INVESTIGATING THE USE OF WASTEWATER SLUDGE-BASED FUELS

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A FINAL YEAR RESEARCH AND DESIGN PROJECT REPORT SUBMITTED TO THE FACULTY OF ENGINEERING, DESIGN AND TECHNOLOGY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A DEGREE OF BACHELOR OF SCIENCE IN CIVIL AND ENVIRONMENTAL ENGINEERING OF UGANDA CHRISTIAN UNIVERSITY

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ABSTRACT

This study examines the potential of wastewater sludge-based fuels through hydrothermal carbonisation, a process of converting biomass into carbonaceous material under elevated temperature and pressure in a closed system. The investigation aims to utilize wastewater sludge from the UCU Wastewater treatment plant as a biofuel, focusing on determining its properties as a suitable feedstock, optimizing process conditions for maximum hydrochar yield and briquette formation, evaluating the fuel characteristics of the resulting briquettes, and conducting a cost-benefit analysis. Proximate analysis, calorimetry, water boiling tests, and AHP analysis were employed. Optimal conditions were found at 230°C with 50% moisture content for 2 hours, yielding a heating value of 14.89 MJ/kg. Briquettes composed of 15% starch, 5% sand, and 80% hydrochar exhibited favourable properties, although reactor instability at high moisture content levels suggests the need for a stirred hydrothermal reactor. Further research to enhance briquette water resistance is recommended to improve durability for diverse applications.

DECLARATION

I, OWINO EMMANUEL, hereby declare that this is my original work, is not plagiarized and has never been submitted to any institution of higher learning for any academic award.

SIGNATURE... DATE................................

OWINO EMMANUEL

APPROVAL

This research and design project report 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 Background to the Study

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 use of 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.

1.4 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.

1.5 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?

1.6 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 the 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.

1.8 Scope of the study

The scope of the project is Ddandira Village located 1.6Km from Wantoni Trading Centre along Katosi Road in Mukono District.

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

CHAPTER TWO: LITERATURE REVIEW

2.1 Theoretical Review

2.1.1 Introduction

Fuels are substances that liberate energy through combustion or chemical reactions, serving essential roles in transportation, electricity production, heating, and industrial operations.

Recovered fuels represent a category of alternative fuel sources obtained from processing and recycling diverse waste materials. These fuels present a sustainable and eco-friendly option compared to conventional fossil fuels. They bring about numerous advantages, such as diminishing waste accumulation in landfills, mitigating greenhouse gas emissions, and preserving natural resources.

Examples of recovered fuels include:

Refuse-Derived Fuel (RDF)

RDF is produced by processing and shredding non-recyclable solid waste materials, such as plastics, paper, and organic waste. These materials are then compressed into fuel pellets or briquettes. RDF is used in various industrial processes, such as cement production and energy generation (Clark, 2023).

Solid Recovered Fuel (SRF)

SRF is similar to RDF but is typically of a higher quality and is specifically designed for use in industrial and energy applications. It is often made from sorted and processed municipal solid waste (MSW) or commercial and industrial waste. SRF can be a valuable source of energy in waste-to-energy facilities (EN ISO:21640, 2021).

Biomass Solid Fuels

These fuels are produced from organic materials such as wood, agricultural residues, and other plant-based waste. When these materials are processed and compacted, they become solid biomass fuels. They can be used for heating and electricity generation and as a replacement for fossil fuels in industrial processes (Ibitoye *et al.*, 2023).

Tire-Derived Fuel (TDF)

TDF is made by shredding and processing discarded tyres. 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 tyre disposal but also conserves energy resources (Gray, 1997).

Plastic Solid Fuels

Some waste plastics can be converted into solid fuels through a process called pyrolysis, which involves heating the plastic in the absence of oxygen. This can produce plastic-derived solid fuels that can be used for heat and power generation (Kohli *et al.*, 2021).

Recovered fuels help address the challenges of waste management, reduce greenhouse gas emissions by offsetting the use of fossil fuels, and contribute to a more sustainable energy mix. However, it's essential to ensure that these fuels are produced and used in an environmentally responsible manner to maximize their benefits and minimize any potential environmental impacts.

Solid recovered fuel

Solid Recovered Fuels (SRF) represent an innovative and environmentally sustainable approach to waste management and energy generation. These fuels are derived from various waste materials, including municipal solid waste (MSW), industrial waste, and sewage sludge, which are processed and transformed into valuable energy resources. The production of SRF from sludge, in particular, has gained considerable attention as it not only addresses the challenges of sludge management but also contributes to reducing the reliance on fossil fuels and minimizing the environmental impact associated with waste disposal. One key aspect of SRF production from sludge is the transformation of what was traditionally considered a waste product into a valuable resource. Wastewater treatment plants produce substantial quantities of sludge as a byproduct of sewage treatment processes. Traditionally, 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.

The production of SRF from sludge typically involves a multi-step process. It begins with dewatering to reduce the moisture content of the sludge, making it more amenable to subsequent treatment. Drying techniques, such as thermal drying or mechanical drying, are then employed to further decrease the moisture content and improve the energy density of the material. In some cases, pyrolysis or gasification processes can be applied to convert the dried sludge into solid fuel with enhanced combustion properties. Co-processing, which involves blending sludge with other waste streams like biomass, can also be utilized to optimize the quality of SRF and improve its combustion efficiency. The quality and characteristics of the resulting SRF are critical for its practical applications. The composition of SRF depends on 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.

From an environmental perspective, generating SRF from sludge offers multiple advantages. It reduces the environmental footprint of sludge disposal, minimizing the release of harmful substances into the environment. Additionally, the use of SRF in place of fossil fuels contributes to a reduction in greenhouse gas emissions, aligning with sustainability and climate change mitigation goals. However, it's important to conduct a thorough assessment of the environmental and economic impacts of SRF production to ensure its overall sustainability. Challenges in the production of SRF from sludge include variations in sludge characteristics, technical feasibility, and regulatory constraints. Further research and development efforts are needed to optimize SRF production techniques, address environmental concerns, and develop innovative technologies that can improve the efficiency and environmental performance of this approach to waste management and energy generation. 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.

The production of Solid Recovered Fuels (SRF) from sludge, a promising approach to address both waste management and sustainable energy generation, has led to the development of a specialized and efficient form known as sludge briquettes. These briquettes represent a remarkable transformation of sewage sludge, a traditionally challenging waste product, into a compact and energy-dense fuel source, offering environmental and practical benefits. This project explores the connection between SRF derived from sludge and the innovative world of sludge briquettes, shedding light on their production, applications, and role in advancing the goals of waste-to-energy initiatives.

Sludge briquettes are a specialized type of Solid Recovered Fuel (SRF) that is produced from sewage sludge, a byproduct of wastewater treatment processes. These briquettes represent an innovative approach to managing sludge, converting what was traditionally considered waste into a valuable resource for energy recovery and waste reduction. The production of sludge briquettes involves a series of treatment and processing steps to transform the sludge into a more efficient and environmentally friendly fuel source.

The first step in the production of sludge briquettes is the dewatering of sewage sludge. Sludge typically has a high moisture content, which makes it challenging to handle and transport. Dewatering involves the removal of excess water to reduce the moisture content and improve the sludge's handling properties. Various techniques such as mechanical dewatering and centrifugation can be employed to achieve this. Once the sludge has been dewatered, it is further processed to create a homogenous and combustible material. This involves mixing the sludge with binding agents, such as biomass or other waste materials, to enhance its energy content and facilitate the formation of briquettes. The mixture is then compacted into the desired briquette shape and size using specialized equipment.

Sludge briquettes offer several advantages. Firstly, they provide an environmentally responsible solution for managing sewage sludge, diverting it from landfills or incineration, both of which can have adverse environmental impacts. Secondly, the briquettes have a higher energy density compared to untreated sludge, making them suitable for various energy applications, including heat and electricity generation. Furthermore, sludge briquettes can be a beneficial source of renewable energy. When used in thermal processes, such as in cement kilns or industrial boilers, they help reduce greenhouse gas emissions and decrease the demand for fossil fuels. This contributes to a more sustainable and circular approach to waste management and energy production.

However, the production of sludge briquettes is not without challenges. 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.

In conclusion, sludge briquettes represent an innovative and sustainable solution for the management of sewage sludge. They demonstrate the potential to convert a challenging waste stream into a valuable energy resource, contributing to both waste reduction and cleaner energy production. As research and development in this field continue, sludge briquettes hold promise as a crucial component of a more circular and environmentally responsible approach to waste management and energy recovery.

2.2 Empirical Review

2.2.1 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) involves the conversion of biomass into carbonaceous material in water at elevated temperature and pressure, typically conducted within closed systems. This process entails submerging solid biomass in water, with temperatures ranging from 180 to 250°C and corresponding pressures of approximately 2 to 6 MPa, for durations spanning from 5 to 240 minutes (Kambo and Dutta, 2015).

Hydrothermal processes diverge into hydrothermal liquefaction and hydrothermal gasification when temperatures exceed 250°C (He *et al.*, 2014). HTC of biomass yields three primary products: hydrochar, a liquid phase comprising bio-oil, water, and minor gases, primarily CO2 (Kambo and Dutta, 2015). The chemical composition and energy content of hydrochar resemble those of natural coal, rendering it suitable for use as solid fuel in conventional combustion processes (Masoumi *et al.*, 2021).

2.2.2 Feedstock

In principle, various types of organic matter and biomass can undergo carbonization under hydrothermal conditions. Materials including cellulose, wood, microalgae, municipal solid waste (MSW), food waste, sewage sludge, and agricultural residues have been effectively processed using the HTC method (Sevilla and Fuertes, 2009). The properties of biomass feedstock, such as its chemical composition, moisture content, volatile matter (VM), fixed carbon (FC), non-combustible matter (ash), and energy content, play a significant role in determining the distribution of products (hydrochar, liquid, and gas phases), as well as the characteristics of these products, conversion efficiencies, and the energetics of the process (Wilk *et al.*, 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 *et al.*, 2012)
Wastewater Sludge	80.2	68.5	16.4	23.27	18.45	(Wang *et al.*, 2012)
Wastewater Sludge	78.4	55.3	19.29	25.38	15.65	(Wang *et al.*, 2012)
Wastewater Sludge	81.9	67.2	9.2	19.3		(Moon *et al.*, 2015)
Wastewater Sludge	73.03	61	10.29	28.71	13.74	(Wen *et al.*, 2023)
Wastewater Sludge	83.7	52.52	12.58	34.9	13.1	(Wen *et al.*, 2023)

Material	**Moisture % (Wet basis)**	**Volatile Matter % (Dry basis)**	**Fixed Carbon % (Dry basis)**	**Ash Content % (Dry basis)**	**Energy Content (MJ/kg)**	**Reference**
Wastewater Sludge	80.97	57	12.31	30.69	13.76	(Wen *et al.*, 2023)
Sewage Sludge	96	70.3	5.3	16	18	(Danso-Boateng *et al.*, 2013)

2.2.3 Mechanisms of HTC

Hydrochar formation involves several sequential steps, including hydrolysis, dehydration, fragmentation, polymerization, and aromatization(Sevilla and Fuertes, 2009).

Hydrolysis

The biological molecules in the sludge are made up of repeating subunits called monomers joined together to form a polymer. When these polymers are heated in water in sub-critical conditions of temperature between 100-175°C, they break the bond between the long chains to shorter chains called oligomers.

$$C_6H_{10}O_5 + nH_2 \xrightarrow{\text{HCl or enzyme}} C_6H_{12}O_6 + C_6H_{12}O_6 \quad (1)$$

This reaction represents the breakdown of cellulose into simpler sugar molecules (glucose/fructose) through the addition of water molecules during hydrolysis.

Dehydration

Dehydration involves the removal of water molecules from organic compounds, resulting in the formation of double bonds between carbon atoms. During the hydrothermal process, dehydration reactions can occur alongside hydrolysis as the temperature increases, leading to the conversion of sugars and other carbohydrates into furans and other intermediate compounds. It occurs at temperatures between 160-280°C.

Under hydrothermal conditions, glucose can undergo dehydration to form hydroxymethylfurfural (HMF), a valuable intermediate compound in biomass conversion processes.

$$C_6H_{12}O_6 \xrightarrow{\text{Acid Catalyst, High Temperature}} C_6H_6O_3 + H_2O \quad (2)$$

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.

$C_6H_6O_3 \rightarrow$ Hydrochar + Byproducts (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.

$C_6H_6O_3$ + Aldehyde $\rightarrow$ Lignin-like Compounds + H_2O (4)

Effect of Process Parameters

The properties of hydrochar are influenced by the characteristics of the feedstock, as mentioned earlier. Moreover, hydrochar production is also affected by various process parameters in the HTC process, including the moisture content of the feedstock, operating temperature, reaction time, pressure, solid load, and pH value.

Moisture Content

Moisture content plays a significant role in the hydrothermal carbonization process. Previous experiments have indicated that the presence of water accelerates the carbonization of biomass. However, biomass located above the water's surface does not undergo carbonization. Thus, adequate water presence is crucial for the effective implementation of the HTC process (Krylova and Zaitchenko, 2018).

Temperature

Temperature stands out as a crucial factor in the hydrothermal carbonization process. Temperature variations directly impact the energy input into the reaction, which is essential for breaking down feedstock particles. Elevated temperatures notably expedite the degradation and polymerization of sewage sludge leading to the formation of hydrochar (Akhtar and Amin, 2011; Wang, Chang and Li, 2019). The carbonization process is most favourable at temperatures up to 250°C. Beyond this range, different products are formed: oil is produced at temperatures up to 375°C, while gas is generated at temperatures above 375°C (He *et al.*, 2014). Consequently, it has been demonstrated that the highest solid yield is achieved at temperatures below 200°C.

Reaction time

The residence time of the hydrothermal carbonization process holds significant importance, as it impacts the energy balance, process efficiency, and operational costs. Moreover, it plays a crucial role in determining the distribution, properties, and chemical composition of the resulting products. It directly influences the progress of the carbonization reaction. The residence time in hydrothermal carbonization exhibits considerable variation, ranging from as short as 15 minutes to as long as 1440 minutes. Typically, a duration of 60 minutes is most commonly observed (Czerwińska, Śliz and Wilk, 2022).

pH value

During the operation of hydrothermal carbonization (HTC), a decrease in pH is typically observed, primarily due to the formation of organic acids such as acetic, formic, and lactic acid (Niinipuu *et al.*, 2020). Studies have explored the application of acid and base additions to adjust pH in the HTC process, revealing significant effects on product characteristics and reaction rates.

