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EFFECTS OF TREE DIAMETER AND HEIGHT ON THE QUALITY OF CHARCOAL PRODUCTION FROM *ACACIA DECURRENS* AT HOLETA AROUND ADDIS ABABA

By Yewbdar Tilahun Haile

Submitted to the Wood Technology Department for the Partial Fulfillment of the Requirements for the Masters of Science in Wood Technology

Advisor: Dr. Yashwant Singh Rawat.

Addis Ababa, Ethiopia

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FEDERAL TECHNICAL AND VOCATIONAL EDUCATION AND TRAINING INSTITUTE

SCHOOL OF GRADUATE STUDIES

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A Thesis Submitted to the Department of Wood Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Wood Technology

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Advisor

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APPROVAL SHEET I

This is to certify that the thesis entitled "Effects of tree diameter and height on the quality of charcoal production from *Acacia decurrens* at Holeta around Addis Ababa" submitted in partial fulfillment of the requirement for the degree of master's specialization in Wood Science Technology by Yewbdar Tilahun Haile carried out under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

Dr. Yashwant Singh Rawat.	________________________	__________________
Name of Major Advisor	Signature	Date

APPROVAL SHEET II

As members of the board of examiners of the final open defense by Yewbdar Tilahun Haile have read and evaluated the thesis entitled “Effects of tree diameter and height on the quality of charcoal production from *Acacia decurrens* at Holeta around Addis Ababa”.Therefore, this is to certify that the thesis has been accepted in partial fulfillment of the requirements for the Degree of Master of Science in Wood Technology.

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Name of External Examiner	Signature	Date

DECLARATION

I, Yewbdar Tilahun Haile, hereby declare that this thesis is my original work and that all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for MSc. degree to the Federal Technical and Vocational Education and Training Institute. This thesis report could be deposited at the Federal Technical and Vocational Training Institute library to be made available to readers, under the rules of the library. I declare this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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Yewbdar Tilahun Haile Signature Date

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List of Abbreviations and Acronyms

ANOVA	Analysis of Variance
ASH	Ash Content
ASTM	American Standard for Testing and Materials
BD	Basic Density
CRD	Completely Randomized Design
CSA	Central Statistical Agency
CV	Caloric Value
Cv	Coefficient Variation
CY	Charcoal Yield
DBH	Diameter at Breast Height
DC	Diameter Classes
DDC	Different Diameter Classes
DS	Diameter Section
FAO	Food and Agricultural Organization
FC	Fixed Carbon
LCA	Life Cycle Assessment
LSD	List Significant Difference
M	Oven Dry Mass
MC	Moisture Content
MC_{coal}	Moisture Content of Charcoal
MC_{gw}	Moisture Content of Green Wood
PAC	Percentage of Ash Content
PFC	Percentage of Fixed Carbon
PVM	Percentage of Volatile Mater
S	Sulfur Content
SO2	Sulfur Dioxide
TP	Total Length of the Selected Tree Sample
V	Green Volume Of A Wood Sample
VM	Volatile Mater
WSG	Wood Specific Gravity

List of Symbols

B	Bottom Portion
L	Total Tree Length
M	Middle Portion
T	Top Portion
W_0	Weight After Dry
W_1	Initial Weight

List of Tables

List of Figures

Table of Contents

ABSTRACT

Effects of tree diameter and height on the quality of charcoal production from *Acacia decurrens* at Holeta around Addis Ababa

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This study investigates the effects of tree diameter on the quality of charcoal production from *Acacia decurrens* around Holeta, Addis Ababa Ethiopia. The research aimed to assess how wood diameter and tree height (top, middle, and bottom) affect charcoal yield and quality, using a barrel kiln method. Results showed that smaller diameter classes, especially 2 to 4 cm, produced the highest charcoal yield (up to 63.61%), particularly from the top and middle sections of the trees. Moisture content of both green wood and resulting charcoal was significantly affected by tree size and position, with smaller diameters generally retaining less moisture. However, other properties like basic density, volatile matter, fixed carbon, ash content, calorific value, and sulfur content showed no significant variation across different diameters or tree positions. Overall, the study concludes that using smaller diameter wood from *Acacia decurrens*, especially from the upper tree parts, leads to higher charcoal yield and better moisture profiles, making it a more efficient and sustainable option for charcoal production in Ethiopia.

Key-words *Acacia decurrens, Ash content, Barrel kiln, Basic density, Calorific value, Charcoal yield, Charcoal, Fixed carbon, Moisture content, Sulfur content and Volatile matter*

CHAPTER ONE

Introduction

1.1 Background of the Study

The growing energy crisis is a prime concern around the globe. Fossil fuels are the main sources of energy at present. The greenhouse gas (GHG) emissions due to the consumption of fossil fuels as energy sources have induced global warming which in turn causes adverse effects on the environment and human wellbeing. Because of the non-renewable nature and growing consumption rate, the fossil fuel stock will decline within the century. Efforts are continuing to find environmentally friendly alternative energy sources. As a substitution for fossil fuels, renewable bio energy sources could play an important role in the global energy systems by reducing GHG emissions (Chum *et al*., 2011).

Forest biomass is a natural resource used all over the world for different purposes, including energy. It is considered to be the backbone of energy sources in developing countries, especially sub-Saharan countries like Ethiopia (Julia *et al*., 2014). Forest biomass is abundantly available in Ethiopia. Studies show that (Virginia *et al.,* 2011) forest biomass is a potentially significant source of renewable energy. Forest biomass has the potential to replace fossil fuels in the energy sector as it is a clean and renewable energy source (Mohammad *et al*., 2022).
Most parts of Sub-Saharan Africa, households both rural and urban are largely dependent on fuel wood (charcoal and firewood) for their energy needs (Ribot, 1995; Girard, 2002; Woldemichael, 2020).

