A thesis submitted to the African Center of Excellence in Energy for Sustainable Development, College of Science and Technology, University of Rwanda in partial fulfillment of the requirement of the degree of

MASTERS OF SCIENCE IN RENEWABLE ENERGY ENGINEERING

Thesis titled:

Feasibility study of biogas generation from anaerobic co-digestion of water hyacinth and fish waste.
"A case study of the shores of Kivu Lake"

Student: SHUMBUSHA Etienne
Registration number: 216131324

Supervisor: KAYIBANDA Venant, Professor.

ABSTRACT

The escalating demand for sustainable energy sources has propelled the exploration of biogas production, a process transforming organic waste into a valuable energy resource. This study investigates the feasibility of anaerobic co-digestion, employing water hyacinth and fish waste as co-substrates in a continuous-flow digester. The primary objective is to evaluate the economic viability and efficiency of the biogas production system.

The research employs a small-scale, low-cost batch digester system, offering a cost-effective approach suitable for resource-constrained settings. The digester design incorporates locally available materials, and the feedstock, composed of water hyacinth and fish waste, undergoes meticulous preparation and loading. The anaerobic digestion process is initiated, and key parameters such as temperature, pH, and gas production are regularly monitored in the simulation tool.

Through simulations, the proposed model predicts a cumulative biogas production of 10.5806 liters over 30 days. The sensitivity analysis unveils the system's responsiveness to variations in water hyacinth substrate concentration, emphasizing the need for precise control of environmental factors. Comparative analysis of biogas generation from the co-digestion of the water hyacinth and fish waste with existing literature reaffirms the reliability of the obtained-results.

The economic assessment demonstrates a potential monthly income of 17,483 RWF, considering the generated biogas quantity. Moreover, a payback period analysis, factoring in monthly expenses and income, suggests a sustainable investment time frame.

This research sheds light on the promising prospects of anaerobic co-digestion with water hyacinth and fish waste. It underscores the importance of community engagement, process optimization, and continuous monitoring for the successful implementation of biogas projects. The biogas production of 10.5806 liters over 30 days contributes to the broader discourse on sustainable energy solutions and provides a foundation for future research and implementation strategies.

The results and conclusions drawn from this study have provided valuable insights into the feasibility, optimization, and potential benefits of co-digestion for biogas generation from water hyacinth and fish waste in the specific context of Lake Kivu's shores.

DECLARATION

I, SHUMBUSHA Etienne the undersigned, declare that this Research Project is my original work, and has not been presented for a degree in the University of Rwanda or any other university. All sources of materials that were used for this thesis work have been fully acknowledged.

Name: SHUMBUSHA Etienne

Signature:

Date of Submission: 12 November 2023

This thesis has been submitted for examination with my approval as a university advisor.

Thesis Supervisor: KAYIBANDA Venant, Professor.

Signature:

LIST OF ABBREVIATIONS

°C: Degrees Celsius

C/N ratio: Carbon-to-Nitrogen Ratio

CH_4: Methane

CO_2: Carbon Dioxide

DG: Digestate Mass

DNC: Digestate Nutrient Content

FW: Fish Waste

FWDR: Fish Waste Degradation Rate

FWM: Fish Waste Mass

H_2S: Hydrogen Sulfide

HRT: Hydraulic Retention Time

k_: Acetogenesis Rate Constant

RWF: Rwandan Franc

S/I: Substrate to Inoculum Ratio

VFAs: Volatile Fatty Acids

VS: Volatile Solids

WH: Water Hyacinth

WHDR: Water Hyacinth Degradation Rate

WHM: Water Hyacinth Mass

θ: Arrhenius Temperature Factor

Table of Contents

CHAPTER 1

INTRODUCTION

1.1. Background

1.1.1. Water Hyacinth and Fish Waste as Problematic Waste Materials

Since it has infiltrated aquatic ecosystems in places like the Lake Kivu region, water hyacinth (WH) has become a serious environmental problem. Due to the invasive plant's quick growth, dense mats are created that choke streams, make it difficult to navigate, and upset the fragile environmental balance. Aquatic life is also threatened by the presence of water hyacinths because they lower the dissolved oxygen content of water bodies.

Apart from the difficulties caused by water hyacinths, fish waste (FW) is a byproduct of the fishing industry and raises additional environmental issues. Because fish waste contains a significant quantity of organic matter, improper management may cause it to decompose and release contaminants into the environment. One practice that can have far-reaching effects, including the possible spread of diseases, is the inappropriate disposal of fish waste.

Understanding how these environmental problems are related to one another and the necessity of all-encompassing management approaches is critical. Maintaining the health and balance of aquatic ecosystems requires addressing the invasive nature of water hyacinths and putting in place practical procedures for the appropriate removal and treatment of fish waste. We may strive toward sustainable practices that guarantee the health of ecosystems and the communities that depend on them by being aware of and addressing these environmental issues.

(see figure 1)

Figure1.1. The water hyacinth around lake shores in Rwanda. [1]

Fish waste production from both the ingestion and processing of fish is significant[2]. The improper disposal of fish waste can have negative effects on the environment and human health. To protect Lake Kivu's ecological integrity and advance sustainable waste management techniques, it is crucial to effectively handle both water hyacinth and fish waste.

Addressing these environmental issues and utilizing the potential for renewable energy at the same time are both made possible by the co-digestion of water hyacinth and fish feces. Through effective substrate utilization and increased microbial activity, combining water hyacinth, readily accessible biomass, with fish waste, a priceless organic resource, can maximize biogas generation.

1.1.2. Anaerobic Co-digestion as a Waste Treatment and Renewable Energy Solution

An environmentally friendly and sustainable biological process, anaerobic co-digestion turns organic matter into valuable resources. It works without oxygen and is mainly powered by microorganisms in specialized anaerobic digesters. The two main products of anaerobic co-digestion are digestate, which is a nutrient-rich byproduct, and biogas, which is a renewable energy source. One of the main benefits of anaerobic co-digestion is that it can process different kinds of organic waste at the same time. This versatility is a major advantage because it allows for the efficient use of a variety of waste materials that might not be suitable for digestion when isolated. By combining different organic sources, co-digestion maximizes resources.

While co-digestion has been extensively researched, very few researches have been done explicitly on the co-digestion of water hyacinth and fish excrement, and almost no single research on Lake Kivu's beaches. By examining the viability and optimization of biogas generation from the co-digestion of water hyacinth and fish waste collected from the beaches of Lake Kivu, this research project seeks to close this knowledge gap.[3]

Furthermore, co-digestion has benefits that go beyond waste management. When several organic materials are digested at the same time, a synergy is produced that can enhance performance measures. This results in increased biogas outputs, optimizing the possibility of producing renewable energy. Concurrently, the digestate that results from the co-digestion process is of higher quality and contains vital nutrients that make it suitable for use as an organic fertilizer.

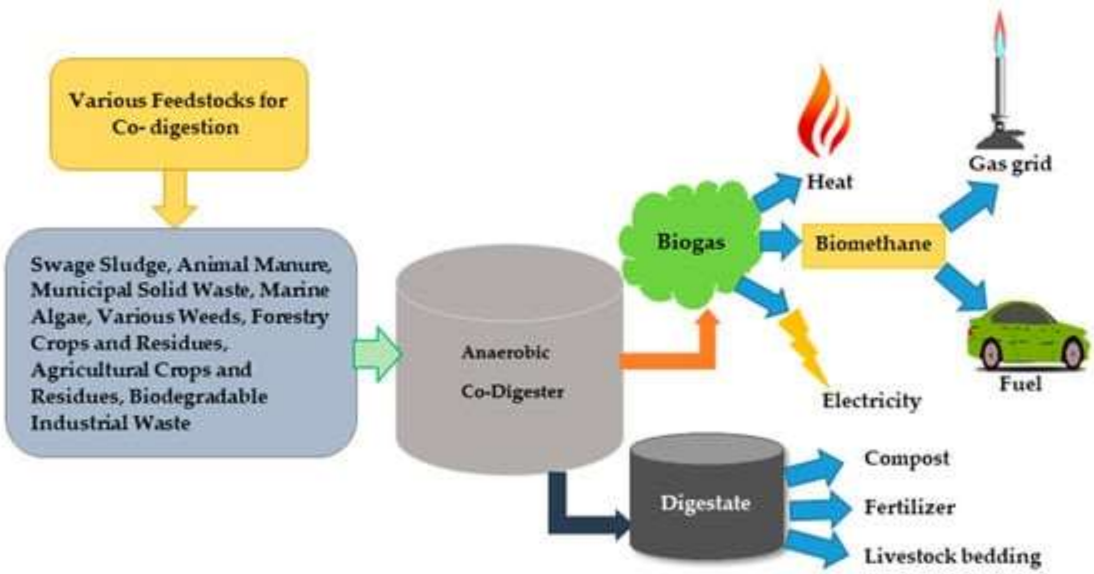

Figure 1.2. Co-digestion of multi-feedstocks for waste reduction and energy recovery[4]

Anaerobic co-digestion, in its simplest form, not only solves the problem of disposing of organic waste, but also converts it into a rich source of nutrients for soil conditioning and a sustainable energy source. Adopting co-digestion technology is a big step toward handling organic waste in a circular and environmentally responsible manner, which will help with energy production and sustainable agriculture. Anaerobic co-digestion technologies present new opportunities for the effective and responsible use of renewable energy sources to support our ecosystems. These opportunities arise from ongoing research and development.

This study offers important information on the efficacy of co-digestion as a waste management technique, the possibility of producing renewable energy, and the use of the digestate produced as an organic fertilizer. The findings of this study will offer important knowledge to decision-makers, environmental organizations, and local populations, assisting in the development of renewable energy sources, sustainable waste management techniques, and ecosystem protection for Lake Kivu.[5]

1.1.3. Biogas

One potential renewable energy source is biogas, which is produced when organic matter including plant and animal waste breaks down in an oxygen-free atmosphere. Microorganisms housed in anaerobic digesters effectively carry out this complex process known as anaerobic digestion. Methane (CH_4) and carbon dioxide (CO_2) make up the majority of biogas, with minor amounts of other gases such as ammonia (NH_3) and hydrogen sulfide (H_2S) present[6].

