

# **INVESTIGATING THE USE OF WASTEWATER SLUDGE-BASED FUELS**

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## ABSTRACT

The environmental damage caused by widespread deforestation for charcoal manufacturing needs the urgent study of sustainable alternatives. This report studies the potential of using waste water sludge from the UCU waste water treatment plant as a renewable feedstock for briquette production, employing the hydrothermal carbonization method, with the goal of reducing the environmental effect of traditional charcoal production. The study investigates the physical, chemical, and combustion aspects of briquettes made from various binding ratios of waste water sludge and compares their performance to traditional market briquettes. The environmental impact analysis also takes into account emissions of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), volatile organic compounds (VOCs), and ash content. The results show that briquettes made from waste water sludge have promising properties, such as a high calorific value, low ash content, and lower CO and CO<sub>2</sub> emissions than ordinary charcoal. Furthermore, using waste water sludge as a feedstock has environmental benefits because it diverts waste from landfills and reduces reliance on unsustainable charcoal production processes. This study highlights the potential of waste water sludge-based briquettes as a sustainable alternative fuel source, helping to reduce deforestation and promote environmental sustainability.

## DECLARATION

I, NAGITTA AISHA THURAYYA, hereby declare that all the work presented in this report is original and has been carried out by me unless otherwise acknowledged. All sources used have been properly cited and referenced. No part of this report has been submitted to any institution of higher learning for any academic award.

Signature.....

Date.....

## **DEDICATION**

This report is dedicated to my parents, teachers and mentors, whose guidance, patience and encouragement have shaped me into the person I am today. Your unwavering support has been instrumental in my academic journey, and I am deeply grateful for your belief in my potential. This achievement is as much yours as it is mine.

Thank you for everything.

## APPROVAL

This research and design project has been submitted for examination with my approval as the university supervisor.

Signature .....

Date .....

Mr. Solomon Azarius Lubaale

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## List of Abbreviations

FC	Fixed Carbon
HTC	Hydrothermal Carbonization
IRR	Internal Rate of return
Kg	Kilogram
MJ	Mega Joules
MPa	Mega Pascals
MSW	Municipal solid waste
MWE	Ministry of Water and Environment
pH	potential of Hydrogen
RDF	Refuse-Derived Fuel
ROI	Return on Investment
SRF	Solid Recovered Fuel
TDF	Tire-Derived Fuel
UCU	Uganda Christian University
UNICEF	United Nations Children's Fund
VM	Volatile Matter
WWTP	Wastewater Treatment Plant

## CHAPTER ONE: INTRODUCTION

### 1.1 Introduction

Over 63% of the people in Africa use wood-based fuel as their primary energy source thus consuming over 90% of the wood extracted in the region (Troncoso and Tesfamichael, 2022). The consumption of wood-based fuel has led to an annual loss of forest cover of approximately 122,000 hectares around Uganda causing environmental stress, degradation and rising vulnerability towards climate change (MWE, 2016). In Uganda, forests supply over 89.7% of Uganda's energy used for cooking while electricity and petroleum provide 1% and 5% respectively (Akumu, 2023). With the current population growth rate, the United Nations predicts that the population in Africa is expected to roughly double to about 2.5 billion people by 2050 (UNICEF, 2014), the fuel demand is bound to increase thus causing further stress on the environment through deforestation. Due to the increased awareness about the dangers of dependence on wood-based fuel, alternative fuels such as briquettes manufactured from organic waste such as carbonized coffee husks and other combustible material have been developed though this industry has not grown and adopted mainly because of the availability of raw materials and the quality of the briquettes produced impact consumer confidence and demand.

Sludge in its raw form is a good biomass feedstock due to the high organic matter in it that when specially processed, has the potential to contain fixed carbon greater than 60%, Volatile matter less than 30%, and ash content less than 18% (Inegbedion, 2022). Sludge is also readily available which will make our produced fuel available for the consumers.

Hydrochar is a high carbon content with a high energy density form of Charcoal obtained from organic matters such as dung, firewood, and agricultural wastes but in our case sludge, produced through a chemical process of hydrothermal carbonization. Hydrothermal Carbonization is a thermochemical process that converts biomass, organic waste, or other carbon-containing materials into a solid carbon-rich product called hydrochar through a combination of high-temperature and high-pressure water treatment. The solid produced can easily be dried into a carbon-rich powder which can be used to make Briquettes. A briquette is a densified block of a combustible biomass material that can be used as a fuel.

### **1.2 Problem statement**

The rising population has led to an increase in fuel need which has caused an incessant dependence on wood-based fuels resulting in environmental degradation through deforestation causing severe consequences to the climate. This study seeks to come up with a more sustainable fuel source that will reduce the dependence on wood-based fuel without drastically changing the cooking technology that households are currently using, thus replacing wood-based fuel with briquettes formed using hydrochar produced from wastewater sludge. This will reduce the burden of dumping sludge in the environment, lower fuel costs, and preserve the forests (Deanna ramsay, 2021).

### **1.3 Main Objectives**

To investigate the use of wastewater sludge generated by the UCU Wastewater treatment plant as a biofuel.

### **1.3.1 Specific objectives**

1. To determine the properties of the wastewater sludge that make it a suitable feedstock.
2. To determine the optimum process conditions to be used to maximize Hydrochar yield and briquette formation.
3. To determine the fuel characteristics of the briquettes formed using the hydrochar.
4. To carry out a cost-benefit analysis of the briquettes formed using the hydrochar.

### **1.4 Research Questions**

1. What are the properties of the wastewater sludge that make it a suitable feedstock?
2. What are the optimum process conditions required to maximize Hydrochar yield and briquette formation?
3. What are the fuel characteristics of the briquettes formed using the hydrochar?
4. What is the cost-benefit analysis of the briquettes formed using the hydrochar?

### **1.5 Scope**

The scope of the study is Ddandira Village Located along Katosi Road in Mukono District.

The source of the wastewater sludge is the Uganda Christian University (main Campus) wastewater treatment plant.

## **1.6 Justification**

Poor disposal of sludge can contaminate soil, groundwater, and surface water bodies. This can lead to the spread of pollutants and harmful substances in the environment, such as pathogens, toxins, and chemical contaminants. If not managed correctly, these substances can pose serious health risks to humans and wildlife. Sludge that is not properly treated and applied to the soil can lead to long-term soil degradation. It may alter soil structure, nutrient balance, and pH levels.

When waste is converted into a biofuel it generates renewable energy that can be used for electricity generation, cooking, and other processes which reduces the demand for fossil fuels and at the same time reduces the volume of waste that needs to be disposed of in landfills or through other methods.

## **1.7 Significance**

When sludge is converted into a solid fuel through carbonization processes like pyrolysis and hydrothermal carbonization, it creates a renewable source of energy that could be used for household cooking, which enables the recovery of energy from waste items that would otherwise need to be processed and disposed of. By doing this, the value recovered from the waste stream is maximized. This lessens the amount of waste that must be disposed of in landfills or incinerated. As a result, it supports a more sustainable approach to waste management. Energy production sources are diversified by adding biofuels obtained from sludge to the mix thus lowering dependence on a single source, this improves energy security.

## CHAPTER TWO: LITERATURE REVIEW

This chapter includes the theoretical framework for this research as well as an empirical analysis of prior studies that have examined the use of waste water sludge to make briquettes. The review of empirical literature comes after the theoretical literature in its order of organization. A review of the current literature is also provided along with an identification of the research need that justifies this study's addition to the body of knowledge.

### 2.1 Theoretical Review

#### Fuel

Fuels are materials that, when burned or subjected to chemical reactions, release energy. They are essential for many different uses, such as industrial processes, heating, transportation, and the production of energy. One kind of alternative fuel source is recovered fuel, which is produced by processing and reusing different waste materials. They are utilized to replace conventional fossil fuels in sustainable and environmentally beneficial manner. They save natural resources, cut down on greenhouse gas emissions, and lessen the amount of waste that ends up in landfills.

Recovered fuels include, for example:

- i. Refuse-Derived Fuel (RDF): Materials such as plastics, paper, and organic garbage are processed and shredded to create RDF, which is a solid waste product. After that, these materials are compacted to create fuel briquettes or pellets. RDF is utilized in several industrial processes, like the making of cement production and energy generation (Clark, 2023).
- ii. Solid Recovered Fuel (SRF): SRF is intended for use in industrial and energy applications and is comparable to RDF, but it is usually of a higher quality.

Commercial and industrial trash, as well as sorted and processed municipal solid waste (MSW), are frequently used to make it. In waste-to-energy facilities, SRF can be an effective energy source (EN ISO:21640, 2021).

- iii. **Solid Biomass Fuels:** Organic materials like wood, agricultural waste, and other plant-based waste are used to make these fuels. These materials become solid biomass fuels after they are treated and compressed. They can be substituted for fossil fuels in industrial processes and used for heating and energy generation (Ibitoye, 2023).
- iv. **Tire-Derived Fuel (TDF):** Used tires are processed and shredded to create TDF. It is a valuable source of energy and is used in cement kilns, industrial boilers, and as a supplemental fuel in power plants. TDF not only reduces the environmental impact of tire disposal but also conserves energy resources (Gray, 1997).
- v. **Plastic Solid Fuels:** By heating waste plastic without oxygen, a procedure known as pyrolysis can turn some waste plastics into solid fuels. This can result in solid fuels made of plastic that can be utilized to generate electricity and heat (Kohli, 2021).

By offsetting the usage of fossil fuels, recovered fuels can reduce greenhouse gas emissions, handle waste management issues, and contribute to a more sustainable energy mix. To maximize their advantages and reduce any potential environmental effects, it is crucial to make sure that these fuels are produced and used in an environmentally responsible manner.

## **Solid recovered fuel**

Solid Recovered Fuels (SRF) are a cutting-edge and ecologically friendly method of managing garbage and producing electricity. These fuels are produced by processing different waste products, such as sewage sludge, industrial waste, and municipal solid waste (MSW), into useful energy resources. In particular, the generation of SRF from sludge has drawn a lot of attention because it not only solves the problems connected with managing sludge but also helps to minimize the environmental impact of waste disposal and lessen dependency on fossil fuels. The conversion of what was once thought of as a waste product into a useful resource is a crucial component of SRF synthesis from sludge. Sludge is a significant byproduct of the sewage treatment procedures of wastewater treatment plants. In the past, this sludge was often landfilled or incinerated, which not only posed environmental concerns but also failed to harness the energy potential within the sludge. By converting sludge into SRF, this underutilized resource is put to more productive use, aligning with the principles of the circular economy. (Wilk, 2022)

SRF is usually produced from sludge through a multi-step process. Dewatering is the first step in order to lower the sludge's moisture content and improve its suitability for further treatment. Then, to further reduce the moisture content and raise the material's energy density, drying methods including thermal or mechanical drying are used. Some dried sludge can be turned into solid fuel with improved combustion qualities by applying pyrolysis or gasification methods. SRF can also be optimized for quality and combustion efficiency through co-processing, which combines sludge with other waste streams like biomass. For its practical uses, the resulting SRF's quality and features are essential. The SRF's makeup is determined by the type of

sludge, the treatment processes involved, and the production methods used. Proper characterization is necessary to ensure that the SRF meets relevant fuel standards and emissions regulations, allowing for its safe and efficient use in various industrial and energy applications. (Wilk,2022)

SRF generation from sludge has several benefits in terms of the environment. It lessens the number of hazardous materials released into the environment during the disposal of sludge, thereby reducing its environmental impact. Furthermore, substituting sustainable renewable energy (SRF) for fossil fuels lowers greenhouse gas emissions, supporting climate change mitigation and sustainability objectives. To guarantee the entire sustainability of SRF production, it is imperative to carry out a comprehensive evaluation of the environmental and economic implications of its production. Variations in the properties of the sludge, technical viability, and regulatory limitations are obstacles in the manufacturing of SRF from sludge. In order to handle environmental issues, optimize SRF manufacturing methods, and create cutting-edge technologies that can enhance the effectiveness and environmental performance of this strategy, more research and development is required. In doing so, SRF from sludge holds the potential to play a significant role in the transition toward cleaner and more sustainable energy sources while addressing waste management challenges. (Dutta,2015)

Sludge briquettes, a specialized and effective form, have been developed as a result of the production of Solid Recovered Fuels (SRF) from sludge, a potential method to address both waste management and sustainable energy generation. With the help of these briquettes, sewage sludge—a historically difficult waste product—has been miraculously transformed into a small, highly efficient fuel source that has both practical and environmental advantages. Through an examination of their

manufacturing, uses, and contribution to the advancement of waste-to-energy programs, this research sheds light on the relationship between SRF made from sludge and the cutting-edge world of sludge briquettes.

Sludge briquettes are a specific type of Solid Recovered Fuel (SRF) made from sewage sludge, a byproduct of wastewater treatment procedures. These briquettes represent a novel method to sludge management, transforming what was previously deemed waste into a useful resource for energy recovery and waste reduction. Sludge briquettes are produced by a series of treatment and processing stages that convert sludge into a more efficient and ecologically friendly fuel source.

The initial stage in making sludge briquettes is dewatering sewage sludge. Sludge often contains a high moisture content, making it difficult to handle and transport. Dewatering is the process of removing surplus water to lower moisture content and improve sludge handling qualities. Various procedures, such as mechanical dewatering and centrifugation, can be used to accomplish this. After dewatering, the sludge is further treated to produce a homogeneous, flammable substance. This entails combining the sludge with binding agents, such as biomass or other waste materials, to increase its energy content and facilitate briquette production. The mixture is then crushed into the proper briquette form and size with specialist machinery.

Sludge briquettes provide numerous advantages. For starters, they offer an environmentally responsible alternative for sewage sludge management, diverting it away from landfills or incineration, both of which can have negative environmental consequences. Second, the briquettes have a higher energy density than untreated sludge, making them useful for a variety of energy applications such as heat and electricity generation. Furthermore, sludge briquettes can be an

effective source of renewable energy. When employed in thermal operations like cement kilns or industrial boilers, they help to minimize greenhouse gas emissions and the demand for fossil fuels. This promotes a more sustainable and circular approach to waste management and energy production.

However, producing sludge briquettes is not without obstacles. The composition and quality of sewage sludge can vary significantly, which can impact the characteristics of the resulting briquettes. Moreover, the regulatory environment, including emissions standards and environmental permits, must be carefully considered to ensure compliance during the production and use of sludge briquettes. (Wilk, 2022)

Finally, sludge briquettes are an innovative and sustainable approach for managing sewage sludge. They exhibit the ability to turn a difficult waste stream into a useful energy supply, so contributing to both waste reduction and cleaner energy production. Sludge briquettes have potential as a key component of a more circular and environmentally responsible approach to waste management and energy recovery, as research and development in this area continues.

## **2.2 Empirical Review**

### **2.2.1 Hydrothermal Carbonization**

HTC is defined as the carbonization of biomass in water at subcritical temperatures and pressures. During the HTC process, the solid material (biomass) is totally immersed in water in closed systems at temperatures ranging from 180-250°C and pressures of 2-6 MPa for a reaction period of 5-240 minutes (Kambo, 2015). At temperatures beyond 250°C, hydrothermal processes are further characterized as liquefaction and gasification (Dutta, 2014). The HTC of biomass produces three

primary products: hydrochar, liquid containing bio-oil combined with water, and a tiny quantity of gasses, primarily CO<sub>2</sub> (Kambo, 2015).

Because the hydrochar's energy content and chemical makeup are comparable to those of natural coal, it can be used as a solid fuel in standard combustion operations (Masoumi, 2021).

### Feed stock

Under hydrothermal circumstances, carbonization of any sort of organic matter and biomass is theoretically possible. HTC processes have been effectively used to treat feedstock, including cellulose, wood, microalgae, MSW, food waste, sewage sludge, and agricultural residues (Sevilla and Fuertes, 2009). The distribution of products (hydrochar, liquid and gas phases), their characteristics, conversion efficiencies, and process energetics are all greatly impacted by the properties of biomass feedstock, including chemical composition, moisture content, volatile matter (VM), fixed carbon (FC), noncombustible matter (ash), and energy content (Czerwińska, 2022).

Table 1 Proximate analysis results for wastewater sludge

Material	Moisture % (Wet basis)	Volatile Matter % (Dry basis)	Fixed Carbon % (Dry basis)	Ash Content % (Dry basis)	Energy Content (MJ/kg)	Reference
Wastewater Sludge	77.8	58.9	10.86	30.14	14.92	(Wang <i>et al.</i> , 2012)
Wastewater Sludge	80.2	68.5	16.4	23.27	18.45	(Wang <i>et al.</i> , 2012)

**Table 1 Proximate analysis results for wastewater sludge**

Wastewater Sludge	78.4	55.3	19.29	25.38	15.65	(Wang <i>et al.</i> , 2012)
Wastewater Sludge	81.9	67.2	9.2	19.3	14.54	(Moon <i>et al.</i> , 2015)
Wastewater Sludge	73.03	61	10.29	28.71	13.74	(Wen <i>et al.</i> , 2023)
Wastewater Sludge	83.7	52.52	12.58	34.9	13.1	(Wen <i>et al.</i> , 2023)
Wastewater Sludge	83.7	52.52	12.58	34.9	13.1	(Wen <i>et al.</i> , 2023)
Wastewater Sludge	80.97	57	12.31	30.69	13.76	(Wen <i>et al.</i> , 2023)
Sewage Sludge	96	70.3	5.3	16	18	(Danso-Boateng <i>et al.</i> , 2013)

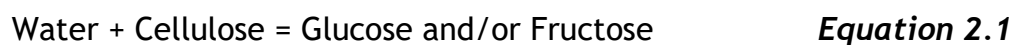
### 2.2.2 Mechanisms of HTC

Hydrochar can be formed by the following steps; **Hydrolysis, Dehydration, fragmentation, polymerization and aromatization** (Sevilla and Fuertes, 2009).

#### Hydrolysis

The biological molecules present in the sludge consist of monomers, which are repeating subunits that are combined to form polymers. These polymers break the

link between their long chains and shorter chains, known as oligomers, when heated in water to sub-critical temperatures of 100-175 °C.



This reaction is an example of how the addition of water molecules during hydrolysis breaks down cellulose into simpler sugar molecules, such as glucose and fructose.