Charcoal producers can use free raw materials collected from natural forests or other sources and turn them into marketable commodities in high demand (Tassie *et al*., 2021). About 230,000 tons of charcoal is being used per year for domestic purposes in Ethiopia (Alem *et al*., 2013).This proves the significance that wood fuel plays in meeting the energy demand of developing countries (Kibet, 2014) mainly Ethiopia, as the country's renewable energy sector is still in its infancy stage (Dingeto and Kalbessa, 2021) .

Charcoal, among the main products of woodland forests, is a critical source of energy in Africa; where close to 80% of the population uses it as the basic resource for cooking and heating (Leo and Robert, 2013; Miyuki et al., 2014; IEA,2014).

Charcoal production provides a significant portion of urban and rural households' energy needs and is also a source of livelihood for 10,000 rural households in the country (Jan and Francesco, 2019). In Ethiopia, charcoal is generally produced from state-owned (public) forests and woodlands and is traditional (Gebremeskel *et al.,* 2023).

Charcoal is an essential renewable energy source, obtained through biomass carbonization in an oxygen-limited environment (Muhammad *et al*., 2022). It plays a crucial role in low-income countries, offering significant income and various socioeconomic benefits, particularly in areas where access to modern energy sources is limited (Nigussie *et al*., 2017; Nigussie *et al*., 2021; Andaregie *et al.,* 2022; Muhammad *et al*., 2022; Gebremeskel *et al.,* 2023; Hido *et al.,* 2023). Globally, 53.2 million tons of charcoals are produced, with Africa contributing around 63% (Dam *et al*., 2017).

Charcoal is the primary cooking fuel for 1.3 billion people worldwide and 195 million people in sub-Saharan Africa (Arnaud *et al.,* 2018; Rose *et al*., 2022).

Wood charcoal plays a vital role in reducing rural-urban migration in Zambia and employing 500,000 individuals in Kenya (Mary *et al.,* 2013). Similarly, in Ethiopia, charcoal and fuel wood play a dominant role in energy consumption, constituting approximately 90% of the total energy used (Mengist, 2020).

Ethiopia ranks as the world's third-largest charcoal producer, with production surpassing 4.4 million tons, following Brazil and Nigeria (Dam *et al*., 2017). Due to limited access to electricity and natural gas, many Ethiopian communities heavily rely on fuel wood and charcoal. Charcoal is extensively used for cooking in households, bakeries, restaurants, and small-scale industries (Hido *et al*., 2023).

Charcoal production is a significant economic activity in many regions, including Ethiopia. *Acacia decurrens,* commonly known as black wattle, is one of the most widely used species for charcoal production due to its fast growth and high calorific value. However, the quality of charcoal can vary depending on various factors, including tree diameter.

This study aims to investigate the effects of tree diameter on the quality of charcoal production from *Acacia decurrens* trees in and around Addis Ababa. Charcoal has been used as a source of fuel for cooking and heating purposes for centuries. In Ethiopia, where access to electricity and clean cooking fuels is limited, charcoal remains a vital energy source for a significant portion of the population. The demand for charcoal has been steadily increasing due to population growth and urbanization.

Acacia decurrens is a fast-growing tree species that has gained popularity among charcoal producers in Ethiopia due to its high biomass productivity and adaptability to various soil types. However, little research has been conducted on how tree diameter affects the quality of charcoal produced from this species. Tree diameter plays a crucial role in determining the quantity and quality of wood available for charcoal production.

Understanding how tree diameter influences the quality of charcoal production from *Acacia decurrens* is essential for sustainable management practices and optimizing resource utilization. By investigating this relationship, we can provide valuable insights into improving charcoal production techniques and enhancing overall efficiency. In General Charcoal production from *Acacia decurrens* has shown considerable advantages for enhancing livelihoods and boosting government revenue in Ethiopia.

However, the current reliance on unsustainable traditional earth mound kilns diminishes these benefits, causing reduced charcoal income and notable environmental damage. Therefore, there is a pressing need to improve the traditional charcoal production system. The objectives of this study will be evaluating barrel kiln charcoal production approaches on charcoal conversion efficiency, charcoal yield and quality charcoal formed from *Acacia decurrens* wood at Holeta, Oromia region around Addis Ababa.

1.2 Statement of the Problem

Charcoal plays a crucial role in Ethiopia's energy sector, but its production remains inefficient, contributing to deforestation and high greenhouse gas emissions. Traditional methods often yield low charcoal quality and quantity due to poor wood selection and ineffective carbonization techniques. A significant gap exists in scientific research on how tree diameter and position affect charcoal yield and quality, especially for *Acacia decurrens*, a commonly used species for charcoal production.

The lack of data on ideal diameter classes and tree parts leads producers to rely on random harvesting methods, which are not optimal for maximizing charcoal output or sustainability. Improving knowledge of these factors could increase production efficiency, reduce waste, and help preserve Ethiopia's forest resources. This study aims to address these issues by identifying the best diameter classes and tree portions for enhancing charcoal yield and quality from *Acacia decurrens.*

1.3 Objectives of the Study

1.3.1 General Objective

The primary objective of this study was to analyze the charcoal quality produced from *Acacia decurrens* wood in Ethiopia, specifically in Holeta, around Addis Ababa, by considering different tree diameter classes and height.