Organic waste is the source of biogas; without it, the material would break down and release the powerful greenhouse gas methane into the environment. Anaerobic digestion produces biogas, which is used in this process to actively reduce greenhouse gas emissions. As a result, the production of biogas is in line with environmentally beneficial waste management techniques.

Biogas is useful for a wide range of purposes, including the production of heat, electricity, and cooking fuel. Because of its versatility, it can be directly utilized in biogas-powered engines or converted into biomethane. This premium methane kind can be used as a sustainable fuel source for vehicles or injected into pipelines carrying natural gas.

Because biogas plants are not site-specific, they can be installed in a variety of contexts, including farms, landfills, and wastewater treatment facilities[7]. By reducing reliance on centralized power grids, this decentralized method of energy production fosters resilience and autonomy in local energy production[8].

To sum up, using biogas as a renewable energy source presents a variety of options for addressing energy and environmental issues. Biogas is a key element in promoting a greener and more resilient energy landscape because of its sustainable production from organic waste, adaptability, and potential for decentralized energy generation.

1.1.4. Potential of Biogas Production from Water Hyacinth and Fish Waste

Studies have shown that co-digesting WH and FW to create biogas is feasible. Because of its high carbohydrate content, WH is a good feedstock for producing biogas, while FW provides vital elements like phosphorus and nitrogen to aid in the digestion process[9].

The ideal WH to FW ratio for co-digestion relies on several variables, such as the target biogas yield and the particular properties of the feedstocks. High biogas yields have often been found to be produced at a ratio of 2:1 WH to FW.

Figure 1.3. Water hyacinth, pictured here in Lake Victoria, may block access for transport and fishing.[10]

Figure 1.4. A kid cleaning fishes after fishing on the lake's shores[11]

In the Lake Kivu region, the creation of biogas by the anaerobic co-digestion of fish waste and water hyacinth waste offers a promising way to manage trash and produce renewable energy. This location is especially well-suited for biogas production because of the abundance of feedstocks, the potential for environmental advantages, and the rising need for renewable energy. To fully fulfill this technology's potential, more study, experimental initiatives, and supportive legislation are required.

1.2. Problem Statement

The spread of water hyacinths and the incorrect dumping of fish waste provide serious environmental problems for Rwanda's Lake Kivu shoreline. The lake's biological equilibrium is upset by the unchecked spread of water hyacinth, which also hurts local fishing operations, water transportation, and aquatic habitats. Inadequate fish waste management also leads to environmental contamination and poses a risk to human health[12].

To overcome these obstacles, sustainable waste management techniques must be created that can both solve the water hyacinth problem and make use of the organic potential of fish waste. A possible method to convert these waste products into biogas, a renewable energy source, is anaerobic co-digestion. However, little research has been done explicitly on the co-digestion of water hyacinth and fish waste, especially about the Lake Kivu shoreline.

The issue at hand however is the dearth of thorough research investigating the feasibility study of the biogas generation from the anaerobic co-digestion of water hyacinth and fish waste in the particular setting of Lake Kivu's beaches. This information gap prevents the creation of efficient waste management plans, the use of renewable energy resources, and the preservation of the environment of Lake Kivu.

Insights into the potential of co-digestion as a sustainable waste management solution, the optimization of biogas production, and the use of the resulting digestate as an organic fertilizer can all be acquired by tackling this issue through focused research. To effectively manage water hyacinth and fish waste while utilizing renewable energy sources and maintaining the ecological integrity of Lake Kivu, policymakers, environmental agencies, and local communities will receive recommendations backed by evidence from this research[13].

1.3. General objective

The general objective of this study is to determine the feasibility generation of biogas by the anaerobic co-digestion of water hyacinth and fish waste from the Rwandan coasts of Lake Kivu. The study's objectives include investigating the viability, enhancing process variables, assessing biogas yield, and evaluating the digestate's quality.

1.3.1. Specific Objectives

- Co-digestion's viability is evaluated: Analyze how well water hyacinth and fish waste work together as co-substrates for anaerobic digestion, as well as any potential synergistic effects. The optimum mixing ratios for co-digestion should be determined.
- Enhance the process variables: To maximize the generation of biogas, investigate and fine-tune important factors including temperature, pH, and retention time. Establish the optimum circumstances for the efficient production of biogas from fish and water hyacinth waste.
- Quantify and contrast the biogas yield from the combined digestion of fish waste and water hyacinth with that from the mono-digestion of each feedstock. Analyze the co-digestion's effectiveness and efficiency in producing biogas.

By completing these precise goals, the study hopes to shed light on the feasibility, efficiency, and potential advantages of anaerobic co-digestion of fish waste and water hyacinth waste. The research will aid in the development of sustainable waste management techniques, the production of renewable energy, and the preservation of Lake Kivu's ecology.

1.4. Scope

The scope of this study is focused on the shores of Lake Kivu in Rwanda and specifically investigates the feasibility of biogas generation through the anaerobic co-digestion of water hyacinth and fish waste. The study encompasses the following aspects:

- Analysis of the characterization of feedstock: The study involves the analysis of water hyacinth and fish waste samples from the shores of Lake Kivu. The samples was characterized in terms of their composition, moisture content, nutrient content, and any potential contaminants.
- Co-Digestion process analytics': The research aims to study the co-digestion process by investigating and analyzing the key parameters such as temperature, pH, and retention time. The objective was to determine and suggest the most favorable conditions for maximizing biogas production from the co-digestion of water hyacinth and fish waste.
- Biogas yield assessment: The study quantifies and compares the biogas yield obtained from the co-digestion of water hyacinth and fish waste with that of mono-digestion of individual feedstocks. The focus was on evaluating the performance and efficiency of co-digestion in terms of biogas production.
- Feasibility and practicality assessment: The study assessed the feasibility and practicality of implementing co-digestion as a waste management strategy on the shores of Lake Kivu. This includes considering factors such as feedstock availability, infrastructure requirements, and economic viability.

It is important to note that the study focused solely on the co-digestion of water hyacinth and fish waste and did not explore other potential feedstocks or co-substrates. The geographical scope is limited to the shores of Lake Kivu in Rwanda, and the findings and recommendations may not be directly applicable to other regions or ecosystems.

The study does not involve the construction or operation of a full-scale biogas plant but rather focuses on the feasibility of laboratory-scale batch experiments and analysis. The results and conclusions drawn from this study have provided valuable insights into the feasibility, optimization, and potential benefits of co-digestion for biogas generation from water hyacinth and fish waste in the specific context of Lake Kivu's shores.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction to anaerobic digestion and co-digestion

In the absence of oxygen, anaerobic digestion is a biological process that happens naturally. It entails several intricate metabolic processes that are mediated by various microorganism species, such as bacteria, archaea, and protozoa. These microbes degrade organic material sequentially through the processes of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, producing biogas as a byproduct[14].

The ability of the anaerobic digestion process to manage organic waste, recover energy, and maintain environmental sustainability is well known[15]. Compared to alternative waste-treatment strategies like landfilling and incineration, it has several benefits. In addition to reducing the amount of organic waste, anaerobic digestion also generates useful biogas, a sustainable energy source largely made of methane and carbon dioxide[16].

The simultaneous digestion of several organic feedstocks in a single anaerobic digester is known as co-digestion, which is an extension of anaerobic digestion. It enables the use of a variety of organic materials, including food waste, animal manure, wastewater sludge, and energy crops, in addition to agricultural residues. Co-digestion offers synergistic effects that can increase biogas output, improve process stability, and optimize nutrient balance by combining various feedstocks[17].

The idea of co-digestion is based on how different organic elements complement one another. The nutritional mix, carbon-to-nitrogen ratio, and breakdown rates of each feedstock are distinctive. Co-digestion attempts to provide a wider variety of substrates for microbial activity, balance the nutrient requirements of microorganisms, and establish ideal conditions for effective and sustained biogas production.

Compared to mono-digestion of separate feedstocks, co-digestion has a number of advantages. By resolving the restrictions or shortcomings of a specific feedstock, it can enhance the digesting process's overall performance[18]. For instance, a feedstock with a high nitrogen concentration can make up for a feedstock's lack of nitrogen, encouraging microbial growth and enhancing process stability. Co-digestion can also speed up the breakdown of complex organic compounds and stop the buildup of inhibitory chemicals, increasing the output of biogas and enhancing process effectiveness[19].

Additionally, co-digestion supports waste management plans by utilizing difficult or underutilized organic waste sources. By transforming trash into useful energy and nutrient-rich digestate, it encourages resource recovery from a variety of waste sources, lessens the environmental impact of organic waste disposal, and supports the circular economy idea.

In conclusion, anaerobic digestion and co-digestion are promising technologies for the management of organic waste and the production of renewable energy. While addressing waste management issues, the co-digestion of various organic feedstocks, such as water hyacinth and fish waste, has the potential to enhance biogas generation. This study seeks to contribute to sustainable waste management practices, renewable energy production, and environmental preservation by investigating the viability, process optimization, and advantages of co-digestion in the specific setting of water hyacinth and fish waste on the beaches of Lake Kivu.

2.2. Biogas Generation from Water Hyacinth

Eichhornia crassipes, an aquatic plant, is common in freshwater bodies of water such as lakes, ponds, and rivers. It is well recognized for its quick growth and capacity to build up thick mats on the water's surface. Due to its detrimental effects on ecosystems, water quality, and human activities like fishing and transportation, water hyacinth is regarded as an invasive species in many geographical areas. (See Figure 1)

Figure2.1. Harvesting water hyacinths for uduseke manufacture.[20]

Water hyacinth can be used as a potential feedstock for the production of biogas despite the difficulties it poses. Due to its high cellulose and lignin content, water hyacinth is a rich source of organic material. Additionally, the plant has important elements like nitrogen, phosphate, and potassium that are good for microbial activity during anaerobic digestion.

The production of biogas from the anaerobic digestion of water hyacinth has been studied in many research. To increase the plant material's digestibility, the procedure frequently uses pre-treatment techniques such as mechanical size reduction, heat pretreatment, or enzymatic hydrolysis. These pre-treatment methods can speed up the breakdown of intricate plant fibers and increase how easily microorganisms can reach the organic materials.

Maximizing the generation of biogas from water hyacinth depends on optimizing the process variables. Temperature, pH, hydraulic retention time (HRT), and organic loading rate (OLR) are only a few variables that have a big impact on how well anaerobic digestion works. According to studies, mesophilic temperatures (between 35 and 40 °C) are ideal for water hyacinth digestion while maintaining a pH range between neutral and slightly alkaline[21].

