MSW) has different ends, which will define its level of contribution to environmental challenges, the destinations differ from landfilling (37%), openly dumped (33%), and modern incineration processes (11%) (Rebellón, 2017; The World Bank, 2021).

Cape Verde (CV) archipelago belongs to a very restricted region, which gives the country a uniqueness when it comes to solutions for the problems faced by the country, such as waste generation and management. The country is part of the Atlantic Island communities and part of the Sub Sahara Africa. São Tomé and Príncipe, Comoros, Guinea-Bissau, Madagascar, Mauritius, and Seychelles are examples of island states that belong to Africa and from them Cape Verde, São Tome e Principe and Guinea Bissau are in the Atlantic Ocean (Hansom, 2010; Surroop & Raghoo, 2018).

Particularly for island states, the problem of waste generation affects them in a deeper sense regarding their adverse geographical conditions compared to the developed economies, population density, land scarcity, and environmental vulnerability leading to severe climate change impacts and strong reliance on the importation of fuel and goods to develop their economies (Mohee et al., 2015).

On the Small Island Development States (SIDS) Waste Management Outlook (WMO) is stated that the waste generated per person per day is on average 1.65 kg in the Atlantic, Indian Ocean, Mediterranean, and South China Sea region (AIMS) (UN Environment, 2019). Even though this can be the reality for most of the islands in this region this data does not portray the Cape Verdean reality, and so it needs to be precise.

In 2015 Cape Verde population generated an average of 170,636 tons/year of waste. The waste generation per capita at the national level was 0.874 Kg/h.day (ANAS, 2016). According to the same source, projections were made to estimate the waste generated by the country in 2030. These projections were made considering three scenarios, which are explained in the Agencia Nacional de Agua e Saneamento (ANAS) or acronym in English National Agency for Water and Sanitation (NAWS) report, due to some reasons exposed by this report, the scenario more likely to happen is the intermediate one where the amount produced would be 362,766 tons/year, if considered that the production of waste per capita will be 1.50 Kg/h/day (ANAS, 2016).

Cape Verde is an archipelago constituted of 10 islands (Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, Boavista, Maio, Santiago, Fogo e Brava), one of them is the study area for this project. São Vicente (SV) island is in the north part of the Cape Verde archipelago. The average waste generated in this locality was 37,588 tons in 2015, with the waste generation per capita around 1.27 Kg/h/day (ANAS, 2016).

In São Vicente Island (SVI) the main way used to treat the generated waste is through dumping, the island accounts also for 6 uncontrolled disposal locations. After the disposal of the waste, there will be a further uncontrolled burning of the waste (ANAS, 2016). According to MARTINS, (2017) when the waste trucks arrive at the landfill there is a slight control, with the purpose to check the amount of waste being transported by the vehicle. Once the trucks are inside the landfill, the waste is disposed of and followed by a preparation process to burn the waste. The remaining fraction is buried after burning.

The waste management in SVI is causing damage to the ecosystem of the island. According to the Ministry & Safety, (2019), some important aspects will define the degree of environmental impact. The amount of waste generated, handling conditions, the disposal time, and anaerobic conditions can lead to the formation of methane (CH4) and acidity. In 2000 the waste sector accounted for about 32% of total methane emissions with 94% from solid waste in the country (ANAS, 2016; Ministry & Safety, 2019).

The municipality of São Vicente spends annually around 120 million ECV (1.1 million euros), this cost includes mainly the collection, transportation, dumping, and burning processes (compaction, stabilization of the waste disposed) (MARTINS, 2017; Silva, 2005). Due to all these issues, that the island is facing in handling the generated waste, the concept of Waste-to-Energy (WtE) could be a solution.

According to (Funk et al., 2020; Screve, 2021) WtE, are various technological methods of producing energy from waste and utilizing it in many applications in the form of heat, electricity, etc. There are several processes through which the energy can be generated such as Thermochemical (Incineration, gasification, pyrolysis), Biochemical (fermentation, anaerobic digestion, landfill with gas capture, Microbial fuel cell), and chemical (Esterification) (Khan et al., 2022).

As stated earlier, one of the processes that can be used to convert waste into energy is fermentation. There are two forms of fermentation, Dark Fermentation (DF), and Photo Fermentation (PF).

For this study, the organic waste fraction will be converted using the dark fermentation process, DF is a process where carbohydrates-rich substrates are anaerobically fermented in the absence of light by a consortium of microorganisms or pure cultures. This process Is the most frequently used around the world among the biological processes, a reason which gives it a wide technological advance in relation to other methods (Kannah et al., 2021).

According to (Patinvoh & Taherzadeh, 2019; Sekoai et al., 2020) stated that DF is a promising technology because it operates at ambient temperature and atmospheric pressure. According to (Mahata et al., 2020) stated that it offers high production rates and excellent capacity to valorize a wide range of feedstock including waste material, which is the feedstock that this study is based on. Another good side of the dark fermentation process pointed out by Surra et al., (2022) is that DF is more environmentally friendly than the thermochemical processes.

Figure 1: Waste burning at the dumpsite in Sao Vicente

Source: Operational plan for waste management Sao Vicente, 2019

In CV, waste management is the responsibility of each of its 22 municipalities. The common practice adopted by these municipalities is the disposal of waste in dumpsites. Despite some islands having more than one municipality, São Vicente Island has only one, which happens to be the second most densely populated in the country.

São Vicente is part of the few islands which have 100% of the population with access to waste collection service, the greatest challenge is encountered when it comes to the disposal and management of this waste (Correia, 2012; MARTINS, 2017; Reis, 2022).

Addressing this challenge requires a scientific approach that considers the environmental and social impacts of dumpsites disposal and explores sustainable waste management alternatives with economic benefits for the island (UN Environment, 2019).

To emphasize the need to find a proper waste management system, it is crucial to understand the negative effects of the current waste management practices on public health, environment, and economy.

Solid waste management is a global concern, it affects even the wealthiest people, but the ones who are more affected by the consequences of improper waste management are often the less fortunate share of society (Kaza, et.al., 2018). In Cape Verde, even with all existent waste management legislation, the population still faces several health issues due to the improper storage, collection, and disposal of waste.

The health authorities in the country have shown that the disposal of waste in open dumpsites, and abandoned constructions, amongst other ways of disposal are attraction sources of flies, mosquitos, rodents, insects, and bad odors including toxic substances, which are vectors for diseases such as malaria, cholera, meningitis, and dysentery (Xavier, 2019).

According to (Martins, 2017), another aspect to consider when regarding health issues is the fact that in almost all the islands, including São Vicente, there is an informal sector of waste pickers in the dumpsites, where this waste is collected for personal reuse, or to be sold as feedstock, and this act is the way of living for the unfavored share of the population.

Due to the consequences on those workers to expose themselves to such risky situations, they are the ones mostly affected by these conditions and suffer the dangerous consequences that are mentioned above.

Together with the release of GHGs mainly Carbon dioxide ($CO2$) associated, not only with the waste burning as shown in Figure 1, but also with the fossil fuel used during the transportation, collection, and the waste processing, Nitrous dioxide ($NO2$) from the waste burning, and ($CH4$) due to the anaerobic decomposition of the biodegradable waste fraction.

Other environmental risks are associated with the mismanagement of solid waste, such as water body contamination. This is a big concern for the island since tourism is one of the main economic activities of the island, so it is crucial to keep the environment clean.

The presence of waste in the coastal area, or the waste ending up in the ocean, leads to water body contamination, not only damaging the island's ecosystem but also affecting the country's economy (Fonseca, 2009; Ministry & Safety, 2019).

Another problem associated with the waste mismanagement is the soil contamination phenomenon which happens when rainwater is mixed with waste forming a bleached mixture that contains bacteria and toxic substances (heavy metals, dioxins, pesticides, and organic compounds) which constitute a threat to the soil and underground water (Carvalho, et. al., 2010).

The last environmental risk considered is the risk of fire, while dumpsite fires are a common occurrence around the world, a recent example of this in Cape Verde was the fire that took place in 2020 at São Filipe dumpsite (name of a locality in Fogo Island). The fire was extinguished and reignited for nonconsecutive days and was caused by a combination of high temperatures and blowing of the wind which ignites the waste material.

This example highlights that this type of fire can occur everywhere where we waste has accumulated, emphasizing the need for a sustainable approach to best manage the Municipal Solid Waste (MSW) (Expresso das Ilhas- Inforpress, 2020, last accessed 27/03/2023).

According to Scarlat et al., (2015), waste management is one of the most complex and cost-intensive public services, even when well organized and properly operated. In developing countries, municipal waste management has the highest share in the municipality budget, varying from 20-50%, and a significant amount from the waste management budget (up to 80-90%) is used in the collection stage (Scarlat et al., 2015).

The SV municipality expenses in the MSW management sector are the highest in the country, even though the outcomes are not that clear, mainly because there is not a defined management plan for the island (Reis, 2022).

Even though MSW management is a crucial topic to be discussed due to the potential of harming the environment (air, land, and water), human health, and biodiversity. For the Cape Verde archipelago, the attention directed to this topic is not in high proportions, still, there are some few studies conducted about solid waste management in the islands.

Some examples are official documents, research studies, studies developed through international partnerships, and some conducted by national authorities, such as PENGer – Plano Estratégico Nacional de Prevenção e Gestão de Residuos, PANA I, and II (Plano de Acção Nacional do Ambiente, National Action Plan for the Environment).

Although all these studies are important for the improvement and sustainability of this public service, none of them with a detailed waste-to-energy approach to help tackle this issue. They focused mainly on the understanding and proposed improvements of the complete MSW chain, from the collection, transportation to further arrival to landfill disposal, where some suggested to upgrade the dumpsite to a controlled landfill system, others mention the implementation of incineration system.

The official documents try to standardize the management of waste throughout the country. The studies conducted through partnerships and national entities try to develop a waste roadmap.

The proposed system that this study will address which is assessing the potential to produce hydrogen through dark fermentation using the Organic Fraction of Municipal Solid Waste (OFMSW), can close the gap that most of the previous studies were not able to address. It offers a solution that can tackle the issue of organic solid waste management.

Where it will be possible to produce renewable sources of energy with a high level of benefits for the environment, some byproducts with economic value, and a waste-to-energy project. This research can serve as a baseline for further research on the topic.

For CV and as well for other nearby islands which are in the same state and facing the same problems as Cape Verde. This research aims to answer the question: Is it feasible from a techno-economic perspective to produce Hydrogen gas (H_2) from the OFMSW through dark fermentation?

The main objective of this research is to assess the techno-economic feasibility of a project to produce biohydrogen and bioproducts from biowaste.

Specifically, this study seeks to estimate the hydrogen production potential using dark fermentation, by covering the following aspects:

1. Understand the current waste management practices in Sao Vicente Island and the characteristics of the waste.
2. Understand the relevant technical aspects of the dark fermentation process and its limitations.
3. Evaluate the potential production of hydrogen and byproducts.
4. Evaluate the economic viability of the proposed project.
5. Evaluate the project’s environmental impact on the island’s ecosystem.

1. Literature Review

The evolution of Municipal Solid Waste Management (MSWM) demands a holistic system able to both handle the constant increase of waste generation caused by (population growth, industrialization, and elevation of living standards) and efficiently valorize waste streams while protecting the environment, as well as minimizing costs (Matthews & Small, 2022; Uche-soria & Rodr, 2019).

African countries still lagging when it comes to such an approach, as the countries face challenges with the basics of waste management collection, transport, and disposal (Luiz & Quelhas, 2021). In African island communities, these basic challenges come together with few others challenges that are inherent to island states, which will make the set of possible management solutions even more delicate.

In São Vicente Island the collection methods used are door-to-door container collection, mixed collection, and dumpster collection. The island territory is 100% covered by the collection system. In 2017 the island counted 16 trucks for the transportation of the waste collected, (consisting of 13 compactor trucks with capacities ranging from 10 to 16 m^3, 2 multi-benne trucks for collecting the dumpsters, and 1 transport truck) (ANAS and Câmara Municipal de São Vicente, 2019).

In contrast with most regions in Africa, these two aspects of waste management for São Vicente Island are relatively well managed. The problems will show up at the time of disposal and treatment. Waste disposal is done in the dumpsite located in Ribeira de Julião 12 Km from Mindelo city center. When arriving at the landfill site the waste will be burned and afterwards will be spread and compacted using a high-truck bulldozer (ANAS and Câmara Municipal de São Vicente, 2019).

While São Vicente Island seems to have a relatively well-managed waste collection system, the process of waste disposal and treatment remains a major challenge. The current method can lead to harmful emissions and contribute to air pollution. Considering these challenges, one possible solution is to shift towards a waste-to-energy approach, which would not only help to mitigate the environmental impact of waste disposal but also generate renewable energy.

However, implementing such a solution would require significant investments in infrastructure and technology, as well as strong political will and community support. The journey towards a more sustainable and environmentally friendly waste management system for São Vicente Island and other regions in Africa will undoubtedly be a long and challenging one, but it is a journey worth taking for the benefit of future generations.

According to Zhang et al., (2021) that the dark fermentation process offers a promising approach to hydrogen production from organic waste and has gained significant interest over the past decade.

The efficiency of hydrogen production depends on several operation factors such as, the type of bacteria used (obligate and facultative) Mishra et al., (2019), the pretreatment method applied (preheating, acid/alkaline hydrolysis, ultrasound-assisted hydrolysis) Jarunglumlert et al., (2017) row material used Zhang et al., (2021), reactor type, which depends on the process (batch, continuous, and semicontinuous) (Shalaby et al., 2018).

The hydrogen produced can be used to provide heat, electricity, and fuel for hydrogen engines where this option might be preferred in comparison with the other gaseous fuel, which has as well the label carbon-free fuel because when used the byproduct is only water and heat (Mishra et al., 2019).