1.3.2 Specific Objectives

- To identify and analyze the key factors (such as wood properties and carbonization parameters) that affect the overall quality of *Acacia decurrens* charcoal.
- To determine the effect of tree diameter and height on the final yield (%)of charcoal produced during the carbonization process.
- To analyze the relationship between tree diameter, tree height and the energy performance (calorific/heating value) of the resulting charcoal.
- To investigate the influence of tree diameter and height on the physical and chemical properties of the produced charcoal.
- To identify the optimal tree diameter range/class required to maximize both charcoal yield and quality.
- To evaluate the impact of different tree diameters and height on the thermal efficiency and energy consumption during the carbonization process.

1.4 Research Questions

1. What factors affect the quality of charcoal production?
2. How does tree diameter affect the yield of charcoal production from *Acacia decurrens*?
3. What is the relationship between tree diameter and the energy performance of charcoal produced from *Acacia decurrens*?
4. How does tree diameter influence the physical properties of charcoal produced from *Acacia decurrens*?
5. What are the optimal tree diameters for maximizing charcoal production and quality from *Acacia decurrens*?
6. How do different tree diameters impact the efficiency and energy consumption of the charcoal production process from *Acacia decurrens*?

1.5 Hypothesis

Once the charcoal has been creating it would be analyzed for various quality indicators such as carbon content, ash content, calorific value, and porosity. These indicators are important for determining the quality of charcoal as they affect its burning efficiency and heat output. The data collected from the analysis would then be compared to the diameter of the trees from *Acacia decurrens* which the charcoal was produced larger diameter trees will produce higher quality charcoal compared to smaller diameter trees. If the hypothesis is correct, there should be a positive correlation between tree diameter and charcoal quality, with larger diameter trees producing higher quality charcoal.

1.6 Scope and Limitations of the Study

This study focuses on *Acacia decurrens* trees in Holeta, near to Addis Ababa. The species was selected due to its abundance in the area and its suitability for charcoal production given its high energy content.

The research involves collecting samples from trees of different diameters, ranging(2 to 4 cm, 4 to 6 cm, 6 to 8 cm and 8 to 10 cm).Standard forestry guidelines were used to determine diameter classes. Laboratory analyses were conducted to assess key quality parameters such as the physical properties of green wood, proximate analysis, and ultimate analysis of charcoal produced.

While this study provides valuable insights into the impact of tree diameter and position on charcoal yield and quality, it is limited to a single species and geographic location. Additionally, other influencing factors such as tree age, growth rate, and climatic conditions are not considered.

1.7 Significance of the Study

Charcoal production is a significant economic activity in Ethiopia, providing livelihoods for many people. Understanding the factors that influence charcoal quality can help improve both the efficiency and profitability of this sector. One key factor affecting charcoal yield and quality is tree diameter and tree position, which influence the physical properties of green wood, proximate analysis, and ultimate analysis.

By analyzing the relationship between tree diameter, tree position, and charcoal quality, this study can provide valuable insights into the optimal selection of trees for charcoal production. These findings will benefit charcoal producers by improving resource utilization and guiding tree selection for better-quality charcoal. Consumers will also benefit from superior charcoal that burns cleaner, produces less smoke and pollution, lasts longer, and generates more heat, making it both cost-effective and environmentally friendly.

Overall, this study is essential for enhancing the efficiency and sustainability of Ethiopia’s charcoal industry also should examine every stage involved in the biomass supply chain, starting from harvesting and transportation to processing, conversion, and final energy utilization. In addition, a detailed carbon footprint analysis should be included to measure greenhouse gas emissions generated throughout the entire life cycle. Sustainability indicators such as energy efficiency, resource consumption, waste generation, land-use impact, and environmental benefits should also be evaluated. Its findings can help improve wood selection practices, leading to higher-quality charcoal with better combustion properties and lower environmental impact.

Finally, this study aims to improve the efficiency and sustainability of Ethiopia's charcoal industry by analyzing the entire biomass supply chain and assessing environmental impacts. Its findings can enhance wood selection practices, resulting in higher-quality, environmentally friendly charcoal.

1.8 Definitions of Key Terms

Acacia decurrens**:** Commonly it is known as Foreign Girar which is a feathery-leafed wattle that grows into a well-shaped tree up to about 14m.

Biomass: is renewable organic material that comes from plants and animals. Biomass contains stored chemical energy from the sun that is produced by plants through photosynthesis. Biomass can be burned directly for heat or converted to liquid and gaseous fuels through various processes.

Carbonization: is the oldest known thermo chemical process that allowed humans to convert wood into charcoal, which is the first bio fuel that has been used by humans to step out of the Stone Age by refining ores into metals.

Calorific value: is a measure of the amount of energy produced from a unit weight of coal when it is combusted in oxygen.

Carbon: is the chemical backbone of all life on earth thus charcoal consists mainly of carbon Charcoal contains varying amounts of hydrogen and oxygen as well as ash and other impurities that, together with the structure, determine the properties. The fixed carbon content of charcoal ranges from a low of about 50% to a high or around 95%.

Charcoal: is a lightweight black carbon residue produced by strongly heating wood (or other animal and plant materials) in minimal oxygen to remove all water and volatile constituents.

Kiln: is the most basic traditional char-making apparatus made from wooden logs and to simple designs in biomass slow pyrolysis carbonization reactors, which often use wood.

Moisture content: is defined as the total amount of water in a piece of wood. Moisture content is also defined by the weight of the water in the wood divided by the weight of the wood. This number is then multiplied by 100 to become a percentage.

Wood ash: is the inorganic and organic residue remaining after combustion of wood or unbleached wood fiber. The physical and chemical properties of wood ash vary significantly depending on many factors.