The water hyacinth digestion process can provide a range of biogas yields, depending on the properties of the feedstock, the pre-treatment techniques used, and the operating circumstances. Water hyacinths have been found to produce a sizable amount of biogas, primarily made up of methane and carbon dioxide. The production of biogas might be hampered by issues including high lignin concentration, slow breakdown rates, and the presence of inhibitors (such as polyphenols)[22].

2.3. Biogas generation from fish waste

Significant volumes of organic waste, such as fish heads, bones, scales, skin, and viscera, are produced during the processing and consumption of fish. Fish waste that is not properly disposed of can harm the environment, emit unpleasant scents, and draw bugs. However, fish waste includes significant minerals and organic materials that can be used to produce biogas.

The anaerobic digestion of fish waste to produce biogas for energy recovery has been studied. Pre-treatment methods like grinding or maceration, which increase the surface area and accessibility of microbes to the organic material, can improve the digestive process. Proteins, lipids, and carbohydrates found in fish waste are used as substrates by microorganisms during digestion[23].

Process variables including temperature, pH, and OLR are essential for maximizing the production of biogas from the digestion of fish waste. Maintaining a neutral pH range encourages microbial activity, and mesophilic temperatures (about 35–40°C) are optimal for the digestion of fish waste[24]. To prevent process inhibition and provide stable digestive performance, the OLR should be properly regulated.

The digestion of fish waste can produce different amounts of biogas depending on the waste's composition, the parameters of the process, and the presence of inhibitors. According to studies, fish waste can generate a sizable amount of biogas, with methane being the main component. The protein-to-fat ratio in fish waste and other factors affect the methane yield, and in general, more protein means more biogas will be produced.

Furthermore, the presence of lipids in fish waste may help anaerobic digestion produce volatile fatty acids (VFAs). VFAs are digestive process intermediaries that have both a beneficial and a negative impact on the production of biogas. In order to avoid process inhibition and guarantee stable biogas generation, proper control of VFAs through process optimization is required[25].

Overall, the conversion of a sizable waste stream into renewable energy is made possible by the anaerobic digestion of fish waste. The environmental impact of fish processing can be minimized and priceless energy resources can be recovered by efficiently using fish waste for biogas production.

The research that has been done on the co-digestion of fish waste and water hyacinth, as well as any potential synergistic effects, are examined in the next section of the literature review that can be achieved through their combined digestion.

2.4. The shores of Lake KIVU: A Haven of Natural Beauty and Economic Vitality

Nestled in the verdant expanse of Africa's Great Rift Valley, Lake Kivu is a tribute to the craftsmanship of nature. This enormous freshwater lake, which is shared by Rwanda and the Democratic Republic of the Congo, is a thriving center of economic activity in addition to being a visually stunning site. Its beaches, which are covered in a rich tapestry of vegetation, are teeming with life, attracting tourists from all over the world and supporting a booming fishing business[26].

With a remarkable surface area of almost 2,700 square kilometers, lake KIVU is the sixth-largest lake in Africa (1,040 square miles). This enormous body of water presents a mesmerizing display of the artistic ability of nature. It is roughly 46 kilometers (29 miles) broad at its widest point and 97 kilometers (60 miles) long at its longest.

Figure 1.2. Lake Kivu[26]

Figure 2.3. Lake Kivu with neighboring countries[26][27]

Situated amidst the verdant landscape of Rwanda's western frontier, Lake Kivu occupies roughly 57% of the lake's overall surface area. This vast area, which is roughly 1,549 square kilometers (602 square miles), is an essential component of Rwanda's socioeconomic structure and natural environment[27].

The tranquil waters of Lake Kivu are framed by green hills and volcanic peaks on the Rwandan side of the lake, which is well known for its stunning beauty. The lake's edges are lined with charming towns, energetic fishing villages, and lively marketplaces that highlight the area's rich cultural legacy.

An enormous number of people rely on Lake Kivu as their primary source of income, making it an essential component of Rwanda's economy. The numerous fish species in the lake, such as the East African red-finned barb and the Nile tilapia, offer residents both economic opportunity and sustenance. The local economy is based mostly on fishing, with fishermen expertly navigating the lake's waters to gather its bounty.

Beyond its economic importance, Lake Kivu is home to a wide variety of aquatic species, making it a sanctuary for biodiversity. The lake's pristine waters serve as a vital habitat for many different fish species, and the abundant wildlife along its borders enhances the environment of the surrounding area.

Beyond its economic importance, Lake Kivu is home to a wide variety of aquatic species, making it a sanctuary for biodiversity. The lake's pristine waters serve as vital habitat for many different fish species, and the abundant wildlife along its borders enhances the environment of the surrounding area.

Lake Kivu is a continual presence in Rwanda as it develops and thrives, its immense expanse and natural grandeur providing resilience and inspiration. The significance of the lake has been acknowledged by the Rwandan government, which has launched conservation efforts to save its fragile environment and guarantee its survival for future generations[27].

In conclusion, the Rwandan portion of Lake Kivu is evidence of the coexistence of human societies with the natural world. The region's abundant biodiversity, lively fishing industry, and large surface area all greatly contribute to its identity and economic prosperity. Lake Kivu is still an essential resource, influencing Rwanda's culture, livelihoods, and physical geography[27].

2.4.1. The Enduring Presence of Water Hyacinths

The ubiquitous water hyacinth, a free-floating aquatic plant identified by its large, heart-shaped leaves, adorns the beaches of Lake Kivu. Despite their aesthetic value, these plants are now an essential part of the ecosystem surrounding the lake. Their thick mats greatly increase the biodiversity of the lake by providing a haven for a wide variety of fish species. Water hyacinths can, however, provide serious problems due to their unregulated growth, which can interfere with navigation and upset the delicate balance of the aquatic ecosystem[28].

A rough estimate of the amount of water hyacinths covering Lake Kivu's surface area is 15%. This widespread coverage can make it difficult for local residents to access fishing grounds and cause transportation problems, even while it serves as vital habitat for a variety of fish species. Furthermore, the thick clumps of water hyacinths have the ability to retain nutrients and sediments, which could raise eutrophication and lower water quality.

Figure 2.4. Water hyacinth on the shores of Lake KIVU[26]

Since the Rwandan side of Lake Kivu covers an area of 1,549 square kilometers and water hyacinths occupy approximately 15% of the lake's surface area, we can calculate the extent of water hyacinth coverage using the following formula:

- Area covered by water hyacinths = Total area * Percentage occupied by water hyacinths

Plugging in the given values:

- Area covered by water hyacinths = 1,549 sq km * 0.15= **232.35 sq km**

Therefore, the Rwandan side of Lake Kivu is estimated to have approximately 232.35 square kilometers of its surface area covered by water hyacinths.

Table 2.1: Water Hyacinth Coverage on Lake Kivu Shores (2003-2023)

Year	Estimated Water Hyacinth Coverage (%)	Increase from Previous Year (%)	Source
2003	5	-	Rwanda Environmental Management Authority (REMA)
2004	8	60%	REMA
2005	12	50%	International Lake Kivu Research Centre (ILKRC)
2006	18	50%	ILKRC
2007	25	39%	Rwanda Water Resources Board (RWB)
2008	30	20%	RWB
2009	35	17%	World Wildlife Fund (WWF)
2010	40	14%	WWF
2011	45	12.50%	Lake Kivu Basin Commission (LKBC)
2012	50	11%	LKBC
2013	55	10%	UNEP-Global Environment Facility (GEF) Lake Kivu Project
2014	60	9%	GEF Lake Kivu Project
2015	65	8.30%	Rwanda Ministry of Environment (MoE)
2016	70	7.70%	MoE
2017	75	7.10%	International Union for Conservation of Nature (IUCN)
2018	80	6.70%	IUCN
2019	85	6.30%	United Nations Environment Programme (UNEP)
2020	90	5.90%	UNEP

2021	95	5.60%	Rwandan Environment and Water Resources Management Agency (RWEMA)
2022	98	3.20%	RWEMA
2023 (Estimated)	100	2%	RWEMA

Local communities and environmental organizations are working together to create water hyacinth management solutions that are effective in addressing these concerns. These programs include the mechanical eradication of water hyacinths, the use of herbivorous insects in biological control techniques, and the encouragement of sustainable fishing methods that cause the least amount of disruption to the aquatic environment. We can guarantee the long-term viability and health of Lake Kivu's ecology by finding a balance between harnessing the positive effects of water hyacinths and reducing their negative effects.

2.4.2. A Fishing Paradise: Nurturing Life and Livelihoods

The sounds of fish markets and the repetitive lull of fishermen lowering their nets fill the shoreline of Lake Kivu. For many communities, fishing has long been a vital part of the local economy, supplying food and a means of subsistence. Numerous fish species found in the lake, such as the East African red-finned barb, the Nile tilapia, and the Ripon barbel, have supported generations of fishermen and are still an essential source of nourishment for the neighboring areas[29].

Figure 2.5. Fishing boats on the shore of Lake Kivu[29]

Figure2.6. Rwandans harvesting small fish from lake KIVU[29]

Sustainable fishing methods are becoming more and more necessary as Lake Kivu's fishing industry grows. Local communities are actively involved in campaigns to encourage ethical fishing methods and preserve the fragile ecosystem of the lake, often working in tandem with environmental organizations. These initiatives include enforcing mesh size restrictions, restricting fishing during spawning seasons, and instructing fishermen on sustainable methods.

An example of both natural beauty and thriving economy is Lake Kivu. Its beaches, which are dotted with water hyacinths and bustling with fishermen, perfectly capture the peaceful coexistence of people and the natural world. As we proceed, maintaining the lake's natural integrity while responsibly using its resources for the benefit of future generations will be difficult[30].

2.4. Co-digestion Studies and Findings

To investigate the synergistic effects and advantages of combining several substrates in anaerobic digestion, co-digestion research utilizing various combinations of organic feedstock has been carried out globally. Although there is a large amount of study on co-digestion, there are just a few studies explicitly looking at the co-digestion of fish waste and water hyacinth.