### **Dehydration**

Double bonds between carbon atoms are created when organic compounds undergo dehydration, which is the elimination of water molecules. As the temperature rises throughout the hydrothermal process, dehydration processes may also take place alongside hydrolysis, converting sugars and other carbohydrates into furans and other intermediate molecules. The temperature range where it happens is 160-280°C.

Glucose has the ability to dehydrate under hydrothermal conditions, forming hydroxymethylfurfural (HMF), a useful intermediate chemical in biomass conversion processes.



### **Fragmentation**

A crucial step in turning biomass into hydrochar is fragmentation, which is breaking down large organic molecules into smaller pieces or building blocks. Biomass constituents including cellulose, hemicellulose, lignin, and proteins are broken down by processes like chemical bond breakage, mechanical pressures, and heat treatments, producing intermediate products such simple sugars, organic acids, and phenolic compounds. Through this procedure, the biomass material's surface area is

greatly increased, exposing more reactive areas for further chemical reactions. Maintaining control over reaction parameters, such as catalyst concentration, temperature, and pressure, is essential to maximize fragmentation efficiency and reduce the production of unwanted byproducts. In general, fragmentation helps biomass become more susceptible to additional chemical transformations, which makes it easier to generate hydrochar with improved qualities for a range of applications, including soil amendment, carbon sequestration, and energy generation.

### **Polymerization**

Polymerization involves the formation of larger molecules (polymers) from smaller precursor molecules (monomers) through chemical bonding reactions, polymerization can occur as intermediate compounds generated from hydrolysis, dehydration, and decarboxylation reactions undergo further condensation and cross-linking reactions, leading to the formation of higher molecular weight compounds such as bio-oils, bio-gas and a carbon-rich solid material known as hydrochar.

Intermediate Compounds → hydrochar

*Equation 2.3*

### **Aromatization**

Under high temperature conditions, the fragmented intermediate compounds generated during HTC can undergo further chemical transformations, including aromatization. Aromatization involves the conversion of aliphatic or cyclic compounds into aromatic compounds through rearrangement and cyclization reactions. Aromatic compounds contribute to the high carbon content and stability of the resulting hydrochar.

During condensation reactions, hydroxymethylfurfural (HMF) and aldehydes can react to form lignin-like compounds, which contribute to the formation of solid carbonaceous materials such as biochar.



***Equation 2.4***

### **Influence of process parameters**

As was previously noted, the qualities of the hydrochar are determined by the feedstock characteristics in HTC feedstock. Furthermore, the HTC process parameters—such as the feedstock's moisture content, operating temperature, reaction duration, pressure, solid load, and pH level—affect the generation of hydrochar.

#### **Moisture Content**

Previous investigations have shown that water speeds up the carbonization of biomass; biomass above the water's surface does not carbonize. One crucial component of the HTC process is having enough water (Krylova and Zaitchenko, 2018).

#### **Temperature**

In the hydrothermal carbonization process, temperature is a crucial parameter. The quantity of energy given to the reaction, which is required for the fragmentation of feedstock particles, is affected by variations in this parameter. Higher temperatures significantly accelerate the degradation and polymerization of sewage sludge (Wang, Chang and Li, 2019) resulting in the formation of hydrochar (Akhtar and Amin, 2011). The carbonization process is favoured for temperatures up

to 250 °C, at temperatures up to 375 °C, oil is formed, while above 375 °C, gas is formed (He *et al.*, 2014). Thus, proved that the highest solid yield was obtained at temperatures below 200 °C.

### **Reaction time**

The residence time of the process is a very important factor, it affects the energy balance, process and operating costs. It also affects the distribution of the resulting products, their properties and chemical composition (Czerwińska, Śliz and Wilk, 2022). Prolongation of the carbonization time correlates with the enhancement of the carbonization reaction, the residence time of hydrothermal carbonization varied considerably, the shortest time period was 15 minutes, while the longest was 1440 minutes. The most common time period was 60 minutes (Czerwińska, Śliz and Wilk, 2022).

### **pH value**

Because organic acids such lactic, formic, and acetic acids are generated during HTC operation, a pH reduction is seen (Niinipuu *et al.*, 2020). The use of acids and bases to adjust pH in the HTC process has been studied, and significant effects on product characteristics and reaction rate have been observed. The effect of feedstock pH on hydrochar yield has also been studied, and the results show that, at pH 1, the strong acid accelerates the hydrolysis reaction in the early stages of HTC (Liang, Liu, and Zhang, 2011). On the other hand, the strong acid prevents polymerization and carbonization. At pH of 3, 5 and 7, the hydrochar yields increased with reaction time and, after 3 h, reached their maximum yields which are very similar (43.57%, 44.6%, and 43.69% for pH of 3, 5, and 7, respectively). Therefore, the suitable pH value of feedstock for the HTC process ranges from 3 to 7 (Jeong *et al.*, 2012).

### 2.2.3 Briquette making

A briquette is mainly a block of compressed biomass waste made from natural materials like agricultural waste, forestry waste, coal pieces, and other biomass material used as fuel in stoves and boilers. The ingredients needed to make briquettes include a fuel source, an accelerant, and a binder (Salmon, 2021).

#### i. Heating fuel

A heat fuel is a substance that is burned to provide nuclear energy, heat, or power. There are various heat fuels that can be used in briquette making, and they include wood charcoal, charcoal fines, mineral carbon, coal, biochar, and other biomass materials. According to previous reports, a higher percentage of heat fuel material about 70-90% of the material make for better briquettes (Jagdish, 2019).

#### ii. Accelerants

Accelerants are substances that increase the rate of a chemical reaction or combustion. Unlike charcoal, briquettes need accelerants to enable them to burn faster. The commonly used accelerants used in briquettes include sodium nitrate, waxes, and sawdust (Salmon, 2021). Sodium nitrate is preferred because, when heated, it gives off oxygen, which aids in ignition and combustion.

#### iii. Binder

A binder is any material or substance that holds or draws other materials together to form a cohesive whole. Most chars or biomass fuel materials are non-plastic and cannot hold shape without adding a binding material. The most common binders include starches like cassava starch, corn starch, and various flours, molasses, cement, clay and tar (NGURECO, 2023).

#### **2.2.4 Summary and Research Gaps**

The exponential increase in energy demand, as well as the subsequent rise in fuel prices, constitute a substantial threat to emerging countries' economies. Alternative and sustainable energy, such as biofuel, appears to be a quick solution to this problem; however, the emerging industry is experiencing a feedstock supply shortage, with some feedstock coming from agricultural byproducts such as coffee husks and wood shavings, which are subject to production seasons. Biofuel production must be consistent and cost-effective for the industry (Oonsivilai et al., 2009).

## CHAPTER THREE: METHODOLOGY

This chapter outlines the systematic approach undertaken to achieve the above listed objectives, addressed through a structured methodology designed to ensure accuracy, reproducibility and reliability of the results obtained.

### 3.1 Determining the properties of the wastewater sludge that make it a suitable feedstock.

A good biomass feedstock is one with has a high energy content, low volatile matter, low ash content and low moisture content.

#### 3.1.1 Experiment to determine the moisture content of the sewage sludge (STM D2974-87).

##### Apparatus

- i. A balance readable to 1g
- ii. A drying oven at 105° C
- iii. Evaporation Dishes

##### Sample Preparation

- The sample was air-dried for two weeks



Figure 1: dried sludge

## Procedure

1. The evaporating dish was weighed and recorded.
2. A sludge sample of not more than 50g was placed into the evaporating dish and the weight recorded.
3. The evaporating dish with the sample were placed in the oven at 105°C for 16-24 hours.

The moisture content was calculated using:

$$\text{Moisture content} = \frac{(W_{\text{wet sample}} - W_{\text{oven dry}})}{W_{\text{wet sample}}} \times 100 \quad \text{Equation 3.1}$$

The results obtained were recorded in the table below.

Table 2: Moisture Content of the raw sludge (Dry basis)

Moisture Content			
Test No	R1	R2	R3
Mass of Crucible (g)	20.897	19.88	19.122
Mass of Crucible + Sample before testing (g)	28.29	26.45	24.034
Mass of Sample (g)	7.393	6.57	4.912
Mass of Crucible + Sample after testing (g)	27.153	25.441	23.289
Mass of Sample after testing (g)	6.256	5.561	4.167
Mass of water (g)	1.137	1.009	0.745
Moisture Content (%)	15.38	15.36	15.17
Average (%)	15.30		

### **3.1.2 Experiment to determine the amount of volatile Matter in the wastewater sludge. (ASTM D3175-07).**

Volatile matter is determined by establishing the loss in weight resulting from heating the dry sludge under rigidly controlled conditions. The measured weight loss, corrected for moisture as determined in Test Method D3173 establishes the volatile matter content.

#### **Apparatus**

- i. 250- $\mu\text{m}$  sieve.
- ii. A balance readable and accurate to 0.1 g
- iii. Crucible with a closely fitting lid
- iv. Furnace capable of maintaining  $950^{\circ}\text{C}\pm 20^{\circ}\text{C}$

#### **Procedure**

1. The sample was crushed and sieved using a 250  $\mu\text{m}$  sieve.
2. The crucibles were heat-treated for 4 hours at  $500^{\circ}\text{C}$  to guarantee that they were totally oxidized before use.
3. A representative sample was weighed and its mass recorded.
4. The mass of the crucible to be used was determined and documented.
5. The crucible containing the sample was then tightly covered to prevent it from burning away.
6. The crucible was put directly into the furnace chamber, maintaining a temperature of  $950^{\circ}\text{C}\pm 20^{\circ}\text{C}$ .
7. After heating for exactly 7 minutes, the crucible was taken from the furnace without disturbing the cover and allowed to cool.

8. The cooled crucible containing the sample was weighed and the results recorded.

The percentage loss of weight minus the percentage moisture equals the volatile matter.

$$\text{Weight Loss}\% = \frac{(\text{Initial weight of dry sample} - \text{weight of remaining sample})}{\text{Initial weight of dry sample}} \times 100 \quad \text{Equation 3.2}$$

$$\text{Volatile Matter} = \text{Weight loss}\% - \text{Moisture}\% \quad \text{Equation 3.3}$$

Table 3: Volatile matter of the raw sludge

Volatile Matter			
Test No	R1	R2	R3
Mass of Crucible (g)	37.954	36.273	40.399
Mass of Sample (g)	1.001	1.01	1.064
Mass of Crucible + Sample Before testing (g)	38.955	37.283	41.463
Mass of Crucible + Sample After testing (g)	38.361	36.688	40.819
Mass loss (g)	0.594	0.595	0.644
Volatile Matter (%)	43.96	43.55	45.36
Average (%)	44.29		

### 3.1.3 Experiment to determine the ash content in the wastewater sludge. (ASTM D3174-12)

Ash, as determined by this test method, is the residue remaining after burning the sludge, it constitutes inorganic constituents present in the original sample.

## Apparatus

- i. Furnace capable of maintaining 750°C
- ii. 250-µm sieve.
- iii. A balance readable and accurate to 0.1 g
- iv. Crucible

## Procedure

1. The sample was pulverized and sieved through a 250µm sieve.
2. A representative sample was weighed and recorded.
3. The mass of the crucible was measured and recorded.
4. The representative sample was then placed in the crucible without a lid and then transferred to a cold furnace.
5. It was then heated at a rate that reaches 500 ±10°C in 1 hour.
6. The sample continued to be heated till the temperature reached 750±15 °C at the same rate.
7. The temperature is then maintained at 750±15 °C for another 2 hours.
8. The sample was then removed from the furnace, a lid placed on the crucible and then allowed to cool.
9. The weight of the Crucible and the ash Residue is taken and recorded.

Ash Content was calculated from the following Formula;

$$\text{Ash content} = \frac{\text{Weight of Crucible and Ash residue} - \text{Weight of the empty Crucible}}{\text{Weight of oven dry sample}} \times 100$$

**Equation 3.4**

Table 4: Ash Content of the raw sludge.

Ash Content			
Test No	R1	R2	R3
Mass of Crucible (g)	37.963	36.278	40.408
Mass of Sample (g)	1.246	1.323	1.009
Mass of Crucible + Sample before testing (g)	39.209	37.601	41.417
Mass of Crucible + Sample after testing (g)	38.32	36.662	40.694
Mass of Sample after testing (g)	0.357	0.384	0.286
Ash Content (%)	28.65	29.02	28.34
Average (%)	28.67		

- Experiment to determine the amount of Fixed carbon in the wastewater sludge.

The fixed carbon will be found by subtracting the sum of percentages of ash content and volatile matter from 100.

$$\text{Fixed Carbon} = 100\% - (\text{Ash content} + \text{Volatile Matter} + \text{Moisture Content})$$

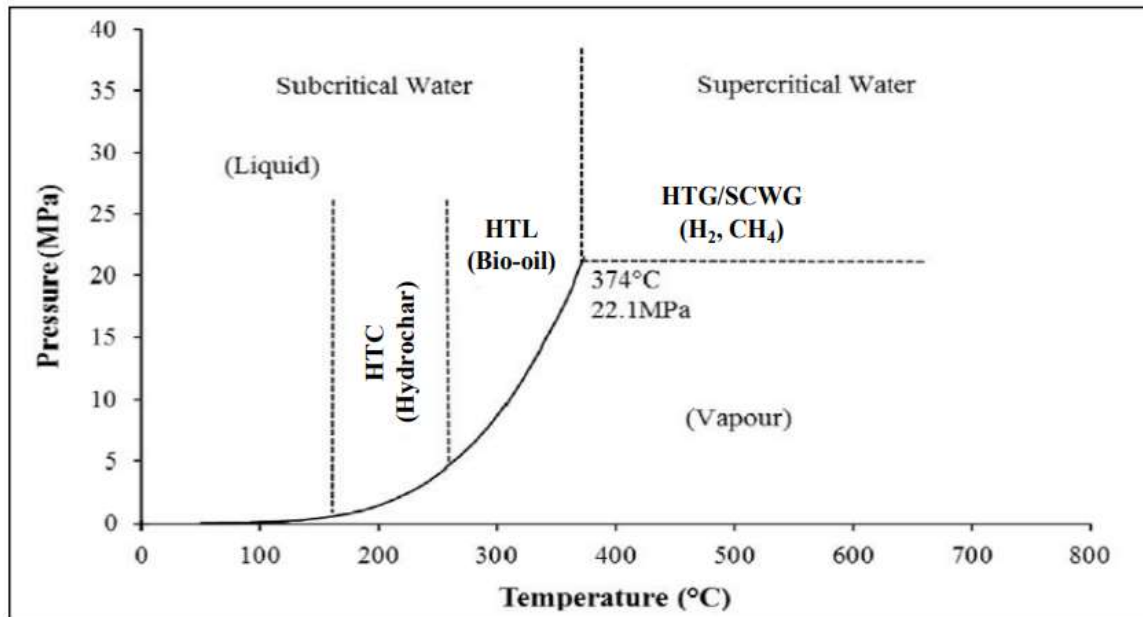
**Equation 3.5**

Table 5: summary of the sludge properties.

Fixed Carbon			
Moisture Content %	15.38	15.36	15.17
Volatile Matter, % m/m	43.96	43.55	45.36
Ash Content, % m/m	28.65	29.02	28.34
Fixed Carbon, %	12.01	12.06	11.13
Average (%)	11.73		

### 3.2 Determining the optimum thermal conditions to be used to maximize Hydrochar yield and briquette formation.

The efficiency of carbonization greatly depends on the three major variables which include the reaction temperature in the reactor, reaction time, and water-biomass ratio as shown in the figure below



Note; HTC: Hydrothermal carbonization  
HTL: Hydrothermal liquefaction  
HTG/SCWG: Hydrothermal gasification or supercritical water gasification

Figure 2: Sub-supercritical water technology for biofuels (Sandeep, 2013).

#### 3.2.1 Experiment to determine the appropriate temperature, water-biomass ratio and residence time combination that will yield higher quality hydrochar

##### Apparatus

- i. A 25ml Hydrothermal Synthesis Reactor.
- ii. Furnace capable of reaching a 250 °C
- iii. Oven at 105 °C
- iv. A balance readable and accurate to 0.1 g
- v. Water bath

## Procedure

1. The sludge sample was tested for moisture content to determine the amount of water present in the sludge prior to the hydrothermal carbonization.
2. The density of the of the dry sludge being used was determined in order to accurately determine the mass to be added in the reactor

$$\text{Density of Sludge} = \frac{\text{Mass}}{\text{Volume of the PTFE Liner}} \quad \text{Equation 3.6}$$

$$\text{Density of Sludge} = \frac{6 \times 10^{-3} \text{ Kg}}{25 \times 10^{-6} \text{ m}^3} \quad \text{Equation 3.7}$$

$$\text{Density of Sludge} = 240 \text{ Kg/m}^3 \quad \text{Equation 3.8}$$

3. To determine the mass of sludge that would occupy a given percentage of the Volume of the PTFE liner, the following formula was used;

$$\text{Mass of Dry Sludge} = \text{Density of Sludge} \times \left( \frac{\% \text{ Volume}}{100} \times \text{Volume of liner} \right)$$

$$\text{Equation 3.9}$$

4. The wet mass equivalent to the dry mass of the sludge was calculated using the formula;

$$\text{Dry mass} = \frac{\text{Wet mass}}{1 + (\text{Moisture Content}/100)} \quad \text{Equation 3.10}$$

$$\text{Wet mass} = \text{Dry mass} \times (1 + \text{Moisture Content}/100) \quad \text{Equation 3.11}$$

5. The wet bulk of sludge was weighed and inserted in the reactor's PTFE liner vessel.
6. The tank was filled to the brim with water and sealed to create a hydrothermal environment. It was then inserted into the reactor and closed tightly.
7. The reactor was placed in a furnace at room temperature, with a heating and cooling rate of 5° C/min.

After heating at 180 °C for 30 minutes, the reactor was quickly cooled by quenching in water to prevent further reaction.