Wood density: defined as the dry mass for a given volume of wood, has been correlated with wood durability and thus may be involved in WD resistance.

Woodlot: is restricted area of woodland usually privately maintained as a source of fuel, posts, and lumber.

Volatile matter: is material that is driven off when coal is heated to 950 °C (1,742 °F) in the absence of air under specified conditions. It is measured practically by determining the loss of weight.

1.9 Organization of the Paper

This thesis paper has five chapters. The study's background, the research problem statement, the study's objectives (both general and specific), the research questions, the hypothesis, the significance, the scope, definitions of key terms, and the paper's organizational structure are all covered in the introduction section of the proposal. The second part was the collection of all related literature from the research, including conceptual and theoretical approaches and frameworks. The third part was a detailed description of the study area and research methods and materials, including: experimental design and sampling method; source of data, study variables, list of materials required; carbonization procedure; determination of physical and combustion properties; method of data analysis. The fourth part was detail analysis of result and discussion. Last chapter have conclusion, recommendation and reference. In general it has five chapters.

CHAPTER TWO

Literature review

2.1 Charcoal

Most parts of Sub-Saharan Africa, households both rural and urban are largely dependent on fuel wood (charcoal and firewood). Production of charcoal is one of the most common methods for processing wood residues to make them cleaner, easier to use and to transport. Charcoal has many favorable characteristics compared with fuel wood, a higher energy density and excellent cooking properties; it can be stored without risk of insect or fungal attack. Charcoal can be made from both hardwood and softwood but hardwood is generally preferred because of higher energy content and easier handle (Kayhan, 2013).

Fuel wood and charcoal account for more than 80% of total household energy requirements. Charcoal production results in a high pressure on the commonly used woody species. For their energy needs in Sub-Saharan Africa, firewood and charcoal contribute more than 80% to the total domestic energy requirements (Garedew and Simon, 2018).

Despite the economic benefits of charcoal production, much concern has been expressed towards the consequences that follow its production. Allen and Barnes (1985) said about 7.5 million hectares of closed forest and 3.8 million hectares of African forests are cleared yearly for a variety of purposes ranging from timber production, construction purposes agriculture as well as charcoal production (Ogundele *et al*., 2011).

Charcoal is an essential renewable energy source, obtained through biomass carbonization in an oxygen-limited environment. It plays a crucial role in low-income countries, offering significant income and various socioeconomic benefits, particularly in areas where access to modern energy sources is limited. Globally, 53.2 million tons of charcoals are produced, with Africa contributing around 63%.

It is the primary cooking fuel for 1.3 billion people worldwide and 195 million people in sub-Saharan Africa in Ethiopia, charcoal and fuel wood play a dominant role in energy consumption, constituting approximately 90% of the total energy used. Ethiopia ranks as the world’s third-largest charcoal producer, with production surpassing 4.4 million tons, following Brazil and Nigeria. Due to limited access to electricity and natural gas, many Ethiopian communities heavily rely on fuel wood and charcoal. Charcoal is extensively used for cooking in households, bakeries, restaurants, and small-scale industries. The charcoal business provides income to around 1.5 million people from over 300,000 households. Eight percent of total households and thirty percent of urban households utilize charcoal for daily cooking. (Tazebewet *et al.*, 2023).

Charcoal is the primary fuel source to urban and rural households of Ethiopia. However, its production is not efficient in most developing countries including Ethiopia (Andaregie *et al*., 2020).

2.2 Charcoal Production from *Acacia Species*

2.2.1 Acacia decurrens wood

Acacia decurrens is a fast-growing tree that reaches up to 6-12m or more high. It grows on sandstone soils with medium nutrients and good drainage. Seedlings should spend 7–8 months in the nursery before planting out. It is more adapted to temperate coastal to cool inland but not dry or hot areas. It grows well in high rainfall areas with 600–1,400 mm (24–55 in) per year, otherwise tolerant to a wide range of conditions. *Acacia decurrens* is generally found on roadsides, along creek lines and in waste areas. It also grows in disturbed sites nearby bush lands and open woodlands (Tamirat and Wondimu, 2019).

Acacia decurrens plantation enhances overall improvements in the household's livelihood, including housing, the feeding system, children's education, the income of farmers, brokers, charcoal producers, and laborers, and job opportunities to reduce the unemployment rate (Tilahun *et al*., 2022).

In general *Acacia* species have been widely studied for their potential in charcoal production. Research on *Acacia decurrens* demonstrated it is fast-growing trees like *Acacia decurrens* (J.C. Wendl). Wild is nature’s gift to the smallholder farmers for soil amelioration, the production of charcoal, fencing and wood for construction (Minichil *et al.*, 2025).

Several studies have investigated the production and properties of charcoal from various Acacia species, which provide insights into the characteristics of *Acacia decurrens*. This study emphasizes the relevance of *Acacia* species in Ethiopia's charcoal industry.

Charcoal production, particularly from Acacia woodlands, contributes significantly to deforestation and land degradation in Ethiopia. A study conducted in Dire-Dawa highlighted how Acacia woodland degradation is linked to unsustainable charcoal production practices (Macrothink, 2018). This calls for the development of sustainable harvesting techniques and improved kiln efficiency to minimize environmental impact.

A study on traditional charcoal production systems in Ethiopia found that wood samples with an average diameter of 6 cm were preferred across different kiln types, leading to improved yield and quality (Tazebewet *et al*., 2023).