The pH of the feedstock has been found to influence hydrochar yield. Research indicates that at a pH of 1, strong acids accelerate the hydrolysis reaction during the early stages of HTC (Liang, Liu and Zhang, 2011). However, strong acids can inhibit polymerization and carbonization processes. Conversely, at pH levels of 3, 5, and 7, hydrochar yields increase with reaction time, reaching their maximum values after approximately 3 hours. These maximum yields are very similar, measuring 43.57%, 44.6%, and 43.69% for pH levels of 3, 5, and 7, respectively. Consequently, the optimal pH range for feedstock in the HTC process is typically considered to be between 3 and 7 (Jeong *et al.*, 2012).

2.2.4 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 materials used as fuel in stoves and boilers. The ingredients needed to make briquettes include a fuel source, an accelerant, and a binder (Salmon, 2021).

Heating fuel

A heat fuel is a substance that is burned to provide nuclear energy, heat, or power. Various heat fuels 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 makes for better briquettes (Jagdish, 2019).

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.

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).

2.2.5 Summary and Research Gaps

The exponential increase in energy demand, as well as the associated rise in fuel prices, pose a significant danger to the economies of developing countries. Alternative and sustainable energy, such as biofuel, seems to be a quick solution to this problem; however, the emerging industry is facing a feedstock supply shortage, some of the feedstock supply comes from agricultural byproducts such as Coffee husks and wood shavings which are subject to production seasons. Biofuel production must be both steady and cost-effective for the industry (Oonsivilai *et al.*, 2009).

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter outlines the methodologies employed to accomplish the study objectives. It focuses on delineating the procedures and intricacies involved in conducting the research, which are elaborated upon within this section.

Below is a list of the methodology that is to be carried out on each objective.

Objective one

Moisture content (ASTM D2974-87), Volatile Matter (ASTM D3175-07), Ash content (ASTM D3174-12), Fixed carbon

↓

Objective two

Determining the appropriate temperature, water-biomass ratio and residence time combination that will yield higher quality hydrochar (Regression Analysis).

↓

Objective three

Water boiling test (WBTP 4.2.3), Shatter Resistance (WBTP 4.2.3), Water resistance test (WBTP 4.2.3).

↓

Objective four

Cost of Production of the Briquettes (AHP analysis).

Figure 1: Research Design

3.2 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.

Determining the moisture content of the sewage sludge (ASTM D2974-87).

Apparatus

A balance readable to 1g

A drying oven at 105°C

Evaporation Dishes

Sample Preparation

The sample was air-dried for two weeks

Figure 2: Sample Preparation

Procedure

The evaporating dish was weighed and recorded.

A sludge sample of not more than 50g was placed into the evaporating dish and the weight was recorded.

The evaporating dish with the sample was placed in the oven at 105°C for 16-24 hours.

The moisture content is calculated using;

$$Moisture\ content = \frac{(W_{wet\ sample} - W_{oven\ dry})}{W_{wet\ sample}} \times 100 \quad (5)$$

The results obtained were recorded in Table 2 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		

Determining the amount of volatile Matter in the wastewater sludge. (ASTM D3175-07).

Volatile matter content is determined by subjecting dry sludge to controlled heating conditions and measuring the resulting weight loss. This weight loss, adjusted for moisture content as determined by Test Method D3173, establishes the volatile matter content.

Apparatus

250-μm sieve.

A balance readable and accurate to 0.1 g

Crucible with a closely fitting lid

Furnace capable of maintaining 950ºC±20ºC

Procedure

The sample was crushed and sieved using a 250-μm sieve.

The crucibles intended for use underwent a heat treatment process lasting 4 hours at a temperature of 500˚C. This process ensured thorough oxidation, preparing them for subsequent use.

A representative sample was weighed and the mass was recorded.

The mass of the crucible to be used was weighed and recorded.

The crucible with the sample was then tightly covered to ensure that the sample did not burn away.

The crucible was then inserted directly into the furnace chamber, and a temperature of 950ºC±20ºC is maintained.

After heating for a total of exactly 7 min, the crucible was removed from the furnace without disturbing the cover and then cooled.

The cooled crucible with the sample was weighed and the results were recorded.

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

$$Weight\ Loss\% = \frac{(\text{Initial weight of dry sample} - \text{weight of remaining sample})}{\text{Initial weight of dry sample}} \times 100 \quad (6)$$

$$Volatile\ Matter = Weight\ loss\% - Moisture\% \quad (7)$$

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		

Figure 3: Volatile matter test

Determining 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

Furnace capable of maintaining 750^{o}C

250-µm sieve.

A balance readable and accurate to 0.1 g

Crucible

Procedure

The sample was pulverized and sieved through a 250µm sieve.

A representative sample was weighed and recorded.

The mass of the crucible was measured and recorded.

The representative sample was then placed in the crucible without a lid and then transferred to a cold furnace.

It was then heated at a rate of 500 $\pm 10^{o}$C in 1 hour.

The sample continued to be heated till the temperature reached 750±15 ^{o}C at the same rate.

The temperature is then maintained at 750±15 °C for another 2 hours.

The sample was then removed from the furnace, a lid placed on the crucible and then allowed to cool.

The weight of the Crucible and the ash Residue is taken and recorded.

Ash Content was calculated from the following Formula;

$$Ash\ content = \frac{Weight\ of\ Crucible\ and\ Ash\ residule - Weight\ of\ the\ empty\ Crucible}{Weight\ of\ oven\ dry\ sample} \times 100 \quad (8)$$

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		

This experiment was done in triplicates.

Figure 4: Ash Content Test

Determining 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.

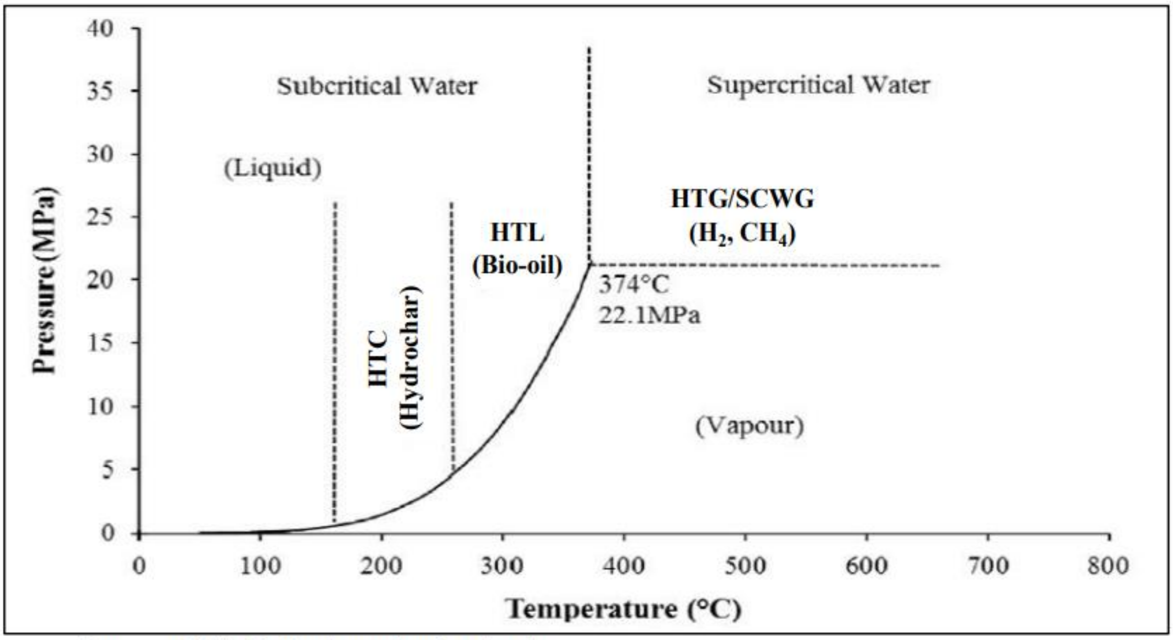
$$Fixed\ Carbon = 100\% - (Ash\ content + Volatile\ Matter + Moisture\ Content) \quad (9)$$

Table 5: Volatile matter test results.

Volatile Matter			
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

3.3 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 5: Sub-supercritical water technology for biofuels (Sandeep, 2013).

Determining the appropriate temperature, water-biomass ratio and residence time combination that will yield higher-quality hydrochar

Apparatus

A 25ml Hydrothermal Synthesis Reactor.

Furnace capable of reaching 250°C

Oven at 105°C

A balance readable and accurate to 0.1 g

Water bath

Procedure

The sludge sample was tested for moisture content to determine the amount of water present in the sludge before hydrothermal carbonization.

The density of the dry sludge being used was determined to accurately determine the mass to be added to the reactor

$$Density\ of\ Sludge = \frac{Mass}{Volume\ of\ the\ PTFE\ Liner} \quad (10)$$

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

$$= 240\ {}^{Kg}/_{m^3} \quad (11)$$

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

$$Mass\ of\ Dry\ Sludge = Density\ of\ Sludge \times \left(\frac{\%\ Volume}{100} \times Volume\ of\ liner\right) \quad (12)$$

The wet mass equivalent to the dry mass of the sludge is calculated using the formula;

$$Dry\ mass = \frac{Wet\ mass}{1 + \left({}^{Moisture\ Content}/_{100}\right)} \quad (13)$$

$$Wet\ mass = Dry\ mass \times \left(1 + {}^{Moisture\ Content}/_{100}\right) \quad (14)$$

The wet mass of the sludge was weighed and placed into the PTFE liner vessel of the reactor.

Water was added to the vessel to the brim and sealed to create a hydrothermal environment and then fitted into the reactor which is closed tightly.

The reactor was introduced into a furnace at ambient temperature, where it underwent heating and cooling at a rate of 5°C per minute.

The reactor was heated at 180°C for 30 minutes and then allowed to cool rapidly by quenching it in water to stop further reaction in the vessel.

After the reactor has cooled to room temperature, the vessel is gently opened, and the liquid was filtered off leaving behind the solid particles.

The solid residue was then carefully transferred to a crucible and oven-dried at 105°C for 24 hours.

The oven-dried sample was weighed and the value was recorded.

The yield was calculated from the following formula;

$$Yield = \frac{Mass\ of\ oven\ dry\ Sample\ after\ heating}{Mass\ of\ oven\ dry\ sample\ before\ heating} \times 100 \quad (15)$$

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

Table 6: Tests carried out to obtain the optimum HTC yield

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

Run	Water Content (%)	Temperature (˚c)	Reaction time (hours)	HTC Yield (%)
5	80	210	0.5	96.26
6	50	210	0.5	93.367
7	50	210	5	
8	65	210	2	75.714
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	

Determining the Calorific Value of the Hydrochar

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

Apparatus

C200 Automated Bomb Calorimeter

Briquetting Machine

Weighing Scale sensitive to 0.0001g

Procedure

The sample to be tested was compressed into a briquette using a briquetting making machine to make the sample easier to handle.

The formed briquette was weighed and trimmed for it to have a weight between Weigh 0.8 to 1.2 g as recommended by the ASTM D5865 standard.

The weight of the briquette sample was weighed and recorded to the nearest 0.0001g.

The Calorimeter was turned on, pure oxygen was connected to the calorimeter and the calibration of the process such as cooling of the water to be used initiated.

The bomb was preconditioned by rinsing it with water to remove residue from previous experiments before assembly.

A fuse of known calorific value was connected to the terminals of the bomb.

The briquette sample was placed into the crucible of the bomb while ensuring that the sample was in contact with the fuse to ensure the ignition of the sample.

The bomb was then carefully assembled.

The parameters such as the weight of the sample being tested and the calorific value of the fuse were fed into the bomb calorimeter.

The assembled bomb was then carefully inserted into the calorimeter and pure oxygen was introduced into the bomb to a consistent pressure of 3MPa.

As the calorimeter vessel was being closed, a known amount of water at 20°C was automatically injected into the vessel from the water reservoir.

Using a stirrer, the temperature is stabilized by ensuring the whole system is at the same temperature.

Once the temperature is stabilized, the charge is fired which burns the fuse that eventually ignites the sample.

The heat generated by the combustion of the sample was then transferred to the water in the calorimeter vessel around the bomb and the temperature change was noted.

The temperature change is monitored until there is no further change in temperature.

The Gross Calorific Value was then Obtained from the machine from the digital display screen.

The Gross calorific Value was then recorded.

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

Table 7: Tests carried out to obtain the optimum heating value.

Run	Moisture Content	temperature	Reaction Time	Heating Value
1	50	180	2	13.588
2	65	190	0.5	13.79
3	80	180	2	13.94
4	80	210	0.5	14.022
5	50	210	0.5	13.7525
6	65	210	2	14.6185
7	50	230	2	14.89
8	50	230	0.5	14.218
9	70	230	2	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.

Figure 6: Using the bomb Calorimeter to determine the calorific value.

3.4 Designing a briquette with the hydrochar produced from optimum process conditions.

When designing and sizing briquettes, density emerges as a pivotal parameter warranting consideration due to its influence on a multitude of crucial factors, including mechanical strength, energy content, combustion efficiency, and handling characteristics. In the context of biomass feedstock, the recommended density range typically spans from 800 kg/m^3 to 1200 kg/m^3.

In the production of briquettes, particular emphasis is placed on achieving high energy content, optimal combustion efficiency, robust mechanical strength, and user-friendly handling properties. Among these attributes, maximizing density is prioritized as it correlates with enhanced calorific value per unit volume, attributed to the denser packing of biomass material within the briquette structure. Elevated density confers improved mechanical resilience and durability to briquettes, rendering them more resilient against stresses incurred during handling and transportation. Additionally, higher density mitigates issues such as dusting and crumbling during storage and handling operations.

Briquettes characterized by moderate to high density are inherently more manageable in terms of handling, transportation, and storage compared to their low-density counterparts. Their reduced volume occupancy translates to lower logistical costs and diminished risks of breakage and degradation during transit, thus optimizing operational efficiency and efficacy.

Design density=1200Kg/m^3

$$Density = \frac{Mass}{Volume} \tag{16}$$

Determining the available space in the stove

The average height of the stove is 70mm.

The average diameter of the stove is 174mm.

A 10mm gap would be left above the briquettes to allow for airflow and easy combustion between the briquettes and the cooking pot, thus the available height is 60mm.

$$Available \text{ Area in } the\ stove = \pi \times \left(\frac{150}{2}\right)^2$$
$$= 17{,}662.5mm^2 \tag{17}$$

Determining the optimum diameter of the briquettes

When determining the dimensions of the briquette, it's crucial to ensure that the number of briquettes fitting into the stove is a whole number, thus avoiding the need to break them when inserting into the stove.

With the stove's usable height predetermined, this height becomes that of the briquette, leaving the diameter as the unknown factor.