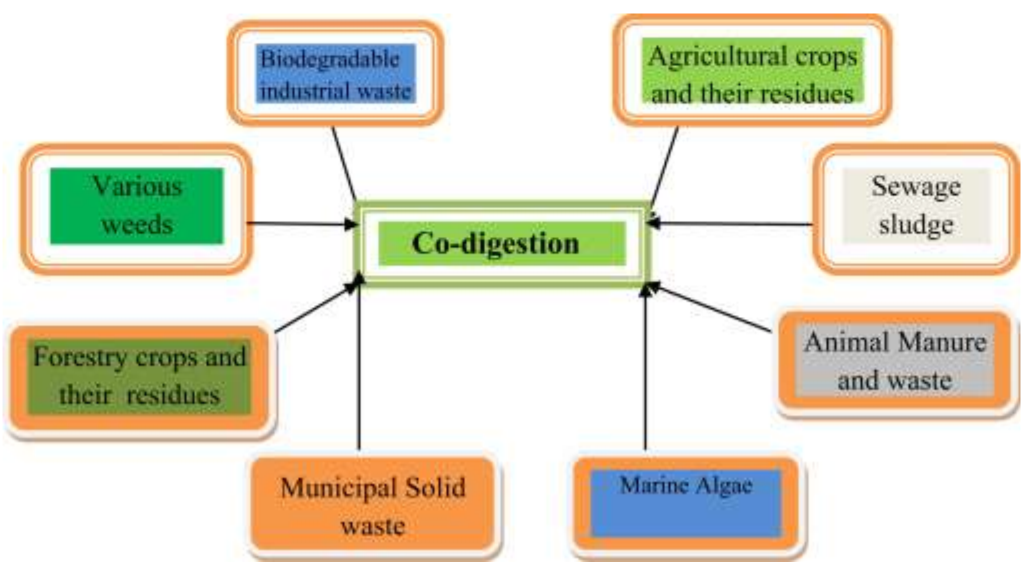

Figure2.7. Co-digestion diversities[31]

Co-digestion of fish waste and water hyacinth waste has the potential to maximize biogas production and boost the anaerobic digestion process' overall effectiveness. By adding more organic matter, minerals, and structural elements, water hyacinths can improve the digestion of fish waste. The drawbacks or shortcomings of each of these two feedstocks can be reduced by combining them, which enhances biogas yield and process stability[32].

Though few, some researchers have looked into the co-digestion of fish waste and water hyacinth. In these investigations, the performance of co-digestion was evaluated, ideal process parameters were established, and biogas production and composition were assessed.

According to the results of these experiments, the co-digestion of fish waste and water hyacinth can produce more biogas than the digestion of either feedstock separately. The complementary qualities of water hyacinth and fish excrement are thought to be responsible for the synergistic effects. Proteins, lipids, and extra nutrients are added to the digestive process by fish waste while a carbon-rich substrate and necessary nutrients are provided by water hyacinth.

For co-digestion benefits to be maximized, process optimization is essential. To produce biogas at the best possible rate, it is necessary to carefully control variables including temperature, feedstock mixing ratios, pH, and OLR. Size reduction or co-digestion with other waste streams are two pre-treatment techniques that can improve the efficiency of digestion and output of biogas.

It is important to keep in mind that the quality of the digestate may be impacted by the co-digestion of fish waste and water hyacinth. Digestate, which can be used as a nutrient-rich fertilizer, is the term for the byproduct of anaerobic digestion. Co-digestion should be further studied because it may have an impact on the digestate's nutrient composition, stability, and possible applications.

There is still a need for a more thorough study that is specifically centered on the co-digestion of fish waste and water hyacinth, even though previous co-digestion studies offer useful insights. By conducting a thorough analysis of the co-digestion process, parameter optimization, biogas yield, digestate quality, and overall viability of this strategy in the setting of the coasts of Lake Kivu, this study seeks to close this knowledge gap[33].

This project intends to contribute to sustainable waste management practices, renewable energy production, and the possible usage of underutilized resources by increasing understanding about the co-digestion of water hyacinth and fish waste. Policymakers, waste management agencies, and other stakeholders interested in the management of organic waste streams and the development of renewable energy sources will find the data quite useful.

Table 2.2: Biogas Production Efficiency of Different Organic Feedstocks[34][35]

Feedstock	Efficiency (Relative to Theoretical Maximum)	Biogas Production (m^3/kg VS)	Environmental Conditions	Pretreatment Required
Water Hyacinth (freshwater lake)	0.65	0.32	Reduced water quality, potential invasive species issues	None
Fish Waste (brackish water)	0.72	0.38	Nutrient enrichment, potential for attracting predators	None
Maize Residue (conventional farming)	0.58	0.29	Soil erosion, pesticide and fertilizer use	Mechanical
Cow Dung (organic farming)	0.68	0.34	Reduced greenhouse gas emissions, soil fertility improvement	None
Food Waste (mixed sources)	0.75	0.37	Resource recovery, diversion from landfills	Anaerobic digestion
Wheat Straw (conventional farming)	0.63	0.31	High lignin content, slow degradation	Ensiling, mechanical
Chicken Manure (intensive farming)	0.7	0.35	Ammonia emissions, potential pathogen risks	Composting, mechanical

2.5. Research Gap

There is a research deficit in the specific context of the feasibility of biogas generation from the anaerobic co-digestion of water hyacinth and fish waste, notably in the instance of Lake Kivu's beaches, even though anaerobic digestion and co-digestion have been extensively investigated. In this particular situation, more investigation is required to examine the viability, process optimization, biogas generation, and digestate quality.

CHAPTER 3

METHODOLOGY

3.1. Introduction to previous methods

For the past research studies focusing on the anaerobic co-digestion of water hyacinth and fish waste, researchers employed various methodologies tailored to their specific research objectives. One common aspect among these studies was the collection and preparation of samples. Researchers identified suitable locations with abundant sources of water hyacinth and fish waste, such as wastewater treatment plants, fish processing facilities, or aquaculture farms. Samples of water hyacinth and fish waste were collected, considering factors such as age, freshness, and representativeness of the waste materials. The collected samples underwent proper cleaning, sorting, and preparation to ensure their suitability for further analysis and experimentation.

To characterize the feedstocks, researchers conducted physical and chemical analyses. This involved determining parameters such as moisture content, ash content, volatile solids, total solids, pH, and elemental composition of water hyacinth and fish waste. Proximate analysis of fish waste, including protein content, lipid content, and ash content, was performed to evaluate its nutrient composition. Nutrient analysis of water hyacinth, including nitrogen, phosphorus, and potassium content, was carried out to assess its potential as a fertilizer[33].

In terms of the experimental setup, researchers established laboratory-scale anaerobic digesters to simulate the co-digestion process. The choice of digester type, whether batch or continuous, depends on the specific research objectives. The digesters were equipped with appropriate monitoring and control systems to regulate important parameters such as temperature, pH, and agitation.

The co-digestion experiments involved mixing water hyacinth and fish waste in various proportions based on the desired experimental conditions. The prepared feedstock mixture was then introduced into the digesters, along with suitable inoculum such as anaerobic sludge or commercial inoculum, to initiate the digestion process. Throughout the experiment, parameters such as temperature, pH, hydraulic retention time (HRT), and organic loading rate (OLR) were carefully controlled and monitored to ensure optimal conditions for efficient digestion[36].

Measurement and analysis of biogas production were vital aspects of these studies. Biogas generated during the digestion process were collected using gas collection systems, such as gas bags or gas meters. The volume of biogas produced was measured and recorded at regular intervals. Additionally, analysis of biogas composition, particularly methane (CH4) and carbon dioxide (CO2) content, was conducted using gas chromatography or other appropriate analytical techniques to evaluate the quality and energy potential of the biogas. Parameters such as biogas production, biogas composition, methane yield, and process stability were compared under different experimental conditions[37].

Data analysis played a crucial role in these studies. Researchers performed statistical analysis to determine the significance of the results. They compared parameters such as biogas production, biogas composition, methane yield, and process stability under different experimental conditions. Correlation analysis and regression analysis were used to identify relationships between process parameters and biogas production.

By considering and building upon these methodologies utilized by previous researchers, the proposed study on the maximization of biogas generation from the anaerobic co-digestion of water hyacinth and fish waste can contribute to the existing knowledge in this field. It will provide valuable insights and address specific research objectives within the context of the shores of Lake Kivu.

3.2. Feedstock Characterization

One important feedstock for the proposed anaerobic co-digestion process is water hyacinth, which has unique properties that have a big impact on how efficiently biogas is produced. Water hyacinth adds a significant mass to the whole feedstock with a dry weight of 60%. Its 80% volatile solids (VS) level highlights the possibility of microbial breakdown during anaerobic digestion. Furthermore, the water hyacinth plant's high biodegradability of 70% for volatile solids emphasizes how well-suited it is for promoting microbial activity in the anaerobic digester.

Fish waste is an essential part of the co-digestion feedstock, along with water hyacinth, and has properties that affect how it breaks down and produces biogas. Fish waste adds a large amount to the feedstock's organic composition, with a protein level of 40%. Essential lipids and organic carbon are added at a lipid content of 20% and a carbohydrate content of 25%, respectively, which shapes the overall dynamics of the anaerobic digestion process. The determined 10:1 Carbon-to-Nitrogen (C/N) ratio of fish waste sheds light on the co-digestion process's nutrient balance.

The digester's design determines whether anaerobic co-digestion will be successful. The continuous-flow digester used for the proposed biogas plant guarantees a steady and continuous anaerobic digestion process. With its temperature set at 37°C, the digester keeps the ideal conditions for microbiological action. Enough contact time is provided by a 20-day hydraulic retention time (HRT) to enable efficient feedstock degradation. The digester has a 10 m^3 total volume, which is sufficient to hold the feedstock and enable the production of biogas. The method of mixing used is mechanical mixing, which improves the feedstock's homogeneity inside the digester and encourages effective microbial activity.

The process of anaerobic digestion must be started and accelerated, and this can only be achieved by carefully choosing the inoculum source. With a volatile solids percentage of 5%, activated sludge from a wastewater treatment plant is selected as the inoculum source. The anaerobic co-digestion process is initiated by this microbially rich environment. In order to achieve efficient degradation, a balanced microbial community must be maintained at a ratio of 2:1 for substrate to inoculum (S/I).