While specific studies on *Acacia decurrens* charcoal production are limited, findings from related Acacia species provide insights into its potential. Further research is needed to optimize sustainable charcoal production from *Acacia decurrens*, balancing economic benefits and environmental concerns.

2.3. Forest Biomass Energy

Biomass is organic material made from plants and animals (microorganisms). Plants absorb the sun's energy in a process called photosynthesis in which carbon dioxide and water are converted into stored energy. Therefore, biomass contains stored energy from the sun. It is a renewable energy source provided that if we always grow more trees and crops and wastes from animals and agriculture are channeled into energy sources. Some examples of biomass fuels are wood, crops, manure, and some garbage. When burned, the chemical energy in biomass is released as heat (Simur, 2012).

In developing countries, wood is the most common residential fuel. As most developing nations have an agriculture-based economy, biomass fuels continue to play a major role in both the residential and industrial sectors (Wondmagegn *et al.*, 2023).

Currently, about 1.5 billion people in developing countries lack access to electricity and about 3 billion people rely on solid fuels for cooking. In sub-Saharan Africa, the number of people without access to electricity and modern fuels is similar (respectively 560 and 625 million people). In Asian regions, while people may have access to electricity, they often lack access to modern fuels. In East Asia and Paciyc, less than 200 million people lack electricity access, but almost 1.1 billion people rely on solid fuels for cooking. Biomass energy has been the major source of domestic energy in the past. Until now, over 80% of the population in sub-Saharan Africa still depends on biomass energy (Neina *et al*., 2011).

About 2.4 billion people rely on traditional biomass, mainly for cooking and heating. Essentially all of those users of traditional fuels dwell in developing countries, and most of them live in rural areas; low incomes and the lack of access to alternative, modern fuels elucidate their choice of traditional energy supply (Nadejda and David, 2002).

Ethiopia has one of Africa’s fastest growing economies, but it has one of the world’s poorest accesses to modern energy supplies. The majority of Ethiopia’s population lives in rural areas and is heavily reliant on agriculture; the primary source of energy for this rural population is biomass (biomass of wood, solid, and agricultural wastes), accounting for approximately 87% of total energy supply (Berhanu *et al.*, 2017).

Biomass users prefer charcoal over other biomass fuels such as wood, residues and dung. Charcoal has a higher energy density than other biomass fuels and can be stored without fear of insect problems (Daniel and Debra, 2005).

It has excellent cooking properties: it burns evenly, for a long time, and can be easily extinguished and reheated. First, the wood fuel equivalent is 4-6 times larger, due to the inefficiency of the production process. Perhaps more importantly, charcoal demand is in densely populated urban areas and the harvesting of wood for charcoal production is an intensive process, concentrated in as small an area as possible over as short a period of time as possible. In some cases, wood is taken illegally from state land, and producers are under pressure to harvest the wood make the charcoal as fast as possible (Daniel and Debra, 2005).

The rural wood fuel users typically collect small amounts of wood daily, and thus the forestry impact is dispersed and much less severe. Also the rural users may collect dead wood, or twigs and branches, which allow the trees to regenerate. Charcoal production, on the other hand, is responsible for the large-scale felling of wood, which may lead more directly to deforestation (Daniel and Debra, 2005).

The energy efficiency of the process is dependent upon many factors: kiln type, moisture content, wood species, wood arrangement, and the skill of the producer. Many programs over the past century have been implemented to increase efficiency of charcoal kilns (Daniel and Debra, 2005).

2.3.1 Forest Biomass Energy Resources in Ethiopia

Ethiopia possesses significant forest biomass resources, including natural forests, woodlands, and plantations. Recent assessments estimate that forest residues account for approximately 56.01% of the total bioenergy potential in the country, translating to a considerable energy source (Wiley Online Library, 2023).

2.4 Efficiency of charcoal production

The efficiency of charcoal production is dependent on many factors, such as kiln type and composition, kiln covering material, moisture content, species, wood density, the arrangement of the wood inside the kiln, the skill and experience of the producer, and even the climatic conditions. One of the factors affecting yield quality is temperature. High yield of charcoal is obtained at low temperatures around 300°C with a high content of volatile material. Temperatures around 600°C give lower yields with a low content of volatiles which makes it a preferred fuel, but charcoal producers generally prefer the higher yield. The charcoal yield decreases as the temperature increases, so charcoal producers take care to control the temperature to increase the yield (Kayhan, 2013).

2.5. Carbonization

Carbonization is the oldest known thermo chemical process that allowed the humans to convert wood into charcoal, which is the first biofuel that has been used by the humans to step out of the Stone Age by refining ores into metals (Mahmoud *et al.*, 2019).

Carbonization was performed in the early ages by gathering the wood into a cone-shaped pile, covering it with earth, slowly combusting the wood, and allowing the water content and volatile substances to exit from a central chimney, turning the wood into coal (Mahmoud *et al.*, 2019).

The conventional charcoal production process has several drawbacks and disadvantages in terms of rate of carbonization, quality, yield, pollution, labor, and land costs (Wondmagegn *et al.*, 2023).

Various carbonization procedures have been used to produce charcoal for thousands of years across the world. Society employs an ancient and rudimentary method of charcoal production that has received little investigation and experimentation (Wondmagegn *et al.*, 2023).

Carbonization is a thermo chemical process that involves heating biomass at a high temperature with a small quantity of oxygen to produce solid fuel, such as charcoal. The kiln was equipped with air vents around the perimeter, a carbonized material intake and exit, an anti-downdraft system, and an exhaust chimney (Wondmagegn *et al.*, 2023).