This study will evaluate the potential of fermentative hydrogen production of OFMSW in São Vicente Island and aims to provide a techno-economic analysis of the proposed system to check its feasibility.

1.1 Overview of H_2 production potential by dark fermentation of MSW

The figure below represents a schematic of the dark-fermentation process, illustrating the breakdown of the substrate into simpler components leading to the formation of hydrogen and bioproducts.

Dark fermentation – The biochemistry of dark fermentation

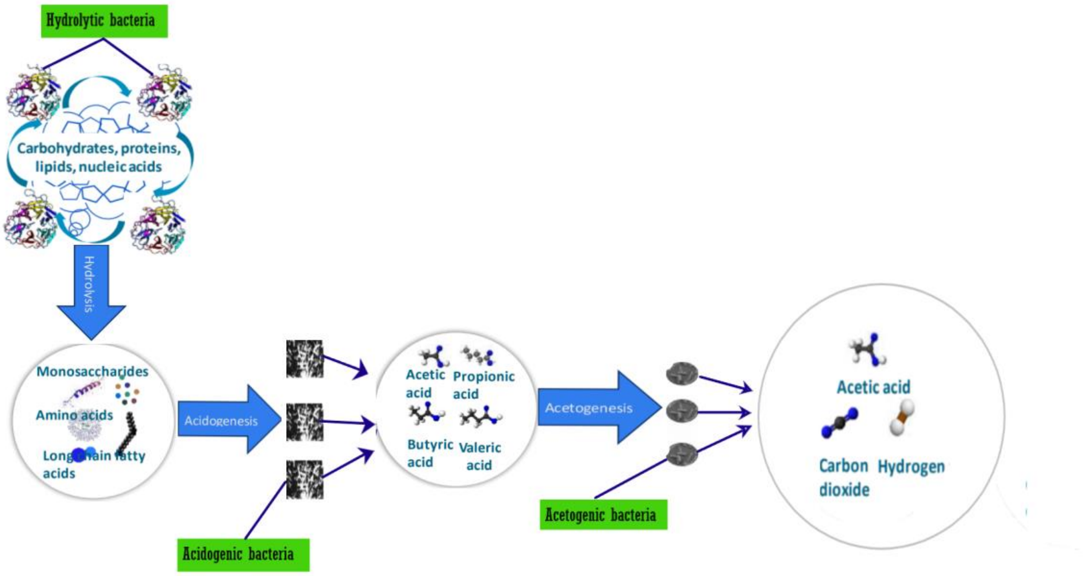


Figure 2: Simple schematic representation of dark fermentation process

Source: Adapted from, Sarker 2019

Dark fermentation is one of the biological hydrogen production methods, where as shown in Figure 2, microorganisms such as anaerobic bacteria with hydrogenase enzyme act to decompose organic matter or carbohydrate-rich subtract into hydrogen gas, and Volatile Fatty Acids (VFA) (acetic acid, butyric acid, and propionic acid) and/or alcohols in the absence of light (Goria et al., 2022).

This process takes place in two main steps, first, the organic substrate is broken down by a hydrolysis process into simple organic compounds either mono- or polysaccharides followed by the second step of an acidogenic process to convert the products of hydrolysis into various types of acids which will be further converted in hydrogen, CO_2, and VFA (Goria et al., 2022; Jarunglumlert et al., 2018; Singh & Sarma, 2022).

The full process can be detailed in three steps as explained below.

Hydrolysis:

The initial stage in anaerobic microbial use of complicated polymers is hydrolysis. Extracellular enzymes including cellulase, amylase, protease, and lipase are used by hydrolytic fermentative bacteria to break down complex organic materials like polysaccharides, proteins, and lipids into simpler components (Oyanedel et al., 2019).

Proteins are broken down into amino acids and peptides, polysaccharides into simple sugars, and lipids into fatty acids and glycerol. These goods then serve as the starting materials for additional fermentation procedures (Oyanedel et al., 2019).

The reaction associated with hydrolysis process is shown in the equation below, where complex components are broken down by the addition of water to simple components, like glucose.

$$C_6H_{10}O_6 + H_2O \rightarrow C_6H_{12}O_6 \text{ (glucose)} + H_2 \tag{1}$$

Acidogenesis

Monosaccharides and amino acids are used as substrates for acidogenic fermentation after being hydrolyzed. These substrates are used by facultative and anaerobic fermentative or anaerobic oxidizing organisms to create chemicals including acetic acid, propionic acid, butyric acid, valeric acid, CO2, and hydrogen. (Oyanedel et al., 2019).

The chemical equations associated with this phase are:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \tag{2}$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2C_2H_5COOH + 2H_2O \tag{3}$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \tag{4}$$

Acetogenesis

In the acidogenesis phase, complex organic compounds undergo degradation, resulting in the production of simpler substances. These products are then channeled into the Acetogenesis phase, where a series of equations govern their conversion into valuable compounds.

$$C_2H_5COO^- + 3H_2O \rightarrow CH_3COO^- + H^+HCO_3^+ + 3H_2 + 2e^- \tag{5}$$

$$C_2H_5OH + 2H_2O \rightarrow CH_3COO^- + 3H_2 + H^+ \tag{6}$$

Acidogenesis fermentation metabolism

Numerous microbial species that can carry out a range of oxidation-reduction processes involving organic chemicals, carbon dioxide, and molecule hydrogen are present in a mixed culture acidogenic fermentation. aerotolerant anaerobes, strict anaerobes, and facultative anaerobes are all types of acidogenic bacteria (Oyanedel et al., 2015).

All biochemical processes carried out by a living being collectively are referred to as the metabolism. Energy production and the creation of new cell material are the two fundamental goals of these processes. Alternative paths to produce these compounds are available to acidogenic bacteria, and the relative quantities of the various products produced are influenced by the environment (Oyanedel et al., 2015).

For this study, special attention will be given to the acetate metabolic pathway where the hydrogen yield is higher. In this type, the main volatile acids formed are acetic acid and butyric acid. Considering glucose as an example, the stoichiometric hydrogen yield would be 4 mol H_2/mol of glucose if the VFA is acetate (Yin & Wang, 2022). In practice, H_2 yields are substantially lower than the theoretical value obtained from the ideal acetate fermentation (Palomo-Briones et al., 2018).

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH(\text{acid acetic}) + 4H_2 + 2CO_2 \tag{7}$$

1.1.1 Hydrogen production and bioproducts

According to Oyanedel et al., (2019), after several experiments the percentages of the byproducts are CO_2 (24%), biomass (5%) acetic acid (19%), and butyric acid (19%). It is also worth noticing that there is no metabolic pathway preferred when mentioning the percentages.

According to Ghimire et al., (2015); Gómez et al., (2011), the maximum hydrogen yield of hydrogen possible to produce from glucose is 33%, meaning that only this percentage of the Chemical Oxygen Demand (COD) can be converted into hydrogen.

From the dark fermentation process the gas phase is a mixture of CO_2 and H_2, which implies that after the process there is a need for purification, especially because pure hydrogen is becoming extremely important in many areas with consumption requirements (i.e., PEM – Proton Exchange Membrane fuel cells) (Tapia-Venegas et al., 2015).

Currently there are two main mature technologies to separate hydrogen gas from other gasses, that are mainly used in chemical and petrochemical industries. The Pressure Swing Adsorption (PSA), and the cryogenic distillation. Both are energy intensive and costly technology (Tapia-Venegas et al., 2015).

One suitable option would be the membrane separation process, which is cost effective when handling low gas volume at continuous operation. It is possible to combine this separation phase with the production phase, which is a huge advantage (Nemestóthy et al., 2020).
Researchers are working to make this technology cheaper, with improved yield and selectivity and materials more commercially attractive (i.e., polymers) (Nemestóthy et al., 2020).

1.1.2 Pros and cons of dark fermentation

Table ***1*** provides an overview of the pros and cons associated with dark fermentation. This comparative analysis highlights the advantages and challenges of this process, shedding light on its potential benefits and areas that require careful consideration.

Table 1: Pros and cons of dark fermentation

Advantages	References	Disadvantages	Reference
Capable of treating a wide variety of waste streams. Simple reactor configuration. High production rate. Operates in independent light conditions.	(Camacho et al., 2022) (Patel et al., 2018) (Kamran, 2021) (Sekoai et al., 2017)	Low yield due to the accumulation of VFA. Low substrate conversion efficiency. Separation between CO_2 and H_2 necessary;	(Patel et al., 2018) (Gopalakrishnan et al., 2019) (Osman et al., 2020)

Fossil fuels are the traditional and primary source of many chemical raw ingredients and energy carriers. Although fossil fuels like gas, oil, and carbon are extremely useful raw commodities, using them has an impact on the ecosystem. Additionally, fossil fuels derived from "primitive biomass" are scarce and may soon run out due to a growing global population (Sołowski, 2018).
As a result, numerous initiatives are made to collect primary substrates and energy carriers from renewable sources to supply the chemical industry. When compared to other energy sources such as solar, wind, tidal, or geothermal energies, hydrogen is a competitive energy carrier due to its high heating value (120 kJ/g) and low density (International Energy Agency, 2019).
Aside from that, as compared to other fuels, hydrogen fuel produces the least pollution. In 2021 the global hydrogen demand was around 94 million tons (Mt), mainly the hydrogen was used as a chemical for industry and was mainly produced from fossil fuels (International Energy Agency, 2019).

Hydrogen characteristics:

1.1.3 Hydrogen characteristics

Table 2 presents a comprehensive overview of the properties of hydrogen gas. Understanding these key properties is essential for various applications, from energy production to industrial processes. This reference table highlights the fundamental characteristics of hydrogen, providing valuable information for both researchers and practitioners.

Table 2: Properties of hydrogen gas

Property	Hydrogen
Density (gaseous) [kg/m^3]	0.09
Molecular weight [kg/kmol]	2.016
Energy density (gaseous) [MJ/dm^3]	3.0
Lower heating value [MJ/kg]	120

1.1.4 Microbiology and enzymology of dark fermentative bio-hydrogen production

In the microbiology of dark fermentation, there are three types of microorganisms: hydrogen producers, hydrogen consumers, and metabolic competitors.

Hydrogen producers

There are a variety of microorganisms from which the inoculum for hydrogen production can be collected from: mixed cultures, pure cultures, and hybrid cultures. Anaerobic sludge is the most used source for hydrogen producers, especially when the substrate used is complex in nature (Rafa et al., 2018).

System-inoculated anaerobic sludge is usually dominated by Clostridium spp., among which Clostridium butyricum, Clostridium pasteurianum, and Clostridium beijerinckii and Bacillus spp. were the most common strains (Rafa et al., 2018; Rafieenia et al., 2018; Shalaby et al., 2018). Clostridium bacteria have been detected in mixed cultures in mesophilic conditions, most likely due to the continuous use of thermal shock pre-treatment on the inoculum.

Thermoanaerobacterium species are primarily selected in thermophilic environments by the operating parameters in mixed cultures (Steyer et al., 2010).

Hydrogen consumers

The undesired non-hydrogen producers are mostly present when mixed cultures are used, including the hydrogen consumers (Homoacetogenic Bacteria (HAB), methanogen), and the strains compete with hydrogen producers for the substrate. To avoid this and to enhance hydrogen production there is a need to free the environment from these organisms (Steyer et al., 2010).

HAB is the type of bacteria that will consume hydrogen to produce CO_2 and acetate. According to Steyer et al., the best way to prevent this, is by controlling the operating parameters such as eliminating CO_2 from the headspace (Steyer et al., 2010).

Methanogens are the primary H_2-consuming species of bacteria in anaerobic conditions, to prevent methane synthesis there are several ways. The most common method of inoculum treatment is to heat the medium to about 100 °C for around 10 min to choose spore-forming, hydrogen-generating microbes. Another efficient method is to maintain the hydraulic retention time (HRT), under 6 h is prescribed for selectively washing out methanogens in consistent reactors (Steyer et al., 2010; Tyagi et al., 2018).

Metabolic competitors

Some bacteria compete with hydrogen producers for food and energy to perform metabolism, and the most common is Lactic Acid Bacteria (LAB). Bacteriocin secretion was identified as inhibitory activity and a temperature range above 50 °C was suggested to eliminate this bacterium from the reactor (Tyagi et al., 2018).

Two essential parameters that should be optimized are the heat pre-treatment time and temperature. The majority of H_2 consumers may not be effectively inhibited by very short pretreatment times or low temperatures, whereas very long pre-treatment times or high temperatures may result in the loss of H_2 producers' activities (Parthiba Karthikeyan et al., 2018).

The ranges for temperature and heating time, according to the literature, are 65–100 °C and 2-15 hr, respectively (Parthiba Karthikeyan et al., 2018). Biological H_2 production is catalyzed by a group of metalloenzymes called hydrogenases that catalyze the reversible reaction of two hydrogen atoms to produce molecular hydrogen.

The equation 8 signifies the action of hydrogenases, enzymes in microorganisms, in converting protons and electrons into molecular hydrogen gas. This reaction is pivotal in various metabolic pathways, including energy production and electron transfer processes (Parthiba Karthikeyan et al., 2018).

$$2\mathrm{H}+\ +2\mathrm{e}-\rightarrow\ \mathrm{H}_2 \tag{8}$$

Hydrogenase can be categorized into three phylogenetically distinct classes based on the type of metal ion present in the active site. The most abundant is the [Ni-Fe]-hydrogenases which are predominant in bacteria and archaea. As the name suggests, they have a nickel and an iron atom at their active site and are composed of two subunits (Singh & Sarma, 2022).