8. Once the reactor cooled to room temperature, the vessel was gently opened and the mixture was filtered, leaving behind solid particles.
9. The solid residue was then carefully transferred to a crucible and oven dried at 105 °C for 24 hours.
10. The oven dried sample was weighed and the value recorded.
11. The yield was calculated from the following formula;

$$Yield = \frac{\text{Mass of oven dry Sample after heating}}{\text{Mass of oven dry sample before heating}} \times 100 \quad \text{Equation 3.12}$$

12. The processes above were repeated with different water content, temperature and reaction time as shown in the table.

Table 6: Tests carried out to obtain the optimum process conditions

Run	Water Content (%)	Temperature (°c)	Reaction time (hours)	HTC Yield (%)
1	65	180	4.5	
2	80	180	2	
3	50	180	2	96.867
4	65	180	0.5	96.714
5	80	210	0.5	96.26
6	50	210	0.5	93.367
7	50	210	5	
8	65	210	2	75.714

Table 6: Tests carried out to obtain the optimum process conditions

9	80	210	5	
10	50	230	2	78.5
11	65	230	0.5	92.333
12	70	230	2	75.056
13	65	230	5	

### Calorific Value

Calorific value was determined using a bomb calorimeter to measure the energy stored in a fuel.

### Apparatus

- i. C200 Automated Bomb Calorimeter
- ii. Briquetting Machine
- iii. Weighing Scale sensitive to 0.0001g



Figure 3: automated bomb calorimeter

### Procedure

1. The sample to be analyzed was crushed into a briquette using a briquetting machine to make it easier to handle.
2. The produced briquette was weighed and trimmed to achieve the recommended weight of 0.8 to 1.2 g per ASTM D5865 standard.

3. The weight of the briquette sample was determined and reported to the closest 0.0001g.
4. The calorimeter was turned on, pure oxygen was attached to it, and the procedure of calibration, such as cooling the water to be used, began.
5. The bomb was preconditioned by rinsing it with water to eliminate residue from earlier experiments before being assembled.
6. A fuse with a known calorific value was connected to the bomb's terminals.
7. The briquetted sample was placed into the crucible of the bomb while ensuring that the sample is in contact with the fuse so as to ensure ignition of the sample.
8. The device was then carefully assembled.
9. The bomb calorimeter accepted characteristics such as the weight of the sample being examined and the calorific value of the fuse.
10. The constructed bomb was then carefully inserted into the calorimeter, with pure oxygen injected at a steady pressure of 3MPa.
11. As the calorimeter vessel was being closed, a known amount of water at 20°C was automatically fed into it from the water reservoir.
12. Using a stirrer, the temperature was regulated by ensuring that the entire system is the same temperature.
13. Once the temperature stabilized, the charge was fired, burning the fuse and eventually igniting the sample.
14. The heat released by the sample's burning was subsequently transmitted to the water in the calorimeter vessel around the bomb, and the temperature difference was observed.
15. The temperature change was observed until no additional changes occur.

16. The Gross Calorific Value was then obtained from the machine's digital display panel.

17. The Gross Calorific Value was then recorded.

*(Refer to figure 18,19 & 20 in the Appendices sector)*

18. The procedures above were repeated for the remaining samples and the results obtained are in the table below.

Table 7: Results of the heating value obtained from the bomb calorimeter.

Run	Factor 1 A: Water Content %	Factor 2 B: Temperature C	Factor 3 C: Reaction time Hours	Response 2 HTC Yield %	Response 1 Heating Value MJ/Kg
1	50	180	2	96.87	13.588
2	65	190	0.5	96.71	13.79
3	80	180	2	87.99	13.94
4	80	210	0.5	96.25	14.022
5	50	210	0.5	93.37	13.7525
6	65	210	2	75.71	14.6185
<b>7</b>	<b>50</b>	<b>230</b>	<b>2</b>	<b>78.5</b>	<b>14.89</b>
8	50	230	0.5	92.33	14.218
9	70	230	2	75.06	14.0685

Using the Box Benken design technique of regression analysis, the relationship between the three variables was determined and the optimum process conditions were obtained as highlighted above.

### **3.2.2 Designing a briquette with the hydrochar produced from optimum process conditions**

Briquette making process

Apparatus

- i. Hydrochar
- ii. Cassava Starch
- iii. Briquetting machine
- iv. Air dryer
- v. Sand
- vi. Weighing scale

Procedure

1. Before making briquettes, the hydrochar was sieved to remove large particles.
2. 1kg of sieved hydrochar was weighed and put in a basin.
3. 168g of cassava starch were weighed, accounting for 15% of the required binder per mix design.
4. 56g of sand were weighed, accounting for 5% of the required filler per mix design.
5. Cassava starch was mixed with cold water to make a paste, then added boiling water and brought to a boil to activate its gluey properties.
6. Sand was then added to the basin with the hydrochar then uniformly mixed.

7. The hot starch was then added to the basin and also mixed thoroughly to ensure that everything is uniformly mixed without being too soft or too hard in order to allow ease in briquetting.



Figure 4: hot starch added to the mixture to form a paste

8. The mixture was then transferred into a mold of 35mm outside diameter, 5mm inner diameter and 55mm length.
9. It was then compacted with the briquetting machine lid to densify the briquettes and then the excess material removed using a trowel.
10. The densified briquettes were then extruded and then placed in an air drier to reduce their moisture content. The briquettes took three days to dry.  
*(Refer to figures 23, 24, 25 & 26 in the Appendices sector)*

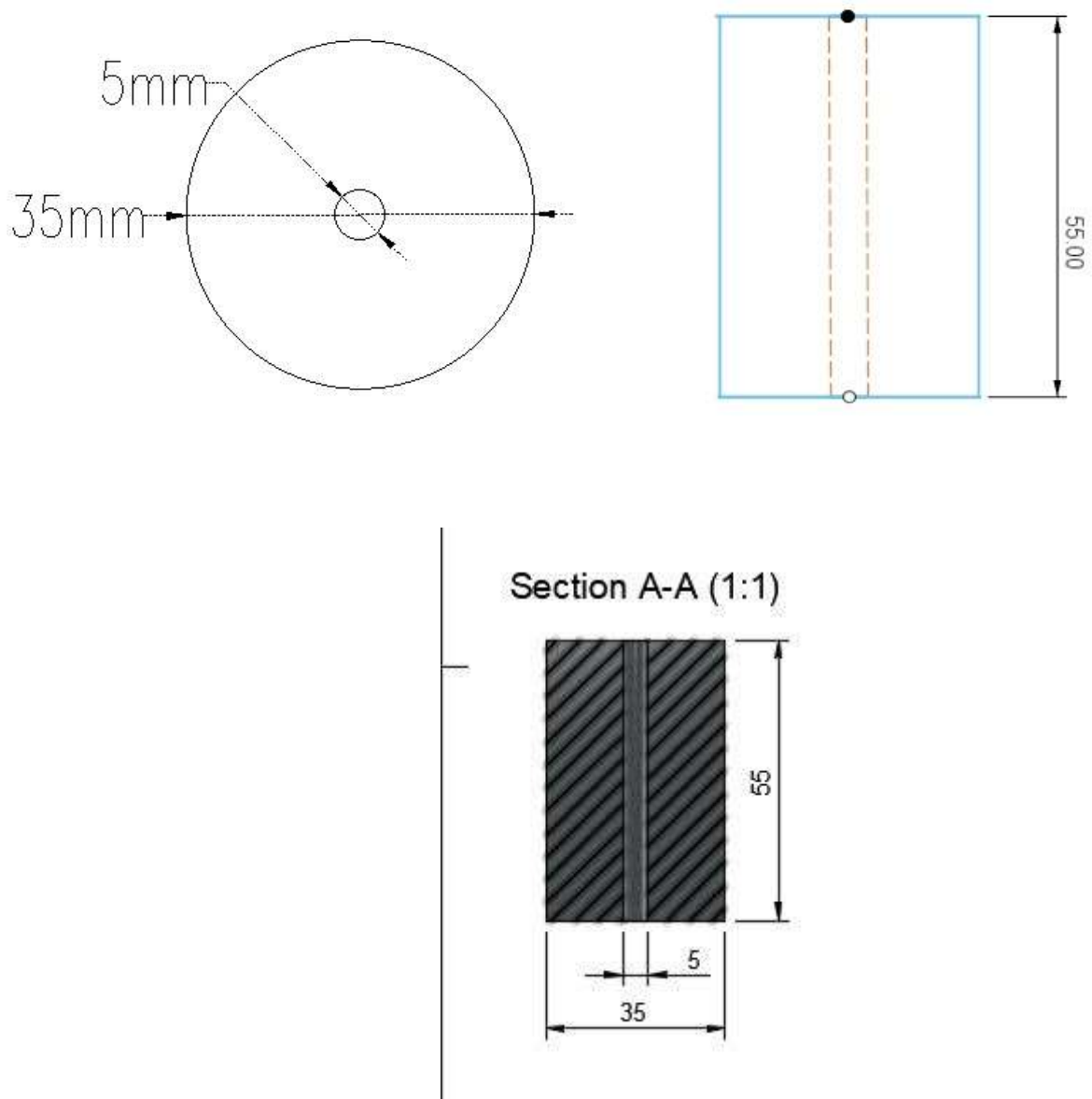


Figure 5: Design of Briquettes (Aisha, 2024)

### **3.3 Determining the combustion characteristics of the briquettes formed using the hydrochar. (ASTM D3172 and ISO 17831)**

In order to understand the characteristics of the briquettes made, a series of tests are carried out to show the characteristics of the briquettes. These include:

#### **3.3.1 Water boiling test**

A water boiling test on briquettes is necessary to examine their combustion qualities, quality, and appropriateness for various applications. This test gives vital information about ignition characteristics, heat output, burning duration, and energy efficiency, allowing designers to maintain product consistency and meet specifications. The Water boiling test was conducted following the water boiling test protocol version 4.2.3. During this test the following parameters were noted; the time taken for water to boil, the mass of fuel of briquette used, mass of water in the pan.

#### **Apparatus**

- i. Stove
- ii. Saucepan with 7 litre Capacity
- iii. Water at room temperature
- iv. Thermometer
- v. Weighing scale sensible to 0.0001g

#### **Preparation**

1. Prepared saucepans for the cold start test.
2. Recorded the dry weight of each saucepan (g).
3. Filled each saucepan with 5 kg of clean room temperature water.

4. The amount of water was determined by placing the pot on the scale, tearing and then adding water until the total weight of pot and water together is 5kg.
5. The same amount of water was used for each phase and each test.
6. With other saucepans, the same preparation procedures were followed for the hot start test with same volumes.
7. The ambient conditions such as air temperature, wind conditions were recorded.
8. The background concentrations for CO<sub>2</sub>, CO, and particulate matter concentrations were measured and recorded.

## Procedure

### Phase 1: High power, cold start phase

- i. The briquettes to be used for each test were weighed and their weight recorded (g)
- ii. The briquettes were ignited using kerosene as the starter of 5% the weight of the briquettes used as per the WBT 4.2.3 protocol guidelines.
- iii. Once the fire ignited, the timer was started.



Figure 6: ignited briquettes in the stove

- iv. The uncovered saucepan was placed on the stove. The WBT protocol requires the container to be uncovered to ensure accurate measurement of the boiling point.
- v. A thermometer was placed into the saucepan so that the temperature of the water is measured in the center, 5cm from the bottom of the saucepan then record the initial water temperature.
- vi. Once the water in the saucepan reached the boiling point, the timer was stopped and the time was recorded.
- vii. The temperature of the water was also measured and recorded.
- viii. The remaining unburnt briquettes were extracted from the stove and extinguished by placing them in sand then the weight recorded.
- ix. The mass of the saucepan with its water was measured and recorded.
- x. The hot water was discarded.

### **Phase 2: High power, hot start**

The same procedure was repeated but this time starting with a hot stove since it had boiled the first time.

- i. The timer was reset and the saucepan was refilled with the same amount of water and the weight of the saucepan with water measured and recorded.
- ii. The initial water temperature of the water was recorded.
- iii. The weight of the second bundle of briquettes was weighed and recorded and then placed into the stove.
- iv. The briquettes were ignited using kerosene as the starter of 5% the weight of the briquettes used as per the WBT 4.2.3 protocol guidelines.

- v. Once the fire ignited, the timer was started and the saucepan was placed on the stove.
- vi. Different emissions were measured and recorded, at the start of ignition, during boiling time and at the end, using a gas meter.

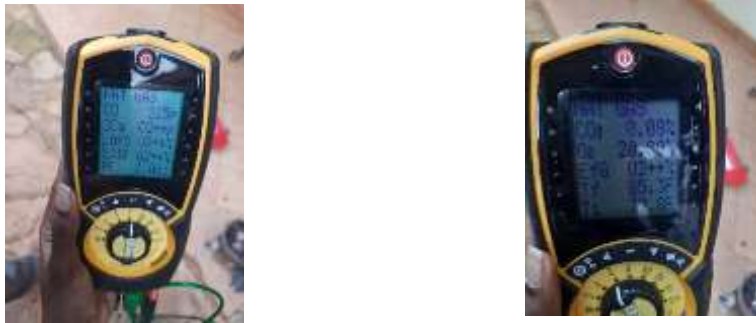


Figure 7: gas meter showing values obtained from measuring the emissions

- vii. When the water in the saucepan reached the boiling point, the timer was stopped and the time was recorded.
- viii. The temperature of the water was also measured and recorded.
- ix. The mass of the saucepan with its water was measured and recorded.

### Drop test

This test measures the briquette's shatter resistance and can be used to imitate the forces involved in shifting from one area to another or unloading briquettes from trucks onto the ground. Furthermore, this experiment testing might be used to evaluate the safe height for briquette loading (Law, Gan, and Gan, 2018). The drop test was done by dropping the briquette onto the concrete floor from 2m high. The shatter resistance was then calculated from;

$$\text{Weight loss}(\%) = \frac{W_1 - W_2}{W_1} \times 100 \quad \text{Equation 3.13}$$

$$\text{Shatter resistance}(\%) = 100\% - \text{weight loss}(\%) \quad \text{Equation 3.14}$$

Where  $W_1$  is the initial weight in g

$W_2$  is the final weight in g

### Water resistance test

This is the test done to measure the water absorption of the briquette and can be used to simulate the amount of water that a briquette can absorb but not crumble (Law, Gan and Gan, 2018).

This test was done by putting a weighed portion of the briquette into a beaker with water for 30 seconds. Once this time elapsed, the piece was removed and its new weight was recorded. The water resistance is then calculated from;

$$\text{Weight gain}(\%) = \frac{W_2 - W_1}{W_2} \times 100 \quad \text{Equation 3.15}$$

$$\text{Water resistance}(\%) = 100\% - \text{weight gain}(\%) \quad \text{Equation 3.16}$$

Where  $W_1$  is the initial weight in g

$W_2$  is the final weight in g

Table 8: The results obtained on the briquette testing.

Parameters	Briquette Type								Standard Parameter
	5% Starch		5% Starch		40% Clay		Market briquette		
	1	2	3	4					
Carbon dioxide (%)	0.82	0.79	0.64	0.7	0.59	0.65	0.61	0.54	
	0.4	0.45	0.35	0.4	0.52	0.52	0.74	0.8	
	0.29	0.3	0.29	0.35	0.37	0.29	0.91	0.85	
Average (%)	0.345	0.375	0.32	0.375	0.445	0.405	0.825	0.825	
Average (%)	0.36		0.3475		0.425		0.825		
Carbon monoxide (ppm)	303	299	446	450	300	345	274	250	
	140	167	358	250	263	296	160	175	

Table 8: The results obtained on the briquette testing.

	138	120	298	209	194	163	145	167	25ppm for hours
Average (ppm)	193.666667	195.333	328	229.5	228.5	229.5	152.5	171	30ppm for hour
Average (ppm)	194.5		278.75		229		161.75		87ppm for Minutes
Water boiling test (time in minutes)	20	18	16	19	23	22	19	21	
Average (%)	19		17.5		22.5		20		
Shatter resistance (%)	95.4	93.3	68.7	65.2	66.9	55.3	26.2	31.7	ASTM D440
Average (%)	94.35		66.95		61.1		28.95		
Water resistance (%)	56.7	54.4	45.3	42.7	0	0	79	74.6	32.6-94.8%
Average (%)	55.55		44		0		76.8		

### 3.4 Assessing the cost-benefit analysis of the briquettes formed using the hydrochar.

- i. Return on Investment (ROI): ROI is a financial statistic used to assess the profitability of an investment over a set period. It calculates the percentage rise or decrease in the value of an investment relative to its starting cost. The formula for calculating the rate of return is  $ROR = (\text{Net Gain} / \text{Initial Investment}) \times 100\%$ . A higher rate of return signifies a more profitable investment, whereas a negative rate of return implies a loss. ROR is frequently used to analyze the performance of various investment opportunities and determine the effectiveness of capital allocation.

$$\text{Return on Investment} = \frac{\text{Net Gain}}{\text{Initial Investment}} \times 100\% \quad \text{Equation 3.17}$$

- ii. Internal Rate of Return (IRR): The internal rate of return (IRR) is a financial indicator used to estimate investment profitability. It calculates the discount rate at which the net present value (NPV) of future cash flows equals zero. In

other words, IRR is the annualized rate of return at which an investment reaches breakeven. The formula for calculating IRR entails determining the discount rate required to equalize the present value of cash inflows and outflows. A greater IRR suggests a more appealing investment opportunity because it represents a better return compared to the initial investment. IRR is commonly used in capital budgeting decisions to assess the viability and attractiveness of investment projects.

- iii. **Payback Period:** The payback period is a financial term that measures how long it takes an investment to recover its initial cost through the generation of cash inflows. It reflects the time required for the total cash inflows to equal the starting investment amount. The payback period is computed by dividing the initial investment by the average annual cash inflows from the investment. A shorter payback period signifies a faster recovery of the initial investment and is often desired because it reflects lower risk and greater liquidity. The payback period is often used as a basic and intuitive measure to assess the risk and liquidity of investment projects, especially when cash flow timing is critical.

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Cash Flow}}$$

**Equation 3.18**

## CHAPTER FOUR: RESULTS AND DISCUSSIONS

This chapter presents the findings and analyses stemming from the methodological endeavors outlined earlier. Through systematic experimentation and analysis, this chapter delves into the key outcomes achieved in pursuit of the defined objectives. from assessing the properties of waste water sludge as a potential feedstock to optimizing process conditions for hydrochar production and briquette formation, each aspect is thoroughly examined and discussed in light of its implications for renewable energy generation.