Carbonization is initiated by heating a pile of wood under low oxygen conditions in a closed space, such as a kiln, with the limited supply of air triggering endothermic and exothermic reactions. High temperatures induce the absorption of heat, which leads to the decomposition of biomass, separating it into volatile gases, vapor and solid char (FAO, 2017).

2.6. Charcoal Quality Parameters and Their Significance

Charcoal quality can be specified and measured in various ways which are usually derived from the end-user requirements; some of these ways are moisture content, volatile matter, ash content and duration time. Consumers also said that the weight of the charcoal is a determinant of its quality. Quite often, good charcoals are usually heavy, while the bad ones are likely to be very light; in addition to this some producer said that charcoal of satisfactory market quality can be made in kilns of any size or type when suitable coaling temperature and time conditions are present (Garedew and Simon, 2018).

In addition, charcoal quality is determined by several key parameters that affect its efficiency, usability, and environmental impact. These parameters include moisture content, ash content, volatile matter, fixed carbon, calorific value, density, hardness, and impurity levels. Understanding these factors is crucial for optimizing charcoal production and utilization in various sectors.

2.6.1. Moisture content

Moisture content and diameter of the sampled wood are important parameters for the evaluation of wood to the charcoal conversion efficiency of a given charcoal kiln (Tazebew *et al.*, 2023).

Regular moisture content analysis and monitoring during the charcoal conversion evaluation are also essential to ensure consistent and efficient charcoal production. Moisture content can be measured using various methods, such as oven-drying or specialized moisture meters. By controlling and maintaining the appropriate moisture level, one can improve the yield of the resulting charcoal. From the dry wood, representing 10% of the total *Acacia decurrens* plantations, three moisture readings were taken from different sections (low, middle, and upper). To ensure consistency, these readings were repeated on the same pieces of dry wood, ensuring that the moisture content remained below 20%. Finally, a final average moisture reading was obtained just before arranging the wood for immediate charcoal carbonization. Once the moisture content value is obtained, it is subtracted from the wood weight to determine the dry weight of the wood. This step is crucial because moisture is not converted into charcoal; rather, it is released as vapor during the carbonization process. By subtracting the moisture-influenced weight, we obtain the precise dry weight of the wood, which is essential for accurate charcoal conversion evaluations. Subsequently, the wood was cross-cut, weighed, and stacked in preparation for the carbonization process (Tazebew *et al.*, 2023).

High moisture levels reduce combustion efficiency, resulting in lower calorific value and increased smoke production. Quality charcoal typically has a moisture content of 5-15% (FAO, 2023). Excessive moisture can cause charcoal to fragment upon heating, leading to undesirable fines in industrial applications (FAO, 2023).

2.6.2. Wood density

Wood is a biological tissue made of cells, or tracheid's, and of walls composed of lignin. The tracheid's are like pipes that transport the sap along the stem and they are filled by water. The density of tree wood is an interesting variable because it tells how much carbon the plant allocates into construction costs. Wood density varies within the plant during the life of the plant, and between individuals of the same species. Also the branches and the outer part of the trunk tend to have a lighter wood than the pith. There are many definitions of wood density. Foresters measure the weight of a given volume of wood that has been 'air-dried'. Depending on the country, conventions differ about air drying: the fraction of water remaining in the wood sample may be 12% or 15%. This causes considerable trouble in the literature. In the present study, wood density is technically defined as the ratio of the oven-dry mass of a wood sample divided by the mass of water displaced by its green volume (wood specific gravity, or WSG). This can be calculated from measurements of oven-dry weight combined with measurement of green volume. (Jerome, 2002).

Wood specific gravity also known as wood density, measures the amount of actual wood material in a unit volume of wood. (Wondmagegn *et al*., 2023).

It is the ratio of a mass of oven-dry wood divided by the green volume of the. The common unit of wood density is g cm-3 or kg m-3. Wood density varies depending on the species of trees, and normally wood quality is classified based on the wood density, i.e., heavy hardwood, medium hardwood, light hardwood, and softwood. The density of wood varies depending on type and growth environment of the trees. The parts of the tree also have different densities: branches usually have a lower wood density than the trunk. (Hamdan, 2021).

Density varies among the tree species age and parts (Bekele, 2021). Acacia has the highest density and the lowest density was recorded in *Acacia abyssinica*. The density of *Acacia decurrens* in was 0.76 g/cm^3. The energy content of *Acacia decurrens* at different ages and parts energy content, proximate analysis of *Acacia decurrens* Willd was also analyzed with basic wood density from 0.321 to 0.842 g/cm^3(Bezashwork *et al*., 2022)

High-density characteristics make *Acacia decurrens* an excellent for firewood (Groves, 1989). Higher basic density is important parameters to fuel wood characteristics. Trees with the highest density can generate large energy per unit volume (Alem , 2013).

2.6.3. Wood ash

Wood ash is the inorganic and organic residue remaining after combustion of wood or unbleached wood fiber. The physical and chemical properties of wood ash vary significantly depending on many factors. Hardwoods usually produce more ash than softwoods, and the bark and leaves generally produce more ash than the inner woody parts of the tree (Mark, 2013).

The American Society for Testing Materials defines ash as inorganic residue remaining after ignition of combustible substances, determined by definite prescribed methods. (Rees *et al*., 1957).

Ash content is the non-combustible residue left after complete combustion. Lower ash content indicates higher purity and better combustion efficiency. According to the Indonesian National Standard (SNI), high-quality charcoal should have ash content below 8%, with premium grades maintaining levels under 4% (Cocologi, 2023).