The larger subunit harbors the active site while the smaller subunit holds the FeS clusters of the electron transport chain. The second variant is [Fe-Fe]-hydrogenases with a dual iron catalytic center, which is prevalent in both eukaryotes and prokaryotes. The third group of the enzyme is termed [Fe]-only-hydrogenases, which rely on an iron-containing cofactor, which produces H_2 only in the presence of methylene-tetrahydromethanopterin (Singh & Sarma, 2022).

This group of hydrogenases is only found in methanogenic archaea. Clostridia, the major hydrogen-producing genus, relies mostly on [Fe-Fe]-hydrogenases, but a few species also possess [Ni-Fe]-hydrogenases (Singh & Sarma, 2022).

1.2 Characteristics and properties of OFMSW

Taking organic wastes as feedstock for biohydrogen production could achieve the dual benefits of clean energy production and waste management. If they are not of biological origin, their disposal has an impact on the natural ecosystem and may take a long time to decompose. Industrial Waste (IW), Medical Waste (MW), Waste of Electrical and Electronic Equipment (WEEE), and MSW are the four broad categories of waste sources (Masud et al., 2023).

MSW turns out to be a cheap, abundant, and rich source of carbohydrates, minerals, vitamins, and micronutrients, which makes it a good substrate for fermentative H_2 production (Panigrahi & Dubey, 2019).

For a better choice of technology to valorize the waste it is important to understand the characteristics of the waste. Several authors have conducted studies trying to understand the influence of Anaerobic digestion on the physical, chemical, and bromatological characteristics of OFMSW around the world.

Physical characteristics

The VALORGAS Project (Valorization of Food Waste to Biogas) conducted investigations on the characterization and management of OFMSW in four European Union nations: Portugal, Italy, Finland, and the United Kingdom. Amongst other situations, the project analyzed the presence of other organics that can conditionate the anaerobic process, such as eggshells, seeds, and bones (Zhu et al., 2021).

A crucial physical characteristic that can affect the digestion of the substrate is particle size. Size reduction is necessary for the OFMSW due to the heterogeneity and size of the particles through pre-treatment methods (Zhu et al., 2021).

Anaerobic digestion calculations and reactor behavior analysis frequently also use the density parameter. The range of densities is 328 to 1052 kg/m3. Less undesired elements and chemicals are present in the wastes with the highest density (Campuzano & Martínez, 2016).

Chemical characteristics

Due to its different components, the OFMSW exhibits a wide range of characteristics from a chemical standpoint. In research related to the management and processing of OFMSW, variables like humidity, solids (total, volatile, fixed), and their ratios, Kjeldahl nitrogen, and total phosphorus, are frequently discovered (Alibardi & Cossu, 2015).

When evaluating OFMSW as a substrate for anaerobic digestion, these characteristics are utilized to evaluate the amount of organic matter (biodegradable or not) and nutrients present. For environmental investigations and valuation for regional, seasonal, and socioeconomic goals, OFMSW must be characterized. It's crucial to comprehend how these qualities impact the digestion process (Alibardi & Cossu, 2015).

Bromatological characteristics

Generally, the OFMSW consists of carbohydrates (30-69%), protein (5-10%), lipid (10-40%) (López-Gómez et al., 2019). In general, OFMSW has a moisture content of 74–90% and the amount of VS is around 80–97%. The C/N ratios of municipal waste fractions commonly range from 14.7 to 36.4 (Serre & McCarthy, 2023). The sources can be lawn, garden waste, grass, food scraps, used paper products, and cardboard (Noor et al., 2020; Serre & McCarthy, 2023).

A study conducted by Pecorini et al. studied the quality of OFMSW in 5 cities, where a bromatological analyses was performed, amongst other analyses, the waste was collected considering the seasons and regions, and the results showed that the bromatological composition of OFMSW from both urban and semi-urban collection systems, cellulose, and lignin were the next most common components after carbohydrates (Pecorini et al., 2020).

The content of these components (carbohydrates, lignin, and cellulose) for the urban region was about 44.2 ± 2.5 %Total Volatile Solids (TVS), 18.1 ± 5.2 %TVS, 19 ± 1.2 %TVS, and 39.8 ± 3.4 %TVS, 26.2 ± 6.1 %TVS, 19.9 ± 1.9 %TVS for semi-urban ones (Pecorini et al., 2020).

Another study performed by Campuzano and Martinez confirmed that carbohydrates are the most predominant components of organic waste, the results were: 15.5 ± 66.6 %TVS of oils and fats, 17.7 ± 5.5 %TVS of proteins, 9.7 ± 5.3 %TVS of lignin, 18.6 ± 15 %TVS of cellulose, 8.6 ± 4.6 %TVS of hemicellulose and 27.6 ± 12 %TVS of carbohydrates (Campuzano & González-Martínez, 2016b).

Some studies confirm also that the lipids and proteins do not influence the hydrogen yield, predominantly the carbohydrates, precisely glucose, is the one giving the hydrogen yield together with the acids (Abdin et al., 2020 & Nath & Das, 2004).

As discussed previously the Organic fraction of the waste has a complex composition, containing food waste, green waste mainly, and it is necessary to find the suitable pre-treatment method, to solubilize the biodegradable material to be fermented.

1.3 Factors affecting H_2 production from MSW

In high- to medium-income nations, the majority of OFMSW is currently landfilled, thermally treated with heat recovery, composted, or anaerobically digested. This portion is discarded in low-income nations with little to no environmental oversight (Tyagi et al., 2018).

Biohydrogen (bioH_2), or H_2 created through biological processes is a fossil fuel that is renewable and carbon-free. In recent years, it has drawn significant attention as a potential replacement for fossil fuels as an energy source. Essentially, H_2 has the highest energy content per mass unit of any fuel that is currently known (Balachandar et al., 2020).

Partial pressure of hydrogen

When Hydrogen Partial Pressure (HPP) is too high, the biohydrogen generation process is inhibited. HPP is the concentration of hydrogen gas created inside the reactor. Below 60 Pa, the HPP does not favor the generation of gas and results in the synthesis of alcohol. A rise in

HPP lowers the H+/H_2 ratio and blocks the flow of electrons, which prevents the electrons from traveling from reduced ferredoxin to molecule H2 via the hydrogenases system (Kothari et al., 2017).

There have been several studies to find the best way to reduce the pressure of hydrogen inside the reactor and the simplest way to do this is by stirring the medium during the process (Rafa et al., 2018). Other methods: Sparging the fermentation mixture with an inert gas, usually nitrogen or CO_2, removal of the gaseous face by vacuum pump, and use of an active membrane (Lee et al., 2012; & Mandal et al., 2006).

Temperature and pH

(Luo et al., (2011) proved that in systems that produce hydrogen, fermentation temperature and pH are the key factors that determine the dominant bacterium. All the previous studies on literature show that hydrogen production by DF were conducted in three different temperature ranges: ambient (15–30 ◦C), mesophilic (32–39 ◦C), and thermophilic (50–64 ◦C) (Kothari et al., 2012).

Previous studies have shown that thermophilic conditions favor hydrogen production., and the optimal range to obtain a good hydrogen yield is between (37-55 °C) (Ghimire et al., 2015; Luo et al., 2011; Sarangi & Nanda, 2020).

The yields of biohydrogen and metabolic byproducts are influenced by the operational pH. Acetate and butyrate are often the main products of a good hydrogen synthesis (Sekoai et al., 2020).The DF is considered stable for pH values between 4.5 and 5.5 since this is the pH interval in which the activity of hydrolytic and acidogenic bacteria is favored (Angeriz-Campoy et al., 2015).

C: N Ratio

The stability of dark fermentation can be significantly impacted by maintaining an ideal C: N ratio. Because their proteins, nucleic acids, and enzymes depend on an appropriate C: N ratio, it is a crucial characteristic for hydrogen producers (Angeriz et al., 2015).

According to the same source, when the C/N ration is not favorable to perform the anaerobic digestion process, it is advised to adjust the ratio. It is possible to add livestock waste such as manure or sludge (Keskin et al., 2019). According to Angeriz et al., the ideal ratio for anaerobic digestion of organic waste is 20-35 (Angeriz et al., 2015) .

Hydraulic Retention Time (HRT)

This is yet another crucial variable that can impact the effectiveness of dark fermentation and control how long the process lasts. HRT is mostly influenced by the properties of the substrate being employed, particularly its biodegradability. Lower HRT conditions are required as substrate breakdown becomes easier (Akhlaghi & Najafpour-Darzi, 2020).

To ensure bacterial proliferation, the HRT should also be higher than the bacterial doubling time and cannot be too low. Moreover, dark fermentation often has a shorter HRT (in hours) than other biological energy recoveries methods such as anaerobic methane generation and bioethanol fermentation, while the other technologies have a longer HRT (in days) (Akhlaghi & Najafpour-Darzi, 2020).

Santiago et al, 2019 studied the implementation of a sequencing batch reactor (SBR) to produce hydrogen from organic solid waste, and the effects of hydraulic retention time (HRT) and Solids Retention Time (SRT) on hydrogen production were examined. The outcomes demonstrated that the maximum hydrogen production and yield were obtained with an HRT of 16 hours and an SRT of 60 hours (Santiago et al., 2020).

The community composition was most significantly impacted by the HRT during the procedure. Moreover, a lengthy SRT and HRT resulted in the largest fatty acid synthesis, while a decrease in the HRT enhanced the rate of substrate hydrolysis. The hydrogen production when considering the HRT of 16h was 1.86 LH2/L*d (Santiago et al., 2020).

Reactor type

The substrates that limit the operational parameters of bioreactors, such as culture temperature (mesophilic or thermophilic), reactor configuration (reactor types, wet, semi-dry, or dry conditions), and feeding mode (mono substrate or co-substrates), determine the process design for dark fermentation (Motte et al., 2013).

The Continuous Stirred Tank Reactor (CSTR) is often used to produce biohydrogen continuously from a variety of substrates. Multilayered photobioreactor, fixed-bed, fluidized-bed, and up-flow anaerobic sludge blanket bioreactor are a few more bioreactors being researched to produce biohydrogen. For this project, a CSTR is assumed to be used to convert complex organic biomass like OFMSW (Sarangi & Nanda, 2020).

1.4 Economic analysis of the dark fermentation process for H_2 production from MSW

Many variables associated with the raw material, process and product affect the price of biohydrogen. The economic evaluation of biohydrogen generation, which considers capital expenditures and yearly costs, will determine the potential for its usage (Yin & Wang, 2022).

Processing costs (Capital and operating costs) are included in the price of producing biohydrogen.

Operating expenses include energy, labor, water, whereas capital costs include one-time expenditures like equipment which the price is always affected by size, temperature and pressure, and land costs, and the product obtained and respective yield, value, and byproducts (Yin & Wang, 2022).

To make up the total capital cost it needs to also include the working capital cost, and direct/indirect costs. The overall investment in raw materials, suppliers, finished and semi-finished goods, accounts receivable, cash for operating costs, accounts payable, and taxes payable makes up an industrial plant's working capital (Peters et al., 2003).

The cost associated with hydrogen safety for storage and handling is included in this component of the costs (Peters et al., 2003). One important component of this expenditure is the feed or raw material costs, the raw material cost includes the pre-treatment cost and purchasing of the feedstock. For the purchasing of the feed is not required when the raw material is the OFMSW (Kannah et al., 2021).

In a way of comparison for PF and DF, respectively, the substrate costs total 144.19 and 867.18 million USD, when considering algae as substrate (Kannah et al., 2021). If we consider MSW is abundant and cheaper, the cost for raw material can be drastically reduced.

The Fixed capital investment (FCI) - brings together the direct costs, which are the costs of the equipment purchase, piping systems, installation of equipment. Indirect costs the engineering and supervision, legal expenses, construction expenses, contractor fees and contingencies (Peters et al., 2003).

Oyanedel & Schmidt studied alternative to Anaerobic Digestion (AD) to produce energy, and hydrogen from DF and byproducts purification presented more profit than other methods (Oyanedel & Schmidt, 2018).

In terms of technology Hosseinzadeh et al., found out that DF has shown better performance in comparison with photo-fermentation, pyrolysis, and gasification. The same study encountered DF process together with gasification with cheapest hydrogen cost 2.3 and 2 US$/g, the CO2 emissions assessment of this study showed fermentation processes as well with the lowest GHGs emissions with 15 Kg CO2-eq/Kg hydrogen (Hosseinzadeh et al., 2022).

In a case study of the generation of biohydrogen from food waste, it was discovered that the total capital expenditure and yearly operating expenses were USD 1,636,560 and USD 548,568 per year, respectively, with a yield of 2.26 mol H_2/mol-hexose and a food waste loading rate of 100 kgCOD/m^3/day. Additionally, $360,000 was the revenue from processing the food waste. The expected annual production of hydrogen was 949,200 m^3-H_2, and the estimated cost per kilogram of hydrogen was 3.2 dollars (Dinesh et al., 2018).

Han et al., studied organic waste treatment to produce hydrogen from fermentation and the initial capital investment obtained from the economic analysis was 632,802 USD (Han et al., 2016).According to Bartels et al., (2010) the Levelized Cost of Hydrogen (LCOH) produced from biomass is 2.7 USD/m^3 H_2.

One of the common methods to economically evaluate the feasibility of a project is through the cost-benefit analysis, which brings together an analysis of four indicators. Cost-benefit analysis is a financial tool known as a cost-benefit analysis compares the costs and advantages of an investment over a certain period (Koopmans & Mouter, 2020).

Key performance measures are calculated using indicators such discounted cash flows, amortization time, and return rates. These metrics offer a brief overview of the forecast and used to communicate and make comparison (Koopmans & Mouter, 2020).