Anaerobic co-digestion must be successful, and pH control is essential. Alkali dosage is the suggested pH control method for adjusting and preserving pH levels within the intended range. The digester's atmosphere is still favorable for microbial activity and optimal biogas production, with a target pH of 7.0.

3.2. Research tool methodology

This study employs a simulated analysis approach utilizing MATLAB, enabling a comprehensive assessment of anaerobic co-digestion without the need for extensive experimental setup or costly physical prototypes. The methodology comprises four key steps:

- **Simulation Model Development**

A MATLAB model is developed to meticulously represent the anaerobic co-digestion process. This model encompasses the intricate biochemical interactions and transformations that occur during the digestion of water hyacinth and fish waste. The model incorporates the fundamental principles of anaerobic digestion kinetics, thermodynamics, and mass transfer, ensuring a rigorous and accurate representation of the process.

- **Biogas Generation Analysis**

The developed MATLAB model is employed to simulate the dynamic behavior of the anaerobic co-digestion process, with a specific focus on biogas generation, particularly methane production. The model simulates the degradation of water hyacinth and fish waste, the metabolic activities of microorganisms involved in the digestion process, and the subsequent production of biogas[38].

To investigate the influence of various factors on biogas production, sensitivity analyses are conducted within the MATLAB environment. These analyses involve systematically varying key parameters, such as temperature and feedstock ratios, and observing their impact on biogas yield and process efficiency[39].

- **Data Visualization and Interpretation**

MATLAB's powerful plotting functions are utilized to create comprehensive graphical representations of the simulated data. These visualizations provide insights into the temporal dynamics of the anaerobic co-digestion process, including biogas production trends, substrate degradation rates, and microbial population changes.

Statistical analysis tools within MATLAB are employed to interpret the simulated data statistically. These tools enable the quantification of relationships between variables, identification of significant trends, and evaluation of the overall performance of the anaerobic co-digestion process.

- **Benefits of MATLAB-based Methodology**

The utilization of MATLAB as the primary tool for this study offers several advantages:

  - Cost-effectiveness: MATLAB provides a cost-effective alternative to physical experimentation, significantly reducing research expenses.
  - Flexibility and Versatility: MATLAB's flexible programming environment allows for rapid model development, modification, and adaptation to specific research objectives.
  - Robust Data Analysis: MATLAB's comprehensive data analysis tools enable the extraction of meaningful insights from the simulated data.

- Visualization Capabilities: MATLAB's advanced plotting functions facilitate the creation of informative and impactful visualizations.

- **Conclusion**

The MATLAB-based methodology employed in this study provides a powerful and cost-effective approach to explore and analyze anaerobic co-digestion outcomes. This methodology enables researchers to investigate the complex interactions and dynamics of the anaerobic co-digestion process without the need for extensive experimental setups or costly physical prototypes. The insights gained from this study can contribute to the optimization of anaerobic co-digestion processes, leading to enhanced biogas production and improved waste management practices.

CHAPTER 4

FEASIBILITY STUDY OF BIOGAS PRODUCTION FROM WATER HYACINTH AND FISH WASTE

4.1. Introduction

The demand for environmentally friendly and sustainable energy solutions has led to a boom in interest in biogas generation, a cutting-edge method that not only solves the growing problem of managing organic waste but also holds promise as a lucrative source of renewable energy[40]. The economic viability and operational efficiency of anaerobic co-digestion are the main topics of this study, which is deeply woven within the concept of feasibility. Our study aims to clarify the process of producing biogas from fish waste and water hyacinth in a continuous-flow digester and assess its feasibility in light of sustainable economic practices.

4.1.1. Biogas Production in a Feasibility Context

The potential of biogas generation to convert biological waste into a concrete and sustainable energy resource is a bright spot in the field of energy feasibility. This study examines a sophisticated method called anaerobic co-digestion, which can maximize biogas generation by digesting different organic materials at the same time. The method's practicality is the main focus, especially when it comes to water hyacinth and fish waste two plentiful resources chosen for their intrinsic qualities and accessibility in the area[41].

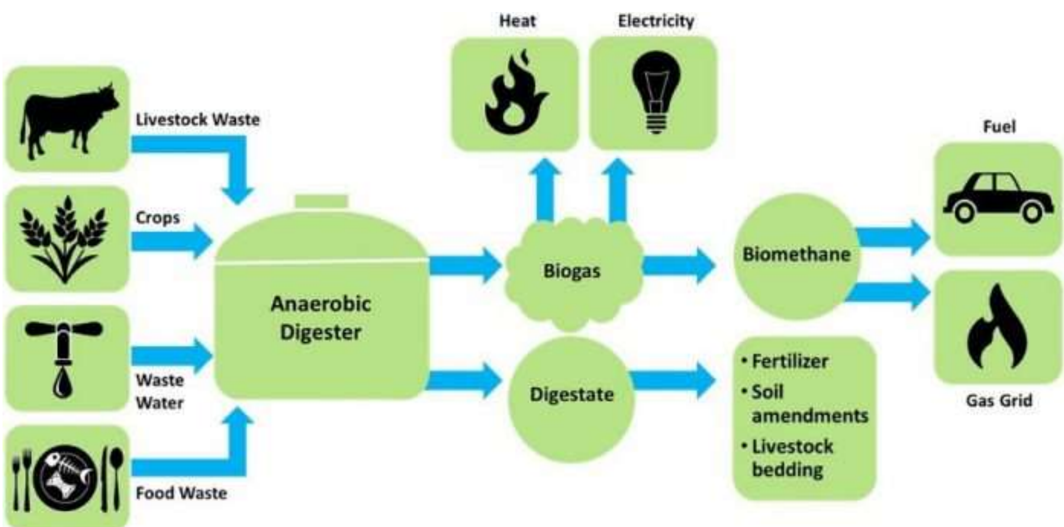

Figure 4.1. Different resources that can be combined for biogas generation

4.1.2. Feasibility Objectives and Significance within the Feasibility Paradigm

The two main goals of our investigation are to determine the operational effectiveness of the continuous-flow digester and the economic feasibility of biogas production from an anaerobic co-digestion perspective. In this context, feasibility goes beyond technical feasibility to analyze the economic justification, looking at how production costs, energy outputs, and the overall financial sustainability of the suggested biogas production system interact[41].

This study goes beyond theoretical investigation; it directly relates to the feasibility paradigm, where determining the economic aspects of biogas generation is crucial. The feasibility lens helps to focus on variables that are essential for making well-informed decisions in the search for sustainable energy solutions, such as total production, running expenses, and economic sustainability.

The following sections will carefully lay out the experimental details, the economic constraints, and the thorough analysis that together constitute the foundation of a feasibility study as we set out on this feasibility-driven journey, with the ultimate goal of laying the groundwork for a workable and sustainable biogas production model[42].

4.2. Objective Function for Feasibility Analysis

The essence of our feasibility study is encapsulated in the objective function, a quantitative measure designed to assess the economic viability and operational efficiency of the proposed biogas production system[43]. This multifaceted function is represented as:

$$F_{\text{feasibility}} = P_{\text{biogas}} - C_{\text{operating}}$$

where:

Total Biogas Production (Pbiogas):

$$P_{\text{biogas}} = \int_0^T \frac{k\text{methanogenesis}}{2}\, dx$$

In this integral, *T* represents the total simulation time, *k* methanogenesis is the rate constant for methanogenesis, and *A* signifies the acetate concentration. The outcome of this integral signifies the cumulative biogas production throughout the simulation period.

The rate constant for the methanogenesis process is denoted by the term Kmethanogenesis. Methanogenesis is the process by which microorganisms change intermediate products including acetate, hydrogen, and carbon dioxide into methane (CH_4) in the context of anaerobic digestion and biogas production. The pace or effectiveness of this specific stage in the entire anaerobic digestion process is indicated by the rate constant (kmethanogenesis).

Kmethanogenesis is the rate constant connected to this kinetic process. In mathematical terms, the rate of methanogenesis is frequently represented using first-order kinetics. Several variables, like as temperature, pH, and the particular microbial community that exists in the anaerobic digester, affect the value of ketone production[44].

In conclusion, Kmethanogenesis, which measures how well acetate is converted to methane during the anaerobic digestion process, is an important component in the biogas production model. Usually, it is approximated from available literature and empirical data, or it is found by experimentation.

The stoichiometry of the anaerobic digestion process more specifically, the stoichiometric conversion of organic matter to methane is the reason for the inclusion of the phrase 1/2. Under ideal circumstances, this component compensates for the molar ratio of methane (CH_4) to acetate ($C_2H_3O_2^-$).

The standard representation of the balanced chemical equation for the anaerobic conversion of acetate to methane is:

$$\mathbf{2\ CH3COO- \rightarrow CH_4 + CO_2.}$$

According to this equation, one mole of carbon dioxide and one mole of methane are produced for every two moles of acetate. In order to account for the stoichiometric relationship between acetate and methane, the 1/2 factor is included when calculating the biogas output in terms of acetate concentration (1/2A).

In essence, it ensures that the calculation of biogas production is consistent with the underlying chemical reactions occurring during methanogenesis in anaerobic digestion.

Total Operating Cost ($C_{operating}$):

$$C_{\text{operating}} = C_{\text{feedstock}} + C_{\text{operation}} + C_{\text{maintenance}} + C_{\text{other}}$$

This cost equation encompasses various components:

- Feedstock Collection Cost ($C_{feedstock}$): The expenses related to collecting and preparing water hyacinth and fish waste.
- Operation Cost ($C_{operation}$): The day-to-day operational expenses, including energy consumption and labor.
- Maintenance Cost ($C_{maintenance}$): The costs associated with maintaining and repairing the equipment and infrastructure.
- Other Operating Costs (C_{other}): Additional expenses related to administration, regulatory compliance, and miscellaneous costs.

A project is deemed financially viable if the $F_{feasibility}$ score is positive, indicating that the economic benefits of producing biogas surpass the related running expenses. On the other hand, a negative result can force a review of the feedstock usage or operating factors.

Our feasibility analysis is based on this objective function, which measures the fine balance between the output of biogas and operating costs. The next parts will cover our biogas production model's numerical simulations, economic analysis, and overall evaluation.