To address this, an initial outer diameter of 5mm for the desired briquette was randomly selected. Subsequently, the volume of a briquette with a 5mm diameter and 60mm height was calculated, as detailed below:

$$Area\ of\ the\ briquette = \pi \times \left(\frac{5}{2}\right)^2 = 19.625mm^2 \tag{18}$$

Determining number of briquettes that fit in the stove

$$\text{Area } of\ Stove \Big/ \text{Area } of\ Briquette = \frac{17{,}662.5}{19.625}\ x\ 0.655$$

$$= \underline{\underline{589.5\ briquettes}} \tag{19}$$

The above procedure was repeated for various diameters at intervals of 5mm, as presented in the table below:

Table 8: Determining the optimum dimensions of the briquettes

Diameter of Briquette (mm)	Height (mm)	Areas (mm^2)	Number of Briquettes
5	55	19.625	589.5
10	55	78.5	147.4
15	55	176.625	65.5
20	55	314	36.8
25	55	490.625	23.6
30	55	706.5	16.4
35	**55**	**961.625**	**12.0**
40	55	1256	9.2
45	55	1589.63	7.3

Diameter of Briquette (mm)	Height (mm)	Areas (mm^2)	Number of Briquettes
50	55	1962.5	5.9
55	55	2374.63	4.9
60	55	2826	4.1
65	55	3316.63	3.5
70	55	3846.5	3.0
75	55	4415.63	2.6
80	55	5024	2.3
85	55	5671.63	2.0
90	55	6358.5	1.8
95	55	7084.63	1.6
100	55	7850	1.5

The optimum design selected was 35mm outer diameter and 60mm height.

$$Mass\ of\ each\ Briquettes = Density \times Volume \tag{20}$$

$$Mass\ of\ each\ briquettes = 12000000 \times \frac{0.00005181}{9.81} \tag{21}$$

Design mass of each briquette =63g/Briquette.

Fabricating the briquettes

Apparatus

Hydrochar

Cassava Starch

Briquetting machine

Air dryer

Sand

Weighing scale

Procedure

The hydrochar to be used to make briquettes was first sieved to ensure that there were no big particles.

The sieved hydrochar was then weighed to obtain 1kg of the hydrochar which was then transferred into a basin in which the other ingredients would be added.

56g of cassava starch were weighed representing 5% of the binder required as per the mix design.

56g of sand were weighed representing 5% of the filler required as per the mix design.

The cassava starch was then mixed with cold water to form a paste, then hot water was added and then brought to a boil to activate the starch's gluey nature.

The sand was then added into the basin with the hydrochar and then uniformly mixed.

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

The mixture was then transferred into a mould of 35mm outside diameter, 5mm inner diameter and 55mm length.

It was then compacted with the briquetting machine lid to densify the briquettes and then the excess material was removed using a trowel.

The densified briquettes were then extruded and then placed in an air drier to reduce their moisture content.

Figure 7: Sample preparation and Compaction

3.5 Determining the characteristics of the briquettes formed using the hydrochar.

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

3.5.1 Water boiling test (WBTP 4.2.3)

The water boiling test was employed to assess the emission levels and energy output of the briquettes. This test adhered to the water boiling test protocol version 4.2.3. Throughout the test, the following parameters were recorded: the duration required for water to reach boiling point, the mass of the briquette fuel utilized, and the mass of water contained in the pan.

Apparatus

Stove

Saucepan with 5-litre Capacity

Water at room temperature

Thermometer

Weighing scale sensible to 0.0001g

Preparation

Preparing saucepans for the cold start test.

The dry weight of each saucepan was m measured and recorded (g)

Each saucepan was filled with 2.5 kg of clean room-temperature water.

The same amount of water for each phase and each test was used.

The ambient conditions such as air temperature, and wind conditions were recorded.

The background concentrations for CO_2, CO, and particulate matter concentrations were measured and recorded.

Procedure

Phase 1: High power, cold start phase

The briquettes to be used for each test were weighed and their weight was recorded (g)

The saucepan was placed on the stove.

A thermometer was placed into the saucepan so that the temperature of the water was measured in the centre, 5cm from the bottom of the saucepan then recorded the initial water temperature.

The briquettes were ignited using kerosene as the starter of 5% of the weight of the briquettes used as per the WBT 4.2.3 protocol guidelines.

Once the fire caught, the timer was started and record the starting time.

The open saucepan was quickly placed onto the stove and the water without being excessively wasteful of the pre-weighed bundle.

When the water in the saucepan reaches the boiling temperature, the time at which the water in the saucepan took to boil was recorded.

The temperature of the water was also measured and recorded.

The remaining unburnt briquettes were extracted from the stove and extinguished by placing them in sand then the weight was recorded.

The mass of the saucepan with its water was measured and recorded.

The hot water was discarded.

Figure 8: Cold start when carrying out water boiling

Figure 9: Flue gas emission test and measuring the change in water temperature.

Phase 2: High power, hot start

The timer was reset but not started yet.

The saucepan was refilled with 5kg of fresh ambient water and the weight of the saucepan with water was measured and recorded.

The initial water temperature was recorded.

The weight of the second bundle of briquettes was weighed recorded and then placed into the stove.

The briquettes were ignited using kerosene as the starter of 5% of the weight of the briquettes used as per the WBT 4.2.3 protocol guidelines.

Once the fire caught, the timer was started and recorded with the starting time.

The open saucepan was quickly placed onto the stove and the water without being excessively wasteful of the pre-weighed bundle.

When the water in the saucepan reaches the boiling temperature, the time at which the water in the saucepan took to boil was recorded.

The temperature of the water was also measured and recorded.

The mass of the saucepan with its water was measured and recorded.

3.5.2 Determining the shatter resistance of the briquettes

This is the test done to measure the shatter resistance of the briquette and may be used to simulate the forces involved in shifting from one location to another or emptying briquettes from trucks onto the ground. Additionally, this particular experiment testing could be used to determine the safe height of briquette loading (Law, Gan and Gan, 2018).

Apparatus

Weighing Scale

Tape Measure

Procedure

The initial weight of a briquette that was to be measured and its weight recorded.

The briquette was raised to a height of 2m and then left to free fall onto concrete.

The remaining biggest particle of the briquette was obtained and its final weight was measured and recorded.

The weight loss was calculated from the following;

$$Weight\ loss(\%) = \frac{W_{Initial} - W_{Final}}{W_{Initial}} \times 100 \tag{22}$$

The shatter resistance was calculated from the following;

$$Shatter\ resistance(\%) = 100\% - weight\ loss\ (\%) \tag{23}$$

Figure 10: Shutter Resistance test

3.5.3 Determining the water resistance of the briquettes

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

Apparatus

Weighing Scale

Beaker

Water

timer

Procedure

The initial weight of a briquette was to be measured and its weight was recorded.

A beaker filled with water was placed on a levelled surface

The briquette was then lowered into the beaker and a timer started

The briquette was then left in the water bath for 30 Seconds and then removed

The excess water on the surface of the briquette and then its final weight was measured and recorded.

The weight gain of the briquette was calculated from;

$$Weight\ gain(\%) = \frac{W_{Final} - W_{Initial}}{W_{Final}} \times 100 \tag{24}$$

The water resistance was calculated from the following;

$$Water\ resistance(\%) = 100\% - weight\ gain(\%) \tag{25}$$

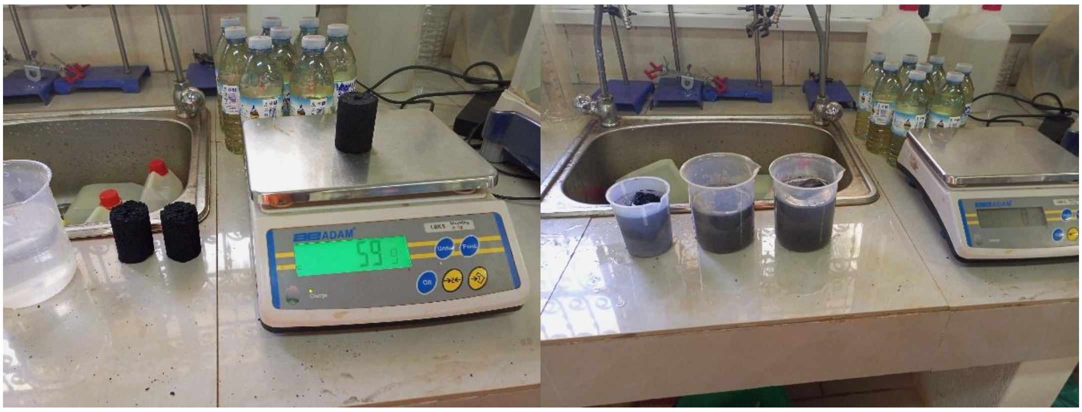


Figure 11: Water resistance test.

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

3.6.1 Cost of Production

Determining the cost of production of a product was crucial as it directly impacts profitability, pricing strategies, and resource allocation. Ultimately, a thorough understanding of production costs is essential for making informed decisions and ensuring the overall financial health and success of the business.

The cost of production for four distinct types of briquettes were analysed including raw materials, energy consumption and labour. Through comparative examination, the total production costs across the four briquette types were evaluated to discern cost-effectiveness and potential market competitiveness. The following table below presents a breakdown of production costs for each briquette type.

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

parameter	Formula	Result
Specific heat Capacity of water		4182J/Kg/ºC
specific heat capacity of wastewater sludge		4180J/Kg/ ºC
Price of Electricity in Uganda for Commercial Consumers		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 ºC to 210 ºC	$Q_1 = mc\Delta T$	$Q_1 = 64 \times 4182 \times (230 - 25)$ $Q_1 = 54.9MJ$
The heat required to raise 64kg of sludge from 25 ºC to 210 ºC	$Q_2 = mc\Delta T$	$Q_2 = 64 \times 4180 \times (230 - 25)$ $Q_2 = 54.8MJ$
Total Heat Required	$Q = Q_1 + Q_2$	$Q = 54.9 + 54.8$

parameter	Formula	Result
		$Q = 109.7MJ$
Energy used	$1MJ = 0.27778KWh$	$= 30.472KWh$
Cost of converting 64Kg of Sludge to Hydrochar	$1KWh = 600.2\ Ushs$	30.472×600.2 = 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 10: Cost of Production of the Various 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
Total Cost of Materials	**488.0/= per Kg**	**394.4/= per Kg**	**338.4/= per Kg**	**350/= per Kg**

3.6.2 AHP Analysis

The Analytic Hierarchy Process (AHP) serves as a versatile decision-making tool, enabling decision-makers to systematically prioritize alternatives or options across multiple criteria or factors. Its primary uses include aiding decision-making by evaluating and selecting the most suitable option, facilitating effective resource allocation by considering various objectives, assisting in problem-solving by breaking down complex issues into manageable components, supporting risk assessment and management, guiding project planning and management processes and optimizing product or service development by prioritizing design features and criteria. AHP provides a structured framework for decision-making across diverse domains, enhancing decision quality and supporting informed strategic choices.

In selecting the desired type of briquette, the Analytic Hierarchy Process (AHP) analysis was employed to systematically evaluate and prioritize various criteria essential to our decision-making process. It provided a structured framework for considering factors such as heating efficiency, cost-effectiveness and environmental impact by breaking down the decision into hierarchical levels and pairwise comparisons.

Table 11: Parameters to be analysed

Criteria	**Price (Ug Shs)**	**CO_2 Emission (%)**	**CO Emission (ppm)**	**Water Resistance (%)**	**Shutter Resistance (%)**	**Boiling Time (Minutes)**
15% Starch	488	0.36	194.5	55.6	94.4	19.0
5% Starch	394.4	0.35	278.8	44.0	67.0	17.5
40% Clay	338.4	0.43	229.0	0	61.1	22.5
Market	350	0.83	161.8	76.8	29.0	20.0

Table 12: Scale of relative importance

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

Table 13: Pair-wise comparison matrix

		4	7	9	3	6	5
		Price	**CO_2 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_2 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 14: Normalized Pair-wise matrix

	Price	CO_2 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_2 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 15: calculating the consistency of the analysis.

Criteria Weights	0.1176	0.2059	0.2647	0.0882	0.1765	0.1471		
	Price	**CO_2 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

Criteria Weights	0.1176	0.2059	0.2647	0.0882	0.1765	0.1471		
CO_2 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

$$\lambda_{max} = \frac{6+6+6+6+6+6}{6} = 6 \tag{26}$$

$$Consistency\ Index\ (CI) = \frac{\lambda_{max} - n}{n-1} = \frac{6-6}{6-1} = 0 \tag{27}$$

$$Consistency\ Ratio = \frac{Consistency\ Index}{Random\ Index} = \frac{0}{1.24} = 0 \tag{28}$$

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.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents results from the tests carried out in this study. The data is analysed and discussed from the results of the tests carried out to determine the properties of wastewater sludge, this was achieved by carrying out moisture content test, volatile matter test, ash content test and fixed carbon. To determine the optimum thermal conditions to be used to maximize Hydrochar yield and briquette formation, regression analysis using the box Behnken design methodology was employed to determine the corelation between the various parameters. To determine the characteristics of the briquettes formed using the hydrochar, water boiling test, shatter resistance, water resistance and flue gas emission tests were carried out. And to determine the cost benefit analysis, the cost of production for various briquettes types was calculated and AHP Analysis was employed to systematically prioritize alternatives or options across various criteria.

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

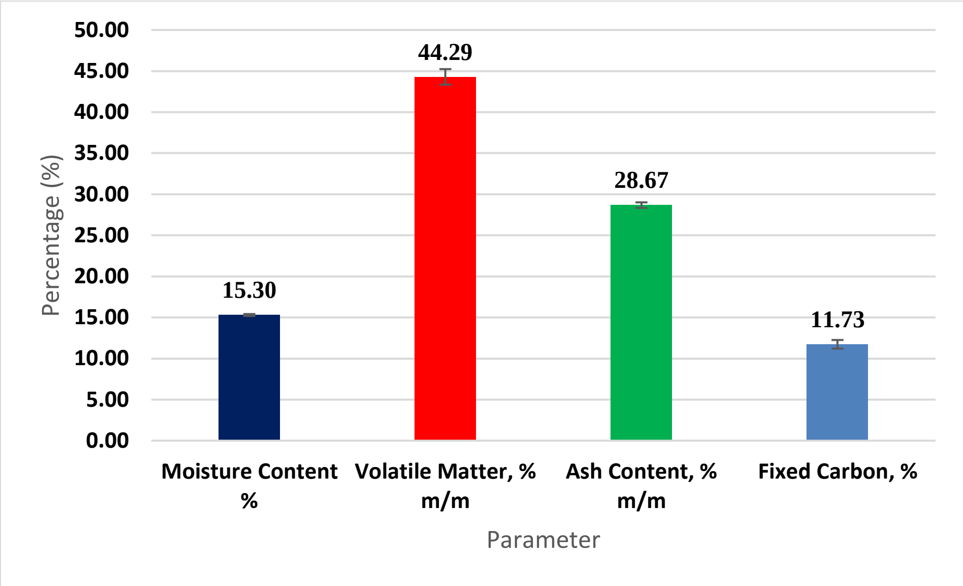


Figure 12: Summary of proximate analysis results of the Sludge at the UCU WWTP.