Net Present Value (NPV) - It entails using a specific discount rate to discount all future cash flows—both in and out—raising from the innovation project and adding them all up. A risky Euro tomorrow is worth less than a certain Euro now, according to the first NPV approach principle. Therefore, annual discounts are applied to future cash flows. The opportunity cost of the money mobilized is reflected in the discount rate and rises in proportion to the perceived riskiness of the innovation opportunity (Žižlavský, 2014).

Internal Rate of Return (IRR)- the IRR is a discount rate that reduces the net cash flows of a project throughout its life to the value of its investment costs. It represents the rate of return on investment in a project that considers the time value of cash flows. IRR is the discount rate that makes the NPV of a project equal to zero, where the present value of cash inflows equals the cash outflows (Miletic & Latinac, 2015).

Benefit Cost ratio (B/C) – This ratio is calculated considering the discounted values for the costs and benefits.

Payback period (PP) – it is the amount of time it takes to recover the investment. In other words, is the number of years with an investment generating revenue where it is possible to recover the capital invested (Business Link, 2020).

Break-even Point - To calculate how many units of a product or service must be sold at a specific price point for a business to break even, apply a breakeven calculation (also known as a breakeven analysis). It is possible to determine the breakeven point for a business's product or service once its fixed and variable costs, or an acceptable approximation of them, are known (Business Link, 2020).

A WtE facility study done in Indonesia presented a break-even point of 6 years, the project was evaluated in a lifetime of 15 years (Soleh et al., 2020).

These four indicators have been used by several studies on biohydrogen production to evaluate the profitability and risk of projects. A study conducted by Ahmed et al., (2021) obtained a payback period of 3.87 years and an IRR of 22%, which shows the project was profitable. According to Yin & Wang, (2022) the payback of biohydrogen production facilities is between 6-10 years.

1.5 Environmental benefits of waste treatment

According to Kumari et al., around 40% of the waste generated globally is burned, contributing for the GHGs emissions, on the report named “What a Waste” the authors stated that in 2016, 1.6 billion of CO_2 equivalent was generated from waste management (Kumari et al., 2019; Silpa Kaza, Lisa Yao, Perinaz Bhada-Tata & Woerden, 2018). As stated earlier this is also a problem faced in Sao Vicente.

Some studies have estimated the amount of CO_2 emitted by the burning of the waste, with some examples are studies performed in localities with realities like the case study of this research. In 2022 a study in Nigeria performed by Okafor et al., found out that an estimated amount of waste between 2.9 to 4.5 million tons/year is burned and the CO_2 emissions were calculated to be 801.2 Kg CO_2-eq/ ton of open burned MSW (Okafor et al., 2022).

According to the Environment Agency, (2020) the amount of CO_2 emitted by burning one ton of MSW (this includes emissions of both fossil CO_2 (e.g., from burning plastics) and biogenic CO_2 (e.g., from burning wood, paper, and food)) is between 0.7 and 1.7 tons.

There are several online tools, which can be used as models to estimate the CO_2 emissions from open burning, based on input data of the waste composition and the amount of waste generated. Some examples are “Estimation tools for GHG emissions from MSW management in a life cycle perspective”, developed by the Institute for Global Environmental Strategies. The other tool is “Solid waste management (SWM) – GHG calculator”, developed by Institute for Energy and Environmental Research (IEER) Heidelberg.

2. Methodology

The aim of this research is to explore a better solution for waste management in Sao Vicente Island. As stated, previous studies done on this field in Cape Verde are scarce, and mostly focused on improvement of current methods of collection, transportation, and disposal but nothing related with energetic valorization of this waste.

Due to constraints in time and resources, it was not feasible to collect primary data at the study site. As a result, this study relied on the use of secondary data sources to address the research question.

2.1 Study Area

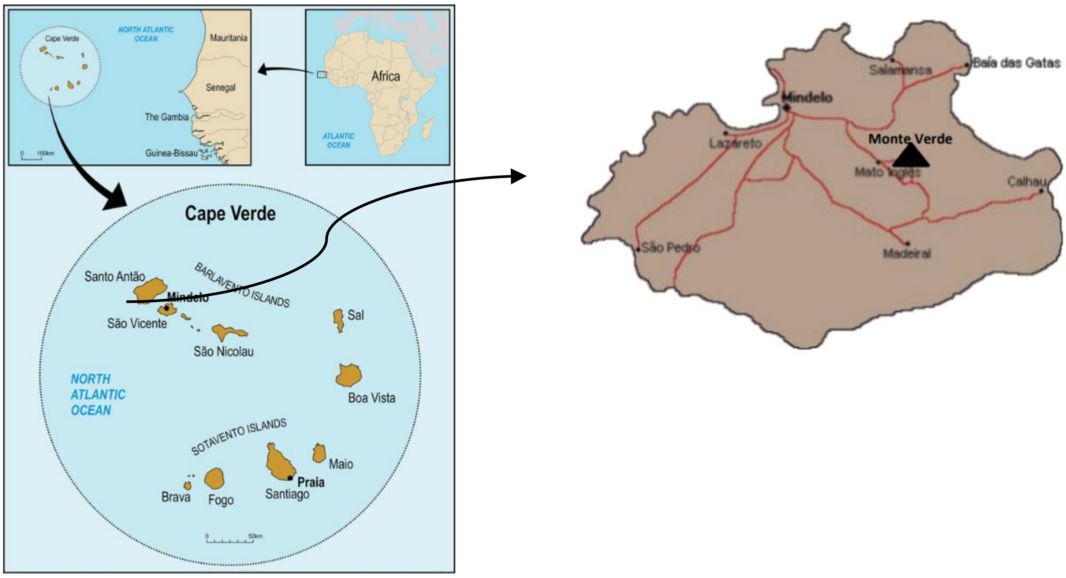


Figure 3: Study area, Sao Vicente

Source: Image of Cape Verde and sao vicente maps - Bing images

As mentioned earlier Sao Vicente is part of the small archipelago, named Cape Verde. All the islands have volcanic origins on the West Coast of Africa, from arid to semi-arid climate. It has an area of 4033 Km^2. Sao Vicente is located between the latitudes of 16° 50' 59.99" N, and the longitudes -24° 57' 59.99" W.

It is one of the islands from Barlavento group, located on the North side. In 2016 the population was around 84000 people. The main city of the island is Mindelo, which is where almost all the population resides.

2.2 Data collection

To achieve this aim, both secondary qualitative and quantitative data was collected. Qualitative data was collected with national authorities, the municipality, and the ANAS, with the publications Plano Estratégico Nacional de Prevenção e Gestão de Resíduos (PENGer) or acronym in English National Strategic Plan for Prevention and Waste Management (NSPPWM) and Operational Plan for Waste Management (OPWM) for SV.

The stated documents helped to understand the actual practices of waste management on the island and to justify the need for this project. Data was brought out as well from academic research where the focus was to obtain the formulas needed to perform the techno-economic analysis and the parameters needed for calculation.

Quantitative data was collected as well on the PENGer and OPWM studies where the waste composition of the island, and some important parameters for the analysis and were from scientific articles. The selected sources are from official documents and from recognized online databases, so reliable and credible sources were used. The data collected from national authorities was obtained through a direct email contact.

The articles and academic research were from online databases such as science direct and google scholar, published in journals such as waste management. The time range was selected considering 2018-2023, except on the cases where the date was not an important factor for the data collected and in cases where more recent data was not available.

Throughout the online survey some keywords were used such as: waste management, dark fermentation, waste-to-energy, CSTR, techno-economic analysis, Sao Vicente, hydrogen, biohydrogen, bioreactor, etc. The main challenge faced when gathering the data is the fact that there is not much work done in this field in the study area, this issue may be related to very particular features that the target area is an island community in Africa, which usually means a lack of data.

2.3 Data analysis

After the data is collected, it is time to describe how to analyze it, to answer the research question and to achieve the objectives stated earlier, to perform the case study.

2.3.1 Physical, biological, and chemical properties on MSW in Sao Vicente Island

The characteristics of the waste were found at the PENGer and in OPWM studies. PENGer provided the data on waste composition, waste generation per capita, and accordingly, the organic fraction was calculated using the formula below. The actual population of the island was obtained from the official website of the municipality.

Amount of waste generated daily in Sao Vicente

$$MSW\ daily\ prod = Per\ capita\ daily\ prod \times Pop \tag{9}$$

According to PENGer, due to the role of tourism on the economy of some municipalities, including Mindelo, the contribution of waste generation from this sector was also included in the overall calculation (ANAS, 2016).

The physical properties used for estimating the products' yields are collected from OPWM report. In this report, three samples were collected (SVC Mind 001, 002, 003), following some criteria exposed on the mentioned report. The analysis was made at the Lab o Inlab, da Inpharma - Indústria Farmacêutica, SA, na Zona Industrial de Tira Chapéu, na cidade da Praia. The present study used those values to perform calculations.

The amount of waste generated daily on the island is essential for the hydrogen estimation, the per capita daily waste generation was taken from the official documents and the population from World Bank data.

Amount of organic waste generated daily

$$OFMSW\ daily\ prod = MSW\ daily\ prod \times 16.9\% \tag{10}$$

As stated previously, carbohydrates are the main component of this fraction of waste, so this information was used to precisely calculate the waste used for the conversion. Glucose, fructose, and sucrose are the main types of carbohydrates which contribute to hydrogen production. Glucose is the component used throughout the study.

2.3.2 Hydrogen production potential

To estimate the hydrogen production potential, the method used is adapted from the study done by Alvarez, (2003) where the mentioned method was stablished for methane production, with HRT of days, here it was reduced to ensure the production of hydrogen.

The three samples' total volatile solids and total fixed solids data were taken, and the average was calculated, with the unit being (mg/Kg), followed by the conversion into percentage using a factor (1%=10000 mg/Kg).

Total volatile solids:
Percentage of total solids in the waste

$$\%TS = \%TFS\ (total\ fixed\ solids) + (\%TVS) \tag{11}$$

Amount of total solids inflow

$$TS\ daily\ inflow = OFMSW\ daily\ inflow\ \times (\%TS) \tag{12}$$

Equation 1: Amount of total volatile solids inserted daily

$$TVS\ daily\ inflow = TS\ daily\ inflow \times \frac{TVS}{TS} \tag{13}$$

Reactor volume:
As stated before, studies were conducted where the HRT was 16h and this is the time used for the calculation, to ensure that the process does not reach the methanogenesis phase.

Reactor volume

$$V_R = HRT \times Q \tag{14}$$

V_R – Reactor volume
Q = feed flow rate (m^3/day)

To calculate the Q parameter, it is important to note that the density of the waste in SV island is known. Which helps to calculate the feed floe rate, and the volume of the reactor.

Daily H_2 production:
To perform the calculation, the substrate was assumed to be mainly formed by glucose, as a higher part of glucose is carbohydrates, and as mentioned before carbohydrates are the main contributors for hydrogen production.

As mentioned earlier, the maximum hydrogen yield possible is 33% of the organic matter. Therefore, the hydrogen yield was calculated from the volatile solids added daily. The hydrogen yield was increased by adding the amount of volatile fatty acids produced from the previous batch back to the reactor, making it part of the process again.

The byproducts estimation was done using the stoichiometry of the breaking of glucose molecule, which allows to obtain the amount of CO2, acetic acid and slurry produced.

Volume of hydrogen produced daily

$$V_H = SGP \times KgTVS/day \tag{15}$$

SGP- Specific gas production (m_3/KgTVS)
V_H- daily hydrogen volume (m_3/day)
SGP = 0.17 m3/KgVS (Cavinato et al., 2012)

To estimate the hydrogen production over the year and the project lifetime, population and waste generation rate data were acquired from the world bank and PENGer databases respectively.

2.3.3 Economic Analysis of the project

The method used to determine the economic feasibility of this study is cost benefit analysis. This method is based mainly on 4 indicators: NPV, IRR, B/C, and (PP). The present techno-economic analysis is based on relevant literature, and all the assumptions are stated.

Total capital costs (TCC)

Can be divided into two categories: Fixed Capital Investment (FCI) and Working Capital Cost (WCC). The FCI is divided into purchased equipment, direct and indirect costs. The currency used throughout the estimation was USD. As the conversion rate from USD to Escudos Caboverdianos (ECV) does not vary significantly throughout the years, the variation in conversion was not considered.

The total capital cost of fermentative hydrogen production from OFMSW treating 3 tons of waste daily is around USD 0.5 million based on literature, so it is assumed that this is the actual cost for this project (Kannah et al., 2021; Ma & Tao, 2023). The distribution of the FCI costs were estimated based on Peters et al., job (Peters et al., 2003).

General total capital cost

$$CC = FCI(direct\ cost, indirect\ cost) + WCC \tag{16}$$

For the land costs, the assumption is that the land will be provided by the government, so the cost was not included in the calculation. The WCC is assumed 6.1% of the total fixed capital cost (Lam et al., 2014).

Operational costs (OC)

According to Yun et al., the operating costs is normally assumed to be 25% of the capital cost (Yun et al., 2018). The maintenance cost is assumed to be 7% of the FCI (Peters et al., 2003).

The administrative salaries, taxes and insurance were accounted together as overhead cost of the facility, by Kannah et al., 50% of the labor and maintenance cost account for overhead of the facility (Yukesh Kannah et al., 2021).The transportation of feedstock cost was not included in this analysis, because this job is done by the municipality.

The inflation rate also was considered to calculate the operational cost throughout the lifetime of the project, currently in Cape Verde the inflation rate is 3.5% according to (Banco de Cabo Verde, 2021)., and this value was assumed to be constant for each year. The same inflation rate was used for the bank loan when estimating the capital cost for the project. For each year the inflation factor was multiplied by the operational cost obtained in the past year.