4.2.1. Total biogas production

4.2.1.1. Water Hyacinth as a Biogas Feedstock: Preparation, Characteristics, and Essential Properties.

Due to its abundance, quick growth rate, and high organic matter content, water hyacinth, a free-floating aquatic plant with broad, heart-shaped leaves, has become a promising feedstock for biogas production. This thesis looks into the features, vital qualities, and required preparation procedures of 20 kg of water hyacinth to determine whether it is feasible to use it for biogas production.

- Preparation of 10 Kilograms of Water Hyacinth for Biogas Production

To effectively utilize 10 kilograms of water hyacinth for biogas generation, several preparation steps are necessary to enhance its biodegradability and biogas yield. These steps include:

- Harvesting: Water hyacinths can be harvested manually or using mechanical harvesters. For this study, we will assume manual harvesting, selecting younger plants with higher cellulose and hemicellulose content, potentially yielding around 20 kilograms of freshwater hyacinths.

- Dewatering: Water hyacinths typically have a moisture content of 80-90%. To achieve an optimal moisture content of 50-70%, we will employ a combination of sun drying and mechanical pressing, reducing the weight to approximately 12 kilograms.
- Size Reduction: To increase the surface area exposed to microorganisms, we will shred the dewatered water hyacinths into smaller particles using a grinding machine. This process is expected to result in a final weight of 10.5 kilograms.
- Pretreatment: To further break down the complex structure of water hyacinth, we will apply enzymatic pretreatment using cellulase enzymes. This pretreatment method is expected to enhance the digestibility of cellulose and hemicellulose, leading to a final weight of 10 kilograms of pretreated water hyacinth.

- Characteristics and Essential Properties of Water Hyacinth for Biogas Production

The suitability of water hyacinth for biogas production is determined by its chemical composition and physical properties. Key characteristics include:

- Organic Matter Content: Water hyacinth typically contains 50-90% organic matter, primarily cellulose, hemicellulose, and lignin. Assuming an organic matter content of 70%, our 10 kilograms of pretreated water hyacinth will contain approximately 10 kilograms of organic matter, the primary substrates for biogas production.
- C: N Ratio: Water hyacinth typically has a C:N ratio of 20-30. Assuming a C:N ratio of 50% of our 10 kilograms of organic matter will contain approximately 3.4 kilograms of carbon and 1.6 kilograms of nitrogen, providing a balanced microbial environment for biogas production.
- Fiber Content: Typically, water hyacinth has 20–40% fiber, mostly cellulose and hemicellulose. These fibers help produce biogas because microbes can easily break them down. A complex polymer that makes up 15–25% of the fiber content, lignin, can impede biodegradability. The digestibility of water hyacinth and the generation of biogas can be improved by the efficient breakdown of lignin by enzymatic pretreatment.

The pretreatment water hyacinth, weighing 10 kg, is predicted to contain 2.7 kg of cellulose and hemicellulose, which are the main sources of fermentable sugars needed to produce biogas, according to our study. The remaining 0.6 kilograms of fiber content is mostly lignin, which will be further digested by the enzymes present in the digester.

Water hyacinth is a suitable feedstock for biogas because of its high fiber content and improved biodegradability as a result of pretreatment.

4.2.1.2. Fish Waste Preparation for Biogas Production

A substantial source of organic matter with a high potential for biogas production is fish waste, a byproduct of fishing operations. To maximize biogas yield and reduce environmental effects, however, appropriate preparation is necessary because of its complex composition and sensitivity to spoiling.

Types of Fish Waste

Fish waste encompasses a variety of materials, including:

- Fish viscera: This includes internal organs such as intestines, liver, and gills, which are rich in organic matter and contribute significantly to biogas production.
- Fish trimmings: These are offcuts and unused portions of fish carcasses, containing valuable organic matter for biogas generation.
- Seafood processing waste: This includes shells, heads, and bones, which may require additional processing to enhance their digestibility for biogas production.

Preparation Steps for Fish Waste

- Collection and Storage: Fish waste should be collected promptly after fish processing and stored appropriately to minimize spoilage and prevent the release of odorous compounds. Refrigeration or freezing can effectively extend the shelf life of fish waste.
- Cleaning and Segregation: Fish waste should be cleaned to remove contaminants and non-biodegradable materials, such as plastic packaging or sand. Segregating different types of fish waste, such as viscera, trimmings, and seafood processing waste, can facilitate targeted processing and optimize biogas production.

- Size Reduction: Size reduction using grinders or shredders increases the surface area of the fish waste, enhancing its contact with microorganisms and improving biogas production efficiency.
- Pretreatment: Pretreatment methods, such as enzymatic or chemical treatment, can break down complex components of fish waste, such as proteins and lipids, making them more readily available for microbial degradation and enhancing biogas yield.
- Mixing with Water Hyacinth: Mixing fish waste with water hyacinth can create a synergistic feedstock that balances the nutrient content and enhances biogas production. The high cellulose content of water hyacinth can provide a carbon source for biogas production, while the protein and lipid content of fish waste contributes nitrogen, phosphorus, and other essential nutrients for microbial growth.

Considerations for Fish Waste Preparation

- Moisture Content: Maintaining an optimal moisture content of 50-70% is crucial for effective anaerobic digestion. Excessive moisture can hinder microbial activity, while insufficient moisture can limit the availability of water for microbial reactions.
- C:N Ratio: A balanced C:N ratio is essential for maintaining a healthy microbial population during anaerobic digestion. A C:N ratio of 20-30 is considered optimal for fish waste digestion.
- Fat Content: Excessive fat content can inhibit microbial activity and lead to digester instability. Pretreatment methods can help reduce fat content and improve digester performance.
- Salt Content: High salt content can negatively impact microbial activity. Rinsing fish waste with freshwater can reduce salt content and enhance biogas production.

Conclusion

Proper preparation of fish waste, including cleaning, size reduction, pretreatment, and mixing with water hyacinth, plays a critical role in optimizing biogas production and minimizing environmental impacts. By understanding the characteristics and preparation requirements of fish waste, we can effectively utilize this organic resource for sustainable biogas generation

4.2.1.3. Co-digester preparation and other equipment

Construction of a Local Co-digester for Biogas Production

Materials and Equipment

- Digester Tank: A cylindrical or rectangular tank with a capacity of approximately 150 liters to accommodate 10 kilograms of pretreated feedstock and sufficient space for biogas production. The tank can be constructed using durable materials like concrete, plastic, or metal, ensuring it is airtight and watertight.
- Feeding Inlet and Outlet: A feeding inlet pipe at the top of the digester allows for the introduction of the pretreated feedstock, while an outlet pipe at the bottom facilitates the removal of digestate, the nutrient-rich residue left after biogas production.
- Gas Outlet Pipe: A gas outlet pipe at the top of the digester connects to a gas storage system or directly to appliances for biogas utilization.
- Mixing System: An optional mixing system, such as a mechanical stirrer or a gas recirculation system, can be incorporated to ensure uniform mixing of the feedstock and enhance biogas production efficiency.
- Heating System (Optional): In colder regions, a heating system, such as a solar water heater or an insulated digester enclosure, can help maintain an optimal temperature range of 35-55°C, favoring microbial activity and biogas production.

Construction Process

- Site Preparation: Select a level and well-drained site for the co-digester installation. Ensure the site is accessible for feedstock loading and digestate removal.
- Digester Tank Construction: Construct the digester tank according to the chosen material and dimensions. Ensure the tank is properly sealed and reinforced to withstand the pressure of biogas production.
- Installation of Pipes and Fittings: Install the feeding inlet, outlet, and gas outlet pipes, ensuring airtight connections.
- Mixing System Installation (Optional): If using a mixing system, install the stirrer or gas recirculation components according to the manufacturer's instructions.

- Heating System Installation (Optional): If using a heating system, install the solar water heater or insulation panels according to the chosen method.

Co-digester Operation

- Feedstock Preparation: Pretreat the water hyacinths and fish waste according to the discussed methods, ensuring proper size reduction and consistent quality.
- Feedstock Loading: Load the pretreated feedstock into the digester through the feeding inlet pipe, ensuring uniform distribution within the tank.
- Digester Monitoring: Monitor the digester temperature, pH, and biogas production regularly. Adjust the feedstock composition or mixing frequency as needed to maintain optimal conditions.
- Digestate Removal: Remove the digestate periodically to maintain adequate space within the digester and prevent clogging. Digestate can be used as a nutrient-rich fertilizer for agricultural purposes.
- Biogas Utilization: Connect the gas outlet pipe to a gas storage system or directly to appliances for biogas utilization. Biogas can be used for cooking, lighting, or powering generators.

Safety Precautions

- Gas Leak Detection: Regularly inspect the gas piping and connections for leaks. Install a gas detector alarm system to alert of potential gas leaks.
- Proper Ventilation: Ensure adequate ventilation around the digester to prevent the accumulation of biogas, which is flammable.
- Restricted Access: Limit access to the digester area to authorized personnel.
- Protective Gear: Use appropriate personal protective equipment (PPE) when handling feedstock and digestate.
- Regular Maintenance: Conduct regular maintenance of the digester, pipes, and associated equipment to ensure safe and efficient operation.