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

Moisture Content:

The sludge sample after 12 days of sun drying still had an average moisture content of 15.30% which would still be high for conventional carbonization processes such as pyrolysis which requires a moisture content not greater than 10% but with the hydrothermal Carbonization process, high level of moisture is not an issue since with it, the higher the moisture, the better the carbonization of the feedstock.

Volatile Matter:

Volatile matter is the gaseous phase formed from the thermal degradation of the material i.e. turned into gas. Good quality char for domestic use should have volatile matter in the range of 20 – 30% with a maximum value of 40% being marginally accepted. High-volatile charcoal is easy to ignite but may burn with a smoke flame. Low-volatile charcoal is difficult to light and burns very cleanly. The samples have an average of 44.29% which is above the acceptable highest which means if used as is would not easily combust but would not burn as clean.

Ash Content:

High ash content significantly reduces the heating value and combustion efficiency of a feedstock, according to literature, proximate analysis carried out on wastewater sludge samples indicates an average ash content of 26% which is close to the 28.67% which is still very high and if used without processing would greatly reduce the heating value and produce a high amount of residue from the briquettes formed.

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.

4.3 Determining the optimum thermal conditions to be used to maximize Hydrochar yield and briquette formation

Using the Box Behnken design, a response surface was formed to understand how the Hydrothermal Carbonization yield changes with changes in temperature, water content and reaction time.

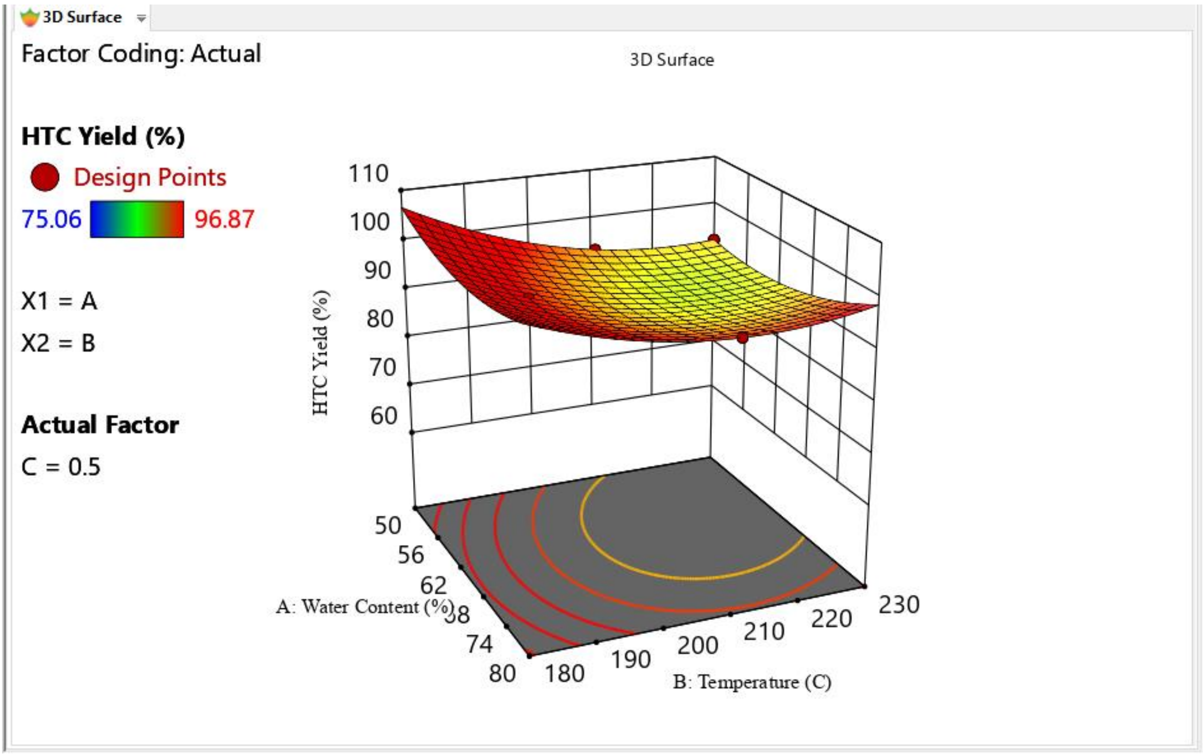


Figure 13: HTC Yield After 30 minutes Reaction time (Source: Owino,2024).

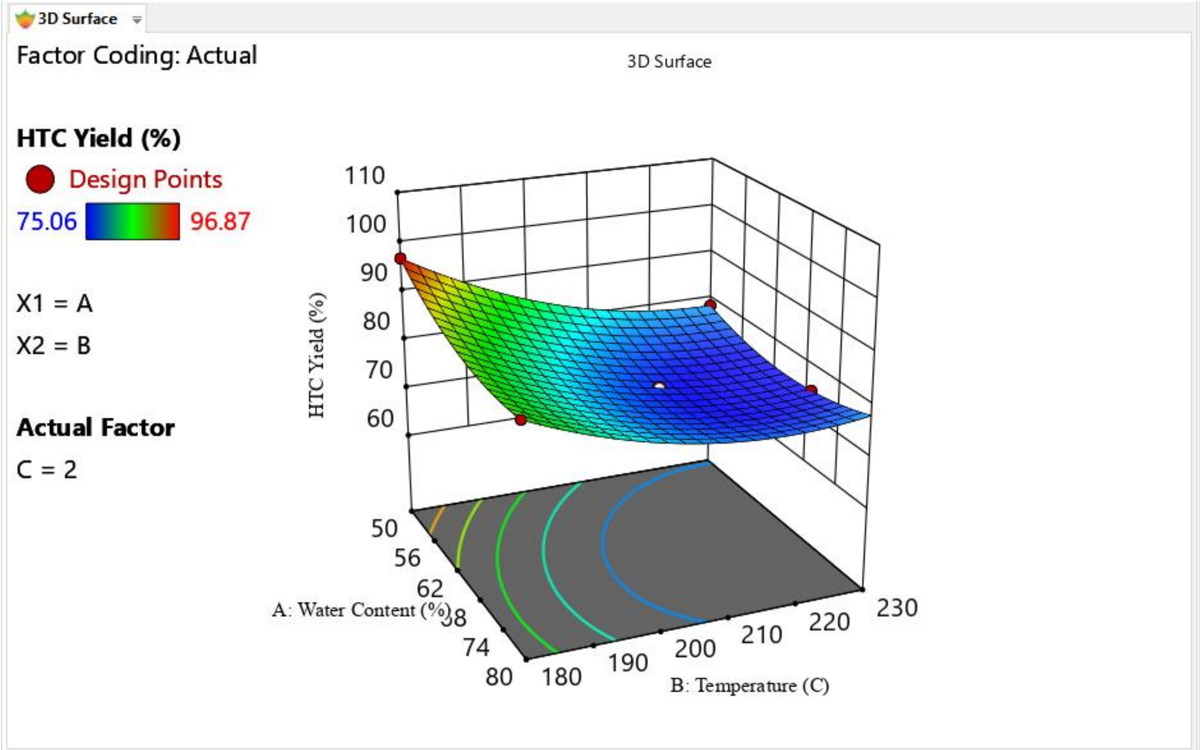


Figure 14: HTC Yield After 2 hours Reaction time (Source: Owino,2024)

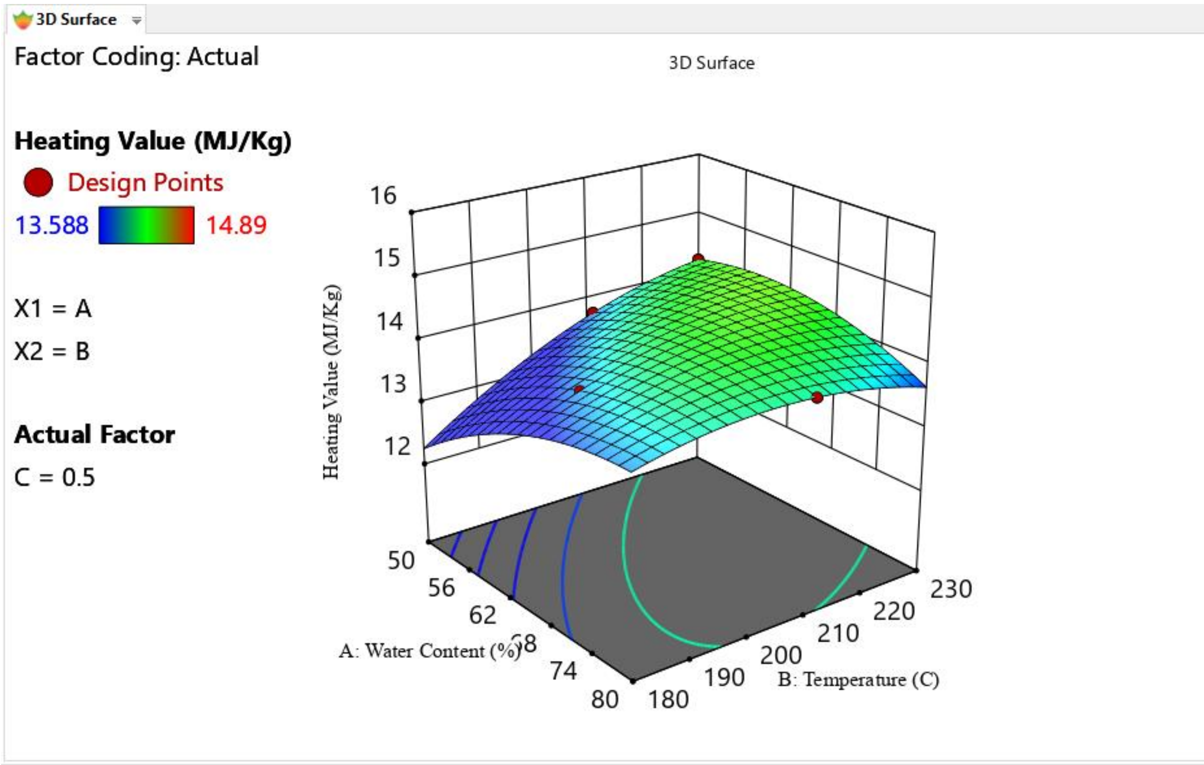


Figure 15: Heating Value after 30 minutes Reaction time (Source: Owino,2024).

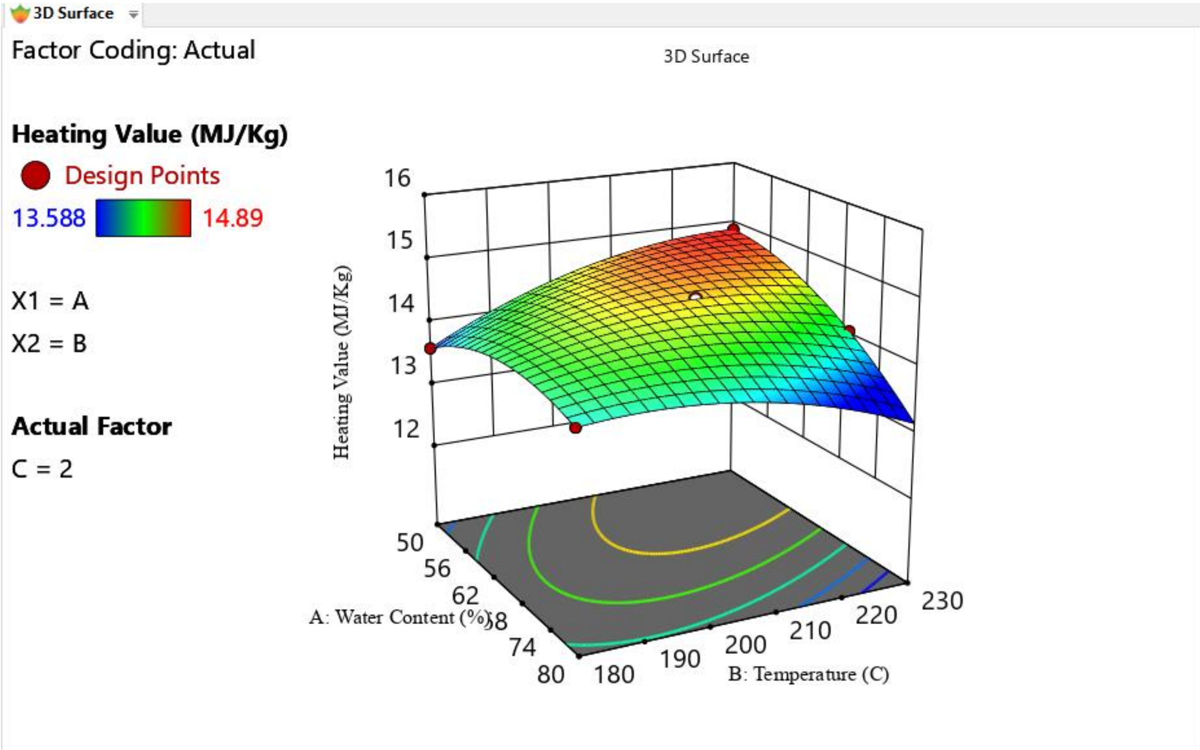


Figure 16: Heating Value after 2 hours Reaction time (Source: Owino,2024).

Factor Coding: Actual

HTC Yield (%)

Actual Factors
A = 65
B = 200.5
C = 2

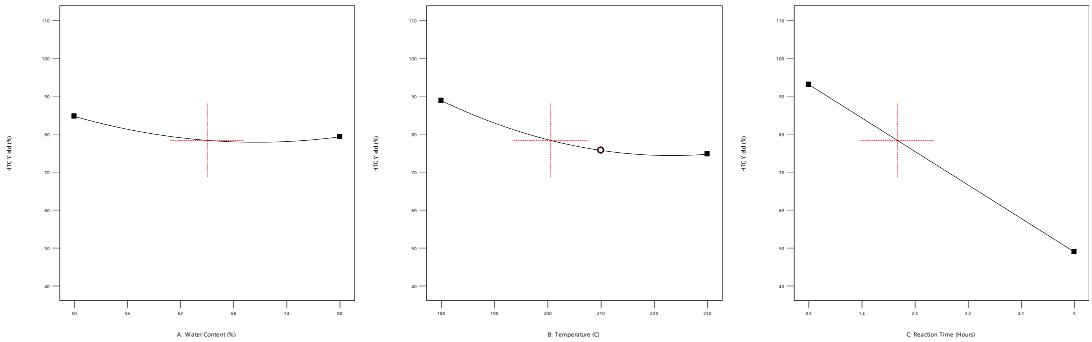


Figure 17: Effect of process parameters on the HTC yield.