### 4.1 Determine the properties of the waste water sludge that make it a suitable feedstock

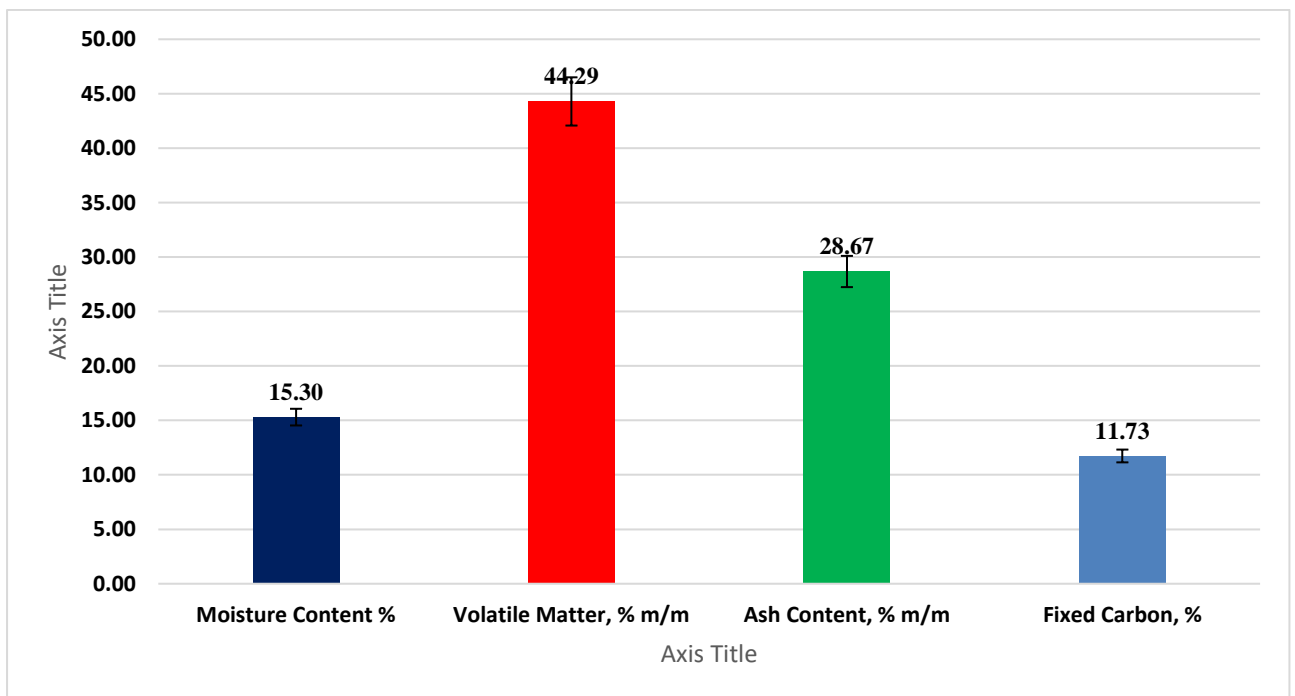


Figure 8: Summary of proximate analysis results of the Sludge at the UCU WWTP

The results above were obtained from experiments conducted on sun-dried Sludge samples and were carried out on dry basis.

**Moisture Content:**

After 12 days of sun drying, the sludge sample had an average moisture content of 15.30%, which is higher than required for conventional carbonization processes like pyrolysis. However, hydrothermal carbonization allows for higher moisture levels, which improves feedstock carbonization.

Hydrothermal carbonization is a high-pressure, high-temperature technique that uses water to accelerate the decomposition of organic substances through complex chemical processes. Water serves as both a reactant and a solvent, promoting hydrolysis, dehydration, polymerization, and aromatization reactions.

Higher moisture levels in the feedstock improve heat transfer and organic compound solubility, increasing conversion efficiency. The presence of water regulates reaction kinetics and avoids the development of unwanted by products.

Hydrothermal carbonization can withstand fluctuations in feedstock moisture content, making it a potential technology for sustainable waste management and bioenergy generation.

**Volatile Matter:**

Volatile matter refers to any material components that vaporize or emit gases when heated in the presence of air. Volatile matter impacts the behavior and performance of the fuel by contributing to its ignition and combustion properties. Higher volatile matter frequently leads to easier ignition and more volatile combustion. The sludge samples had an average of 44%, which is significantly lower than the results obtained by (Oliveira et al. 2013) on various feed stocks, which ranged between (49.9-95.2) % and averaged around 75% volatile matter, indicating that it has the ability to light but not so much that it compromises the energy content.

**Ash Content:**

Ash content, an inorganic residue, influences heating value and combustion efficiency. High ash content dilutes the energy content of the fuel, lowering the total heating value. Ash particles interfere with combustion reactions, resulting in lower efficiency, incomplete combustion, and higher emissions. The study found that ash levels ranged from 3% to 38% in diverse feedstocks, with an average of less than 10%.

The sludge sample had a higher average ash concentration of 28.67%, indicating that considerable inorganic elements contribute to the ash residue, however it was within the range from diverse feedstocks. Understanding ash content is critical for improving combustion operations and addressing issues such as diminished energy efficiency and higher emissions.

**Fixed Carbon:**

A higher fixed Carbon content directly correlates to a higher energy value of the feedstock since it is the carbonaceous material available for combustion, the sludge samples had an average fixed carbon of 11.73% which is lower than the low if used as a fuel directly, but when processed through hydrothermal Carbonization, it's enough to encourage particle growth after the polymerization and aromatization stages of the soluble polymers hence concentrating the amount of Fixed Carbon thus bringing it to the acceptable limits for a fuel.

## 4.2 Determining the optimum process conditions to be used to maximize hydrochar yield and briquette formation.

The Box-Behnken design is a response surface methodology used in experimental design and optimization. It is especially useful for investigating the reaction of a process or system to various input factors while reducing the number of experimental runs. It has a spherical or nearly spherical design space with factor levels set at low, medium, and high values, which makes fitting quadratic models to response surfaces easier and allows for curvature estimation in the relationship between input variables and response. Using the Box-Behnken, a response surface was formed in order to understand how the Hydrothermal Carbonization yield changes with change in temperature, water content and reaction time.

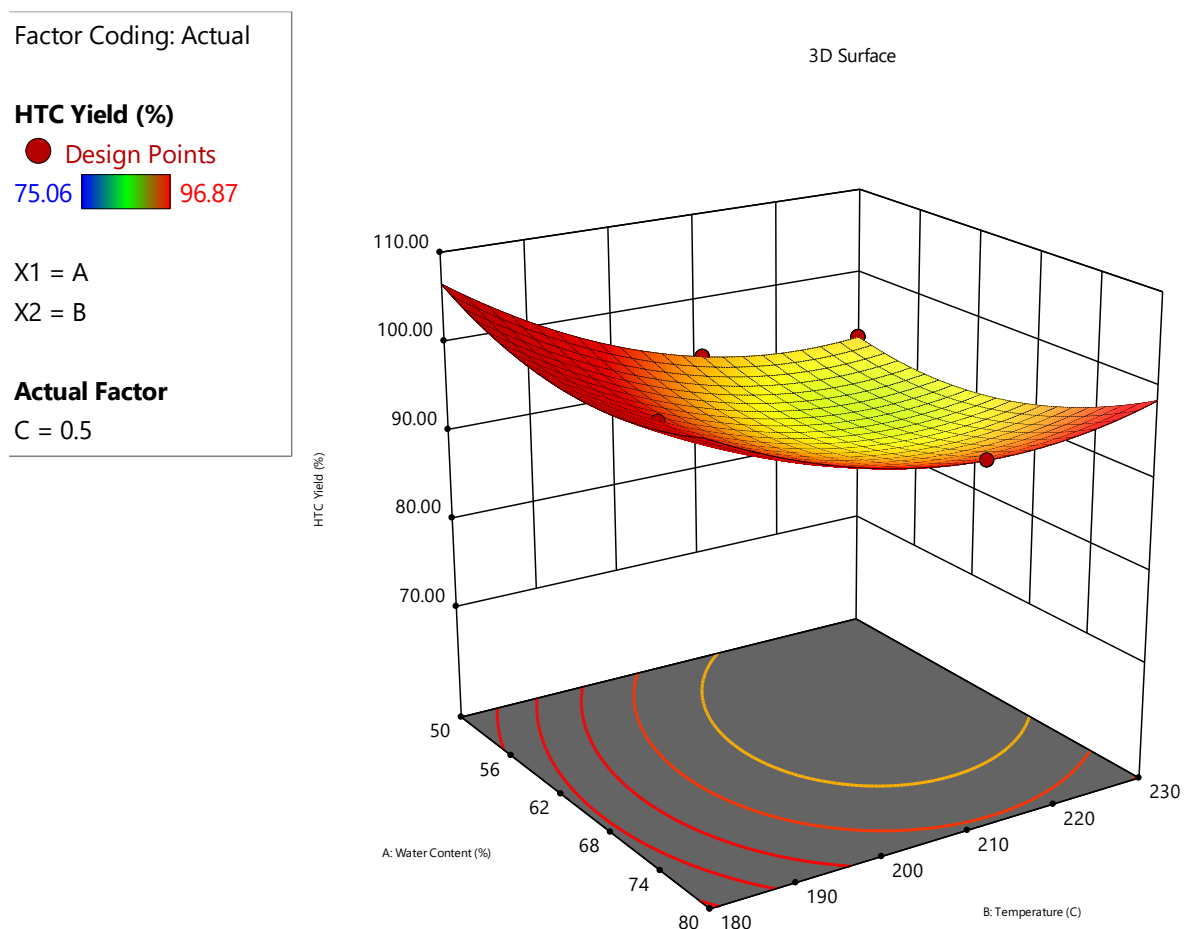



Figure 9: HTC Yield After 30 minutes reaction time

Factor Coding: Actual

**HTC Yield (%)**  
 ● Design Points  
 75.06  96.87

X1 = A  
 X2 = B

**Actual Factor**  
 C = 2

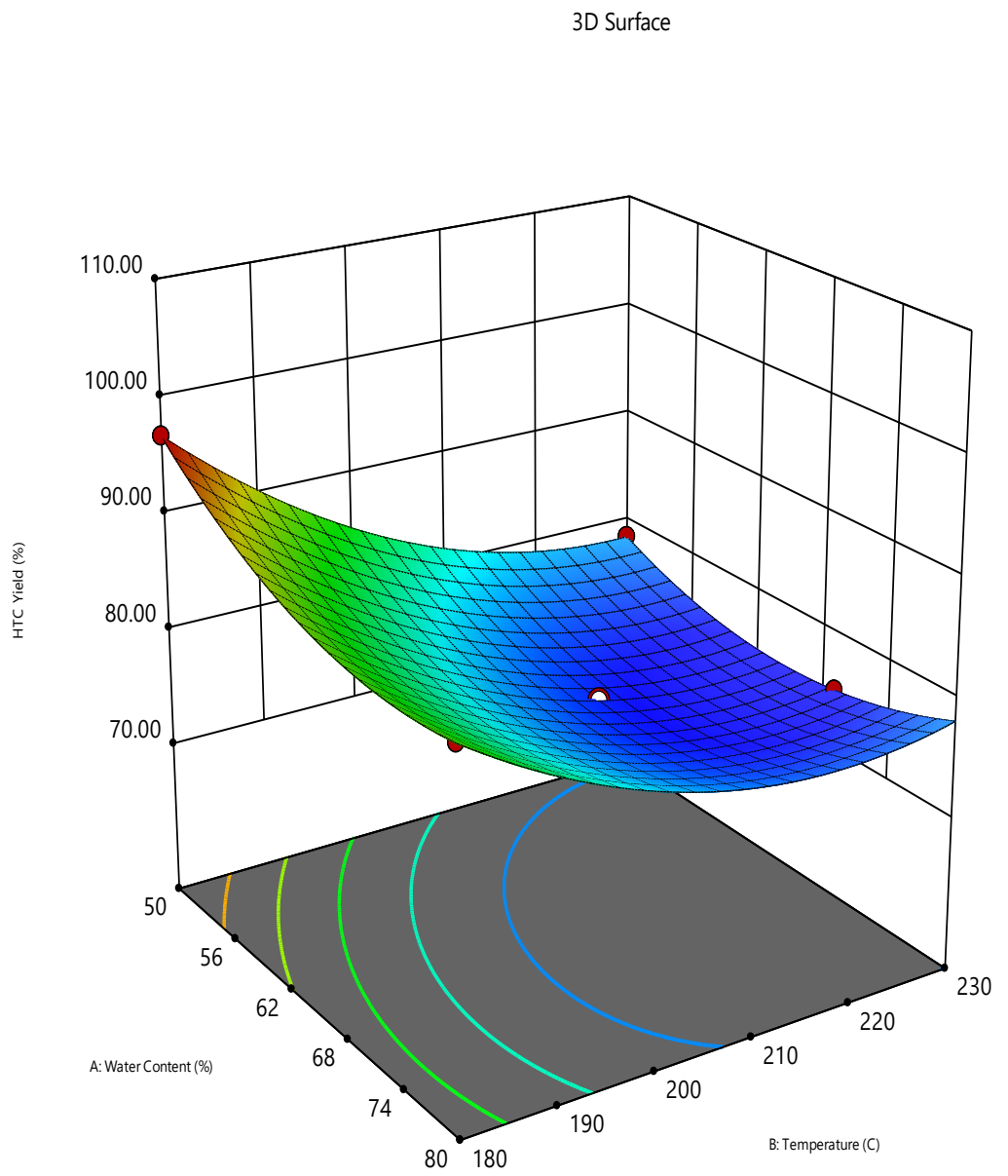


Figure 10: HTC Yield After 2 Hours reaction time

Factor Coding: Actual

3D Surface

Heating Value (MJ/Kg)

● Design Points

13.588  14.89

X1 = A

X2 = B

Actual Factor

C = 0.5

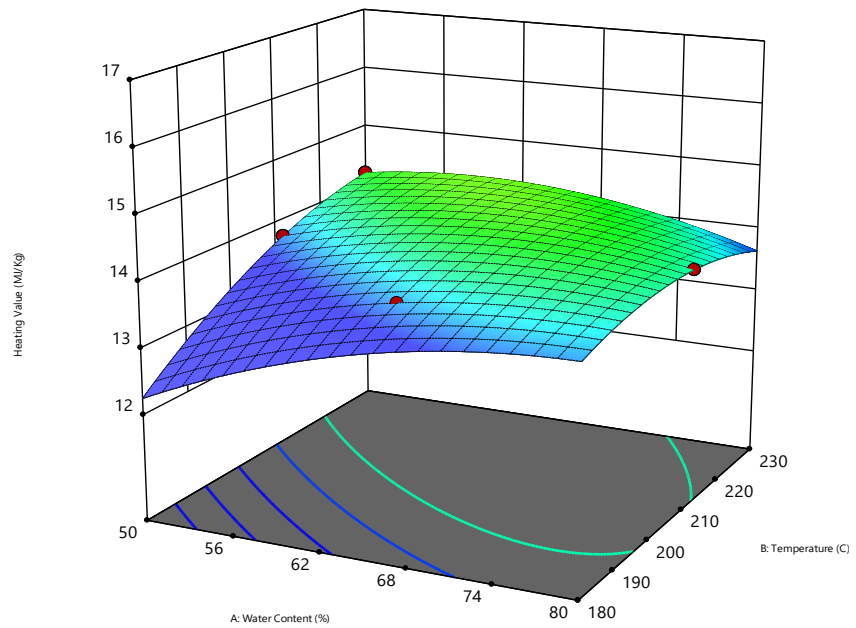


Figure 11: Heating Value after 30 minutes reaction time.

Factor Coding: Actual

3D Surface

Heating Value (MJ/Kg)

● Design Points

13.588  14.89

X1 = A

X2 = B

Actual Factor

C = 2

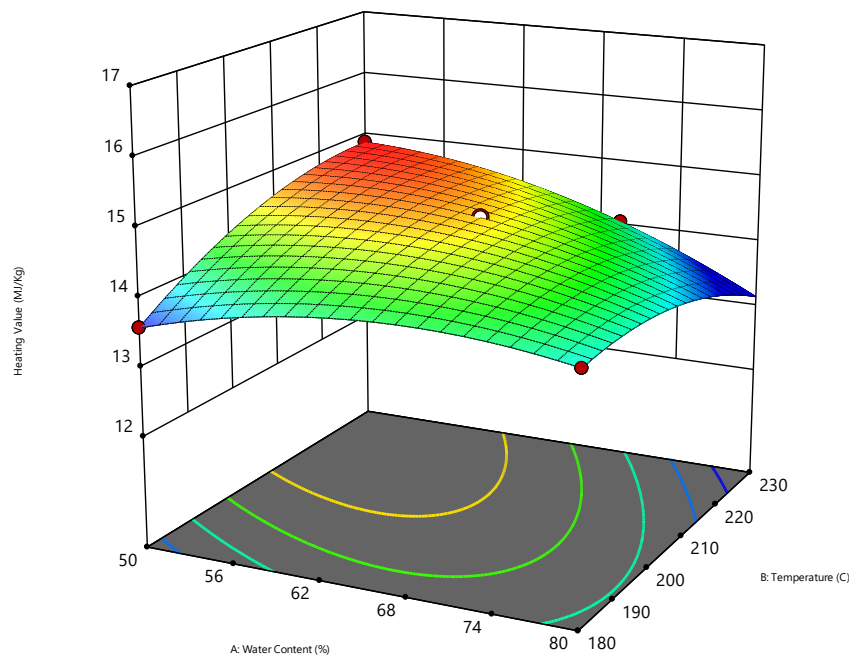


Figure 12: Heating Value after 2 hours reaction time

Factor Coding: Actual

### HTC Yield (%)

#### Actual Factors

A = 65  
B = 200.5  
C = 2

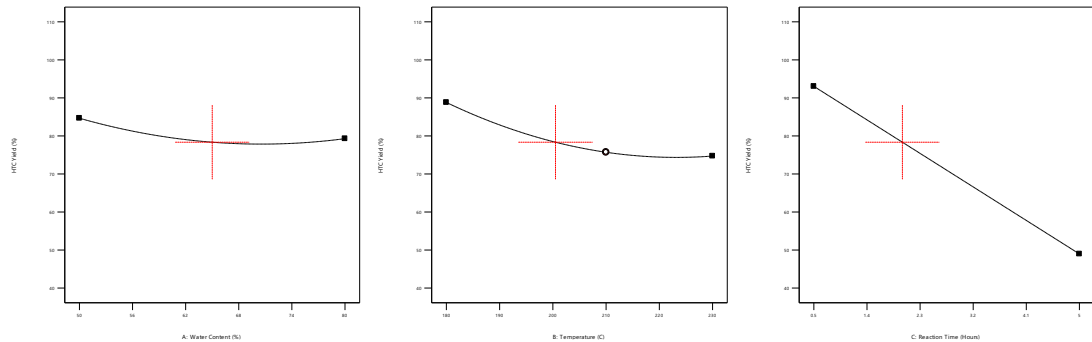


Figure 13: Effect of process parameters on the HTC yield.