2.6.4. Volatile matter

Volatile matter is material that is driven off when coal is heated to 950°C (1,742°F) in the absence of air under specified conditions - components of coal, except for moisture, which is liberated usually as a mixture of short and long chain hydrocarbons, aromatic hydrocarbons and some Sulphur – measured practically by determining the loss of weight Consists of a mixture of gases, low-boiling-point organic compounds that condense into oils upon cooling, and tars. Volatile matter decreases as rank increases (Brian and Marty, 2008).

Volatile matter is determined by establishing the loss in weight resulting from heating wood under rigidly controlled conditions (ASTM, 2013).

Volatile matter in coal and coke is defined by the American Society for Testing Materials at 1954 as "those products, exclusive of moisture, given off by a material as gas or vapor, determined by definite prescribed methods which may vary according to the nature of the material." It is one of the important determinations in the proximate analysis for use in certain classification systems and for evaluating coals as to combustion and coking characteristics (Rees *et al.*, 1957).

Volatile matter consists of gases and organic compounds released when charcoal is heated. High volatile matter content increases smoke production and undesirable emissions. Reducing volatile matter enhances combustion quality, making charcoal more suitable for industrial use (Cocologi, 2023).

2.6.5. Fixed Carbon

Fixed carbon represents the proportion of carbon available for combustion after volatile matter has been expelled. Higher fixed carbon content correlates with greater energy efficiency. Charcoals used in metallurgical applications typically contain 74-77% fixed carbon (Science Direct, 2023).

2.6.6. Calorific Value

Calorific value measures the energy released during combustion, expressed in kilojoules per kilogram (kJ/kg). Higher calorific values indicate more efficient fuel. Indonesian charcoal, even at its lowest quality, typically has a calorific value of around 5000 cal/g (Cocologi, 2023).

2.6.7. Density and Porosity

The density and porosity of charcoal influence its burning characteristics. High-density charcoal burns longer and is preferred for industrial applications requiring sustained heat. Porosity determines ignition ease and combustion rate. Activated charcoal, for example, has high understanding and controlling these quality parameters is essential for producing high-performance charcoal suited for various applications. Proper assessment and adherence to international quality standards ensure efficiency, sustainability, and minimal environmental impact.

2.6.8. Charcoal yield; Caloric Value and Carbon content

Calorific value is a measure of the amount of energy produced from a unit weight of charcoal when it is combusted in oxygen. A measured sample of fuel charcoal is completely combusted in a bomb calorimeter, which is a device for measuring heat (ASTM method D5865; ASTM method 2023).

According to the study Rabi *et al.*,(2020), the charcoal calorific value and yield stated that a high process condition increases the calorific value, which results in a decrease in the charcoal yield. The lowest temperature gives a yield of 70.18 wt. % and calorific value of 25.30 MJ/kg while the highest temperature produces a yield for as low as 26.57 wt. % and a high calorific value of 30.15 MJ/kg. Furthermore, the charcoal yield tends to decrease from 51.99 to 33.10 wt. % and the calorific value increases as the residence time increases from 15 to 45 min.

Over-all charcoal can replace the use of fossil fuels because it presents energy content higher than that of lignite and similar to that of coal. (FAO, 2020; Eric, 2023).

2.7. Challenges and Future Prospects

The forest sector in Ethiopia holds huge potential for biomass energy production, offering a renewable and sustainable energy source. While challenges such as deforestation and inefficient utilization exist, adopting modern bioenergy technologies and sustainable forestry management can enhance the sector's contribution to Ethiopia’s energy security and economic development.

2.8. Summary

The literature review discusses the significant reliance on charcoal and fuel wood for household energy needs in Sub-Saharan Africa, with charcoal production being a common method for processing wood residues. Charcoal is preferred due to its higher energy density and easier handling compared to fuel wood.

However, there are concerns about deforestation caused by charcoal production, with millions of hectares of forests being cleared annually. Despite these concerns, charcoal production serves as a means of livelihood for many in developing nations due to high deficiency levels. Charcoal plays a crucial role in low-income countries, providing income and socioeconomic benefits where access to modern energy sources is limited.

Charcoal is a widely used energy source in many households, providing income and various socioeconomic benefits, especially in areas with limited access to modern energy sources. In Ethiopia, charcoal plays a dominant role in energy consumption, with approximately 90% of the total energy used coming from charcoal and fuel wood. Ethiopia is actually the world's third-largest charcoal producer, with an annual production of over 4.4 million tons. The charcoal business supports around 1.5 million people from over 300,000 households, providing income and livelihood opportunities. It is extensively used for cooking in households, bakeries, restaurants, and small-scale industries.

The literature review also discusses the importance of moisture content and wood density in evaluating wood for charcoal conversion efficiency. Moisture content analysis during charcoal production is essential for consistent and efficient results.

Controlling moisture levels improves charcoal yield. Methods like oven-drying or specialized meters are used to measure moisture content.

Wood density, which varies within and between plant species, is defined as the ratio of oven-dry mass to the mass of water displaced by green volume.

Wood specific gravity measures the amount of wood material in a unit volume. Wood ash is the residue left after wood combustion, with properties varying based on factors like tree species. Hardwoods produce more ash than softwoods, and bark and leaves yield more ash than inner woody parts.

2.9. Gap

However, it's worth noting that charcoal production in many developing countries, including Ethiopia, is not very efficient. This can have negative consequences, such as deforestation and the clearing of forests for charcoal production. It's important to find sustainable and environmentally friendly methods for charcoal production to minimize these consequences and there is a lack of discussion on sustainable charcoal production techniques.