Factor Coding: Actual

Heating Value (MJ/Kg)

Actual Factors
A = 65
B = 205.5
C = 2

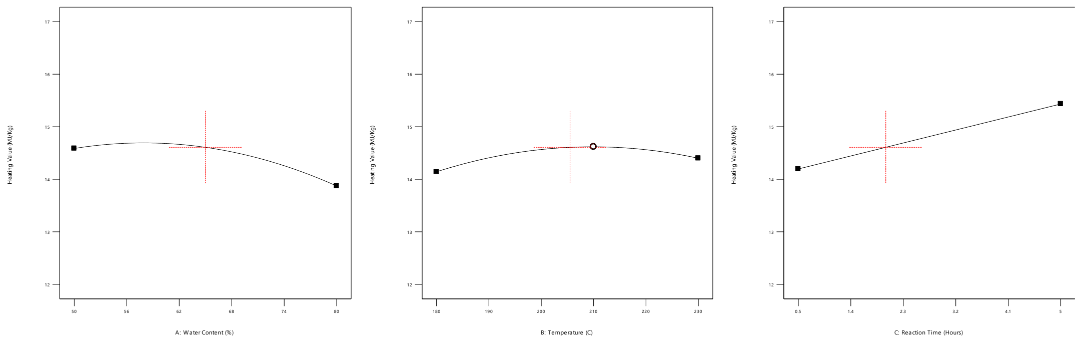


Figure 18: Effect of process parameters on the heating value.

Concerning hydrochar yield, Figure 4 shows that HTC fed with higher moisture contents of wastewater sludge generated lower hydrochar yields because the high amount of water increased the solubility of the wastewater sludge and readily hydrolysed samples. A reduction in the mass of the feedstock during the process is indeed a positive indicator. This reduction signifies the conversion of the organic material into hydrochar or solid carbonaceous material, which is the desired outcome of the HTC process due to the decomposition and carbonization of the feedstock resulting in the formation of hydrochar, the hydrochar yields of 65-80% were found comparable with those of the other studies (Li *et al.*, 2013).

Effect of temperature and reaction time

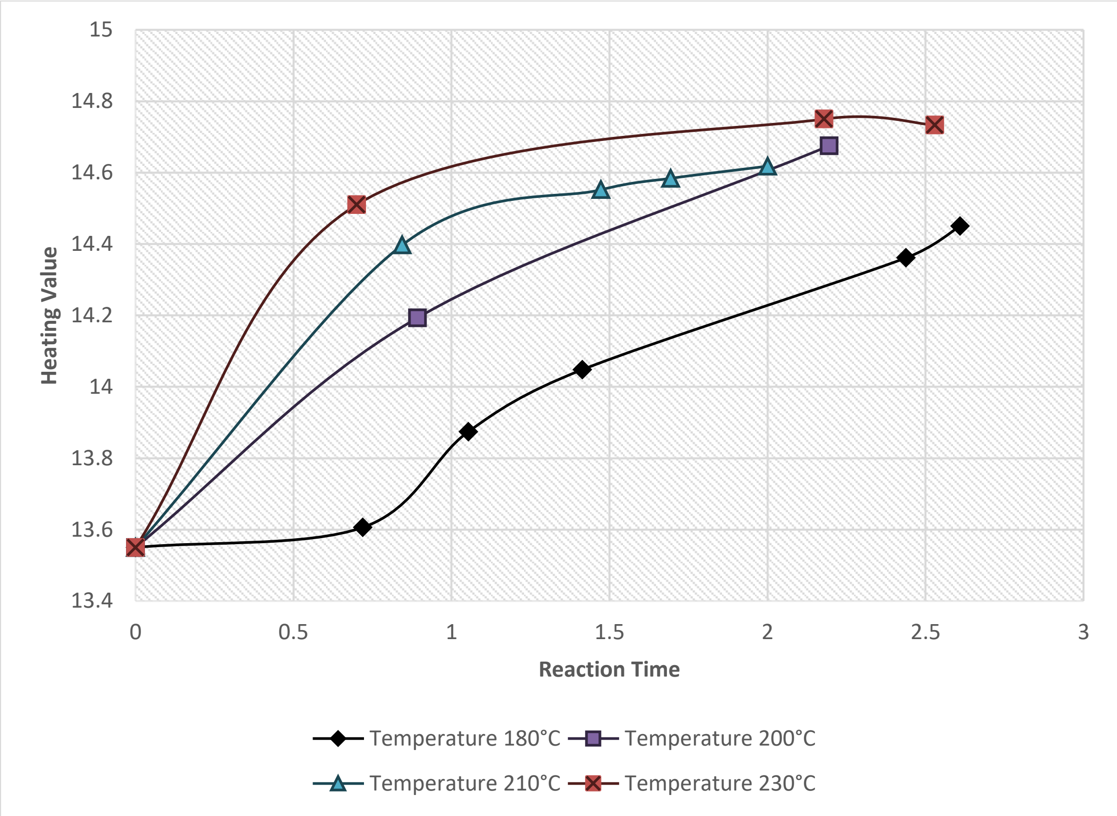


Figure 19: A graph showing the relationship between Calorific Value and Reaction time at Various Temperatures.

The highest energy content of 14.8 MJ/kg could be achieved at the temperature of 230 °C and reaction time of 2.25 h, while the lowest energy content of hydrochar was found at the temperature and reaction time of 180 °C and 0.5 h

These energy contents were comparable with the results of (Wang *et al.*, 2012; Moon *et al.*, 2015; Wen *et al.*, 2023) found hydrochar produced from sewage sludge with energy contents ranging between 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 hydrolysed products (Kambo and Dutta, 2015).

According to (Titirici, 2013), the typical operating temperatures of HTC are in the range of 130- 250 °C. At higher temperatures up to 350 °C, hydrothermal liquefaction could take place (Kruse, Funke and Titirici, 2013) resulting in the generation of more liquid and gas by-products and consequently, less hydrochar yield.

The HTC yield from the wastewater sludge rapidly decreased from 96.8-93.4% and from 96.7-75.7% for reaction times 30 minutes and 2 hours respectively at 65% water content with an increase from 180°C-210°C and then further gradually decreased to 92.3 and 75.1% respectively with an increase from 210°C-230°C, this is mainly because the key stages of the hydrothermal Carbonization for various polymers present in sludge occurs at relatively low temperatures. According to (Bobleter, 1994), hemicellulose is almost completely hydrolysed at the temperature of 180-200°C, lignin 180-220°C, and cellulose approximately greater than 220 °C. Dehydration and polymerization require temperatures greater than 160 °C, and solid-solid conversion requires relatively high temperatures in the range of 200-280 °C (Falco, Baccile and Titirici, 2011).

From the results obtained, the hydrolysis, dehydration, polymerization, and solid-solid conversion processes took place between 180°C -230°C

Effect of Moisture content on the hydrochar.

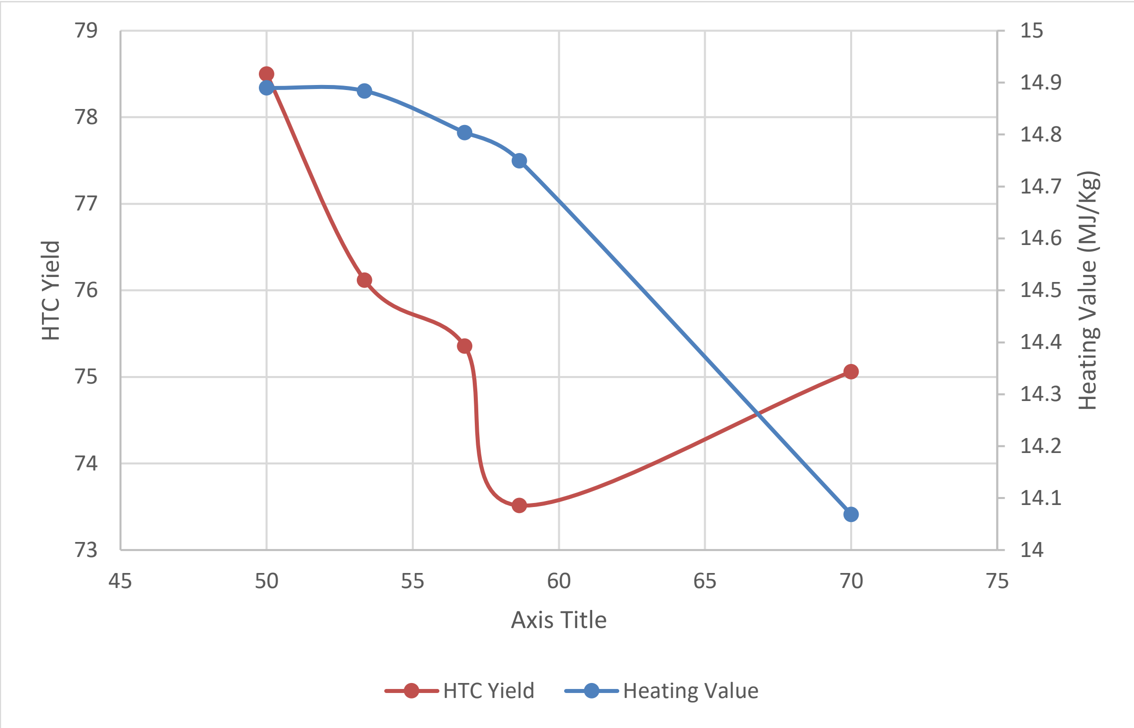


Figure 20: A graph showing the effect of moisture content on HTC Yield and Calorific Value at a temperature of 230°C and reaction time of 2 Hours.

The observed trend in the graph depicting HTC conducted at 230°C for 2 hours reveals a notable relationship between moisture content and the calorific value of the hydrochar produced. Initially, at 50% moisture content, the calorific value peaks at 14.89 MJ/kg, indicative of optimal conditions for efficient carbonization. This can be attributed to the facilitative role of moisture in enhancing reaction kinetics and promoting hydrolysis and dehydration reactions, leading to the production of hydrochar with desirable properties. However, as moisture content increases beyond 50%, there is a gradual reduction in calorific value. This decline can be attributed to the diminishing efficiency of the carbonization process, as excess moisture hinders reaction rates and necessitates higher energy input for evaporation, ultimately resulting in lower-quality hydrochar with reduced energy density.

4.4 Determining the characteristics of the briquettes formed using the hydrochar.

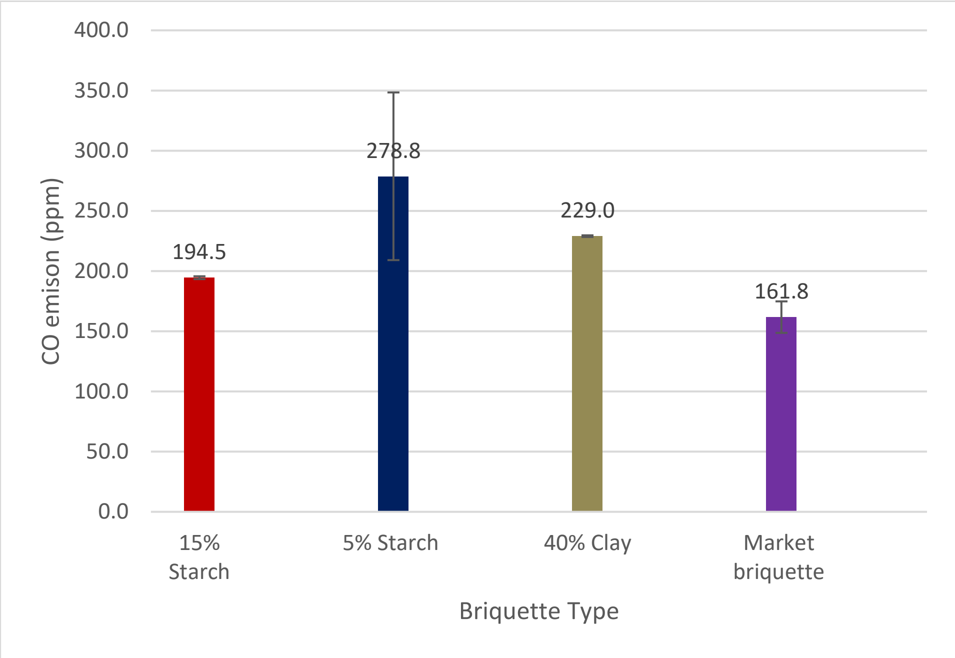


Figure 21: CO Emission.

The CO emissions of the 15% starch was 20.24% higher than the market briquette, the one with 5% starch was 72.33% higher than the market briquette while the one made with 40% clay was 41.57% higher than the market briquettes. This is because the hydrochar used to make the briquettes had a high volatile matter content that couldn't be combusted by the stove being used for testing. However, the ones made with 15% starch had a lower emission because starch being a natural binder, it facilitated better cohesion of the hydrochar particles leading to a more uniform combustion and distribution of heat within the briquette thus reducing the formation of Carbon monoxide.

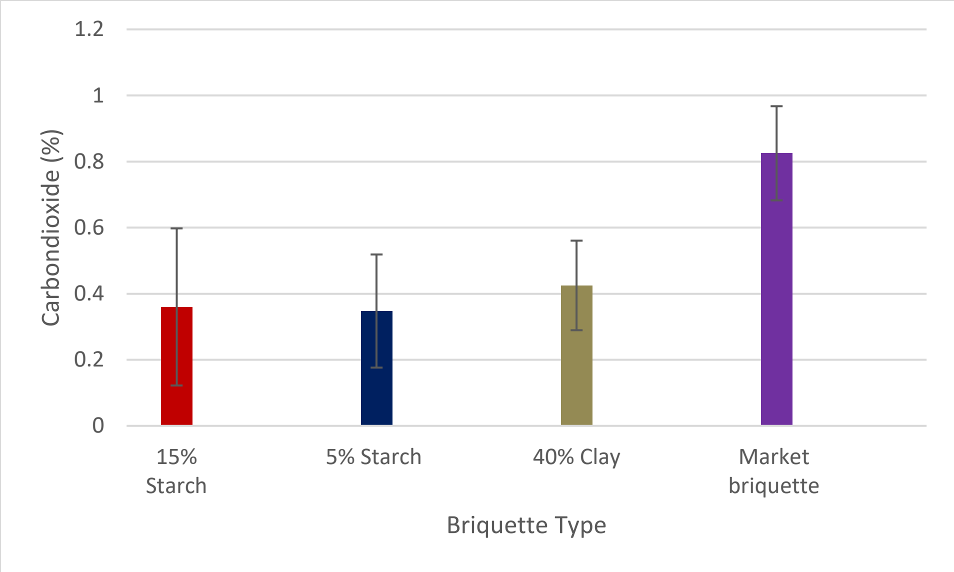


Figure 22: CO2 Emission.