Factor Coding: Actual

### Heating Value (MJ/Kg)

#### Actual Factors

A = 65  
B = 205.5  
C = 2

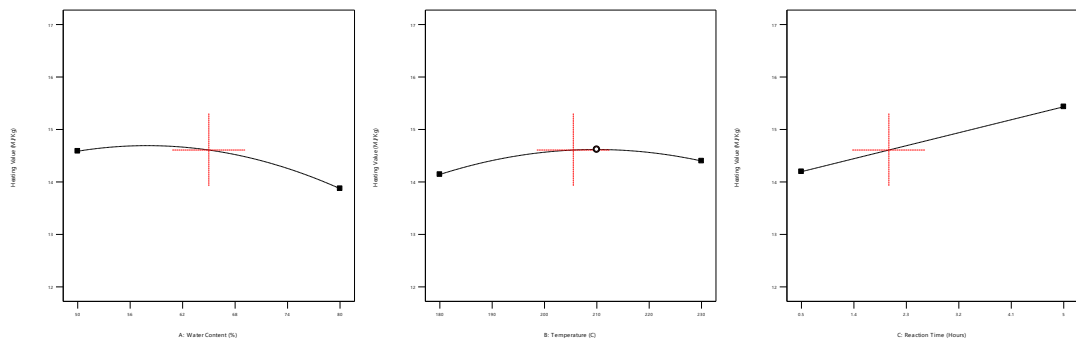


Figure 14: Effect of process parameters on the heating value.

In terms of hydrochar yield, Figure 4 demonstrates that HTC fed with higher moisture levels of wastewater sludge produced lower hydrochar yields because the high amount of water enhanced the solubility of the Faecal Sludge and made it easier to hydrolyze samples. A reduction in feedstock mass during the procedure is a favorable indicator. This reduction represents the conversion of organic material into hydrochar or solid carbonaceous material, which is the desired outcome of the HTC process. Hydrochar yields of 65-80% were found to be comparable to those of other studies (Li et al., 2013).

## Effect of temperature and reaction time

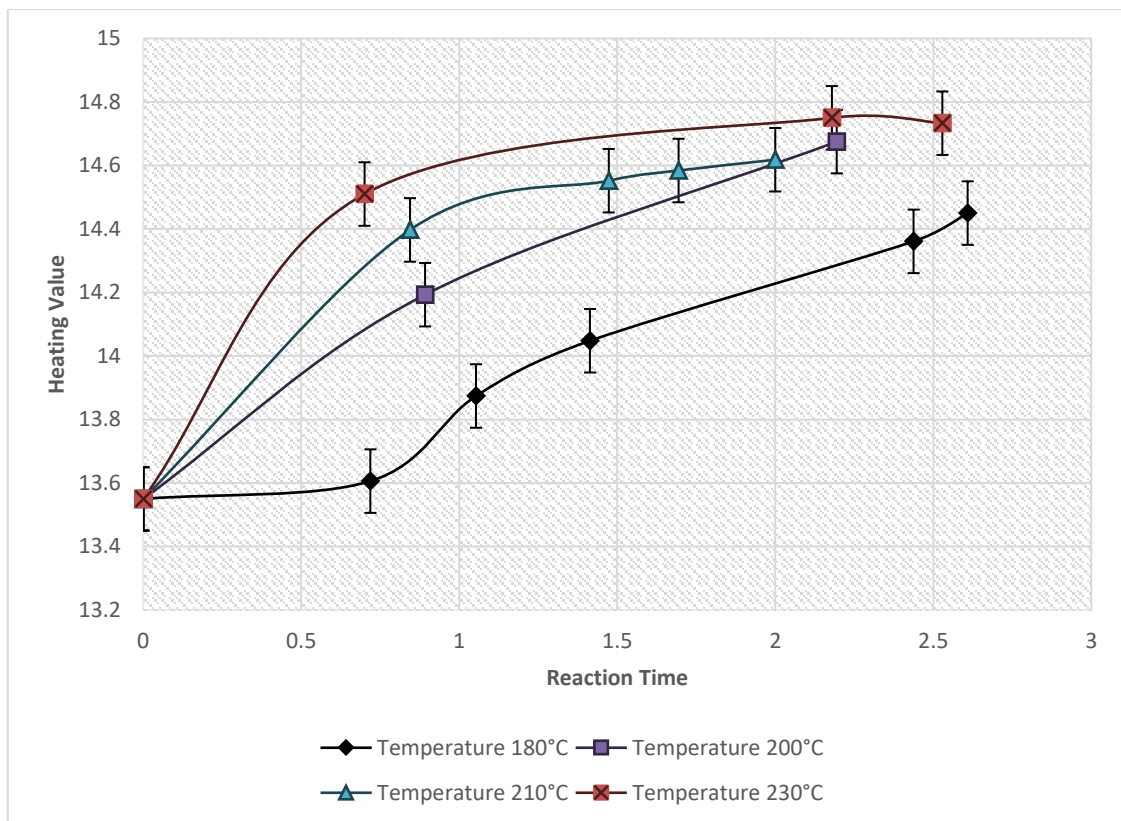


Figure 15: showing the relationship between calorific value and reaction time at various temperatures.

The highest energy content of 14.8 MJ/kg was produced at 230°C and reaction time of 2.25 h. The lowest energy content of hydrochar was observed at 180°C and 0.5 h.

These energy contents were comparable to the results of (Wang et al., 2012; Moon et al., 2015; Wen et al., 2023), who discovered hydrochar produced from sewage sludge with energy contents ranging from 13.1-18.4 MJ/kg, with an average of 15.37MJ/kg, which was achieved between 210°C and 250°C, as shown in Table 1.

In general, increasing the temperature in the HTC reactor would result in more dehydration of the hydrolyzed products (Kambo and Dutta, 2015).

Increasing the temperature from 180 to 200°C and 200 to 230°C resulted in approximately 10% and 4% increases in the energy content of the generated hydrochar, respectively.

According to (Titirici, 2013), HTC's usual operating temperatures range from 130 to 250 degrees Celsius. Higher temperatures (up to 350°C) can cause hydrothermal liquefaction, leading in more liquid and gas by-products and lower hydrochar yield (Kruse, Funke, & Titirici, 2013).

The HTC yield from wastewater sludge rapidly decreased from 96.8-93.4% and 96.7-75.7% for reaction times of 30 minutes and 2 hours, respectively, at 65% water content, as the temperature increased from 180°C to 210°C, and then gradually decreased to 92.3 and 75.1%, respectively, as the temperature increased from 210°C to 230°C. This is primarily due to the fact that the key stages of hydrothermal carbonization for various polymers present in sludge occur at relatively low temperatures. According to (Bobleter, 1994), hemicellulose is almost entirely hydrolyzed at 180-200°C, lignin at 180-220°C, and cellulose at temperatures above 220°C. Dehydration and polymerization demand temperatures above 160°C, while solid-solid conversion necessitates temperatures between 200-280°C (Falco, Baccile, & Titirici, 2011).

From the results obtained, the hydrolysis, dehydration, polymerization, and solid-solid conversion processes took place between 180°C -210°C.

## Effect of Moisture content on the hydrochar.

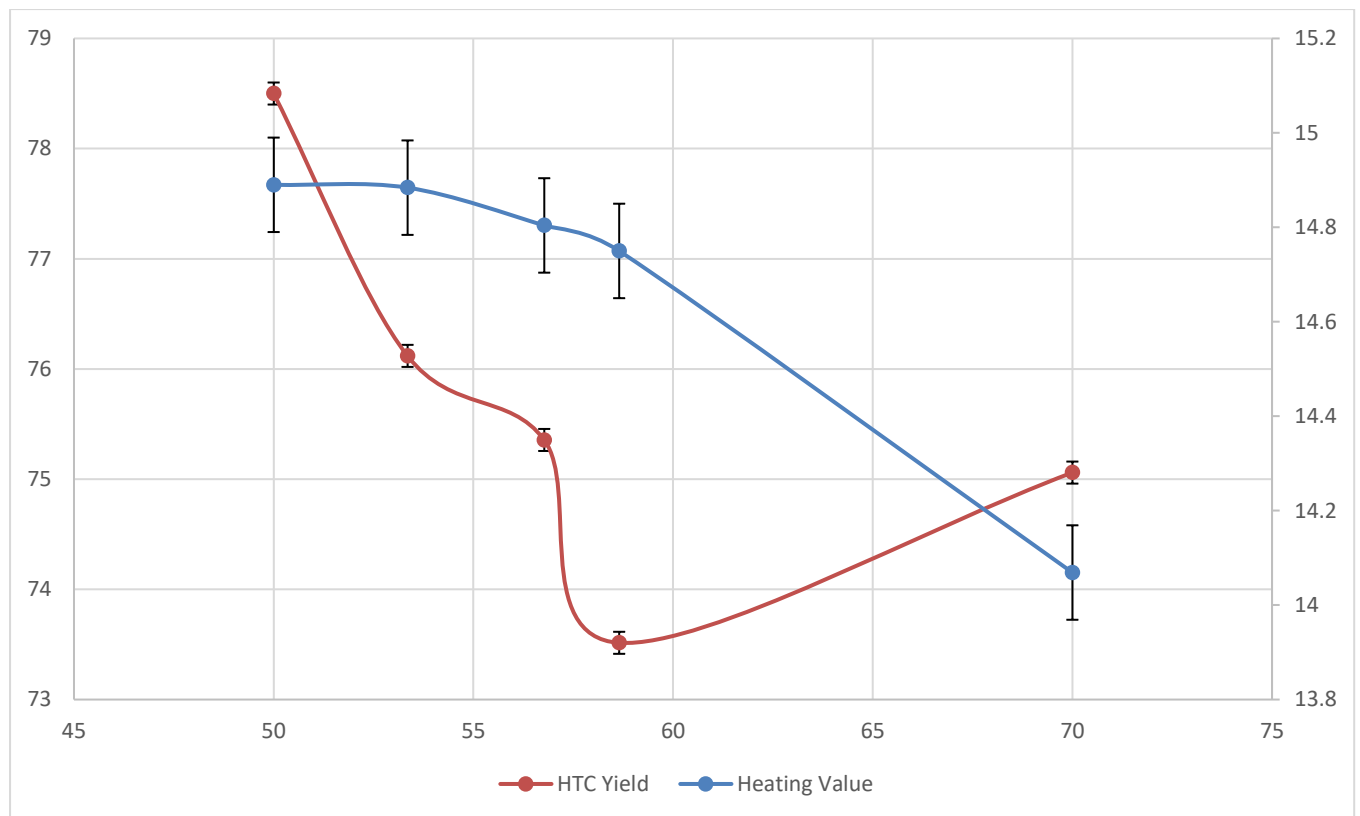


Figure 16: showing the effect of moisture content on HTC yield and calorific value at 230<sup>0</sup> C for 2 hours.

The graph that depicts the influence of moisture content on calorific value shows a continuous decline as moisture level increases. This decrease is due to the diluting effect generated by greater levels of moisture in the substance. Essentially, moisture content represents the proportion of water in the biomass, and as this proportion grows, the concentration of carbon, the material's principal source of energy, falls. As a result, the energy content per unit mass drops, lowering the calorific value. This relationship represents the fundamental notion that increased moisture levels reduce the material's energy density, making it less efficient as a fuel source. Thus, the declining trend in caloric value with rising moisture content

emphasizes the need of minimizing moisture content in biomass to optimize its energy potential. (Wang *et al.*, 2012; Wen *et al.*, 2023)

In contrast, the curve indicating the effect of moisture content on HTC yield initially drops before reaching a minimum, then increases as moisture content increases. This pattern demonstrates the intricate relationship between moisture content and the hydrothermal carbonization (HTC) process. Initially, as moisture content increases, water molecules become more available, competing with carbon molecules for reaction sites during hydrothermal carbonization. This rivalry reduces the output of carbonaceous material, lowering HTC yield. However, at a particular moisture content threshold, the introduction of more water molecules can improve hydrothermal reaction kinetics. This improvement promotes the breakdown of complex organic molecules found in biomass, resulting in enhanced carbonization and, eventually, better HTC output. Consequently, curve depicts the complex impacts of moisture content on HTC process efficiency, emphasizing the significance of adjusting moisture levels to optimal carbonization yield. (Funke and Ziegler, 2010)

The crossing point of these curves is the moisture content level at which the impacts on HTC yield and calorific value cancel one other out. At this ideal moisture content, the decrease in calorific value caused by water dilution is offset by an increase in HTC production assisted by improved reaction kinetics. In other words, increased moisture levels may lower the material's energy density, but they also encourage more efficient carbonization, resulting in a higher output of carbonaceous material. Beyond this threshold, subsequent increases in moisture content cause a dominant effect of dilution, resulting in a decrease in calorific value despite a rise in HTC production. As a result, the intersection point indicates a key threshold at which the

trade-off between HTC yield and calorific value is balanced, providing valuable insight into the optimal conditions for maximizing both parameters simultaneously in the production of biomass-derived fuels.

### 4.3 Determining the fuel characteristics of the briquettes formed using the hydrochar.

#### 4.3.1 Water boiling test

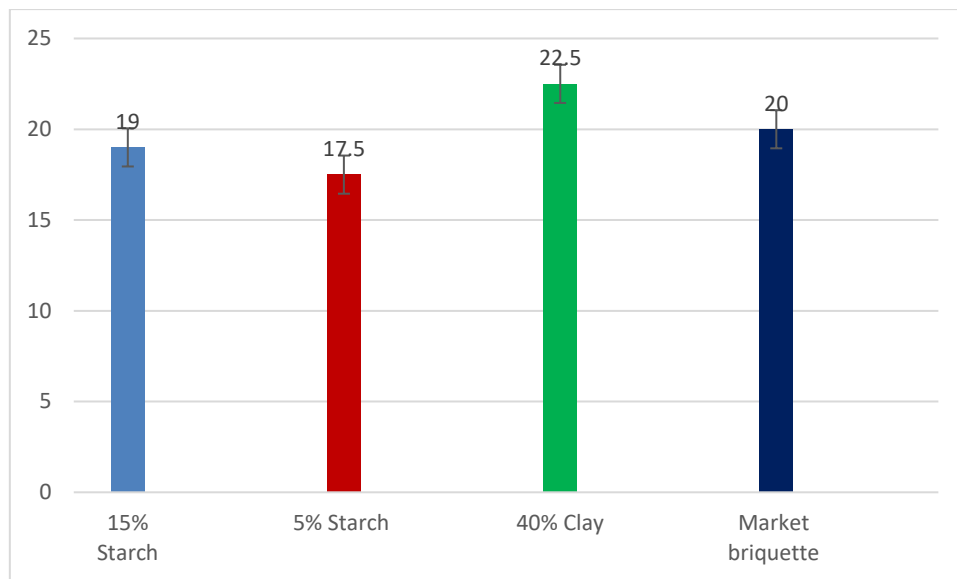


Figure 17: showing the time taken to boil 2.5 liters of water using briquettes of different binder ratios.

The briquette with 15% starch content had a boiling time of 19 minutes, which was marginally less than the market briquette's 20 minutes. This shows that the 15% starch content acts as an effective binder, increasing the briquette's cohesion and allowing for efficient combustion. Starch has good binding properties, such as high adhesion and carbonization during burning, which can improve heat transfer and speed up ignition. As a result, the briquette with 15% starch content shows remarkable combustion efficiency, potentially providing an efficient and dependable alternative to typical market briquettes.

Similarly, the briquette with 5% starch content had a boiling time of 17.5 minutes, showing faster combustion than the market briquette and the 15% starch content briquette. Despite the decreased starch concentration, the 5% starch briquette benefits from starch's binding characteristics, although to a lesser level. This implies that even a small amount of starch can greatly improve the cohesiveness and combustion efficiency of briquettes, resulting in faster heat release and shorter boiling durations. As a result, the 5% starch briquette is a potential solution for combustion applications that require efficiency and cost savings.

In contrast, the briquette with 40% clay content had a longer boiling time of 22.5 minutes, indicating slower ignition and burning than both starch-based briquettes and the market briquette. Clay, while commonly employed as a binder in briquette manufacture, may have different combustion properties than starch. Its higher clay content may result in lower combustion efficiency, longer ignition periods, and slower heat release during combustion. As a result, the 40% clay briquette may not provide the same degree of performance and efficiency as starch-based briquettes or standard market briquettes. This emphasizes the need of properly selecting and optimizing binder materials in briquette production in order to obtain the necessary combustion characteristics and performance.

### 4.3.2 Water Resistance Test

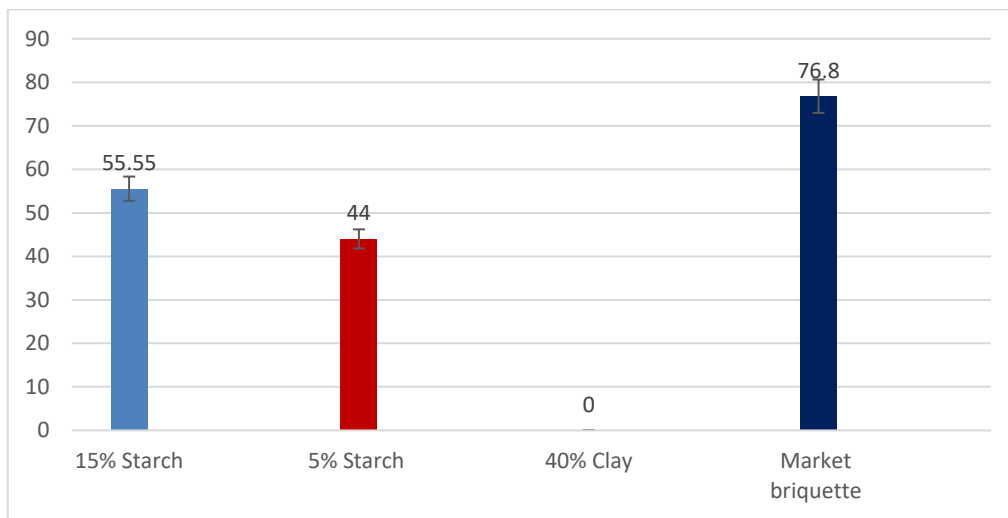


Figure 18: showing the water resistance of briquettes with different binder ratios.