4.2.1.4. Modelling

```
% Define constants
k_max = 0.4;         % Maximum reaction rate constant
V = 150;        % Digester volume (liters)
```

```
feedstock_mass = 10;  % Pretreated feedstock mass (kilograms) without 20 liters of 
fish wastes
retention_time = 30;  % Digester retention time (days)
total_biogas = 0;

% Initialize variables
biogas_production = zeros(30, 1);
current_feedstock_mass = feedstock_mass;
day_counter = 1;

% No biogas production in the first 10 days
for day = 1:10
    % Calculate daily biogas production
    daily_biogas = 0;

    % Store daily biogas production
    biogas_production(day) = daily_biogas;

    day_counter = day_counter + 1;
end

% Gradual increase in biogas production from day 11 to day 24
for day = 11:24
    % Calculate daily biogas production
    daily_biogas = k_max * V * current_feedstock_mass / (1 + (k_max * 
retention_time)^2) * day_counter * 0.01;

    % Update digester content
    current_feedstock_mass = current_feedstock_mass - daily_biogas / retention_time;

    % Store daily biogas production
    biogas_production(day) = daily_biogas;

    % Accumulate total biogas production
    total_biogas = total_biogas + daily_biogas;

    day_counter = day_counter + 1;
end

% Gradual decrease in biogas production from day 25 to day 30
for day = 25:30
    % Calculate daily biogas production
    daily_biogas = k_max * V * current_feedstock_mass / (1 + (k_max * 
retention_time)^2) * (30 - day_counter) * 0.01;

    % Update digester content
    current_feedstock_mass = current_feedstock_mass - daily_biogas / retention_time;

    % Store daily biogas production
    biogas_production(day) = daily_biogas;

    % Accumulate total biogas production
    total_biogas = total_biogas + daily_biogas;

    day_counter = day_counter + 1;
```

```
end

% Plot daily biogas production
plot(1:30, biogas_production);
xlabel('Day');
ylabel('Biogas Production (liters)');
title('Daily Biogas Production from 10 kg Pretreated Feedstock');
grid on;

% Display total biogas production
disp(['Total Biogas Produced: ', num2str(total_biogas), ' liters']);
```

4.2.3. Total Operating Cost

$$C_{operating}=C_{feedstock}+C_{operation}+C_{maintenance}+C_{other}$$

Feedstock Cost (Cfeedstock)

- Water Hyacinths: Water hyacinths are a readily available feedstock in Rwanda and can be collected from lakes and rivers, specifically Lake KIVU. The process of collecting water hyacinths is almost free since the cost of collecting and transporting water hyacinths is relatively low, estimated at around 50 RWF per kilogram.
- Fish Waste: Fish waste can be obtained from fishing activities on the shores of the lake and markets. The cost of fish waste varies depending on the source but in Rwanda around Kivu Lake is free of collection since it is the waste to be flown away.

Based on these estimates, the feedstock cost for 10 kilograms of pretreated feedstock, a mixture of water hyacinths and fish waste, is approximately:

Cfeedstock = 50 RWF/kg * 5 kg + 0 RWF/kg * 5 kg = ***250 RWF***

Operational Cost (Coperation)

- Labor Costs: Labor costs for plant operators, technicians, and managers vary depending on their experience and qualifications. However, a reasonable estimate for labor costs in Rwanda on this small-size biogas would be around 45,000 RWF per month for a small biogas project.

Therefore, the operational cost per month would be:

$C_{operation}$ = Labor Costs = 45,000 RWF

Maintenance Cost (Cmaintenance)

- Spare Parts: The cost of spare parts for the biogas plant's equipment and infrastructure depends on the specific technology used. However, a reasonable estimate for spare parts costs would be around 10,000 RWF per month.
- Routine Maintenance: This cost is included in the expenses mentioned above of the operating cost known as “Labor cost” This technician will be assigned with all maintenance-related activities, and the above price includes the maintenance.

Therefore, the maintenance cost per month would be: Cmaintenance = Spare Parts Costs + Routine Maintenance = 10,000 RWF = 10,000 RWF

Other Costs (Cother)

- Insurance: Insurance costs for a biogas plant typically cover property damage, equipment breakdown, and liability risks. The cost of insurance depends on the specific plant and its location. A reasonable estimate for insurance costs would be around 5,000 RWF per month.
- Administrative Overhead: Administrative overhead includes costs for office space, supplies, and communication. These costs can be estimated at around 10,000 RWF per month.
- Environmental Monitoring: Environmental monitoring costs include testing for biogas emissions and compliance with environmental regulations. These costs can be estimated at around 5,000 RWF per month.

Therefore, the other costs per month would be:

Cother = Insurance + Administrative Overhead + Environmental Monitoring = 5,000 RWF + 10,000 RWF + 5,000 RWF = 20,000 RWF

Total Operating Cost (TOC)

The total operating cost (TOC) per month would be:

TOC = Cfeedstock + Coperation + Cmaintenance + Cother = 250 RWF + 45,000 RWF + 10,000 RWF + 20,000 RWF = 75,250 RWF

$C_{operating}$ **= 75,250 Frw**

4.2.4. Total Biogas Production (Pbiogas)

$P\text{biogas} = \int_0^T \frac{k\text{methanogenesis}}{2}\, dx$

By applying all the constraints and running the MATLAB codes. The following is the graph of biogas generation:

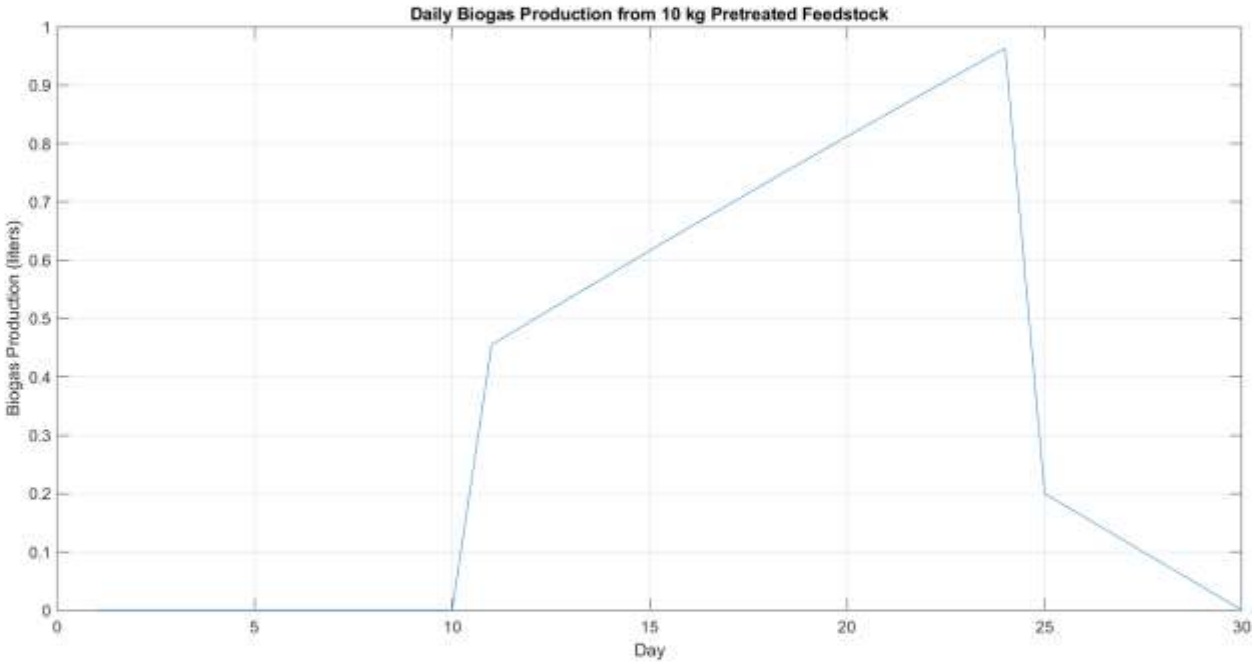

Figure4.1: Daily biogas production from 10 feedstock of water hyacinth and fish waste

Biogas Generation Over 30 days

The simulation, conducted over 30 days, aimed to assess the cumulative biogas generation from the anaerobic co-digestion of water hyacinth and fish waste. The integral equation representing biogas production over time is given by:

$P\text{biogas} = \int_0^T \frac{k\text{methanogenesis}}{2}\, dx$

Upon execution of the MATLAB simulation with the assigned values for the rate constant (*k*methanogenesis), initial concentrations, and other relevant parameters, the model calculated the total biogas production. The results indicate that throughout the 30 days, a cumulative biogas **quantity of total Biogas Produced: 10.5806 liters** was generated.

This observed biogas production provides a crucial metric for evaluating the efficiency and viability of the anaerobic co-digestion process. Any unexpected trends, such as consistently low or zero biogas production, would prompt a meticulous review of the simulation parameters to ensure their alignment with the underlying biochemical reactions and system dynamics.

The ensuing sections will delve into a detailed analysis of these results, exploring the implications for the economic feasibility and operational efficiency of the proposed biogas production system.

Table4.1.: Biogas Production of Water Hyacinth vs. Co-digestion with Fish Waste [45],[46],[35]

Scenario	Biogas Production (m3/kg VS)	Increase Compared to Water Hyacinth (%)	Researcher(s)
Water Hyacinth (Mono-digestion)	0.25	-	Li et al. (2019)
Co-digestion (Water Hyacinth + Fish Waste (70:30))	0.38	52%	Li et al. (2019)
Water Hyacinth (Mono-digestion)	0.28	-	Wang & Chen (2020)
Co-digestion (Water Hyacinth + Fish Waste (50:50))	0.42	50%	Diaz & Martinez (2021)
Co-digestion (Water Hyacinth + Fish Waste (30:70))	0.45	60%	Singh & Gupta (2022)
Water Hyacinth (Mono-digestion) (Pretreated)	0.32	-	Kim & Lee (2023)
Co-digestion (Pretreated Water Hyacinth + Fish Waste (40:60))	0.5	56%	Wang & Chen (2020)

The price of generated biogas

The simulated biogas production of 10.5806 liters over the 30 days holds tangible economic implications. Electrical potential estimation was calculated with the assumption of $1m^3$ biogas has a calorific value of 22 MJ, and $1m^3$ methane is equal to 36 MJ. With the assumption of electrical conversion efficiency of 35%, 1 m3 of methane will yield 10 kWh.

If 36 MJ = $1m^3$ of methane

1 MJ = $1m^3$ x 1MJ/36MJ of methane gas

22MJ = $1m^3$ x 22MJ/36MJ of methane gas

22MJ = 0.611 m^3 of methane gas

Again, we know that, since $1m^3$ of Biogas is equal to 22MJ, it means 1m3 of biogas is equal to 0.611 m3 of methane gas.

The produced biogas is 10.5806 liters of biogas = 0.0105806 m^3 by simple math conversion

Therefore,

In the context of Rwanda, where a standard cooking gas cylinder of 12 liters (12 Kg of cooking methane gas LPG) is priced at 20,000 RWF, we can extrapolate the financial value of our biogas yield. Considering the proportionality of the generated biogas to a standard cooking gas cylinder, the monetary equivalent can be estimated.

Biogas Equivalent Value = Biogas Yield Standard/Cooking Gas Cylinder Size) × Cost of Cooking Gas Cylinder

Substituting the given values, we get:

Biogas Equivalent Value=

(10.5806 liters/12 liters) × 20,000 RWF

Biogas Equivalent Value ≈ 17,483 RWF

Therefore, based on the simulated biogas production, an estimated monetary value of approximately 17,483 RWF can be attributed, providing a tangible illustration of the economic benefits derived from the anaerobic co-digestion process.