The carbon dioxide emissions from the hydro char briquettes show minimal variations among different compositions tested. both the 15% and 5% Starch Briquettes exhibited similar CO_2 emissions with only a 2.8% variation suggesting that starch content doesn’t significantly impact Carbon dioxide emissions. However, the 40% Clay briquettes showed a higher Carbon dioxide emission by 15.29% that of the 15% starch indicating that clay influences combustion efficiency and contributes to additional combustion byproducts. The market briquettes exhibited a 56.36% higher Carbon monoxide emission compared to the experimental ones made using hydrochar suggesting a difference in composition characteristics.

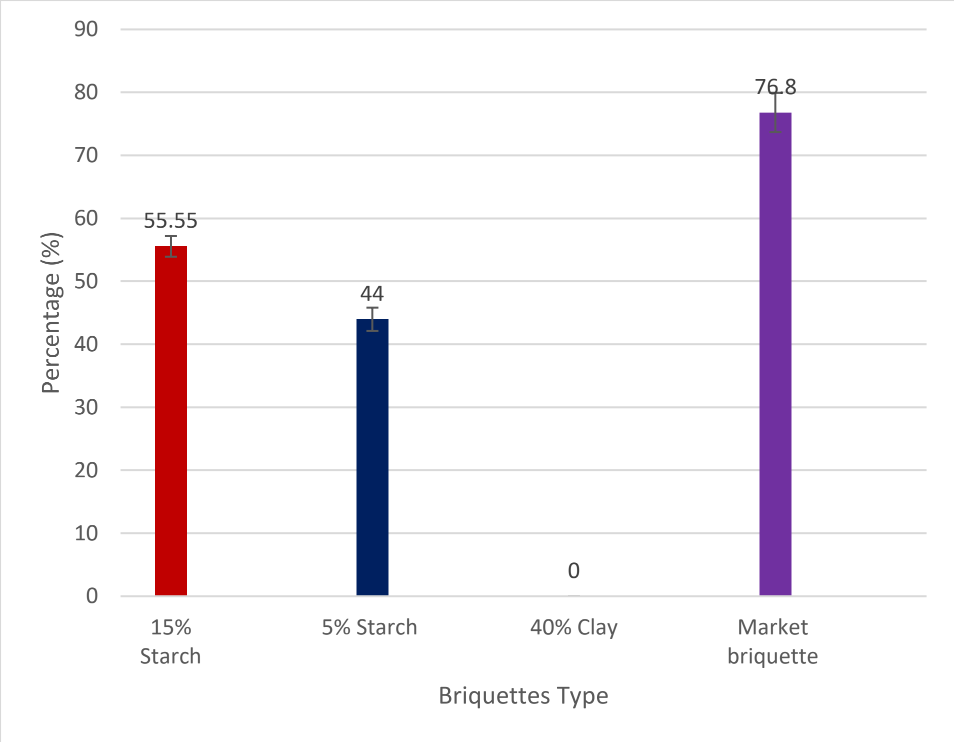


Figure 23: Water Resistance.

The water resistance test results reveal that the composition of the briquettes significantly affects their ability to withstand water exposure. The briquettes with 15% starch exhibited the highest water resistance due to the cohesive properties of starch as a binder facilitating strong particle adhesion, those with 5% starch showed a 20.79% reduction in the water resistance while the absence of water resistance in the 40% clay suggests that a high clay content may compromise cohesion. In contrast, market briquettes demonstrated superior water resistance of 27.67% higher than the 15% starch likely due to the optimized binder selection and manufacturing process. Overall, the findings highlight the importance of binder selection and composition optimization in enhancing the water resistance of briquettes.

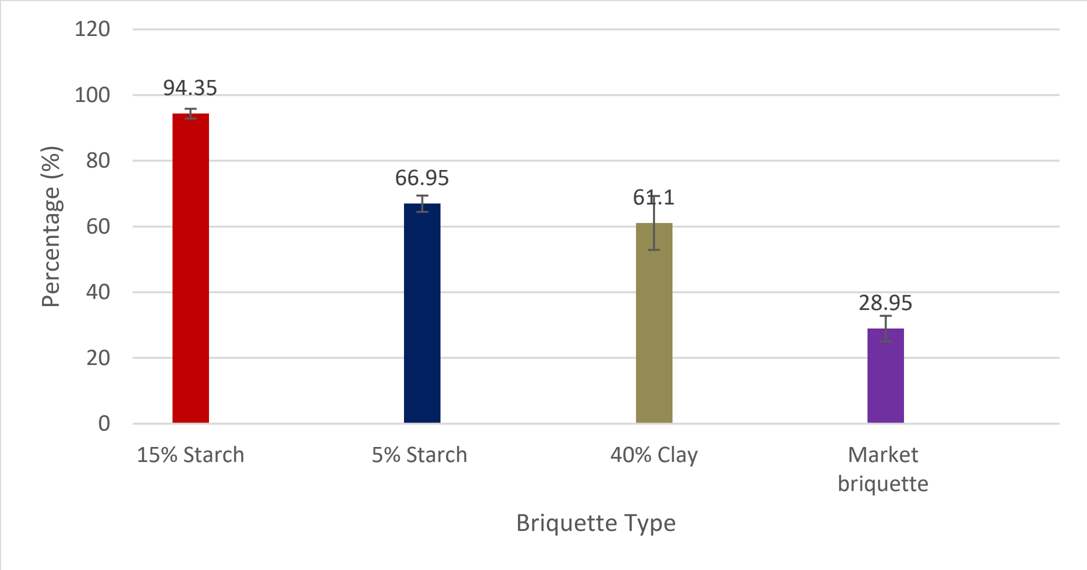


Figure 24: Shatter Resistance.

The shatter resistance test results indicate the ability of briquettes to withstand mechanical stress without breaking apart. Briquettes containing 15% starch exhibited the highest shatter resistance likely due to the cohesion properties of starch as a binder, providing strong interparticle adhesion. Those with 5% starch also showed relatively good shatter resistance though 29.04% lower than the 15% starch briquettes. However, the 40% and the market briquettes demonstrated lower shatter resistance suggesting that an excessive clay content may compromise the structural integrity. The results highlight the importance of binder composition and optimization in enhancing the shatter resistance of briquettes.

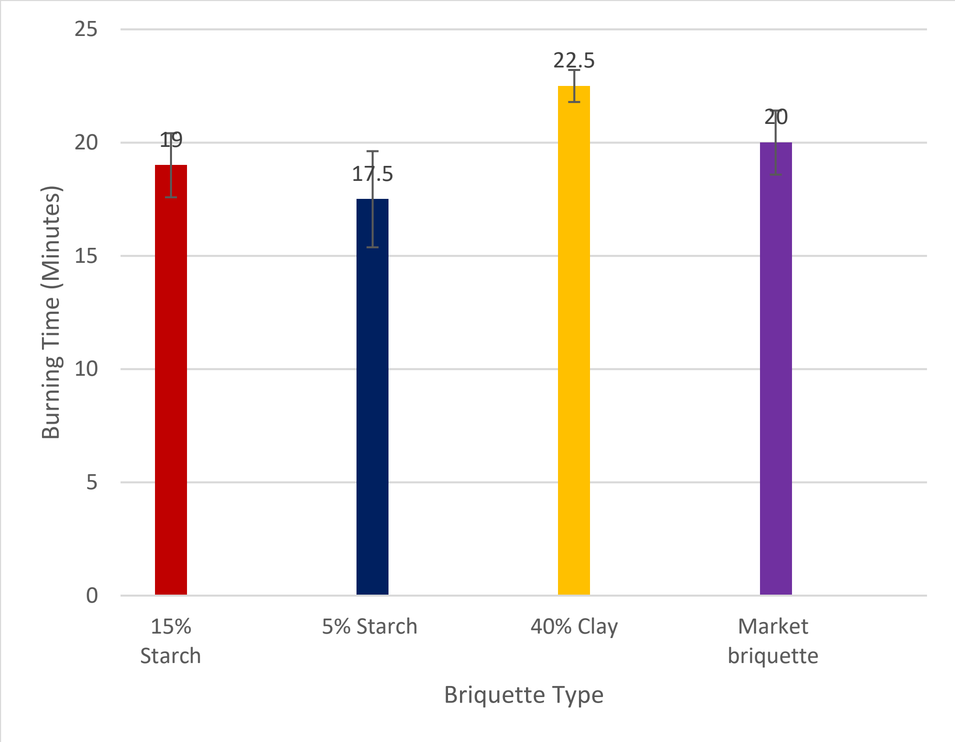


Figure 25: Time to boil 2.5 Litres of water.

The graph above, it observed that the briquettes made with starch exhibited a lower boiling time as compared to those made with clay and the market briquette, this is because the briquettes made with starch had at least 40% more char than those made with clay and the market ones but too much of it lowers the combustion rates due to incomplete burning and increased ash content. The clay in the briquettes serves as a structural component influencing their density and porosity. The briquettes with 40% Clay exhibited a longer boiling time due to their denser composition which requires more energy to reach the boiling point of water. The combustion efficiency of briquettes is influenced by their composition, particularly the ratio of combustible materials to inert components like clay. The briquettes with 5% starch content exhibited a better combustion efficiency leading to a shorter boiling time compared to the ones made with 15% Starch.

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

4.5.1 Cost of Production

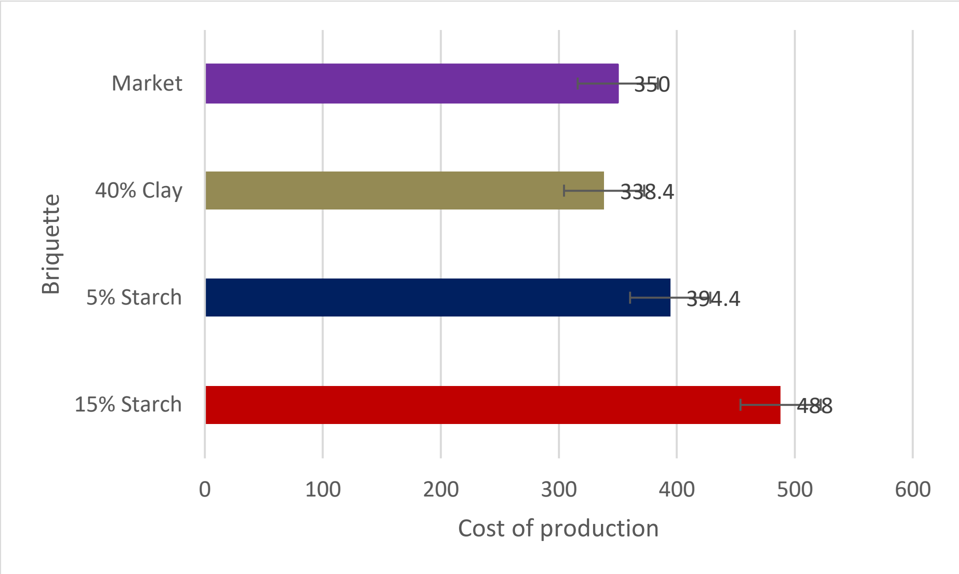


Figure 26: A graph showing the cost of production of the different briquettes.

When comparing production costs, it was found that briquettes containing 15% starch were 28.3% and 30.7% more costly than those available on the market and those composed of 40% clay, primarily due to the higher percentage of char used. Notably, the char composition in the 15% starch briquettes was nearly double that of those made with clay. However, selecting the optimal briquette cannot rely solely on production costs, as higher-priced options demonstrated superior qualities like resistance to shattering and reduced burning time. Hence, an Analytical Hierarchy Process (AHP) analysis was employed to make a more comprehensive evaluation.

4.5.2 AHP Analysis

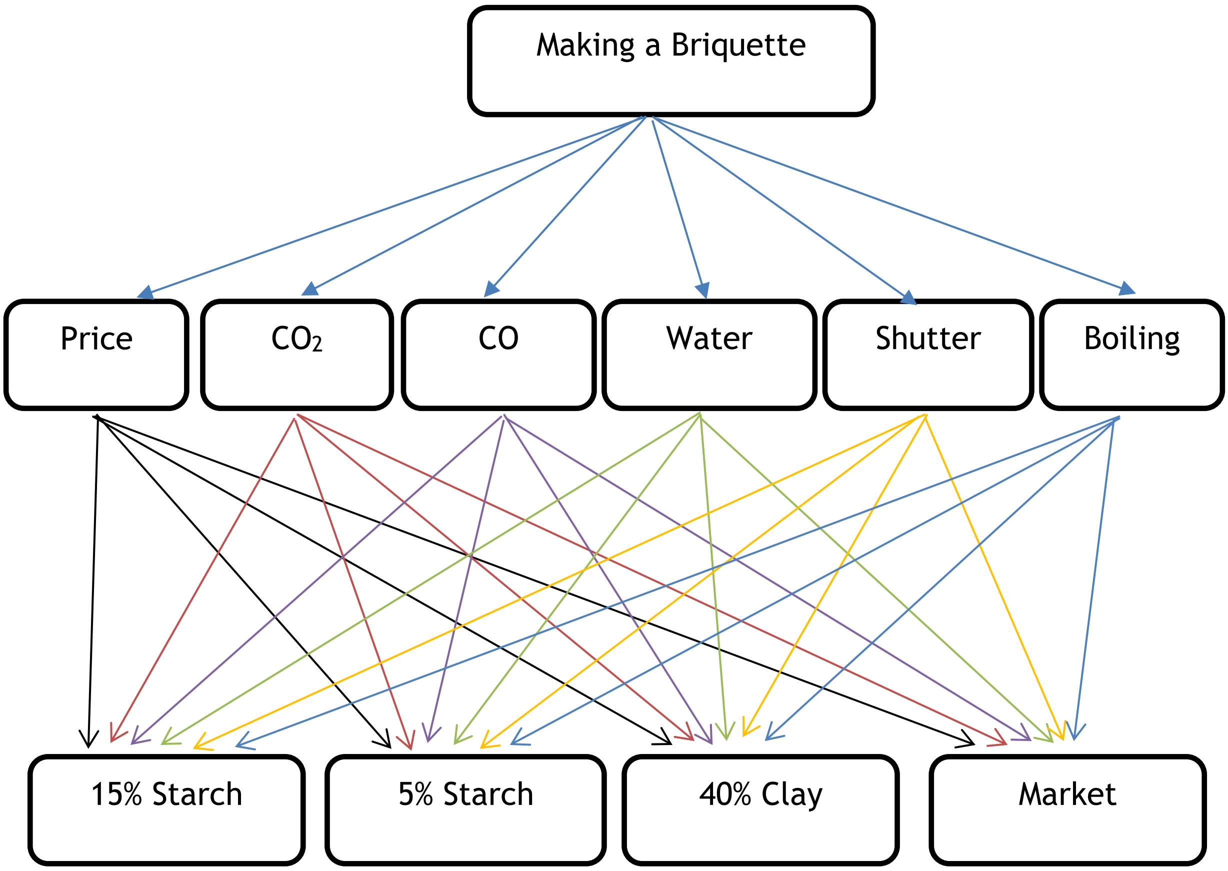


Figure 27: AHP Decision tree

Table 16: Ranking the Briquettes based on their performance

Criteria	**Rank**	**15%**	**Product**	**5%**	**Product**	**40%**	**Product**	**Market**	**Product**
CO emission	**6**	3	18	1	6	2	12	4	24
CO_2 emission	**5**	3	15	4	20	2	10	1	5
Shutter resistance	**4**	4	16	3	12	2	8	1	4
Boiling time	**3**	3	9	4	12	1	3	2	6
Price	**2**	1	2	2	4	3	6	4	8
Water resistance	**1**	3	3	2	2	1	1	4	4
	Total		**63**		**56**		**40**		**51**

The different criteria were assessed by assigning weights and calculating the weighted sum value, as well as determining the product of the rank and performance of each briquette. Subsequently, the cumulative sum was calculated to ascertain the most preferred briquette. Those crafted with 15% Starch demonstrated the highest desirability, achieving a cumulative sum of 63, which surpassed the market briquette by 19% in terms of desirability, owing to its favourable properties.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The proximate analysis results reveal that the sludge sample exhibits characteristics suitable for use as a heating fuel, owing to its high volatile matter content, moderate fixed carbon content, and ash content, which collectively make it a promising heating fuel option.