Water resistance is critical for briquettes since it directly affects their longevity, performance, and usability in a variety of applications. Briquettes exposed to moisture from rain, humidity, or during storage and transit may lose structural integrity, resulting in disintegration, clogging, and decreased combustion efficiency. Briquettes with high water resistance retain their structure, consistency, and energy content even when exposed to moisture, resulting in consistent combustion performance, a longer shelf life, and a lower environmental effect. Water-resistant briquettes serve an important role in addressing the energy needs of households, companies, and communities by providing continuous heat generation, ease of handling, and low environmental contamination. They also promote sustainability and efficiency in fuel consumption.

The briquette with 15% starch content had a water resistance of 55.55%, which is moderate but falls short of the market briquette's resilience of 76.8%. Starch, a typical binding component in briquette manufacture, offers some water resistance

due to its adhesive qualities. However, at this concentration, the starch may not form a strong enough matrix to tolerate prolonged contact with moisture. As a result, the briquette's water resistance is lower than the market norm. Nonetheless, with additional optimization, the 15% starch briquette's water resistance might be improved to match that of the market briquette.

On the other hand, the briquette with 5% starch content had a poorer water resistance of 44%, showing a lesser capacity to endure moisture than both the market briquette and the 15% starch variation. With such a low starch concentration, the binding capacity may not be sufficient to keep the briquette together when exposed to water. As a result, the structural integrity of the briquette may be jeopardized, resulting in disintegration or decreased performance. This finding emphasizes the relevance of the binding agent concentration in determining briquette water resistance, with lower concentrations producing inferior performance.

In contrary to starch-based briquettes, the 40% clay briquette showed negligible water resistance, demonstrating clay's weakness as a binding agent in this context. Despite its binding capabilities, clay is extremely vulnerable to moisture absorption, leading the briquette to easily dissolve when exposed to water. As a result, the 40% clay briquette lacks any significant water resistance, making it unsuitable for applications where moisture exposure is an issue. This striking contrast underscores the need of choosing binding agents with suitable water resistance to ensure briquette longevity and performance in a variety of environments.

### 4.3.3 Shutter Resistance

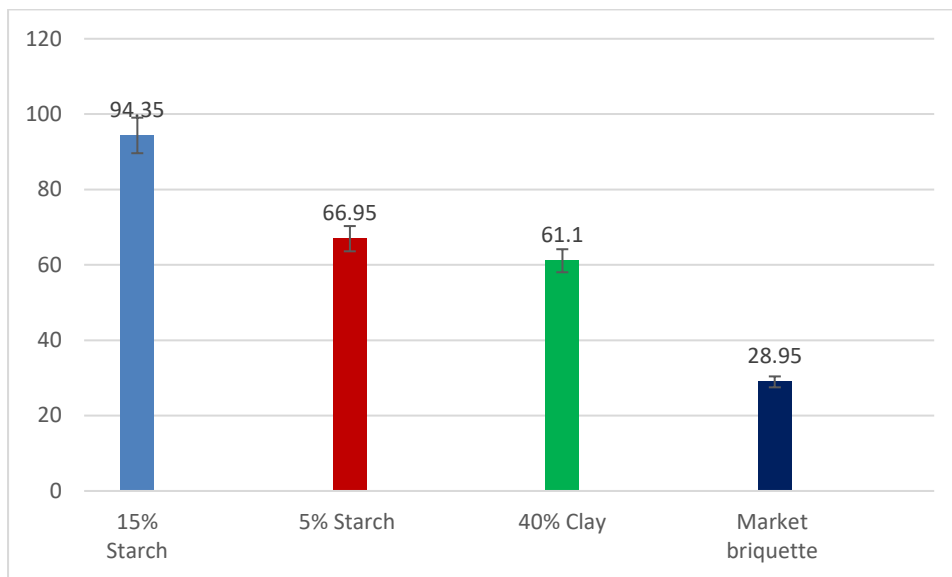


Figure 19: showing the shutter resistance of briquettes with different binder ratios.

Shatter resistance is critical for briquettes since it directly influences their handling, transportation, and combustion efficiency. Briquettes with high shatter resistance are less likely to break or fragment during loading, unloading, and handling, reducing waste and assuring a continuous supply of undamaged fuel. Furthermore, shatter-resistant briquettes are less likely to be damaged by vibrations or impacts during transportation, lowering the risk of spillage or loss. Furthermore, entire briquettes enable uniform heat release and combustion in combustion processes, which improves energy efficiency and reduces pollutants. Overall, shatter resistance is critical for increasing the usability, efficiency, and environmental performance of briquettes in a variety of applications, making them a dependable and sustainable fuel source.

The briquette with 15% starch content has the best shatter resistance (94.35%), greatly surpassing the industry standard. Starch, which is recognized for its adhesive

characteristics, successfully bonds the briquette particles together, resulting in a strong and cohesive structure that is very resistant to breaking on impact or during handling. This improved shatter resistance indicates that the 15% starch briquette is more durable and reliable during transit, handling, and combustion than the market briquette.

Similarly, the 5% starch briquette had a shatter resistance of 66.95%, representing a significant improvement over the market standard. Despite the decreased starch concentration, the 5% starch briquette profited from starch's binding characteristics, although to a lesser amount. This implies that even a small amount of starch can greatly improve the shatter resistance of briquettes, resulting in less breakage and greater usability when compared to market standards.

In comparison, the 40% clay briquette had a shatter resistance of 61.1%, which is better than the market briquette but lower than the starch-based briquettes. Clay, while often employed as a binding agent, may not have the same adhesive power as starch, resulting in significantly reduced shatter resistance. However, the 40% clay briquette outperforms the market standard in terms of durability, indicating that it may be suitable for applications that require moderate shatter resistance.

#### 4.3.4 CO emissions

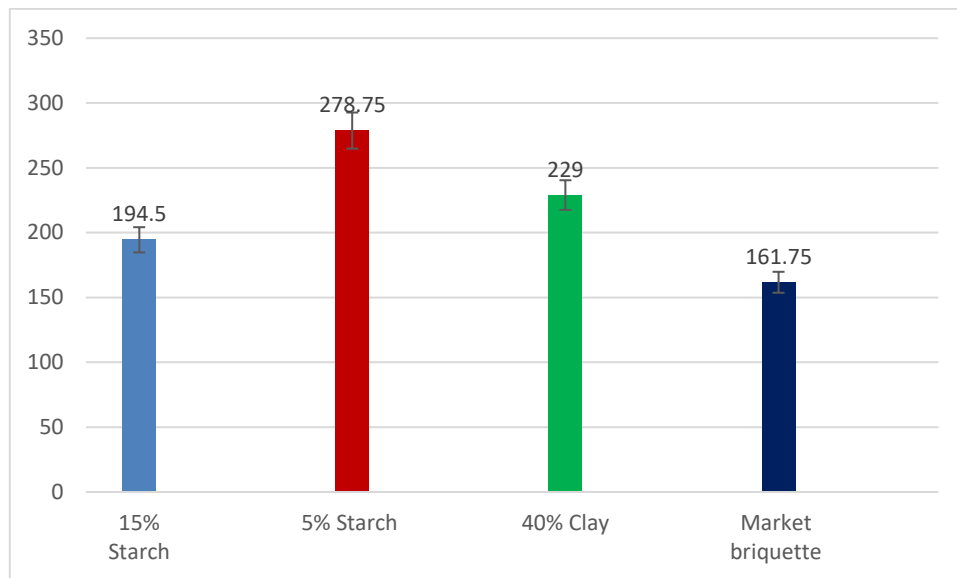


Figure 20: showing the amount of Carbon monoxide emitted after burning briquettes with different binder ratios.

CO formation poses significant environmental and health risks due to its harmful effects on the environment. It contributes to the formation of ground-level ozone and fine particulate matter, causing respiratory issues and cardiovascular diseases. CO also contributes to climate change by trapping heat in the atmosphere. Reducing CO emissions is crucial for mitigating pollution and addressing climate change challenges.

The briquette with 15% starch content produced the highest level of CO at 194.5 ppm, showing a potential disadvantage of utilizing starch as a binding agent. Despite starch's adhesive capabilities, which help to briquette cohesion, its burning characteristics may result in higher CO emissions. The observed higher CO levels could be due to incomplete combustion or differences in combustion efficiency. As a result, while starch may improve the structural integrity of the briquette, its effect

on combustion performance and emissions should be carefully examined in briquette production processes.

In comparison, the 5% starch briquette produced significantly higher CO emissions (278.75 ppm), indicating a considerable increase over both the market briquette and the 15% starch variation. The lower starch concentration in this briquette may diminish binding capacity and combustion efficiency, resulting in higher CO emissions during combustion. This shows that even little differences in binding agent concentration can have a significant impact on combustion performance and emissions, emphasizing the necessity of exact formulation and optimization in briquette production processes.

On the other hand, the 40% clay briquette emitted 229 ppm of CO, which is slightly more than the market briquette but lower than the starch-based briquettes. Clay, a typical binding agent in briquette manufacture, may contribute to CO emissions due to its burning properties or ash concentration. While clay has some advantages as a binder, such as cost-effectiveness and availability, its effect on combustion emissions should be addressed when choosing binding materials for briquette production. As a result, the disparities in CO emissions across the briquettes demonstrate the intricate interplay between binding ratios, materials, and combustion performance, underlining the importance of full evaluation and optimization to reduce emissions and assure environmental compliance.

### 4.3.5 CO<sub>2</sub> Emissions

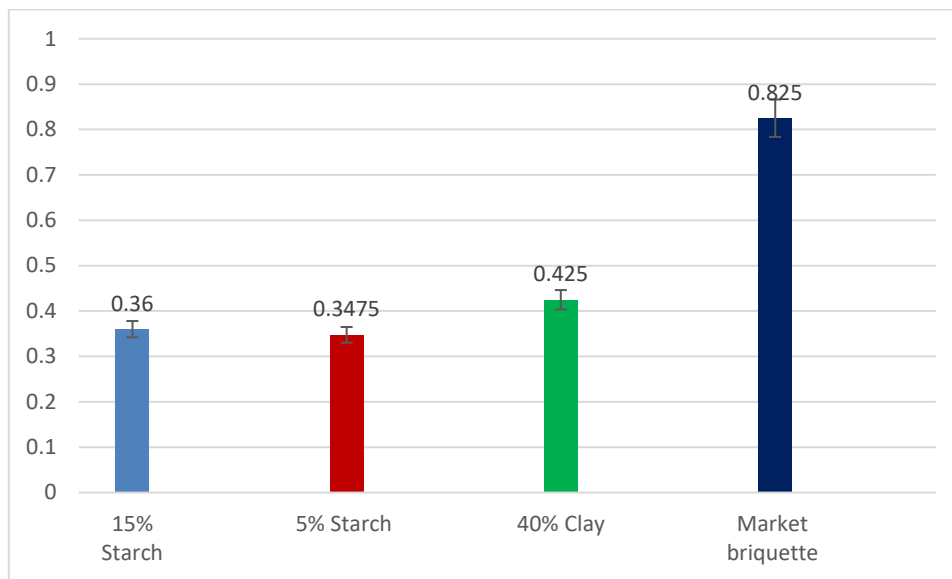


Figure 21: showing the percentage of Carbon dioxide emitted after burning briquettes of different binder ratios.

Human activities, including burning fossil fuels and deforestation, have significantly contributed to climate change and global warming. This has led to increased atmospheric CO<sub>2</sub> levels, causing environmental impacts like altered weather patterns, ocean acidification, melting ice caps, biodiversity loss, and threats to human health and livelihoods.

The briquette with 15% starch content emitted low amount of CO<sub>2</sub>, 0.36%, indicating a relatively efficient combustion process. Starch, as a binding agent, may help to promote cleaner combustion and lower CO<sub>2</sub> emissions. Its adhesive qualities are believed to promote greater fuel consolidation and combustion, resulting in lower CO<sub>2</sub> emissions than other briquettes. This shows that briquettes with higher starch content may provide environmental benefits by reducing CO<sub>2</sub> emissions during combustion, making them a better choice for environmentally sensitive applications.

In contrast, the 5% starch briquette emitted slightly less CO<sub>2</sub> (0.3475%) than the 15% starch variety, but still less than the market briquette. Despite the lower starch percentage, this briquette burns quite efficiently, resulting in lesser CO<sub>2</sub> emissions. The reduced starch concentration of the briquette may change its binding capacity and burning properties, thereby influencing CO<sub>2</sub> emissions. However, the difference in CO<sub>2</sub> emissions between the 5% starch briquette and the market briquette demonstrates that even slight changes in binding agent concentration can have an impact on environmental performance, emphasizing the necessity of optimizing binding ratios to reduce emissions.

In contrast, the 40% clay briquette emitted more CO<sub>2</sub> (0.425%) than both starch-based briquettes and market briquettes. Clay, a frequent binding agent, may contribute to higher CO<sub>2</sub> emissions due to its burning properties or ash concentration. While clay has some advantages as a binder, such as cost-effectiveness and availability, its effect on CO<sub>2</sub> emissions should be addressed when choosing binding materials for briquette production. Overall, the differences in CO<sub>2</sub> emissions across the briquettes demonstrate the importance of binding ratios and materials in impacting combustion efficiency and emissions performance, with starch-based briquettes emitting less CO<sub>2</sub> than clay-based or regular market briquettes.

#### 4.4 Cost Benefit Analysis

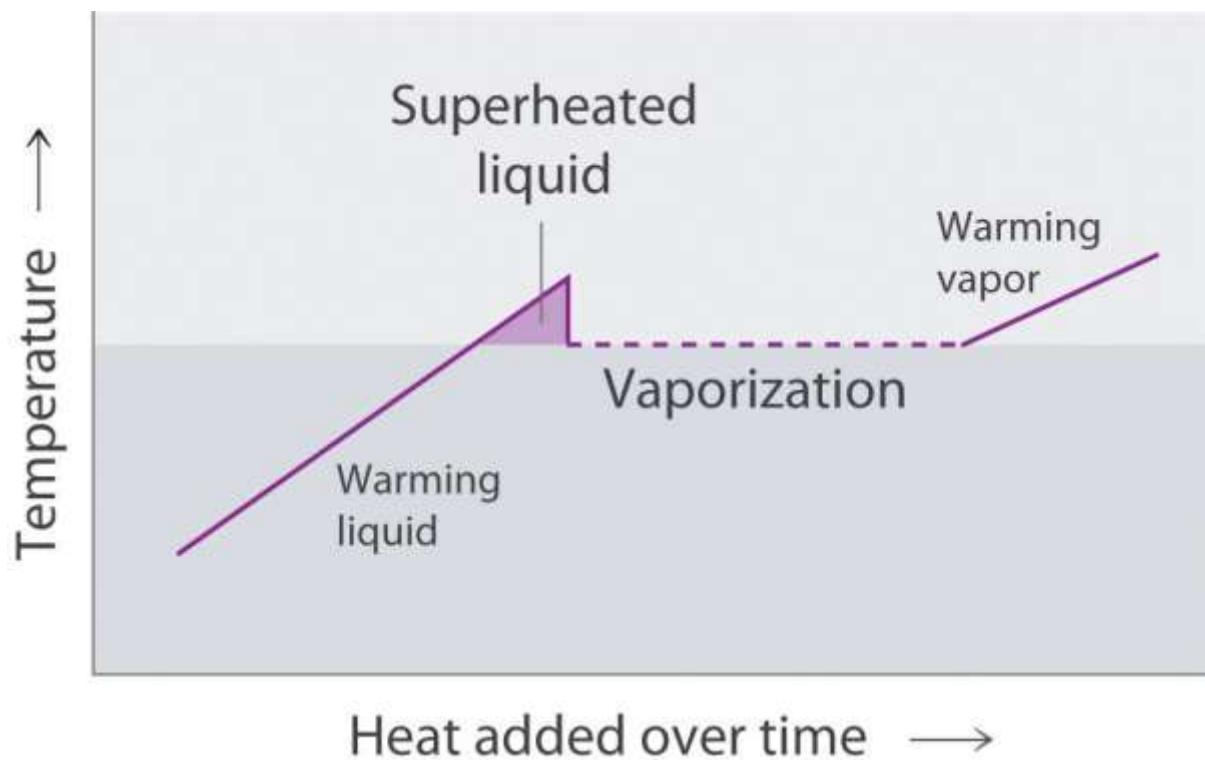


Figure 22: Temperature Change with heat added (2021)

According to the national charcoal survey, homes in Central Uganda use 2.2Kg of charcoal per day, with an average calorific value of 28.9MJ/Kg, implying that each household in Ddandira village requires 63.58MJ of energy (MEMD, 2016).

On average, the Uganda Christian University wastewater treatment facility has a capacity of 350 m<sup>3</sup> and generates roughly 0.2 kg/m<sup>3</sup> of solid sludge, with the amount of solid sludge being 64Kg each day. (Siyasa, 2023)

Table 9: Cost of production of Hydrochar and the pricing of Briquettes

parameter	Formula	Result
Specific heat Capacity of water		4182J/Kg/°C
specific heat capacity of wastewater sludge		4180J/Kg/ °C
Price of Electricity in Uganda for Commercial Use		Ushs 600.2/=
Amount of water to be heated	50%	64 Kg
Amount of Sludge to be heated	50%	64 Kg
Heat requirements per household		63.58MJ
The heat required to raise 64kg of water from 25 °C to 210 °C	$Q_1 = mc\Delta T$	$Q_1 = 64 \times 4182 \times (230 - 25)$ $Q_1 = 54.9MJ$
The heat required to raise 64kg of sludge from 25 °C to 210 °C	$Q_2 = mc\Delta T$	$Q_2 = 64 \times 4180 \times (230 - 25)$ $Q_2 = 54.8MJ$
Total Heat Required	$Q = Q_1 + Q_2$	$Q = 54.9 + 54.8$ $Q = 109.7MJ$
Energy used	$1MJ$ $= 0.27778KWh$	$= 30.472KWh$
Cost of converting 64Kg of Sludge to Hydrochar	$1KWh$ $= 600.2 Ushs$	$30.472 \times 600.2$ $= Ushs 18,289.6/=$
Estimated Cost of Briquettes		
Hydrochar Yield	78.5%	$= \left(\frac{78.5}{100} \times 64Kg\right)$ $Kg = 50.2Kg$
Cost of Producing 1Kg of Hydrochar		$= \left(\frac{18,289.6}{50.24}\right)$ $=364.04/= Per Kg$

Table 9: Cost of production of Hydrochar and the pricing of Briquettes.