Cost during the project lifetime

The project lifetime was assumed to be 15 years. The discount rate in Cape Verde is 5.43% according to (Banco de Cabo Verde, 2021). The cost was estimated for the total lifetime, and discounted.

Present value (PV) of the cost

$$PV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{17}$$

Benefits during the project lifetime

Throughout the project's lifetime, a range of significant benefits emerges, stemming from the utilization of hydrogen, CO2, and the solid byproduct. These benefits extend beyond immediate gains, encompassing environmental advantages, economic viability, and sustainable waste management.

Hydrogen selling

With the estimation of H_2 amount produced done previously, it is possible to calculate the selling price for it.
LCOH – levelized cost of hydrogen

Levelized cost of hydrogen (LCOH)

$$LCOH = \frac{disocunted\ CO}{quant\ H2\ prod}\ (over\ the\ lifetime\ of\ the\ project) \tag{18}$$

Hydrogen selling tariff

$$\text{Selling tariff} = \text{LCOH} + \text{profit margin} \tag{19}$$

The profit margin was assumed, which was added to the LCOH to obtain the selling tariff for the hydrogen.

Hydrogen revenue

$$\mathrm{Revenue} = \mathrm{selling\ tariff} \times \mathrm{Kg(H2)sold} \tag{20}$$

The revenue was calculated based on the assumption taken from literature that the facility works at 90% of its capacity (Ahmed et al., 2021; Mona et al., 2020).

CO2 and slurry selling

The selling of the solid residues and CO_2 were also included as benefits of the project. The selling price for each one of them was taken from literature and followed by the calculation of the discounted revenue (López-Gómez et al., 2019).

Carbon dioxide (CO2) revenue

$$\mathrm{Revenue} = \mathrm{selling\ tariff} \times \mathrm{Kg(CO2)sold} \tag{21}$$

Slurry revenue

$$\mathrm{Revenue} = \mathrm{selling\ tariff} \times \mathrm{Kg}(Slurry)\mathrm{sold} \tag{22}$$

Total revenue of the project

$$PV = \sum_{t=0}^{n} \frac{B_H}{(1+i)^t} + \sum_{t=0}^{n} \frac{B_{CO2}}{(1+i)^t} + \sum_{t=0}^{n} \frac{B_{slurry}}{(1+i)^t} = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} \tag{23}$$

Net present value (NPV)

This indicator will help to define if the project is worth to invest or not. If:

NPV > 0 -> The project is profitable, worth to invest.

NPV < 0 -> Project not profitable, may not be a good investment opportunity, economically speaking.

NPV = 0 -> The project may not provide a considerable return on the investment made.

Net present value (NPV) of the project

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} - \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} \tag{24}$$

Where:

I = discount rate

t = number of years

For the estimation of revenues during the 15 years of the project’s lifetime, the year zero was estimated based on actual values, while projections were made for the remaining years. The procedure followed to do the projections for each product of the system is the same as the one used for the first year.

Internal rate of return (IRR)

Another indicator used to determine if the project is economically feasible is IRR, the formula <IRR> on excel will be used to calculate it.

Benefit cost ratio (B/C)

This indicator will also give an important input whether the project is profitable. If:
B/C > 1 -> the project can be implemented and there is profit.
B/C < 1 -> is not economically profitable to implement the project.

Benefit cost ratio

$$BCR = \frac{disc\ cash\ inflow}{disc\ cash\ outflow} \tag{25}$$

Payback period (PP)

To implement the project there is a need for a loan, with this there is a need to estimate how many years will the owner of the project need to be able to liquidate the debt.

Payback period

$$PP = \frac{Initial\ inv}{Ave\ annual\ Casflow} \tag{26}$$

Initial investment – TCI plus the operational cost in year zero of the project.
Cashflow – the difference between the discounted benefit and cost.
With these four (4) indicators, the decision makers will be in a good position to take a decision considering the future of the project.

Break-even Point (BEP)

Break-even Point (BEP)

$$BEP\ = \frac{Fixed\ costs}{Selling\ price - Variable\ costs} \tag{27}$$

Fixed costs: the operational cost is composed of the fixed costs and the variable costs. To obtain the total fixed costs it is necessary to remove the variable costs amount from the total operational cost.
Selling price: as the study performed is related to selling 3 products, there is a need to obtain the Weighted Average Selling Price (WASP) which is the selling price of each product multiplied by the percentage that the product represents on the total sales. The selling price is taken from previous assumptions and the percentage is calculated considering the weight of each product on the total revenue of the project. The total WASP is the summation of the three values.
Variable costs: The unit variable cost for each product was calculated dividing the total variable cost by the total amount of each product. The units' variable cost was used to calculate the contribution margin (selling price – variable cost). The Weighted Average

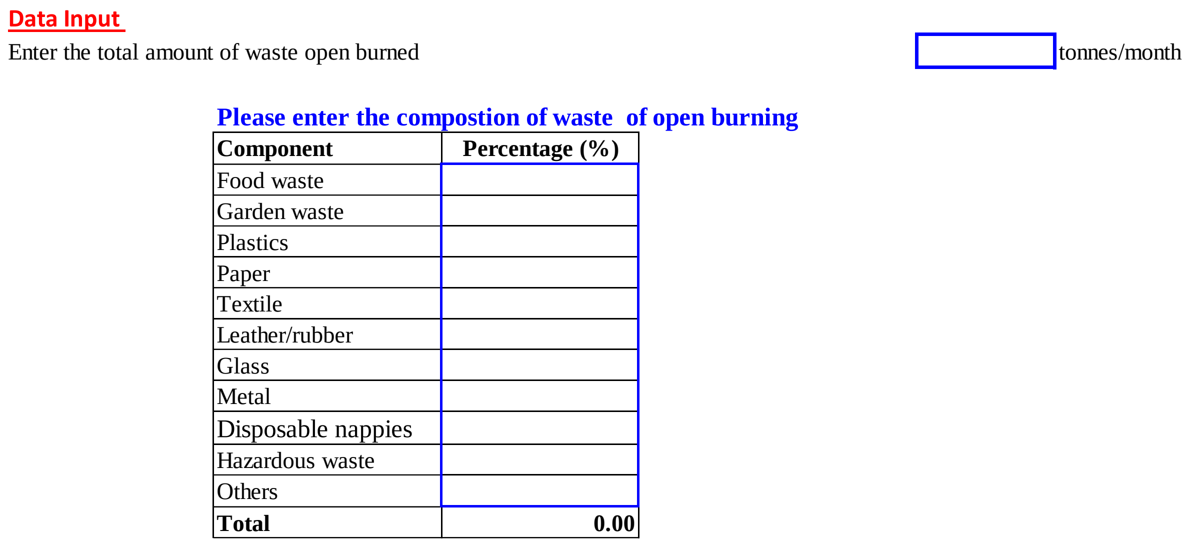
Contribution Margin (WACM) is the sum of the individual ones. The variable cost was calculated (WASP-WACM) (Gutierrez & Dalsted, 2022).

To analyse the results from this analysis graphs were plotted. Where after calculating the break-even point using the proper equation. Six points were chosen to be plotted considering the value obtained in the BEP calculation. On the plot, the goal was to see where the cost and the revenue graphs intersect with each other, as they define the BEP.

2.3.4 Environmental benefits from waste treatment

Estimation tool for GHG emissions from MSW management in a life cycle perspective was used, which is developed by the Institute for Global Environmental Strategies, III version (Menikpura et al., 2021).

Under the spreadsheet on excel, the table exposed in *Figure 4* was used, which requires the monthly waste composition in percentages, and the amount of waste burned. The output was CO2 equivalent per ton of waste burned.



Data Input

Enter the total amount of waste open burned ☐ tonnes/month

Please enter the compostion of waste of open burning

Component	Percentage (%)
Food waste	
Garden waste	
Plastics	
Paper	
Textile	
Leather/rubber	
Glass	
Metal	
Disposable nappies	
Hazardous waste	
Others	
Total	**0.00**

Figure 4: Waste streams for CO_2 savings

Source: Tool for GHG emissions from MSW management in a life cycle perspective, 2021

The results obtained refer to the monthly CO_2, because the model takes into consideration the fossil CO_2 emissions only. To estimate the emissions from organic waste burning, another method was adopted.

As stated previously based on a report carried out by the Environmental Agency, the emissions per ton of waste burned are the same in range regardless of the source. So, this was taken into consideration when assuming that the same emission value per ton of waste burned between organic sources and non-organic (Environment Agency, 2020). To obtain the savings the difference between the two emissions values were calculated.

3. Results and Discussion

3.1 Organic fraction of municipal waste daily production estimation

The Figure 5 shows the average composition of Municipal waste in Sao Vicente Island, the organic fraction is the one presenting the highest share with 16.9% having a moisture content and C/N ratio of 69.1%, and 126 respectively, followed by other residues (15.90%), glass bottles (15.50%), and paper/ cardboard (13.10%).

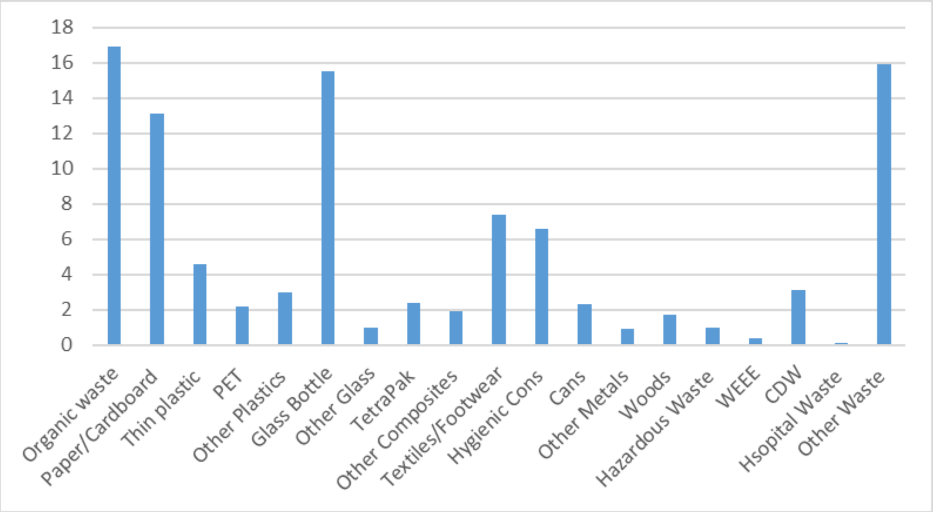


Figure 5: Waste composition in Sao Vicente Island

WEEE-Waste Electrical and Electronic Equipment
CDW-Construction and Demolition Waste
Source: Adapted from, PENGer, 2016

3.2 OFMSW in Sao Vicente for hydrogen production

The *Table* ***3*** presents the organic stream of the waste which will contribute to the hydrogen production, as stated previously only 69% of the organic waste will contribute for the hydrogen yield.

The theoretical amount of waste which could be converted to hydrogen is 8 tons daily, in practice only the volatile solids will be converted.

Table 3: Amount of waste for hydrogen production

Population in 2023	Production per capita	Waste generated	OFMSW	For hydrogen production
83467 people	0.86 Kg/hab*day (Source: ANAS)	68442.94 Kg	11600 Kg	8000 Kg

As stated earlier, the management of MSW is challenging due to the complexity of its characteristics, so the municipality takes the option which is less costly and demands no advanced technologies to perform it. The abundance of waste proved by the statistics presented above can be an energy source if a better management approach is adopted.

This is reinforced by Panigrahi & Dubey when they stated that OFMSW is a cheap, abundant, and rich source of carbohydrates, minerals, vitamins, and micronutrients making it a good substrate for biohydrogen production (Panigrahi & Dubey, 2019).

3.2.1 Proposed project

Until now all this waste generated has a unique final destiny which is open burning, and the main purpose of this research is to find out a solution which will help on tackling this problem. In the process flow chart presented on *Figure 6*, the proposed solution can be found.

The organic waste will be introduced into the reactor where it will undergo first the breaking down of the complex substrate into simple units (fructose, glucose, sucrose), the focus of this project will be glucose being it the main contributor for hydrogen production.

The two steps after hydrolysis where the acidogenic and acetogenic bacteria will convert the organic matter into acids mainly acetic acid, CO_2, H_2 and slurry. As illustrated the acids will be inserted back into the hydrolysis process to enhance the substrate amount and, the gas stream will be separated and purified using PSA systems, making the CO_2 and H_2 ready to be sold.

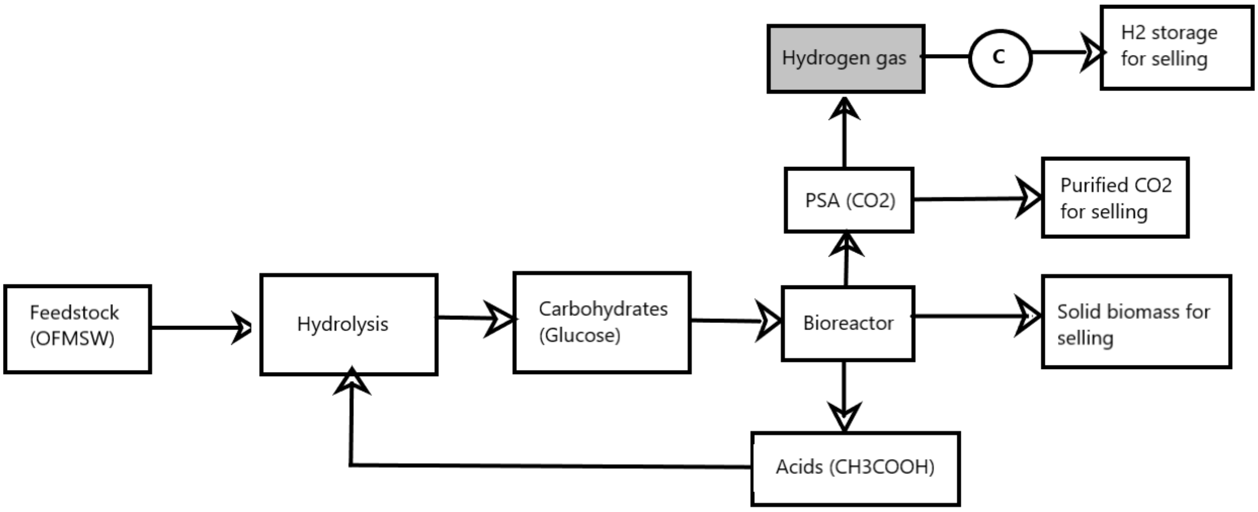


Figure 6: Process flow chart

3.3 Hydrogen Estimation

Based on the samples collected by the OPWM study, on the table below it is possible to find the values observed for the solids content. The value in percentage 27.02%.