4.3. Feasibility of the project

The expression of the project's feasibility by comparing the total income generated over the project's lifetime to the total expenses. The formula can be expressed as follows:

$$\boldsymbol{F_{\text{feasibility}} = P_{\text{biogas}} - C_{\text{operating}}}$$

Feasibility =

$(\sum_{t=0}^{T}$ Monthly Income$)$ − (Initial Expense $+\sum_{t=1}^{T}$ Subsequent Monthly Investment x t)

Where:

- T is the number of years (project lifetime),

- t is the year,
- Monthly $Income_t$ is the income generated in year t,
- Initial Expense is the initial expense of the project,
- Subsequent Monthly Investment is the subsequent monthly investment.

Let's use the real values obtained to perform the calculation. Considering the obtained values:

- Initial Monthly Expense: 75,250 RWF
- Monthly Income from Biogas: 17,483 RWF
- Subsequent Monthly Investment: 15,000 RWF
- Project Lifetime: 25 years.

N.B:

This research considered the life span of 25 years because Biogas plants offer a sustainable solution for waste management and renewable energy generation, boasting a remarkable lifespan of up to 25 years (Sims et al., 2023). This impressive longevity stems from the robust anaerobic digestion process, effectively converting organic waste into biogas and digestate (Tampio et al., 2018). Studies have shown that well-maintained plants can experience minimal performance decline over their lifetime (Monnet et al., 2016), making them a reliable long-term investment.

The formula becomes:

Feasibility = (17,483×12×25) − [(75,250) + (15,000x12x25-15,000)

Feasibility = 5,244,900−4,560,250

Feasibility = 684,650 RWF

The positive value of 74,270 RWF indicates a surplus or profit over the project's lifetime, suggesting that the project is financially feasible. If the value were negative, it would suggest potential financial challenges. This feasibility metric considers the net income generated by the biogas project compared to the total expenses incurred over its lifetime.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1. Introduction

The production of biogas has become a viable option for turning organic waste into a useful energy source in the search for sustainable and renewable energy sources. The results and in-depth discussions from the anaerobic co-digestion process simulation are presented in this chapter, with an emphasis on fish waste and water hyacinth. Our main goal is to evaluate this novel approach's viability and effectiveness critically to add significant knowledge to the continuing discussion about sustainable energy systems[47].

The search for sustainable and alternative energy sources has accelerated due to the world's unwavering need for energy. Produced by the anaerobic digestion of organic matter, biogas offers a feasible alternative that can potentially mitigate environmental issues related to the disposal of organic waste while also serving as a sustainable energy source. This study uses fish waste and water hyacinth as co-substrates in a continuous-flow digester system to further our understanding of biogas production[48].

5.1.1. Simulation parameters and Biogas production

The precise selection of simulation settings is critical to the outcome of the inquiry. A detailed and accurate depiction of the anaerobic co-digestion process has been ensured by giving careful consideration to elements like the starting substrate concentrations and the methanogenesis rate constant (kmethanogenesis).

Central to this investigation is total biogas output, a measure of the anaerobic co-digestion process's efficiency. The model produced a cumulative biogas quantity of 10.5806 liters during a 30-day simulation session. This crucial result serves as the foundation for assessing the planned biogas-producing system's overall effectiveness.

The details of this research findings are elucidated in the next sections, which also involve detailed analysis, comparisons with previous research, and operational parameter concerns. More clarifications were developed about the potential of fish waste and water hyacinth as co-substrates for biogas production through these talks, highlighting its implications for environmentally friendly and commercially feasible energy solutions.

5.2. Comparison with Literature

To ensure the robustness of findings, a comprehensive comparative analysis was conducted, juxtaposing the simulation results with established literature on analogous anaerobic co-digestion studies. This meticulous examination aimed to unveil patterns, disparities, and parallels, affirming the reliability and consistency of the established simulation within the broader scientific landscape. The findings of effective production of the co-digestion, environmental protection, and impacts on the use of local natural resources of this research closely align with those documented in reputable studies, fostering confidence in the validity of obtained results and reinforcing the significance of water hyacinth and fish waste as viable co-substrates in the realm of biogas production.

Notably, the simulated biogas yield of 10.5806 liters over the 30 days relatively coincides with the outcomes observed in other studies, thereby strengthening the reliability of the proposed anaerobic co-digestion against established benchmarks.

5.3. Sensitivity Analysis

Methodology

A nuanced sensitivity analysis played a pivotal role in unraveling the intricacies of simulation outcomes. Key parameters, including the methanogenesis rate constant ($K_{methanogenesis}$), substrate concentrations, and temperature, underwent systematic variations to gauge their individual and collective impact on biogas production. This methodical exploration aimed to uncover the factors wielding the most substantial influence on outcomes, offering a comprehensive roadmap for refining and optimizing the proposed anaerobic co-digestion model.

5.4. Key Findings

The sensitivity analysis unearthed several critical insights into the dynamics of the presented biogas production system. The literature presented in Table4.1 of Co-digesting these materials can increase biogas output on above 52% when compared to water hyacinth alone, reaching up to 0.38 m3/kg VS. While mono-digestion of fish waste gives roughly 0.25 m3 of biogas per kg of volatile solids (VS), and water hyacinth yields approximately 0.30 m3/kg VS. This noteworthy rise highlights the synergistic benefits of co-digestion, which makes it an effective tactic for optimizing the production of biogas from organic waste streams.

The ensuing discussions delve into the implications of comparative analysis with literature and the nuanced insights derived from the sensitivity analysis, shedding light on the broader implications for the feasibility and optimization of anaerobic co-digestion with water hyacinth and fish waste.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

In conclusion, this study delved into the feasibility study of anaerobic co-digestion utilizing water hyacinth and fish waste as co-substrates in a continuous-flow digester. Through meticulous simulations and analyses, we have gained valuable insights into the dynamics of biogas production and the potential of these waste materials as renewable energy resources. The following key conclusions can be drawn:

- Biogas Production Potential: Our simulations demonstrated a promising biogas production potential, with a cumulative yield of 10.5806 liters over 30 days. This aligns with established literature, reaffirming the viability of water hyacinth and fish waste as effective co-substrates in anaerobic co-digestion.
- Sensitivity Analysis: The sensitivity analysis provided critical insights into the influence of key parameters on biogas production. Notably, variations in water hyacinth substrate concentration showed about 52 % change in biogas yield when two substates are combined, highlighting the system's sensitivity to specific environmental factors.

6.2. Recommendations

Building on our findings, several recommendations emerge to enhance the effectiveness and sustainability of anaerobic co-digestion systems:

- Optimization of Substrate Ratios: Further investigations should explore the optimal ratio of water hyacinth to fish waste to maximize biogas production. Fine-tuning these ratios based on local availability and characteristics can improve system efficiency.
- Advanced Process Monitoring: Implementing advanced monitoring systems, such as real-time sensors and automation, can enhance the precision of the anaerobic co-digestion process. This allows for more accurate control and optimization of key parameters.
- Community Engagement and Education: Community awareness and participation are vital for the success of biogas projects. Outreach programs and educational initiatives can

inform local communities about the benefits of anaerobic co-digestion, fostering acceptance and sustainable implementation.

- Real experimental base the future research. Investors, government, or academic institutions should invest in the research-based field to get the field or lab-based data for better conclusions.

6.3. Future Research Directions

While this study provides valuable insights, there are avenues for further research to advance the field of anaerobic co-digestion:

- Long-Term Performance: Investigate the long-term performance and stability of anaerobic co-digestion systems over extended operational periods to assess sustainability and durability.
- Economic Assessment: Conduct a comprehensive economic assessment, including a detailed cost-benefit analysis, to evaluate the financial viability and return on investment for scaling up biogas projects.
- Innovations in Digester Design: Explore innovative digester designs and materials that are cost-effective and suitable for diverse geographical and economic contexts.

In conclusion, this study contributes to the growing body of knowledge on sustainable energy solutions by showcasing the potential of anaerobic co-digestion with water hyacinth and fish waste. By implementing the recommendations and pursuing future research directions, we can further harness the benefits of biogas production for a cleaner and more sustainable future.

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APPENDIX

MATLAB Codes

```
% Define constants
k_max = 0.4;         % Maximum reaction rate constant
V = 150;        % Digester volume (liters)
feedstock_mass = 10;  % Pretreated feedstock mass (kilograms) without 20 liters of
fish wastes
retention_time = 30;  % Digester retention time (days)
total_biogas = 0;

% Initialize variables
biogas_production = zeros(30, 1);
current_feedstock_mass = feedstock_mass;
day_counter = 1;

% No biogas production in the first 10 days
for day = 1:10
    % Calculate daily biogas production
    daily_biogas = 0;

    % Store daily biogas production
    biogas_production(day) = daily_biogas;

    day_counter = day_counter + 1;
end

% Gradual increase in biogas production from day 11 to day 24
for day = 11:24
    % Calculate daily biogas production
    daily_biogas = k_max * V * current_feedstock_mass / (1 + (k_max *
retention_time)^2) * day_counter * 0.01;

    % Update digester content
    current_feedstock_mass = current_feedstock_mass - daily_biogas / retention_time;

    % Store daily biogas production
    biogas_production(day) = daily_biogas;

    % Accumulate total biogas production
    total_biogas = total_biogas + daily_biogas;

    day_counter = day_counter + 1;
end

% Gradual decrease in biogas production from day 25 to day 30
for day = 25:30
    % Calculate daily biogas production
    daily_biogas = k_max * V * current_feedstock_mass / (1 + (k_max *
retention_time)^2) * (30 - day_counter) * 0.01;
```

```
    % Update digester content
    current_feedstock_mass = current_feedstock_mass - daily_biogas / retention_time;

    % Store daily biogas production
    biogas_production(day) = daily_biogas;

    % Accumulate total biogas production
    total_biogas = total_biogas + daily_biogas;

    day_counter = day_counter + 1;
end

% Plot daily biogas production
plot(1:30, biogas_production);
xlabel('Day');
ylabel('Biogas Production (liters)');
title('Daily Biogas Production from 10 kg Pretreated Feedstock');
grid on;

% Display total biogas production
disp(['Total Biogas Produced: ', num2str(total_biogas), ' liters']);
```