Through experimentation, it has been demonstrated that wastewater sludge can be effectively converted into hydrochar using HTC processes. The optimal conditions for achieving the highest normalized energy yield were determined to be a moisture content of 50%, a reaction time of 2 hours, and a temperature of 230°C. Under these conditions, the resulting hydrochar exhibited an energy content of 14.89 MJ/kg and a yield of 78.6%.

Briquettes produced from the hydrochar, following an 80:15:5 mix ratio, displayed favourable performance in water boiling tests and exhibited superior resistance to shattering compared to market-available briquettes.

The production of these briquettes proves to be cost-effective, with a production cost of 637.8 Ugandan Shillings per kilogram. With a market selling price of 1000 Ugandan Shillings per kilogram, the profits generated can cover additional expenses, ensuring financial viability.

5.2 Recommendation

Validation of Optimum Process Conditions: Conduct experiments using reactors of varying sizes to confirm the validity of optimal process conditions.

Utilization of Stirred Hydrothermal Reactor: Employ a hydrothermal reactor equipped with a stirrer to address reactor instability, particularly at high moisture content levels.

Implementation of Insulated Reactors: Utilize insulated reactors to minimize heat losses to the environment, thereby enhancing the efficiency of the hydrothermal carbonization process.

High Aspect Ratio Vessel for Scaling Up: When scaling up the project, utilize vessels with a high aspect ratio to prevent reactor instability and ensure even distribution of heat throughout the wastewater sludge.

Waste Heat Recovery Research: Explore methods for waste heat recovery to utilize excess heat generated during the HTC process. This recovered heat can be employed to pre-heat biomass feedstock, thereby reducing the energy required for biomass carbonization.

Investigation into Improving Briquette Water Resistance: Conduct further research to develop techniques aimed at enhancing the water resistance of briquettes, thereby improving their durability and usability in various applications.

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APPENDIX

APPENDIX A: Laboratory Works

Figure 28: Sample Preparation

Figure 29: Reactor Preparation

Figure 30: Rapidly cooling the reactor with water

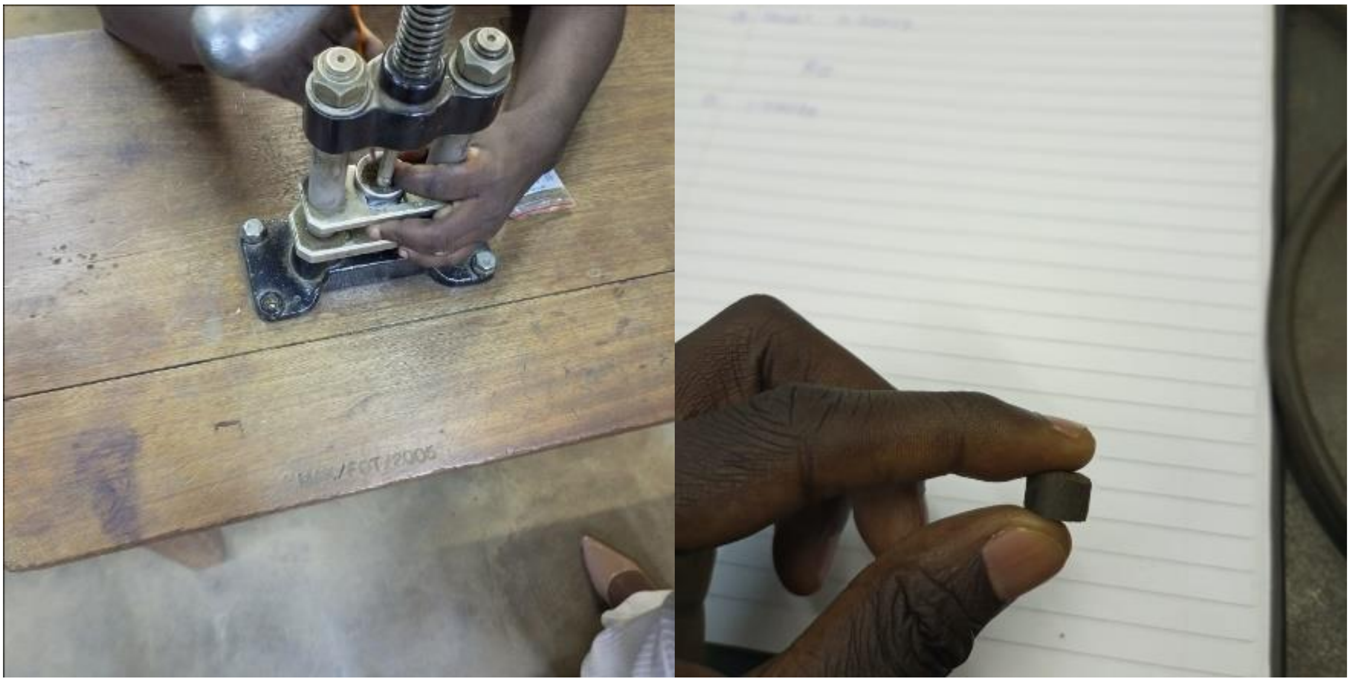

Figure 31: Briquetting the sample before testing.

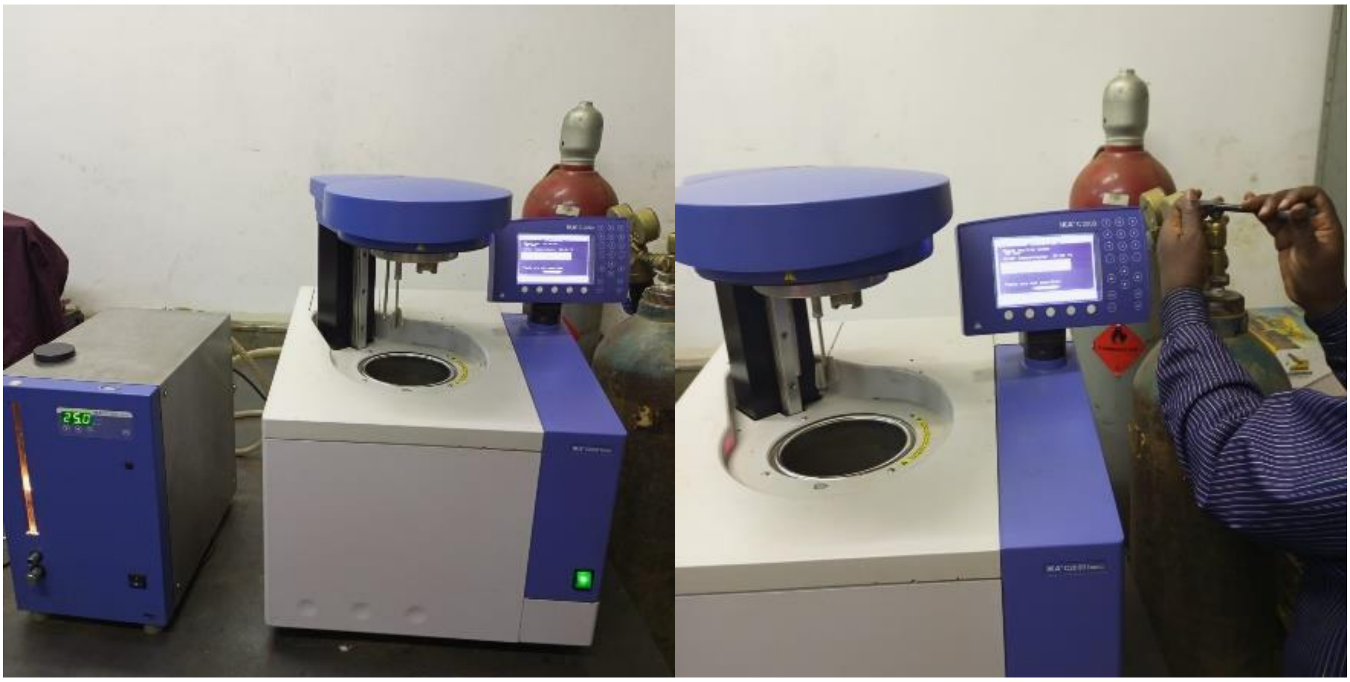

Figure 32: Setting the calorimeter before testing.

Figure 33: Loading the sample into the bomb

Figure 34: Inserting the Bomb into the calorimeter and starting the test.

Figure 35: Results output from the test.

Figure 36: Hydrochar preparation

Figure 37: Mixing the various proportions.

Figure 38: Injecting the mixture into the briquette machine

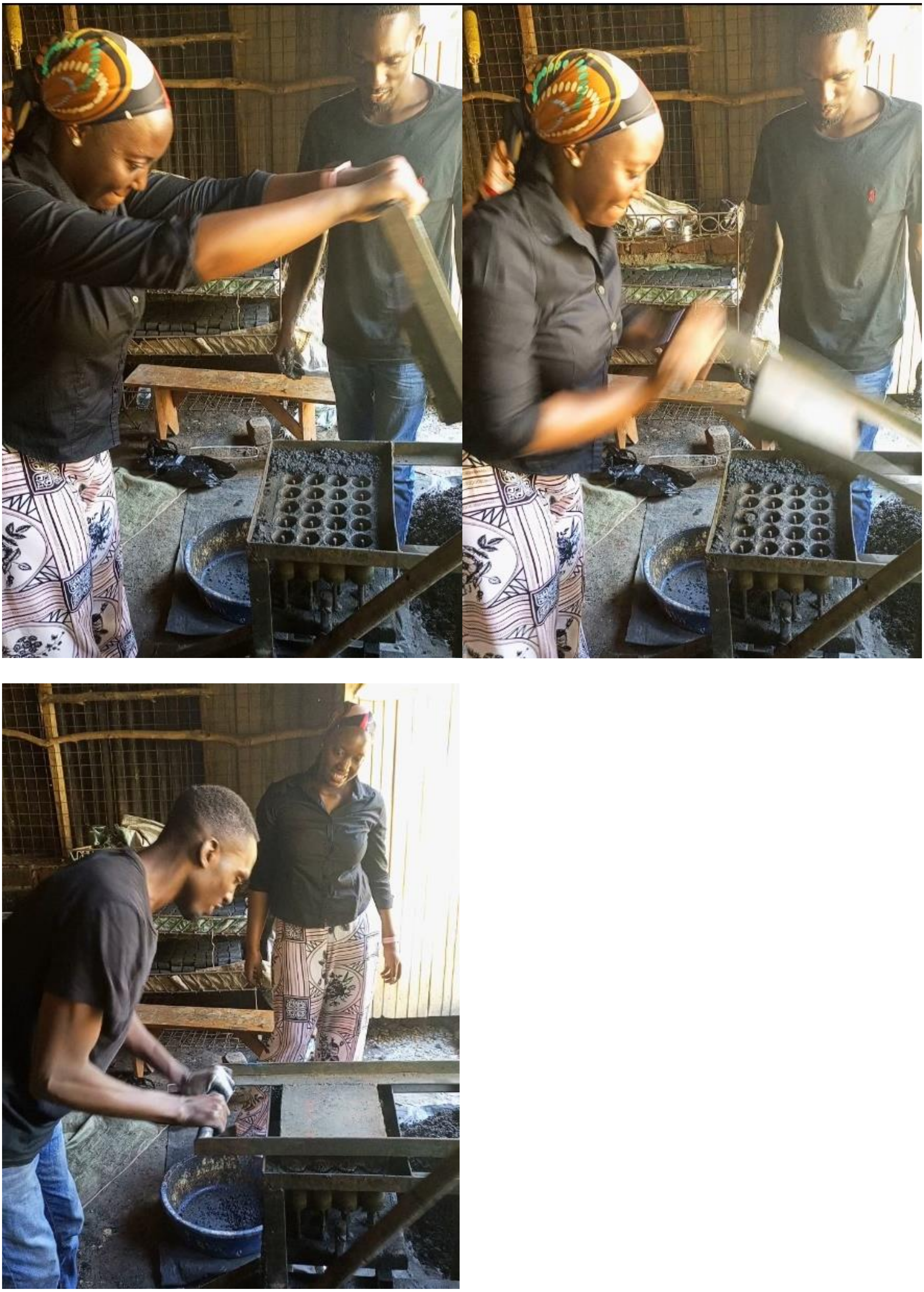

Figure 39: Compacting the mixture into a briquette

Figure 40: Extruding the briquettes from the briquetting machine.