	15% Starch	5% Starch	40% Clay	Market
Mix Ratio	80:15:5	90:5:5	60:40	50:50
Amount of Char Used	800g	900g	600g	500g
Price of Char Used	$\left(\frac{80}{100} \times 364.04\right)$ =291.232/=	$\left(\frac{90}{100} \times 364.04\right)$ =327.636/=	$\left(\frac{60}{100} \times 364.04\right)$ =218.424/=	$\left(\frac{20,000}{50Kg} \times 0.5\right)$ =200/=
Price of Binder Used	$\left(\frac{1300}{1000g} \times 150\right)$ =195/=	$\left(\frac{1300}{1000g} \times 50\right)$ =65/=	$\left(\frac{15,000}{50Kg} \times 0.4\right)$ =120/=	$\left(\frac{15,000}{50Kg} \times 0.5\right)$ =150/=
Price of Filler	=1.8/=	=1.8/=	0	0
Cost of labor	=70/=	=70/=	=70/=	=70/=
<b>Total Cost of Materials</b>	<b>558/= per Kg</b>	<b>464.4/= per Kg</b>	<b>458.4/= per Kg</b>	<b>420/= per Kg</b>

### AHP Analysis

The Analytic Hierarchy Process (AHP) is a decision-making technique that simplifies complex decision-making by organizing problems into hierarchies of criteria and options, which are then compared for relative importance using pairwise comparisons. AHP uses mathematical computations to synthesize these comparisons, determining priorities and making rational conclusions based on judgment consistency. It allows decision-makers to quantify subjective judgments, prioritize

criteria, and choose the best alternative based on both qualitative and quantitative aspects, increasing decision transparency and assisting with issue resolution across multiple domains.

This technique was used to decide on what briquette is more efficient basing on the different criteria each has as shown below.

Criteria	Price (Ug Shs)	CO <sub>2</sub> Emission (%)	CO Emission (ppm)	Water Resistance (%)	Shutter Resistance (%)	Boiling Time (Minutes)
<b>15% Starch</b>	558	0.36	194.5	55.6	94.4	19.0
<b>5% Starch</b>	464.4	0.35	278.8	44.0	67.0	17.5
<b>40% Clay</b>	458.4	0.43	229.0	0	61.1	22.5
<b>Market</b>	420	0.83	161.8	76.8	29.0	20.0

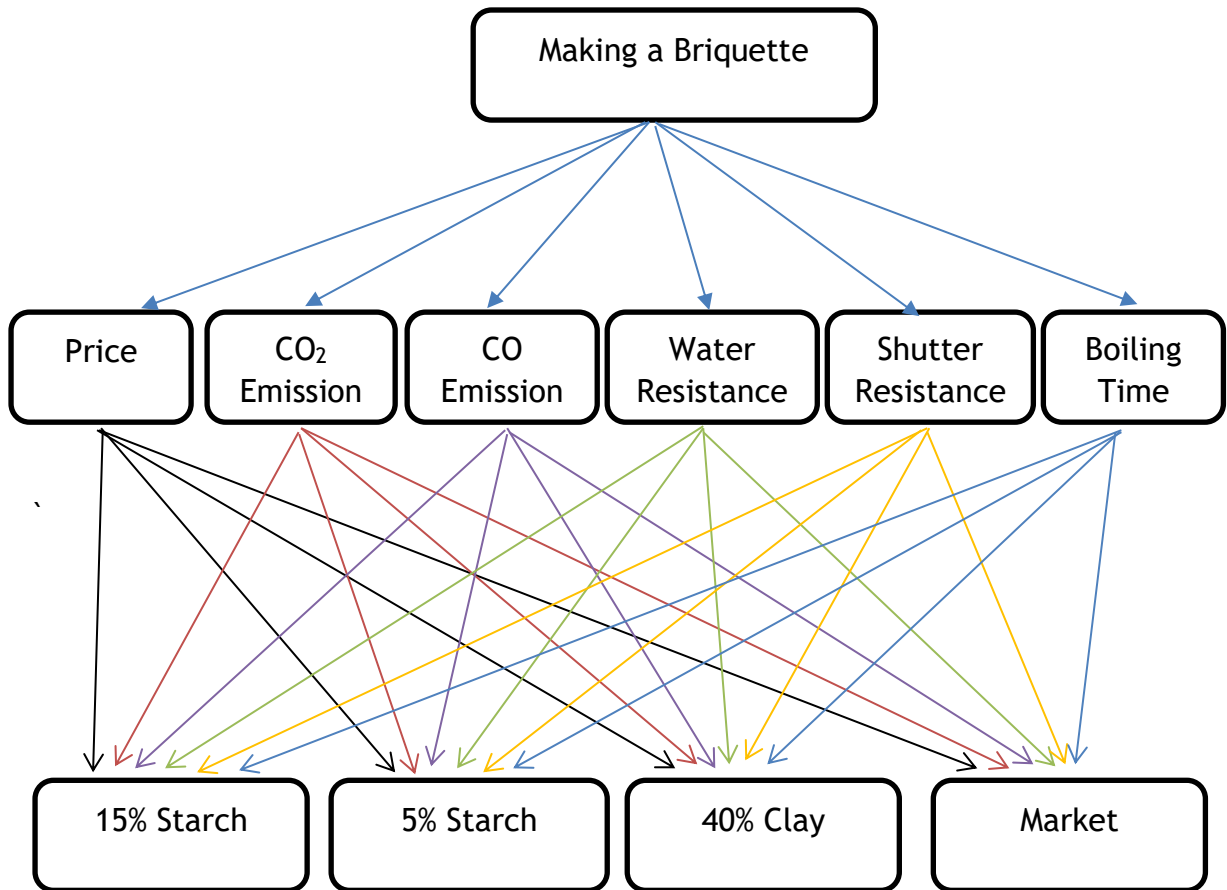


Table 10: Scale of relative importance

	Level of importance
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very strong Importance
9	Extreme Importance

Table 11 Pair-wise comparison matrix

		4	7	9	3	6	5
		Price	CO <sub>2</sub> Emission	CO Emission	Water Resistance	Shutter Resistance	Boiling Time
4	Price	1.0000	0.5714	0.4444	1.3333	0.6667	0.8000
7	CO <sub>2</sub> Emission	1.7500	1.0000	0.7778	2.3333	1.1667	1.4000
9	CO Emission	2.2500	1.2857	1.0000	3.0000	1.5000	1.8000
3	Water Resistance	0.7500	0.4286	0.3333	1.0000	0.5000	0.6000
6	Shutter Resistance	1.5000	0.8571	0.6667	2.0000	1.0000	1.2000
5	Boiling Time	1.2500	0.7143	0.5556	1.6667	0.8333	1.0000
	Total	8.5000	4.8571	3.7778	11.3333	5.6667	6.8000

Table 12: Normalized Pair-wise matrix

	Price	CO <sub>2</sub> Emission	CO Emission	Water Resistance	Shutter Resistance	Boiling Time	Criteria Weights
Price	0.1176	0.1176	0.1176	0.1176	0.1176	0.1176	0.1176
CO <sub>2</sub> Emission	0.2059	0.2059	0.2059	0.2059	0.2059	0.2059	0.2059
CO Emission	0.2647	0.2647	0.2647	0.2647	0.2647	0.2647	0.2647
Water Resistance	0.0882	0.0882	0.0882	0.0882	0.0882	0.0882	0.0882
Shutter Resistance	0.1765	0.1765	0.1765	0.1765	0.1765	0.1765	0.1765
Boiling Time	0.1471	0.1471	0.1471	0.1471	0.1471	0.1471	0.1471

Table 13: calculating the consistency of the analysis.

Criteria Weights	0.1176	0.2059	0.2647	0.0882	0.1765	0.1471		
	Price	CO <sub>2</sub> Emission	CO Emission	Water Resistance	Shutter Resistance	Boiling Time	Weighted Sum Value	
Price	0.1176	0.1176	0.1176	0.1176	0.1176	0.1176	0.7059	6.0
CO <sub>2</sub> Emission	0.2059	0.2059	0.2059	0.2059	0.2059	0.2059	1.2353	6.0
CO Emission	0.2647	0.2647	0.2647	0.2647	0.2647	0.2647	1.5882	6.0
Water Resistance	0.0882	0.0882	0.0882	0.0882	0.0882	0.0882	0.5294	6.0
Shutter Resistance	0.1765	0.1765	0.1765	0.1765	0.1765	0.1765	1.0588	6.0
Boiling Time	0.1471	0.1471	0.1471	0.1471	0.1471	0.1471	0.8824	6.0

$$\lambda_{max} = \frac{6+6+6+6+6+6}{6} = 6$$

**Equation 4.1**

$$Consistency\ Index\ (CI) = \frac{\lambda_{max} - n}{n - 1} = \frac{6 - 6}{6 - 1} = 0$$

**Equation 4.2**

$$Consistency\ Ratio = \frac{Consistency\ Index}{Random\ Index} = \frac{0}{1.24} = 0$$

**Equation 4.3**

Since the Consistency Ratio is 0 which is less than the standard of 0.10, the matrix is consistent and therefore can be used for analysis.

Table 14: Ranking the Briquettes based on their performance

Rank	15%	Product	5%	Product	40%	Product	Market	Product
6	3	18	1	6	2	12	4	24
5	3	15	4	20	2	10	1	5
4	4	16	3	12	2	8	1	4
3	3	9	4	12	1	3	2	6
2	1	2	2	4	3	6	4	8
1	3	3	2	2	1	1	4	4
<b>Total</b>		<b>63</b>		<b>56</b>		<b>40</b>		<b>51</b>

## CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusions

- Comprehensive investigation revealed that wastewater sludge has desirable qualities as a feedstock for hydrochar production. The sludge has sufficient moisture content of 15.3%, volatile matter of 44.29%, ash content of 28.67% and fixed carbon of 11.73% for hydrothermal carbonization. These findings confirm the viability of using wastewater sludge as a sustainable feedstock for hydrochar production, thereby contributing to resource recovery and waste management initiatives.
- The experimental investigation indicated the best process conditions for increasing hydrochar yield and briquette formation. By altering factors such as temperature, residence time, and pressure, it was discovered that a combination of moderate temperature (230°C), extended residence time (2 hours), and moisture content (50%) produced the most hydrochar and aided effective briquette manufacturing. These revised process conditions show the possibility for scalable manufacture of hydrochar-based briquettes with higher yield and quality.
- The characterization of briquettes made using hydrochar gave important information about their fuel properties. Among the various binder ratios tested, briquettes produced with 15% starch demonstrated superior fuel qualities, such as boiling time of 19 minutes, water resistance of 55.55%, shutter resistance of 94.35%, gas emissions of 194.5ppm Carbon monoxide and 0.36% Carbon dioxide, and improved combustion efficiency. These findings highlight the significance of binder selection in improving the fuel properties of hydrochar-based briquettes. The use of 15% starch as the ideal binder helps

to generate briquettes with higher energy content and combustion performance, establishing them as viable alternatives to traditional fuels.

- The cost-benefit analysis of hydrochar-based briquettes, particularly those using 15% starch as a binder, shows promising economic and environmental benefits. The ideal binder ratio not only improves the fuel properties of the briquettes, but it also adds to cost-effectiveness and sustainability in production. The use of 15% starch as the preferred binder improves briquette quality, lowers manufacturing costs, and increases market competitiveness. Furthermore, the environmental benefits of hydrochar-based briquettes, such as lower greenhouse gas emissions and waste utilization, contribute to their economic feasibility and sustainability. Overall, choosing 15% starch as the best binder accords with the goal of optimizing the economic and environmental benefits of hydrochar-based briquettes, enhancing their status as a renewable energy source with good cost-benefit outcomes.

## 5.2 Recommendations

- **Binder Ratio Optimization:** Additional binder ratios and combinations could be investigated in order to develop optimal formulations that improve the fuel characteristics and mechanical properties of hydrochar-based briquettes. This could entail conducting a systematic study employing several binders and their combinations to meet the specified performance parameters.
- **Alternative Binders:** Research should focus on examining binders other than starch and clay, such as bio-based polymers, molasses, lignin, and waste-derived compounds. Investigating the effects of various binders on the attributes of hydrochar-based briquettes may provide insights into sustainable

binder alternatives that increase both performance and environmental sustainability.

- **Long-Term Performance Evaluation:** Long-term performance studies could be done to assess the durability, stability, and combustion behavior of hydrochar-based briquettes in real-world scenarios. This would entail field experiments or extensive laboratory testing to evaluate the briquettes' performance over time, including storage stability and resistance to degradation.
- **Life Cycle Assessment (LCA):** A thorough life cycle assessment (LCA) of hydrochar-based briquettes would provide a full understanding of their environmental impact when compared to traditional fuels. This would entail evaluating the environmental impact of the entire manufacturing process, including raw material procurement, manufacture, transportation, and end-of-life disposal, in order to discover areas for further optimization and sustainability improvements.
- **Market Analysis and Techno-Economic Evaluation:** Studies are being conducted to determine the commercial viability and competitiveness of hydrochar-based briquettes in comparison to other fuel choices. This would entail investigating market trends, demand dynamics, regulatory frameworks, and cost structures in order to identify potential hurdles and opportunities for market penetration and commercialization.

By addressing these recommendations through additional study, we may expand our understanding and implementation of hydrochar-based briquettes as sustainable energy solutions, helping to shift the energy landscape toward one that is more sustainable and resource efficient.

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## APPENDICES

### Appendix A: Laboratory Works



Figure 23: Sample Preparation



Figure 24: Volatile Matter Test



Figure 25: Ash Content Test



Figure 26: Reactor Preparation



Figure 27: Rapidly cooling the reactor with water



Figure 28: Briquetting the samples prior to testing.

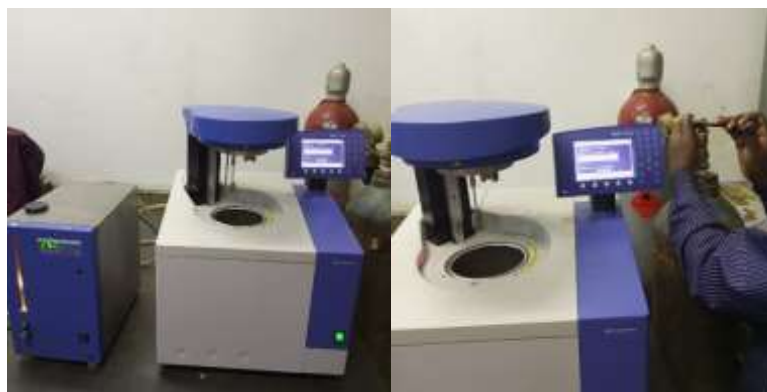


Figure 29: Setting the calorimeter prior to testing.



Figure 30: Loading the sample into the bomb



Figure 31: Inserting the Bomb into the calorimeter and starting the test.



Figure 32: Results output from the test.



Figure 33: Hydrochar preparation



Figure 34: Mixing the various proportions together



Figure 35: Injecting the mixture into the Briquetting machine



Figure 36: Compacting the mixture into a briquette



Figure 37: Extruding the briquettes from the briquetting machine



Figure 38: Drying the Briquettes made in n air dryer



Figure 39: Weighing briquettes bought at 2000



Figure 28: Stove ignition



Figure 29: Ignited stove



Figure 30: Measuring initial temperature of the water

## Appendix 2: Laboratory Results



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### Laboratory Test Results

Student Names: OWINO EMMANUEL, S20B32/215

: NAGITTA AISHA, S20B32/311

Date of Analysis: 11<sup>th</sup> January 2024

Sample Type: WASTEWATER SILAGE

S/no	Test Parameters	R1	R2	R3	Average
1	Volatile matter, % m/m	43.96	43.55	45.36	44.29
2	Ash content, % m/m	28.65	29.02	28.34	28.67
3	Moisture content, % m/m	15.38	15.36	15.17	15.30
4	Fixed Carbon, % m/m	12.01	12.06	11.13	11.73

Analysis carried out by:

WAIBALE WILBER

Scientist Chemistry Lab

— 0773379437





**COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY  
SCHOOL OF ENGINEERING  
DEPARTMENT OF MECHANICAL ENGINEERING**

Wednesday, 28 February 2024

**Re: Heating Value of the waste sludge samples you sampled and submitted our laboratory**

I refer to your request dated 26<sup>th</sup> Feb 2024 to carry out the above tests on the samples you sampled and submitted to our laboratory

**(i) Apparatus**

The apparatus used included: An IKA C2000 Automated Digital bomb calorimeter shown in figure 1 and a Precision Denver S1-234 Digital Weighing scale (+/- 0.0001g)



**Figure 1: IKA C2000 Automated Digital bomb calorimeter**

**(ii) Samples and methods**

Two specimens were extracted from the submitted sample and weighed independently placed in the bomb witnessed by the students and the procedure described below is followed to carry out the tests

---

*J. W. Zule* 28 February 2024

Page 1

The higher heating value of the samples was measured using an internal programme in the IKA C2000 Digital bomb calorimeter. Samples weighing between 700 mg to 1500 mg are placed in the bomb calorimeter and subject them to complete combustion in an adiabatic environment which is internally stabilized by a computer, heaters and circulating water. The lower Heating Value is calculated from measured temperature increase in the adiabatic system by a software and displayed on the digital screen. The results are given in table 1

**Results**

*Waste Sludge*

**Table 1 Heating Values of the ~~Waste~~ Samples**

Sample name	Weight (g)	Heating Values (MJ/Kg)
Sample 1-1	0.9642	14.183
Sample 1-2	0.8200	13.954
Sample 2-1	1.0603	14.827
Sample 2-2	1.0605	14.953
Sample 3-1	0.9040	14.689
Sample 3-2	0.6422	14.545
Sample 4-1	1.0494	14.022
Sample 5-1	1.0345	13.556
Sample 5-2	0.9009	13.620

I hope the results will be of help in your research  
 Tests and report done by

*J. Wabwire*

Wabwire Andrew  
 Chief Technician - Mechanical Engineering





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FACULTY OF ENGINEERING, DESIGN AND TECHNOLOGY

TO WHOM IT MAY CONCERN

18<sup>th</sup> March, 2024.