Table 4: Physical composition of the organic waste

Components	Mind 001 (mg/Kg)	Mind 002 (mg/Kg)	Mind 003 (mg/Kg)	(mg/Kg)	Percentage (%)
TVS (total volatile solids)	317468	233343	243445	264752	26.48
TFS (total fixed solids)	4762	5782	5754	5433	0.5
Total solids				270185	27.02

The results presented on the table above, refer to the solids present in all the waste, for the conversion to happen there is need to know the solids content of the organic fraction which will undergo the anaerobic digestion.

The daily total solids inflow is around 2.2 tons, considering that the inorganic matter content is not a huge amount, the total volatile solids daily inflow is around 2.1 tons, this amount is eventually what will be converted to hydrogen.

The volume of the reactor is a parameter that will ideally stablish that the process will produce hydrogen, because the hydraulic retention time defined as 16h will ensure the interruption of the reaction on the acetogenesis phase which is where we have hydrogen production. To calculate the reactor volume, volume flow rate of total volatile solids was calculated, and the waste density is 116 Kg/m^3 therefore the volume is 18.02 m^3.

It is stated in literature that the dark fermentation process is limited by a factor of 33/100, where the reaction is never able to convert more than 33% of the feeding (Ghimire et al., 2015) . This factor was taken into consideration to make the process more realistic. The daily inflow volume was calculated to be 6.01 m3 and the mass 873.85 Kg, it is worth noting that after the first day of production the quantity of acids produced will be added as feed material.

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH(\text{acid acetic}) + 4H_2 + 2CO_2 \qquad (28)$$

The estimation of the products yield of the above reaction is explained below. For the hydrogen estimation, to make it more precise to dark fermentation process a formula involving the specific gas production were used. Where the value used was 0.17 m^3/KgTVS, and this value multiplied by the mass of the daily inflow volatile solids, gave the volume of hydrogen produced daily.

The volume of the other products was based on the stoichiometric ratios. The value obtained was then multiplied by the factor stated earlier on for each product (CO_2, CH3COOH, and slurry).All the yields of the production process were multiplied by the capacity factor of 90%, throughout the day, year, and the lifetime of the project, the results obtained can be observed on the

*Table **5**.*

Table 5: Estimated production of hydrogen and bioproducts

	Production capacity		
	Daily	Yearly	Lifetime
H_2 (m^3)	201.47	73,535.06	1,176,560.98
CO_2 (Kg)	368.29	134,427.62	2,016,414.36
Acid (CH3COOH) (Kg)	795.66	290,417.32	4,356,259.86
Slurry (Kg)	188.46	68,786.87	945,152.32

The results obtained from the hydrogen estimation showed that in this case the total volatile solids present in the substrate is 26.48% which means that from the 8 tons of organic waste generated daily only 2.1 tons will be converted to hydrogen and byproducts.

With these specifications the hydrogen, CO2, acetic acid, and slurry produced daily is 201.47 m^3, 368.29 Kg, 795.66 Kg, and 188.46 Kg respectively. The acids present a higher yield which is because of the limitation of the dark fermentation process. To estimate the product yields over the years the population growth rate was taken being 0.9% and the waste growth rate is estimated to be 3.5% (ANAS, 2016; Masud et al., 2023).

The hydrogen yield observed in this study are higher than the analyses done by Santiago et al., performed with the same HRT 16 hours, where the hydrogen production observed were 20.3 m^3/day (Santiago et al., 2020).

3.4 Economic analysis of the project

One common way to evaluate if a project is feasible economically is through the cost benefit analysis.

3.4.1 Total capital cost

The total capital cost was divided into fixed capital investment (direct and indirect costs) and working capital. The total capital cost, fixed capital investment and working capital were 603,500.22 USD, 537,115.20 USD, and 32,764.03 USD. When considering the bank loan inflation of 3.5%, which is used when doing the cost projection. And the specifications can be found on the table below.

Table 6: Total capital investment of the project

	Direct cost	**Percentage of TCC**	**Cost**
Fixed capital investment	Purshased equipment installed	30%	$ 181,050.07
	Instrumantaion and control installed	7%	$ 42,245.02
	Piping installed	6%	$ 36,210.01
	Buildings (including services)	5%	$ 30,175.01
	Yard improvement	2%	$ 12,070.00
	Indirect cost		
	Service facilities installed	12%	$ 72,420.03
	Engineering and Supervision	7%	$ 42,245.02
	Construction	8%	$ 48,280.02
	Legal and Contractor fees	4%	$ 24,140.01
	Project contigencies	8%	$ 48,280.02
FCI		89%	$ 537,115.20
H2 safety related			$ 33,621.00
Working capital cost			$ 32,764.03
Total capital cost	**FCI+WC**		**$ 603,500.22**

Hydrogen production from dark fermentation involves costs associated with the direct operation unit sch as the purchased equipment, involving all the equipment necessary to make the plant operational, and some other costs control system, the cost associated with the installation of these equipment, piping, buildings, and yard. And the costs that are not directly related to the daily operation of the facility, such as services, engineering and supervision, construction, legal and contractor fees, and the contingencies.

All the costs were defined based on the percentage of the total capital cost. The total capital cost was estimated based on the facility size considering the amount of waste treated daily.

The working capital cost is the cost associated with the initialization of the production process, training for the operating labor, costs associated with the feedstock. To define the percentages of the direct and indirect costs data from the research performed by Peters et al., (2003) was used.

According to the results expressed the FCI including the purchased equipment are the main constraint of fermentation process for hydrogen production, 89% of the TCC were dedicated to the FCI. A study performed by Dinesh et al., (2018), where were used a raw material with similar properties, the total capital cost was 1,636,560, treating 100 tons of organic waste per day.

3.4.2 Purchased Equipment

The set of equipment used was based on the flowchart proposed for the project and based on the previous table.

Table 7: Purchased equipment for the setup of the facility

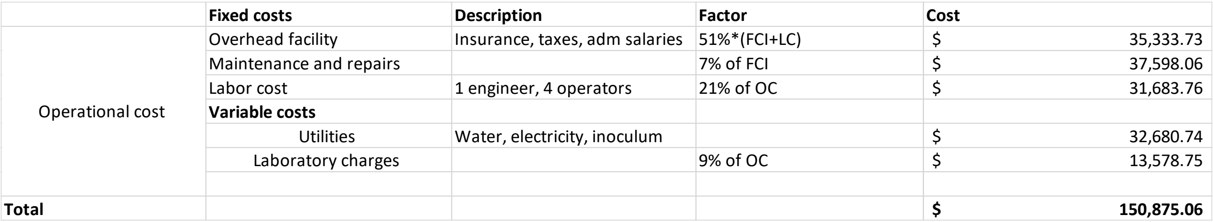
Purchased Equipment	
Equipment	**USD**
Bioreactor	$ 181,050.07
Purification system	
Pretreatment	
Pump	
Storage tanks (H2 and CO2)	

The purchased equipment was defined as a factor of 30% of total capital cost, which cost a total of 181,050.07 USD to purchase all the necessary equipment to set up the hydrogen production site. This cost includes the installation cost. From the study mentioned above even though treating more waste than this proposed project, the costs of purchased equipment are still lower, there is no mention of the installation cost being included.

3.4.3 Operational costs (OC)

The OC was estimated to be 150,875.06 USD for the first year of the project, and afterwards the projection of the cost was estimated taking into consideration the inflation rate and the lifetime of the project. The most significant share of it is dedicated to the fixed costs, specifically the overhead facility costs, maintenance, and labor costs and repairs 35,333.73 USD, 37,598.06 USD, 31,683.76, respectively.

Table 8: Operational cost of the project



	Fixed costs	**Description**	**Factor**	**Cost**
Operational cost	Overhead facility	Insurance, taxes, adm salaries	51%*(FCI+LC)	$ 35,333.73
	Maintenance and repairs		7% of FCI	$ 37,598.06
	Labor cost	1 engineer, 4 operators	21% of OC	$ 31,683.76
	Variable costs			
	Utilities	Water, electricity, inoculum		$ 32,680.74
	Laboratory charges		9% of OC	$ 13,578.75
Total				**$ 150,875.06**

The annual production costs were assumed to be 25% of the total capital cost. The overhead annual costs are around 23% of the operational costs, this cost refers to the costs of insurance, taxes, administrative salaries, rent. All these estimations are according to the study done by (Peters et al., 2003).

3.5 Costs and benefits of the project

3.5.1 Lifetime costs of the project

With a discount rate of 5.43%, project lifetime of 15 years, the yearly discounted cost for the project on average is 194,266.62 USD. The initial investment in year zero is 754,375.28 USD.

Table 9: Lifetime costs of the project

	Year	Costs	Present Value
Discounted total cost	0	$ 754,375.28	$ 754,375.28
	1	$ 188,919.71	$ 179,189.71
	2	$ 194,385.16	$ 174,877.80
	3	$ 200,041.90	$ 170,697.97
	4	$ 205,896.62	$ 166,645.04
	5	$ 211,956.26	$ 162,714.11
	6	$ 218,227.99	$ 158,900.48
	7	$ 224,719.23	$ 155,199.67
	8	$ 231,437.66	$ 151,607.39
	9	$ 238,391.24	$ 148,119.57
	10	$ 245,588.19	$ 144,732.28
	11	$ 253,037.04	$ 141,441.82
	12	$ 260,746.59	$ 138,244.60
	13	$ 268,725.98	$ 135,137.22
	14	$ 276,984.65	$ 132,116.43
Total		**€ 2,680,879.41**	**$ 2,913,999.36**
Average		**€ 178,725.29**	**$ 194,266.62**

As shown in the *Table 9* for the initial investment in year zero the cost was obtained by the addition of the total capital cost and the operational cost, for the next years the costs were the working capital and the operational cost. The initial investment falls in the range of previous studies, as proved by the study conducted by Han et al., where the initial capital investment was around 0.6 million USD (Han et al., 2016).

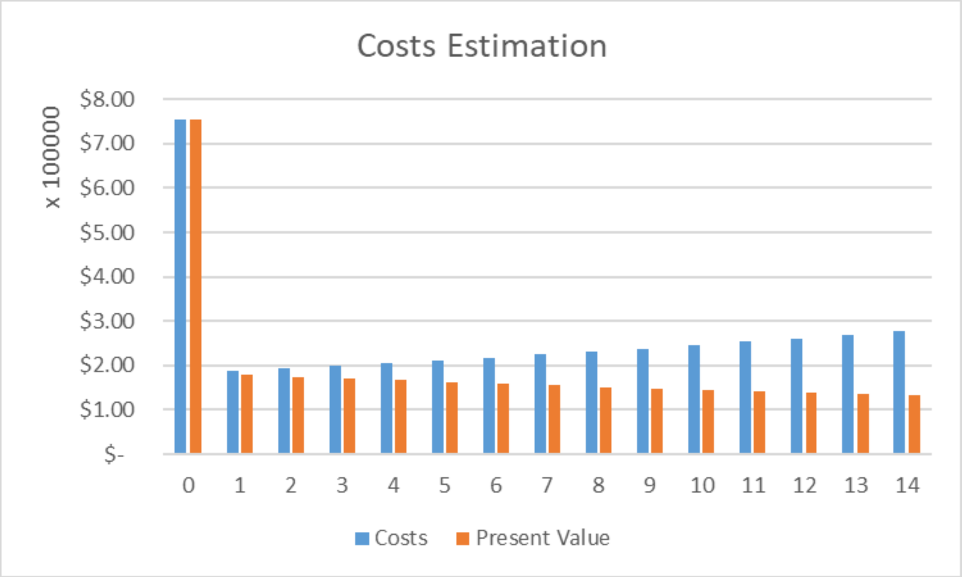


Figure 7: Cost Estimation throughout the project lifetime

The Figure 7 displays the project's expenses from year one to year 15. In the first year (year zero), the cost is notably high because it includes all initial capital and ongoing operating expenses. In the following years, costs decrease as we only consider the money needed for day-to-day operations, making the project more financially manageable.

3.5.2 Lifetime benefits of the project

3.5.2.1 Hydrogen selling

The revenue obtained from the hydrogen selling throughout the project lifetime is expressed in the table below, where the total amount of hydrogen produced yearly was multiplied by the hydrogen selling tariff (5 USD/m^3). The LCOH obtained was 2.64 USD/m^3. Which means for every m3 of hydrogen sold the profit margin will be 2.35 USD.