Figure 41: Drying the Briquettes made in an air dryer

Figure 42: Weighing briquettes bought at 2000/=

Figure 43: Igniting the Briquettes

Figure 44: Flue gas testing

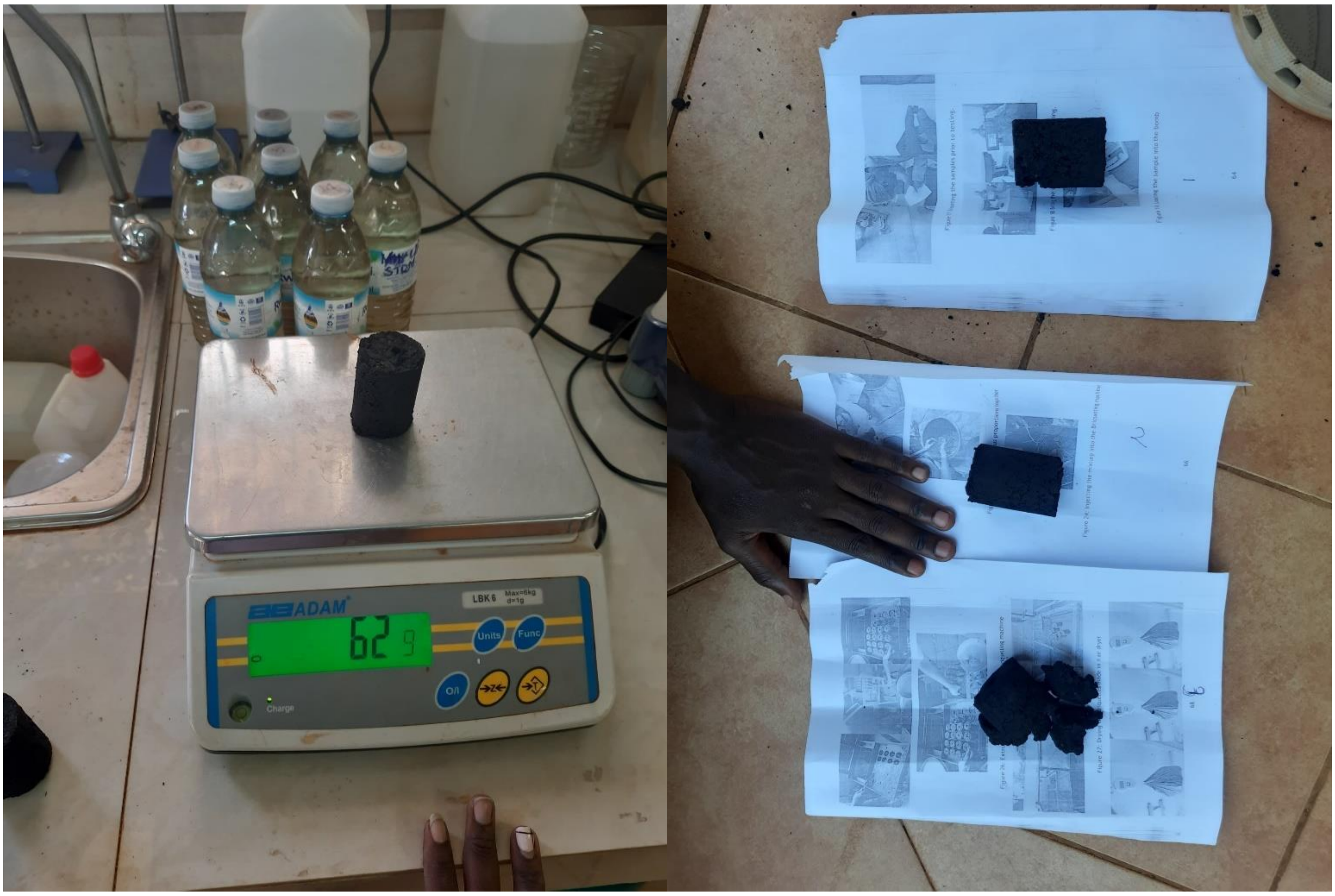

Figure 45: Drop test

Figure 46: Water boiling test

APPENDIX B: Laboratory Results

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Laboratory Test Results

Student Names: OWINO EMMANUEL, S20B32/215

: NAGITTA AISHA, S20B32/311

Date of Analysis: 11th 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:

— 0773379437

WAIBALE WILBER

Scientist Chemistry Lab

UGANDA INDUSTRIAL RESEARCH INSTITUTE
23 JAN 2024
P. O. BOX 7086, KAMPALA

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Figure 47: Proximate analysis results

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FACULTY OF ENGINEERING, DESIGN AND TECHNOLOGY

TO WHOM IT MAY CONCERN

18th 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 *14th February, 2024* to *13th 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: 14th February, 2024 – 13th March, 2024

Materials used: WUCU wastewater Sludge.

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

Yours in service

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

…………………………

Ramsey Ramathan

Lab Technician

Figure 48: Proof of Carbonization of the feedstock

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

LABORATORY TEST REPORT

Certificate Number: A007		
Client Name: AISHA THURAYYA NAGITTA & EMMANUEL OWINO **Client Address and Contact:** UCU P.O Box 4, Mukono 0700200131	**Sample Receipt Date:** 14/02/2024	**Analysis Start Date:** 14/02/2024
Lab Sample ID: A007/2024 **Client Sample ID:** Wastewater sludge from UCU treatment plant **Sample type and Location:** Wastewater sludge from UCU treatment plant	**Date of analysis completion** 18/03/2024	**Date of issue of the certificate** 18/03/2024
State of the sample on delivery: Semi-solid sludge	**Testing Conditions:** 105^{0}C for 24 hours **Testing Methods:** 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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Figure 49: Hydrothermal Carbonization yield results

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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 26th 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

Figure 50: Calorific value test results 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

Table 1 Heating Values of the ~~[illegible]~~ Waste Sludge 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 researc

Tests and report done by

[signature]

28 FEB 2024

Wabwire Andrew

Chief Technician – Mechanical Engineering

28 February 2024 **Page 2**

Figure 51: Calorific value test results 2

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

LABORATORY TEST REPORT

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

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 0.40 0.29	0.79 0.45 0.30	0.64 0.35 0.29	0.70 0.40 0.35	0.59 0.52 0.37	0.65 0.52 0.29	0.61 0.74 0.91	0.54 0.80 0.85
Carbon monoxide (ppm)	303 140 138	299 167 120	446 358 298	450 250 209	300 263 194	345 296 163	160 145 274	175 167 250
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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Figure 52: Water boiling test results 1

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Department of Engineering and Environment

Laboratory Technician

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Figure 53: Water boiling test results 2

Table 17: Extrapolated results obtained from Regression Analysis

Number	Water Content	Temperature	Reaction Time	Heating Value	HTC Yield	Desirability	
1	68.787	196.061	2.530	14.591	74.171	1.000	
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**	**Selected**
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	

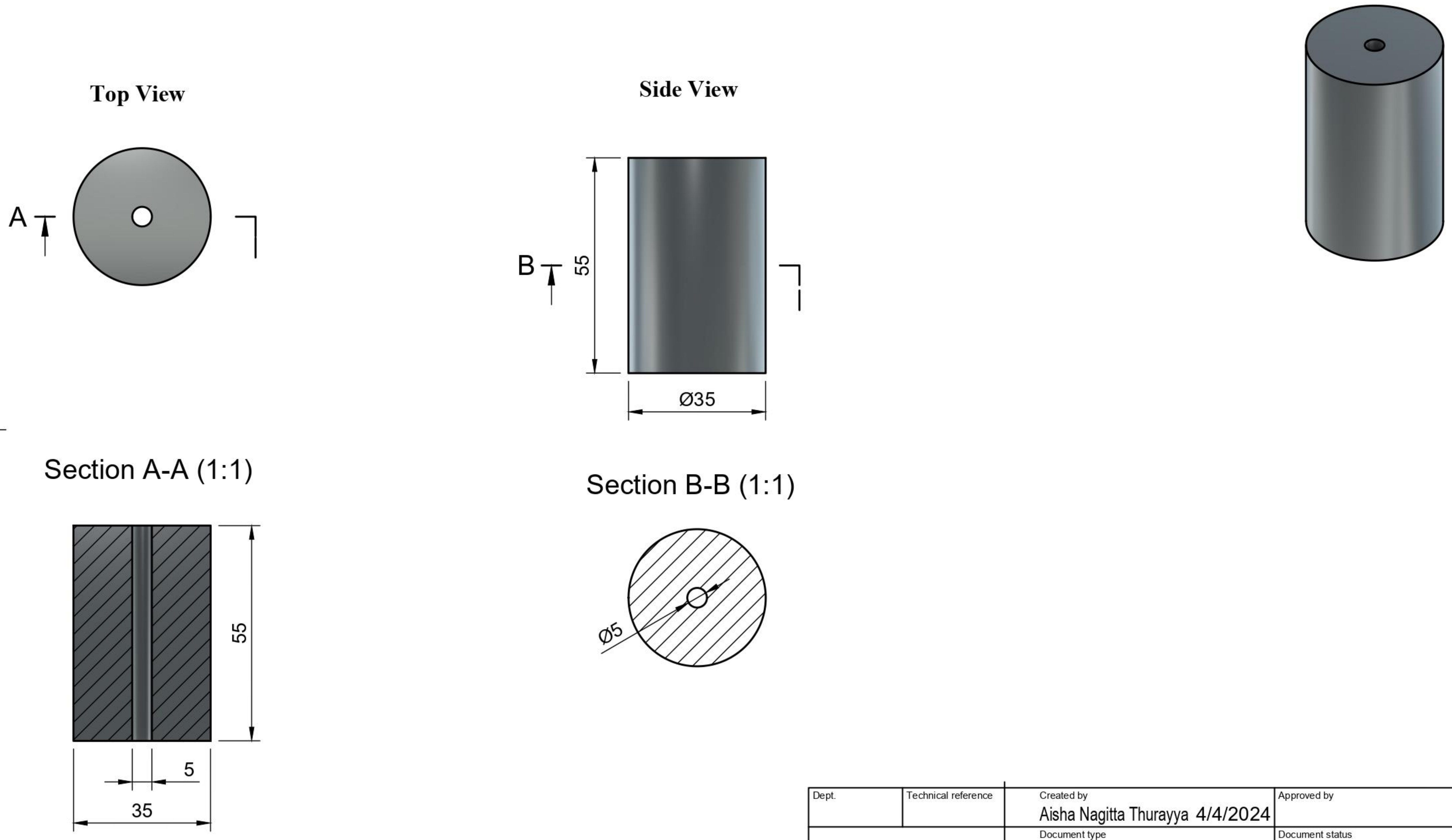
Number	Water Content	Temperature	Reaction Time	Heating Value	HTC Yield	Desirability	
24	74.678	185.996	4.659	14.711	56.364	1.000	
25	63.101	200.645	0.892	14.193	89.250	1.000	
26	78.525	210.715	4.202	13.619	49.673	1.000	
27	70.572	192.628	3.893	14.837	61.590	1.000	
28	52.452	187.622	1.416	13.632	94.087	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	

Number	Water Content	Temperature	Reaction Time	Heating Value	HTC Yield	Desirability	
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	

Number	Water Content	Temperature	Reaction Time	Heating Value	HTC Yield	Desirability	
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	

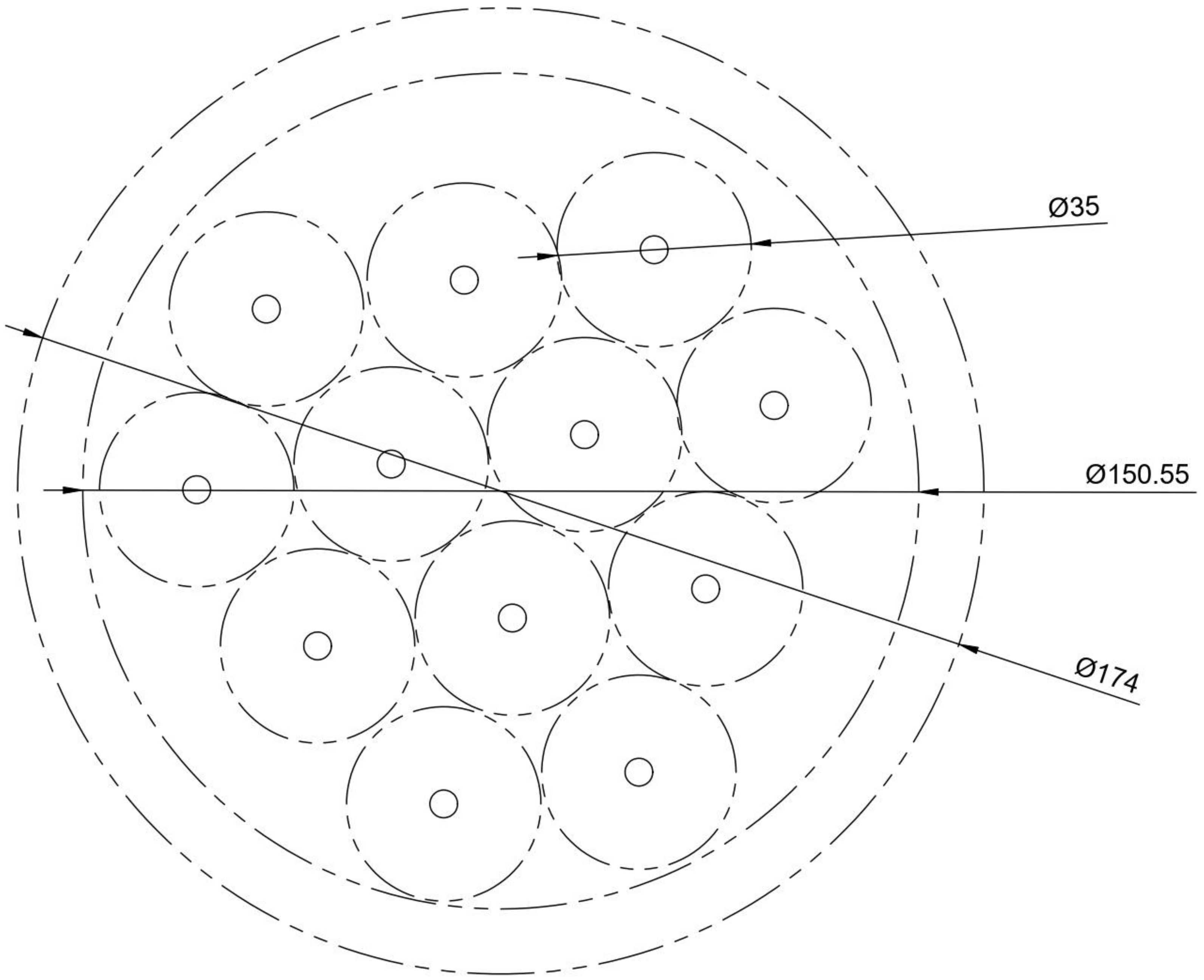
Number	Water Content	Temperature	Reaction Time	Heating Value	HTC Yield	Desirability	
96	69.539	217.873	3.977	14.456	51.960	1.000	
97	53.251	195.681	1.715	14.208	87.097	1.000	
98	71.698	215.425	3.274	14.290	60.135	1.000	
99	56.111	224.514	1.918	14.789	76.827	1.000	
100	60.058	180.685	2.609	14.450	85.339	1.000	

SHEMATICS OF THE BRIQUETTES FORMED USING THE HYDROCHAR



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

Illustration of the briquettes in a stove



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