**SUBJECT: CONFIRMATION OF HYDROTHERMAL CARBONIZATION TESTS CONDUCTED BY AISHA THURAYYA NAGITTA AND EMMANUEL OWINO AT UGANDA CHRISTIAN UNIVERSITY ART LAB.**

This is to confirm that the above-mentioned students conducted a hydrothermal Carbonization experiment on 14<sup>th</sup> February, 2024 to 13<sup>th</sup> March, 2024 at our laboratory. The purpose of this experiment was to get the hydrochar yield and the Calorific Value of the wastewater sludge at various water content, temperature and reaction time.

## KEY DETAILS OF THE EXPERIMENT

Experiment Title: Hydrothermal Carbonization of wastewater sludge.

Date of experiment: 14<sup>th</sup> February, 2024 – 13<sup>th</sup> March, 2024

Materials used: WUCU wastewater Sludge.

Safety protocols and standard operating procedures were followed throughout the experiment.

Yours in service  
  
Ramsey Ramathan  
Lab Technician

UGANDA CHRISTIAN UNIVERSITY  
DEPARTMENT OF VISUAL ARTS AND DESIGN  
18 MAR 2024



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
FACULTY OF ENGINEERING, DESIGN, AND TECHNOLOGY  
Department of Engineering and Environment

## LABORATORY TEST REPORT

<b>Certificate Number: A007</b>		
<b>Client Name:</b> AISHA THURAYYA NAGITTA & EMMANUEL OWINO	<b>Sample Receipt Date:</b>  14/02/2024	<b>Analysis Start Date:</b>  14/02/2024
<b>Client Address and Contact:</b> UCU P.O Box 4, Mukono 0700200131		
<b>Lab Sample ID:</b> A007/2024	<b>Date of analysis completion</b>  18/03/2024	<b>Date of issue of the certificate</b>  18/03/2024
<b>Client Sample ID:</b> Wastewater sludge from UCU treatment plant		
<b>Sample type and Location:</b> Wastewater sludge from UCU treatment plant		
<b>State of the sample on delivery:</b>  Semi-solid sludge	<b>Testing Conditions:</b> 105 <sup>o</sup> C for 24 hours	
	<b>Testing Methods:</b> BS 1377	

Volume of Vessel	25ml								
Test No:	R4	R6	R11	R8	R12	R10	R5	R3	R1
Water-biomass	65	50	65	65	70	50	80	50	65
Dry mass	2.1	3	2.1	2.1	1.8	3	1.2	3	2.1
Moisture content	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Wet mass	2.421	3.459	2.421	2.421	2.075	3.459	1.384	3.459	2.421
wet mass before heating	2.444	3.471	2.492	2.463	2.086	3.489	1.373	3.483	2.421
Mass After oven drying	2.031	2.801	1.939	1.59	1.351	2.355	1.155	2.906	1.906
HTC Yield %	96.7143	93.3667	92.3333	75.7143	75.0556	78.5	96.25	96.8667	90.7619

Laboratory Technician



MUGISHA ARNOLD

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# UGANDA CHRISTIAN UNIVERSITY

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## FACULTY OF ENGINEERING, DESIGN, AND TECHNOLOGY Department of Engineering and Environment

### LABORATORY TEST REPORT

<b>Certificate Number: A007</b>		
<b>Client Name:</b> AISHA THURAYYA NAGITTA & EMMANUEL OWINO	<b>Sample Receipt Date:</b>  14/03/2024	<b>Analysis Start Date:</b>  14/03/2024
<b>Client Address and Contact:</b> UCU P.O Box 4, Mukono 0700200131		
<b>Lab Sample ID:</b> A007/2024	<b>Date of analysis completion</b>  19/03/2024	<b>Date of issue of the certificate</b>  19/03/2024
<b>Client Sample ID:</b> Solid Briquettes from UCU waste water sludge		
<b>Sample type and Location:</b> Solid Briquettes from UCU waste water sludge	<b>Testing Conditions:</b> 105 <sup>0</sup> C for 24 hours	
<b>State of the sample on delivery:</b>  Solid Briquettes	<b>Testing Methods:</b> <b>WBTP 4.2.3</b>	

PROPERTIES	VALUES							
	15% Starch		5% Starch		40% Clay		Market briquette	
	1:1	1:2	2:1	2:2	3:1	3:2	4:1	4:2
Carbon dioxide (%)	0.82	0.79	0.64	0.70	0.59	0.65	0.61	0.54
	0.40	0.45	0.35	0.40	0.52	0.52	0.74	0.80
	0.29	0.30	0.29	0.35	0.37	0.29	0.91	0.85
Carbon monoxide (ppm)	303	299	446	450	300	345	160	175
	140	167	358	250	263	296	145	167
	138	120	298	209	194	163	274	250
Water boiling test (time in minutes)	20	18	16	19	23	22	19	21
Shatter resistance (%)	95.4	93.3	68.7	65.2	66.9	55.3	26.2	31.7
Water resistance (%)	56.7	54.4	45.3	42.7	-	-	79.0	74.6

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## Solutions

Number	Water Content	Temperature	Reaction Time	Heating Value	HTC Yield	Desirability	
1	68.787	196.061	2.530	14.591	74.171	1.000	Selected
2	70.000	230.000	2.000	14.069	75.060	1.000	
3	50.000	210.000	0.500	13.752	93.370	1.000	
4	65.000	210.000	2.000	14.618	75.710	1.000	
5	50.000	180.000	2.000	13.588	96.870	1.000	
6	80.000	210.000	0.500	14.022	96.250	1.000	
7	80.000	180.000	2.000	13.940	87.990	1.000	
8	50.000	230.000	2.000	14.890	78.500	1.000	
9	50.000	230.000	0.500	14.218	92.330	1.000	
10	56.775	226.648	2.043	14.804	75.356	1.000	
11	63.232	226.890	4.016	14.816	52.388	1.000	
12	68.859	183.355	3.041	14.632	76.025	1.000	
13	59.224	190.277	2.916	14.886	76.989	1.000	
14	75.809	215.608	3.629	13.838	55.763	1.000	
15	57.861	220.489	1.023	14.470	85.327	1.000	
16	68.616	210.281	2.846	14.603	66.225	1.000	
17	69.272	222.810	3.750	14.311	54.029	1.000	
18	78.644	186.184	2.271	14.074	81.424	1.000	
19	57.080	195.500	1.517	14.206	86.987	1.000	
20	76.985	193.156	0.974	14.075	92.456	1.000	
21	52.189	220.658	1.777	14.749	79.888	1.000	

22	70.327	189.052	2.800	14.561	74.595	1.000	
23	66.513	183.579	2.041	14.274	85.765	1.000	
24	74.678	185.996	4.659	14.711	56.364	1.000	
25	63.101	200.645	0.892	14.193	89.250	1.000	
26	78.525	210.715	4.202	13.619	49.673	1.000	
27	70.572	192.628	3.893	14.837	61.590	1.000	
28	52.452	187.622	1.416	13.632	94.087	1.000	
29	56.023	200.385	1.442	14.276	86.028	1.000	
30	76.394	212.003	2.150	14.011	74.308	1.000	
31	76.294	183.916	3.958	14.453	64.644	1.000	
32	59.641	208.824	2.328	14.848	74.027	1.000	
33	61.773	186.008	0.719	13.606	96.989	1.000	
34	77.866	207.916	1.841	14.002	78.997	1.000	
35	75.657	228.061	1.304	13.802	85.108	1.000	
36	74.813	209.121	4.141	14.146	51.083	1.000	
37	60.812	189.445	1.053	13.874	92.591	1.000	
38	61.191	226.248	2.992	14.839	64.208	1.000	
39	68.018	183.022	2.933	14.611	77.520	1.000	
40	63.023	227.300	4.097	14.834	51.553	1.000	
41	63.536	201.788	2.195	14.675	76.320	1.000	
42	63.426	208.646	2.554	14.817	70.706	1.000	
43	63.279	218.112	1.694	14.584	77.964	1.000	
44	69.622	201.868	3.586	14.759	60.701	1.000	
45	52.602	226.091	1.664	14.729	80.458	1.000	

46	78.281	198.371	1.839	14.069	81.311	1.000	
47	51.344	198.156	1.076	13.774	91.917	1.000	
48	74.899	228.382	1.223	13.862	85.883	1.000	
49	67.082	207.783	0.796	14.312	88.629	1.000	
50	71.543	209.692	3.184	14.432	62.289	1.000	
51	59.932	229.360	2.632	14.783	68.409	1.000	
52	60.848	222.684	2.532	14.822	69.314	1.000	
53	54.440	216.293	2.082	14.856	76.714	1.000	
54	68.567	212.484	3.128	14.609	62.668	1.000	
55	58.651	229.239	2.179	14.750	73.515	1.000	
56	70.925	185.468	3.389	14.681	70.725	1.000	
57	52.980	180.723	2.288	14.026	92.169	1.000	
58	68.202	227.885	3.865	14.237	52.633	1.000	
59	63.227	227.859	2.689	14.621	66.997	1.000	
60	64.236	217.028	0.844	14.397	86.984	1.000	
61	63.006	229.058	3.763	14.734	55.178	1.000	
62	76.337	216.692	3.824	13.713	53.224	1.000	
63	70.549	206.493	4.215	14.691	51.973	1.000	
64	54.564	224.715	1.950	14.825	77.039	1.000	
65	71.651	215.033	3.678	14.312	55.521	1.000	
66	72.696	181.744	3.411	14.571	72.476	1.000	
67	54.885	196.575	2.344	14.679	80.758	1.000	
68	76.430	213.323	4.551	13.761	44.915	1.000	
69	56.573	217.190	1.752	14.711	78.839	1.000	

70	54.377	207.640	0.527	13.926	92.225	1.000	
71	63.943	228.652	3.302	14.612	60.037	1.000	
72	61.931	213.380	1.473	14.552	80.879	1.000	
73	67.983	199.258	3.198	14.802	66.210	1.000	
74	57.295	218.560	1.708	14.696	78.893	1.000	
75	66.754	221.945	3.907	14.612	52.877	1.000	
76	74.160	219.127	2.949	13.959	63.607	1.000	
77	70.392	188.748	2.789	14.553	74.853	1.000	
78	52.758	211.981	0.766	14.104	89.780	1.000	
79	74.089	216.333	4.810	13.941	41.497	1.000	
80	59.502	181.595	2.938	14.680	82.382	1.000	
81	60.018	181.244	2.438	14.361	86.332	1.000	
82	68.249	191.302	3.295	14.814	69.021	1.000	
83	73.743	183.165	1.552	14.064	90.099	1.000	
84	77.601	192.436	2.136	14.128	79.887	1.000	
85	51.968	182.499	2.993	14.638	86.765	1.000	
86	68.023	212.681	3.020	14.632	63.900	1.000	
87	53.129	190.076	1.847	14.090	89.097	1.000	
88	67.271	227.349	0.649	14.292	90.207	1.000	
89	75.406	194.814	3.247	14.346	66.413	1.000	
90	61.371	226.713	2.529	14.733	69.101	1.000	
91	75.329	182.760	3.273	14.393	72.695	1.000	
92	62.913	187.262	1.414	14.048	90.087	1.000	
93	53.352	229.176	2.091	14.884	76.119	1.000	

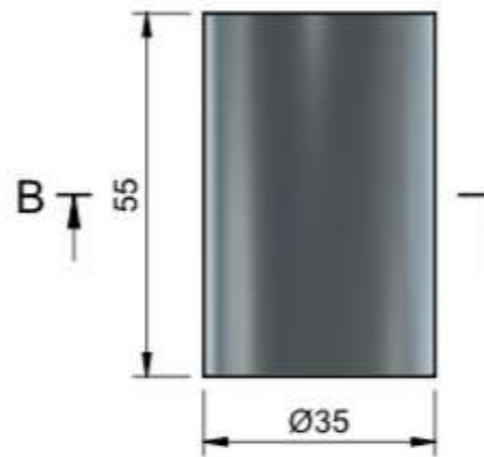
94	71.687	191.784	3.933	14.768	61.293	1.000	
95	75.724	220.531	1.891	13.899	76.932	1.000	
96	69.539	217.873	3.977	14.456	51.960	1.000	
97	53.251	195.681	1.715	14.208	87.097	1.000	
98	71.698	215.425	3.274	14.290	60.135	1.000	
99	56.111	224.514	1.918	14.789	76.827	1.000	
100	60.058	180.685	2.609	14.450	85.339	1.000	

# SCHEMATICS OF THE BRIQUETTES FORMED USING THE HYDROCHAR

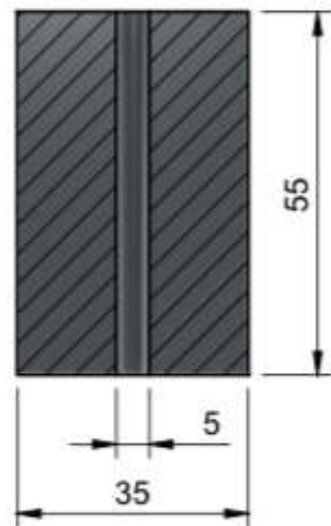
**Top View**



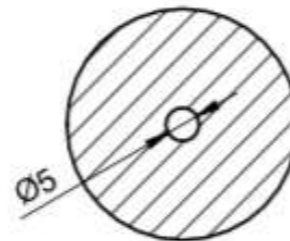
**Side View**



**Section A-A (1:1)**

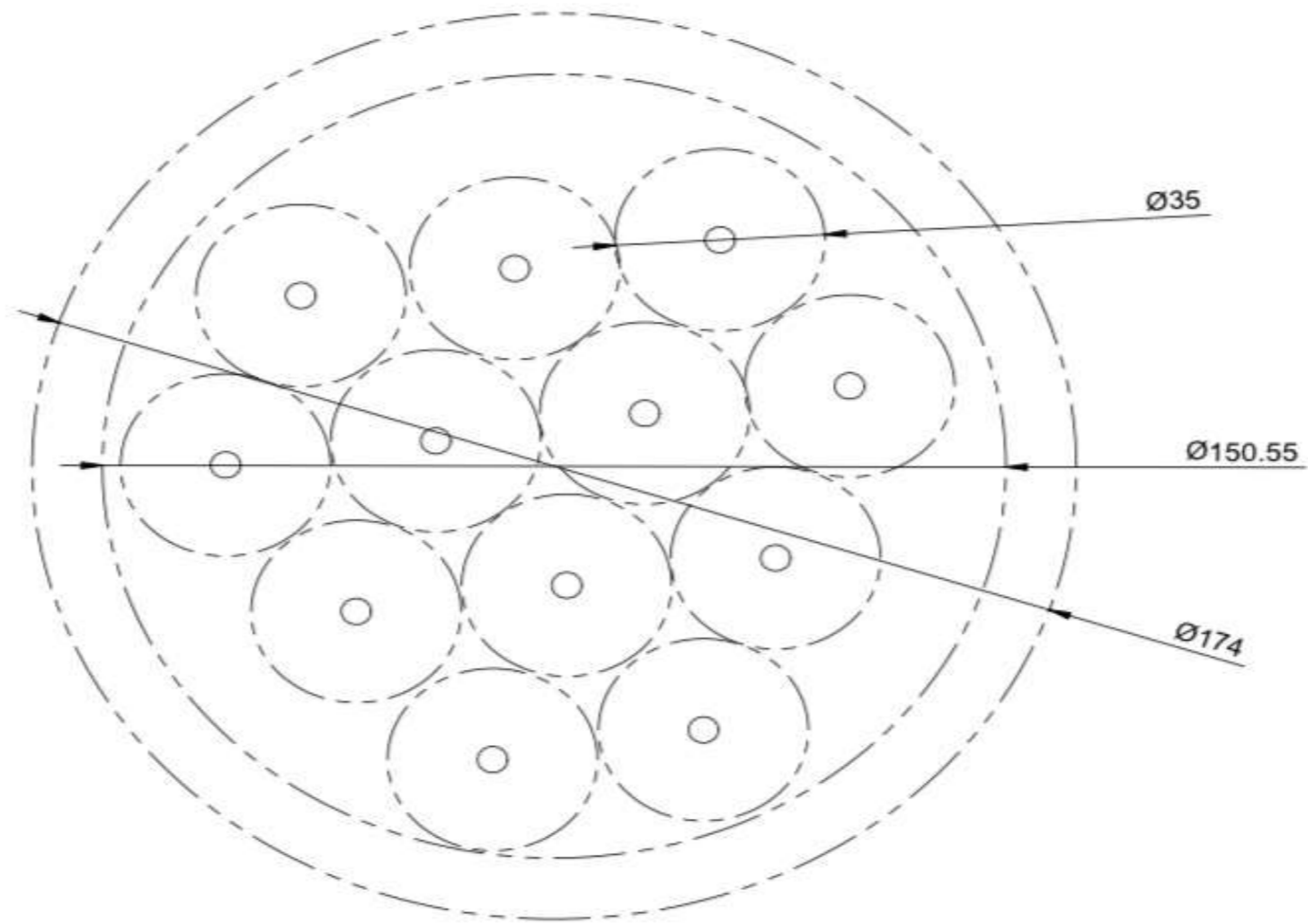


**Section B-B (1:1)**



Dept.	Technical reference	Created by <b>Aisha Nagitta Thurayya 4/4/2024</b>	Approved by	
		Document type	Document status	
		Title <b>Briquette Design</b>	DWG No.	
		Rev.	Date of issue	Sheet <b>1/1</b>

## Illustration of the briquettes in a stove



Dept.	Technical reference	Created by Aisha Nagitta Thurayya 4/10/2024	Approved by	
		Document type	Document status	
		Title Stove with briquettes	DWG No.	
		Rev.	Date of issue	Sheet 1/1