Table 10: Benefits of the project from hydrogen selling

Year	Revenue	Present value
0	$ 243,999.86	243,999.86
1	$ 303,657.62	288,018.23
2	$ 314,106.63	282,584.73
3	$ 324,738.58	277,103.02
4	$ 335,555.86	271,586.39
5	$ 346,560.87	266,047.08
6	$ 357,755.99	260,496.37
7	$ 369,143.62	254,944.66
8	$ 380,726.14	249,401.49
9	$ 392,505.94	243,875.61
10	$ 404,488.74	238,377.01
11	$ 416,673.81	232,910.96
12	$ 429,067.05	227,486.01
13	$ 441,667.54	222,106.26
14	$ 454,481.38	216,779.00
		$ 3,775,716.67
		$ 251,714.44

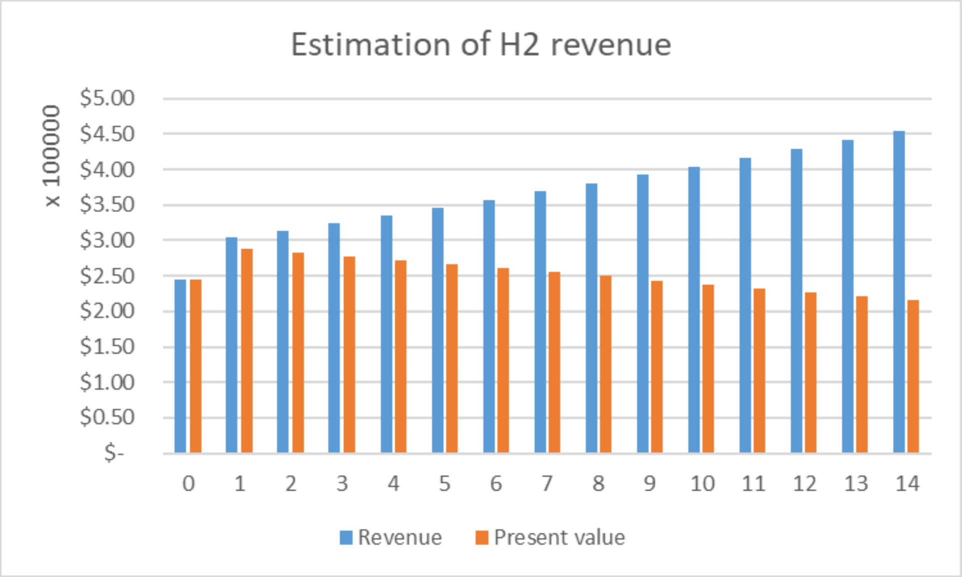


Figure 8: Hydrogen revenue estimation

3.5.2.2 CO_2 selling

The revenue obtained from the CO_2 selling was calculated based on the quantity of gas produced multiplied by the market selling price of it, taken from literature (0.3 USD/Kg), and the discounted value was calculated the same way done by hydrogen.

Table 11: Benefits of the project from CO2 selling.

Year	Revenue	Present value
0	$ 30,599.35	30,599.35
1	$ 31,887.09	30,244.79
2	$ 33,197.47	29,865.96
3	$ 34,530.79	29,465.51
4	$ 35,887.36	29,045.89
5	$ 37,267.46	28,609.40
6	$ 38,671.41	28,158.20
7	$ 40,099.51	27,694.25
8	$ 41,552.04	27,219.41
9	$ 43,029.31	26,735.39
10	$ 44,532.04	26,244.03
11	$ 46,060.14	25,746.54
12	$ 47,614.34	25,244.53
13	$ 49,194.53	24,739.00
14	$ 50,801.48	24,231.34
		$ 413,843.59
		$ 27,589.57

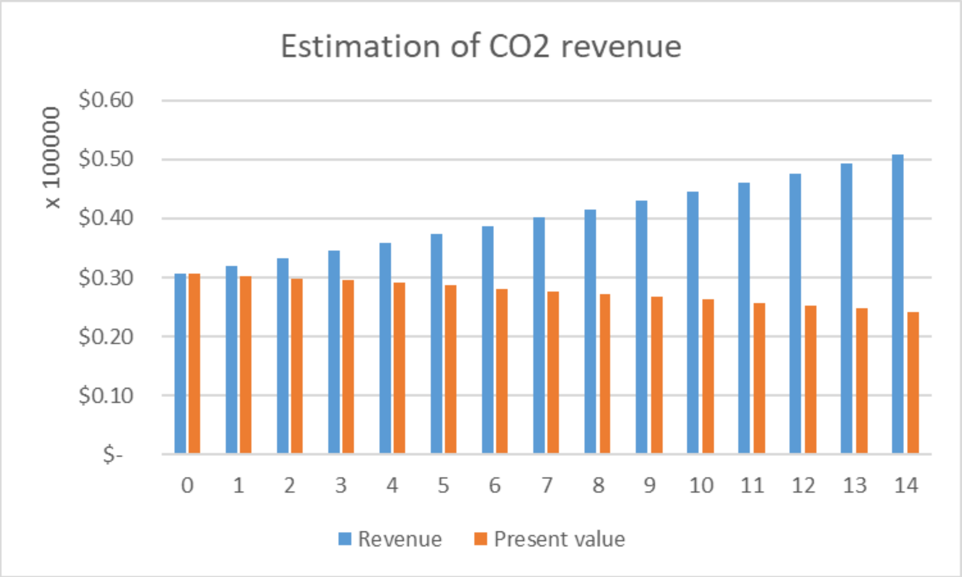


Figure 9: CO_2 revenue estimation

3.5.2.3 Slurry selling

The selling price for the slurry was 0.15 USD/Kg.

Table 12: Benefits of the project from slurry selling.

Year	Revenue		Present value
0	$	7,828.87	7,828.87
1	$	8,158.34	7,738.16
2	$	8,493.60	7,641.24
3	$	8,834.74	7,538.78
4	$	9,181.81	7,431.42
5	$	9,534.92	7,319.74
6	$	9,894.12	7,204.30
7	$	10,259.50	7,085.60
8	$	10,631.13	6,964.11
9	$	11,009.09	6,840.27
10	$	11,393.56	6,714.56
11	$	11,784.53	6,587.28
12	$	12,182.17	6,458.84
13	$	12,586.47	6,329.50
14	$	12,997.61	6,199.61
			105,882.27
			7,058.82

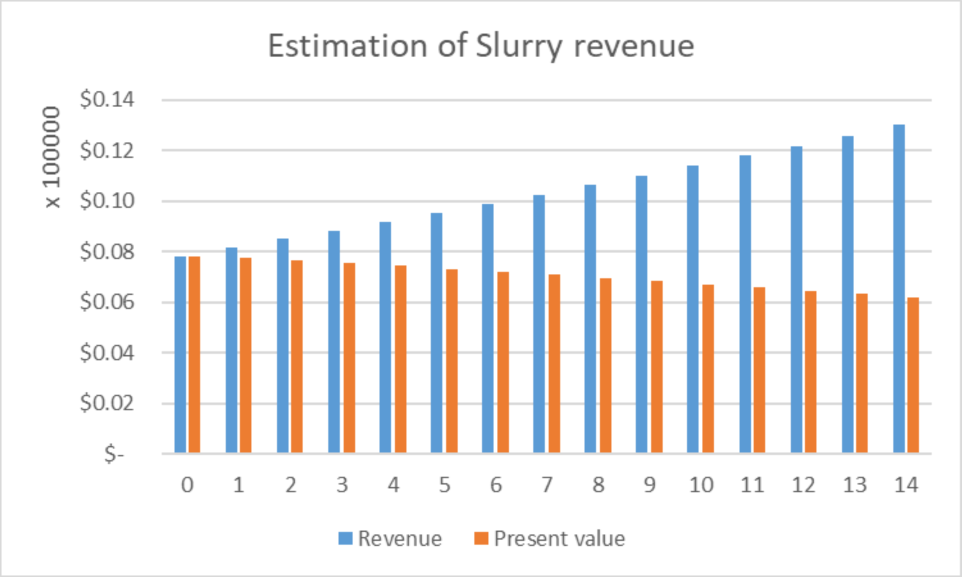


Figure 10: Slurry revenue estimation

3.5.2.4 Total benefits of the project

The total revenue from the project was obtained from the addition of the three streams of benefits.

Table 13: Total average revenue from the project.

Benefits	**Selling tariff**	**Unit**	**Annual Revenue (USD)**
Hydrogen	5	USD/m3	$ 251,714.44
CO2	0.3	USD/Kg	$ 27,589.57
Solid biomass	0.15	USD/Kg	$ 7,058.82
Total			**$ 286,362.84**

The cost of hydrogen production per cubic meter was calculated dividing the total discounted cost associated with the production by the amount of hydrogen produced during the lifetime. The value obtained is lower than the one from the market price currently (2.7 USD/m^3 H_2) (Bartels et al., 2010).

Considering the annual production of hydrogen, CO_2, and slurry 73,535.06 m3, 134,427.62 Kg, and 68,786.87 Kg respectively. The annual profit from the three items if the selling tariff considered is 5 USD/m^3, 0.3 USD/Kg, and 0.15 USD/Kg is 251,714.44 USD, 27,589.57 USD, and 7,058.82 USD respectively as shown in the table above.

3.5.2.5 Break-even analysis

The fixed cost is roughly around 1.5 million USD, the variable costs started from zero when no units are sold and achieved the maximum value of ¼ of a million USD. The total with the minimum value equal to the fixed cost and the maximum value does not exceed 1.6 million USD. The revenue increases from zero to a little over 2.2 million USD.

The break-even point units obtained was 351773.71, which means that for the costs and the benefits of the project to be the same there is need to sell 351773.71 units of the products. Regarding the revenue it is 1559412.87 USD, and the years estimated for the project to break-even is 8 years.

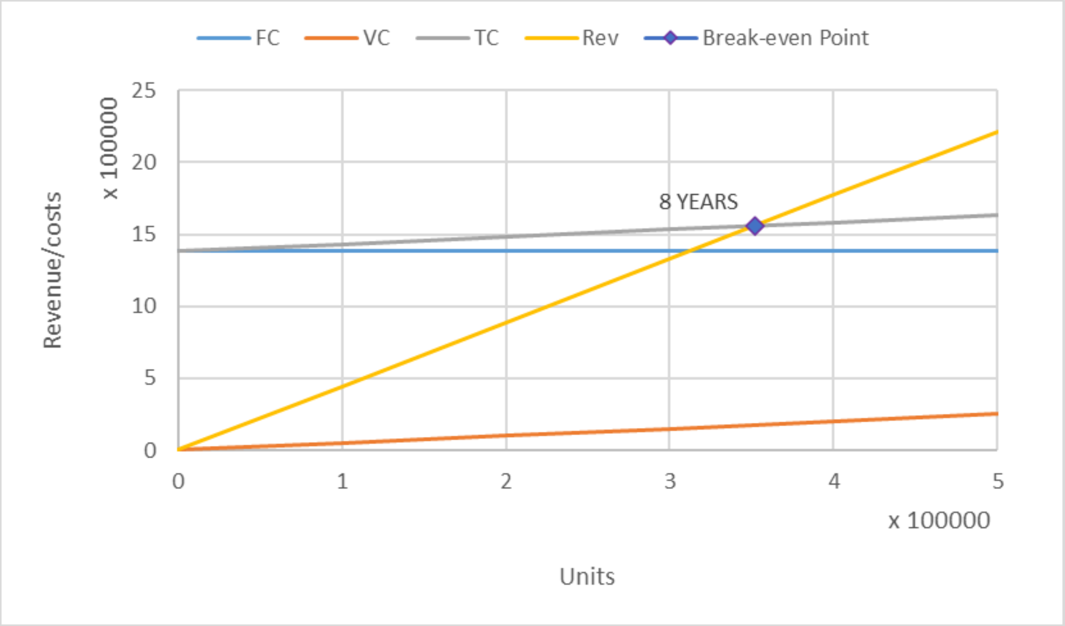


Figure 11: Break-even Point analysis

The variable costs will depend on the unit variable cost (0.5 USD) according to calculations using the notion of weighted average and the amount of units sold. The break-even depends as well on which product will be sold from this number of units obtained. It is possible to deduce that 309560.87 of the units sold must be from hydrogen, 35177.37 must be from the selling of CO2 and 7035.47 from the slurry.

A waste to energy facility studied in Indonesia with the lifetime of 15 years, obtained a break-even point of 6 years, which shows not a huge difference between both studies (Soleh et al., 2020).

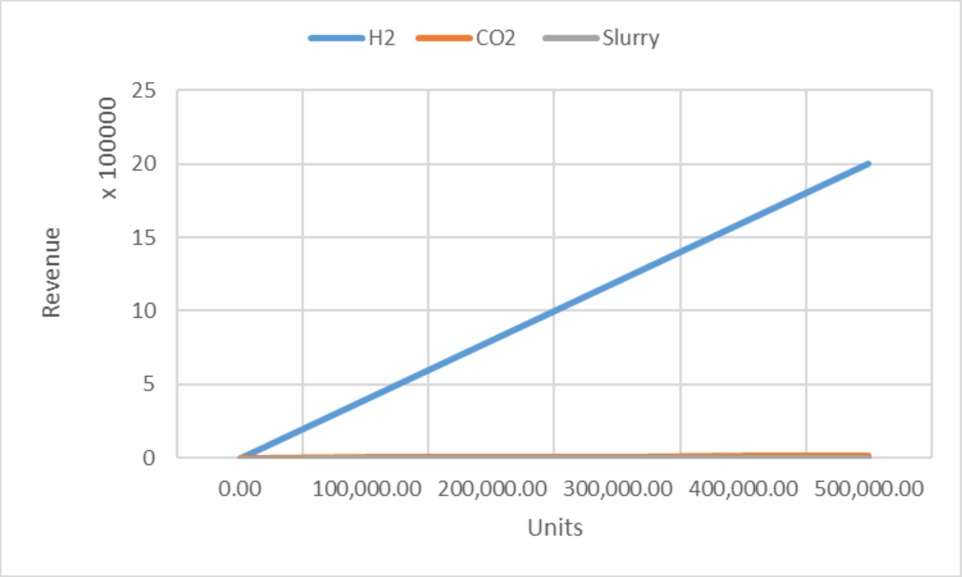


Figure 12: Projection of the project revenue, break-even

The figure above shows the revenue considering the three items sold, the period considered is related to the break-even point. On the graph it is possible to see that the revenue is coming mainly from the hydrogen selling.

3.5.2.6 The cost benefit indicators, analysis

The economic analysis goal was to come up with the four indicators. The NPV which is the difference between the total benefit and the cost of the project. If the NPV were to be 0 the discount rate had to be 29%. And the ration expresses that the project is feasible because he benefits overcome the costs, but for this the payback period had to be 8 years.

Table 14: Indicators of cost benefit analysis

Cost Benefit parameters	Value	Unit
NPV	1381443.18	USD
IRR	29%	%
B/C	1.474071201	
PP	8.19	years

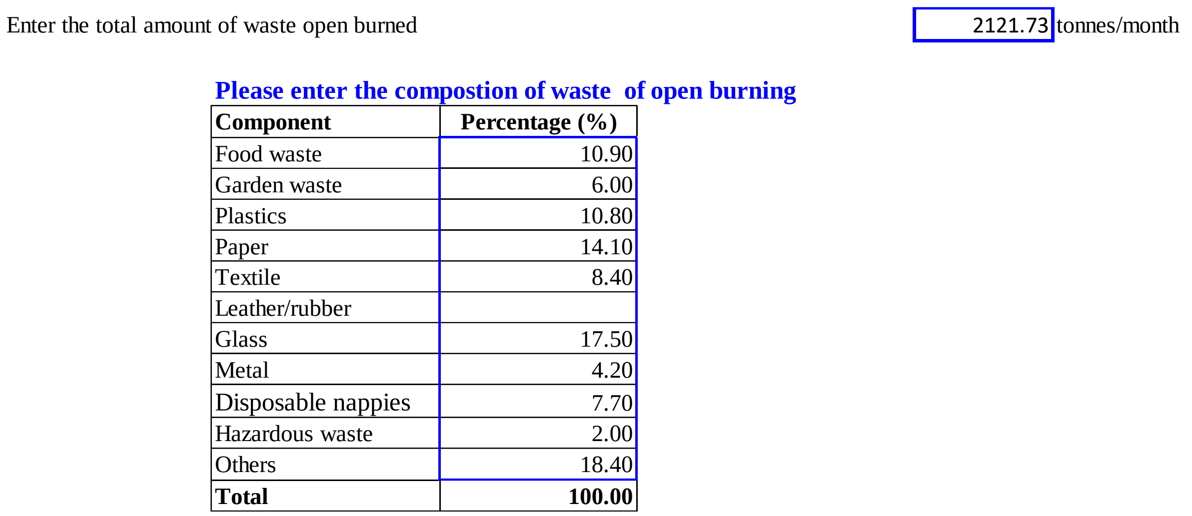
The need to take profit from the byproducts relied on the fact that only the hydrogen production will not be enough to make the project profitable. The study of these 4 parameters had the intention to make the economic analysis more practical, because when used only one of them some aspects are not taken into consideration. If considered only the NPV which shows 1,381,443.18 USD of profit throughout the lifetime, the conclusion would be the project is feasible, and profitable.

The IRR of 29% means that 29% is the discount rate which the NPV is equal to zero, considering that the discount rate used on this project is 5%, this indicates that the project is profitable because the IRR is higher than the discount rate. The benefit cost ratio of 1.5 shows, shows that the discounted benefits divided by the discounted costs is superior to 1, which means that for each unit of cost the benefits overcome it by 1.5 units, indicating as well that the project is profitable and not risky.

The PP indicates that the project needs 8.19 years of production to recover the money invested, which makes it feasible and profitable if compared with other projects where the payback period calculated was between 5-10 years, according to (Yin & Wang, 2022).

3.6 Environmental benefits of waste treatment

The total waste generated monthly is 2121.73 tons and composition based on the required inputs shows the organic waste composition of 16.9%. The glass fraction presents a higher amount 17.50, if considered that the fraction others is a mixture of waste.



Enter the total amount of waste open burned 2121.73 tonnes/month

Please enter the compostion of waste of open burning

Component	**Percentage (%)**
Food waste	10.90
Garden waste	6.00
Plastics	10.80
Paper	14.10
Textile	8.40
Leather/rubber	
Glass	17.50
Metal	4.20
Disposable nappies	7.70
Hazardous waste	2.00
Others	18.40
Total	**100.00**

Figure 13: Filled waste streams for CO2 savings.

To adapt to the model used, some waste categories were merged, without changing the nature of the waste composition on the island.

The results obtained from the tool used are presented based on the fossil fuel emissions per ton of waste burned which were 191.14 Kg of CO_2-eq. This value is the amount of CO2-eq emitted when one ton of waste is burned.
The objective was to find out when the organic fraction of the waste is burned what is the amount of CO2 which will be emitted if considered that one ton of burned waste release 191.14 Kg of CO2-eq.
As presented on the *Figure* ***14***, the amount of organic waste generated monthly is 358.57 tons. Considering that this amount of waste will probably be used on the facility, it will not be burned. Saving an amount of 68,537.56 Kg CO2-eq/ ton of organic waste.
A study performed by Okafor et al., (2022) conducted research to estimate the amount of CO2 emitted by the burning of waste in a year on Nigeria, where the amount of waste generated yearly is around 2.2 million tons, and the results showed that CO_2 emission per ton of waste burned was 801.2 Kg.

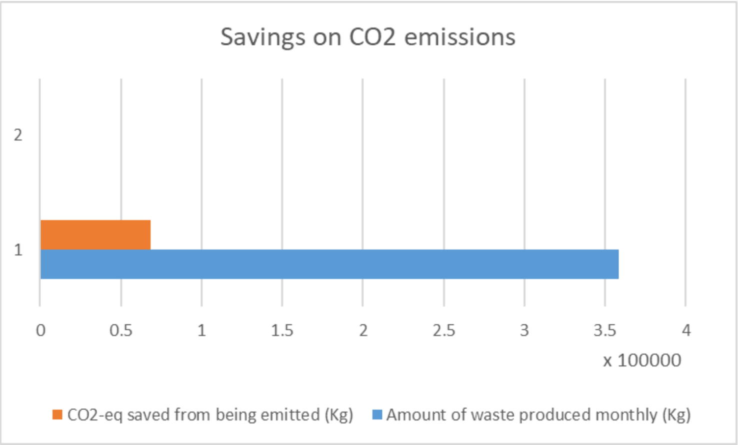


Figure 14: CO_2 saved from being emitted

A waste-to-energy facility in Sao Vicente Island is a possibility to change the waste management in the island. This research was based on the idea of producing hydrogen and valuable byproducts, where the techno-economic feasibility was studied, and an environmental component was included as well. First the understanding of the waste sector and properties was conducted. Secondly the relevant dark fermentation parameters were estimated based on literature to maximize the substrate conversion. The economic analysis based on cost benefit analysis offered a clear view on the project viability, and the benefits regarding CO2 emission reduction studied as well, suggested that the project can help protect the island ecosystem.

According to the calculations the waste generated daily in Sao Vicente is around 68 tons, and this waste is burned at the dumpsite. The organic fraction represents the biggest share 16.9% making up to 11.6 tons, the elaborated project proposes the valorization of this waste, which will add together with the improvement in waste management, the possibility of producing energy from the waste. From this amount only 2.1 tons of waste can be converted daily.

To ensure the hydrogen production dark fermentation process requires a low hydraulic retention time, and for this process was assumed the HRT being 16h, this parameter has a huge impact on the process because it will avoid the formation of hydrogen inhibitors. Another aspect considered was the limitation presented by the dark fermentation process, the maximum conversion to hydrogen possible is 33%.

The hydrogen production estimated daily is around 201.47 m3/day, the acids, CO2, and slurry production were 795.66 Kg, 368.29 Kg, and 188.46 Kg respectively.

The total capital cost for such a project was assumed based on literature to be 583092 USD, after the addition of the inflation rate the cost raised up to 754,375.28 and this amount was consequently divided amongst the fixed capital investment and working capital.

The operational costs were assumed to be 25% of the TCC so, 150,875.06 USD, based on these parameters the yearly and lifetime costs of the project were estimated. The annual average cost is 194,266.62 USD, and the total cost is 2,913,999.36 USD.

To ensure the profitability of the project the revenues considered come from the selling of hydrogen, CO2, and slurry. The total and annual revenue obtained throughout the lifetime of the project was 4,295,442.54 USD, and 286,362.84 respectively.

The 4 indicators of cost benefit analysis were calculated NPV, IRR, B/C, PP, and the results were 1,381,443.18 USD, 29%, 1.5, and 8.19 years respectively. For the foreseeable profits the break-even analysis was performed where in terms of units the project must sell in total 351,773.71 units for the cost and benefit to be equal.

In terms of the environment, the emission saved by this project are expressed in terms of emitted CO2- eq per ton of waste burned. If the project is implemented the monthly emissions will reduce from 405,539.61 to 337,002.05 Kg of CO2, 17% reduction.

Conclusion

While it is common understanding that waste dumped and burned is not the best solution for waste management, as it causes serious damage to the environment, health, and economy of a society. The waste-to-energy approach is being adopted throughout the world, and for Sao Vicente Island, this study proposed a way to valorize the organic waste generated using a fermentative process for hydrogen and byproducts production.

This research found that the waste generated in Sao Vicente has a considerable amount of organic matter which has in its constituent carbohydrates, main contributor for hydrogen production, the hydrogen estimated fell in the same range of other studies that used a similar approach. To complete the techno-economic analysis, three of out of the four cost benefit analysis indicators showed positive results but the payback period showed a less positive result.

The daily quantity of organic waste which will contribute to hydrogen production is around 2.1 tons due to the percentage of total volatile solids on the organic waste composition which is around 26%. From this amount of waste, the system produced 201.47 m^3 of hydrogen, 368.29 Kg of CO_2, 188.46, Kg of slurry, and 795.66 Kg of acids. The former three elements (H_2, CO_2, and slurry) are sold and the last one (acids) is reintegrated back into the process to enhance productivity. This method was adopted because the quantity of acids produced is way higher than the other products due to the dark fermentation limitations, therefore, to waste this amount of organic matter would be inefficient.

This project is economically feasible according to the cost benefit indicators (NPV, IRR, and benefit cost ratio, and Payback period) (1,381,443.18 USD, 29%, 1.5, and 8.19 years, respectively). The NPV indicates that the discounted total benefit is superior to the discounted total cost, making the project profitable, nevertheless, even if this indicator shows a positive result, it is not feasible to rely only on it. The IRR considers the NPV zero, which indicates that 29% is the annual return that makes the discounted cost and benefit equal. The B/C indicates profitability as well as the payback period which is within the range considered as a standard for this type of project. In terms of the year that the project will start generating profit, the break-even point indicates that in 8 years the cost and benefit will be equal and therefore profit generation.

If the project is realized, it will suspend the emission of 68,537.56 Kg of CO_2-eq per ton of waste burned. When considered that one ton of waste burned emits 191.14 Kg of CO_2-eq.

This research could be important and valuable in theory and practice. Researchers interested in this field of study could use the data from the estimated volatile solids and propose other technologies to couple with the one proposed in this research or to be used independently to valorize the waste.

And the research is valuable in practice because the government could use it as a starter point for taking a decision when considering a better approach for waste management in the island and the rest of the archipelago. With the implementation of such a project, the benefits are not only economic and environmental, but will also affect the lifestyle of the population, in particular, the people living around the dumpsite. Because if before working on the sorting of the waste was considered informal work, with the project implemented there will be the possibility of working in a safe environment, where health, wellbeing, and stability are priorities, similarly to any work environment.

Another practical aspect to consider is the inclusion of another renewable energy vector in the energy mix of the island and byproducts like CO_2, which is normally used by the industries, as well as the slurry, which can be used by the locals for animal feeding, and/or fertilization of the soil. The hydrogen produced could be used to produce electricity, heat generation for industries or for exportation, which in all cases will add value to the island and the country's economy.

Some limitations were detected when performing this study, which are the lack of secondary data on the field of waste-to-energy in Cape Verde, made the specification of some parameters hard to achieve, so one was obliged to make several assumptions. As well as the amount of carbohydrates in the organic waste, SGP of the reactor. While the assumptions made on the economic and environmental analyses were based on international standards.

The logistics was a factor which conditionate the primary data collection for the performing of the research, considering that with primary data collection the study would be portraying the current waste management situation in Sao Vicente. Moreover, a lack of experience in the research field made the researcher use relatively simple analysis techniques.

Due to the unavailability of data the estimation of hydrogen production method used took into consideration a limited number of parameters HRT, TVS, moisture content, reactor volume.

As recommendations, further research could focus on updating and diversifying studies related to the properties of the waste generated in Sao Vicente and make some analysis more detailed where all the parameters of the ultimate and proximate analysis would be studied.

A detailed market study to analyze how ready the society and the island are for waste-to-energy facilities.

Due to time constraints, a sensitivity analysis was not performed, which would have served to try to understand how the assumptions influence the results obtained and with this support even more the decision-making process.

The same approach could be studied as a possibility for the other islands, regarding the fact that some of them produce even more waste than SV and with a higher organic fraction.

A study related to the best application for the products obtained in this research could be done.

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