The review mentions that charcoal production is not efficient in most developing countries, including Ethiopia, but does not investigate into specific strategies or technologies that could improve the efficiency and sustainability of charcoal production. Exploring sustainable charcoal production methods could be a valuable addition to the literature, addressing environmental concerns while supporting the livelihoods of communities reliant on charcoal production.

One potential research gap for investigating the effects of tree diameter on the quality of charcoal production from *Acacia decurrens* could be the limited understanding of the optimal tree diameter range for maximizing charcoal quality. While there may be some general knowledge about the importance of tree diameter in charcoal production, there is a lack of specific information on the ideal tree diameter range for *Acacia decurrens*.

This research gap presents an opportunity to investigate the relationship between tree diameter and charcoal quality, determining the specific range of tree diameters that result in the highest quality charcoal. This information would be valuable for informing sustainable harvesting practices and optimizing charcoal production processes.

2.10. Conceptual frame work of the study

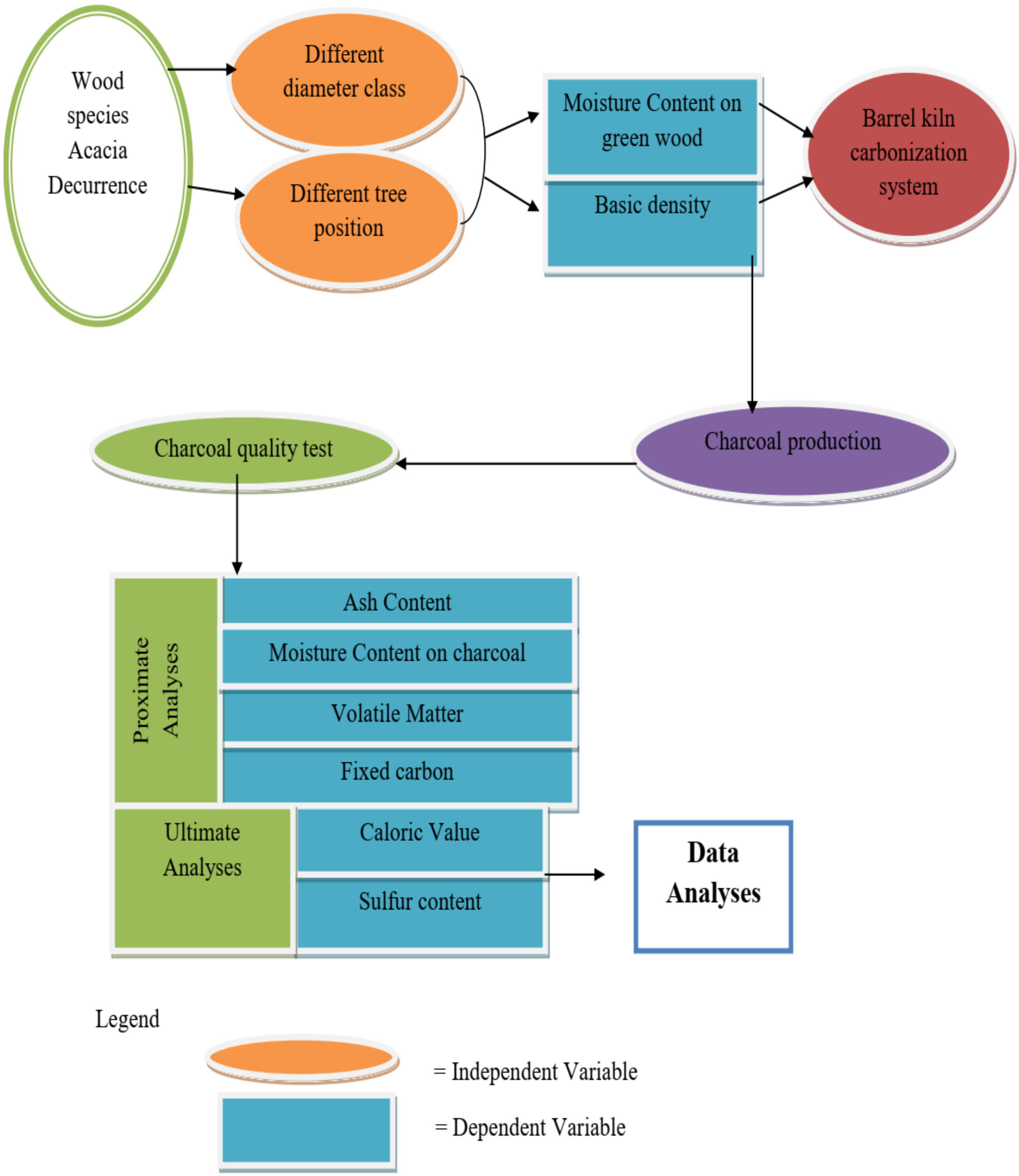


Figure 2-1 Conceptual frame work

CHAPTER THREE

Materials and Methods

3.1. Study Site

3.1.1. Description of the Study Area

The study was conducted in plant management site, it is managed by Ethiopian Forestry Development in -Holeta town near to Addis Ababa during December ,2025. Holeta is situated in the Walmara Woreda of the West Shoa Zone, Oromia Regional State, Ethiopia (Figure 3.1). The Town is located 45 km Southwest of Addis Ababa at latitude of 9° 3' N and longitude of 38° 30' E, with an elevation of 2400 m above sea level. The region experiences a mild subtropical climate, with temperature ranging from 2°C to 9°C in the colder months and 20°C to 27°C in the warmer months. The area has a bimonthly rainfall pattern, with the long rainy season occurring from July to September and a short rainy season from March to April, receiving an annual rainfall of 1060 mm (CSA, 2010).

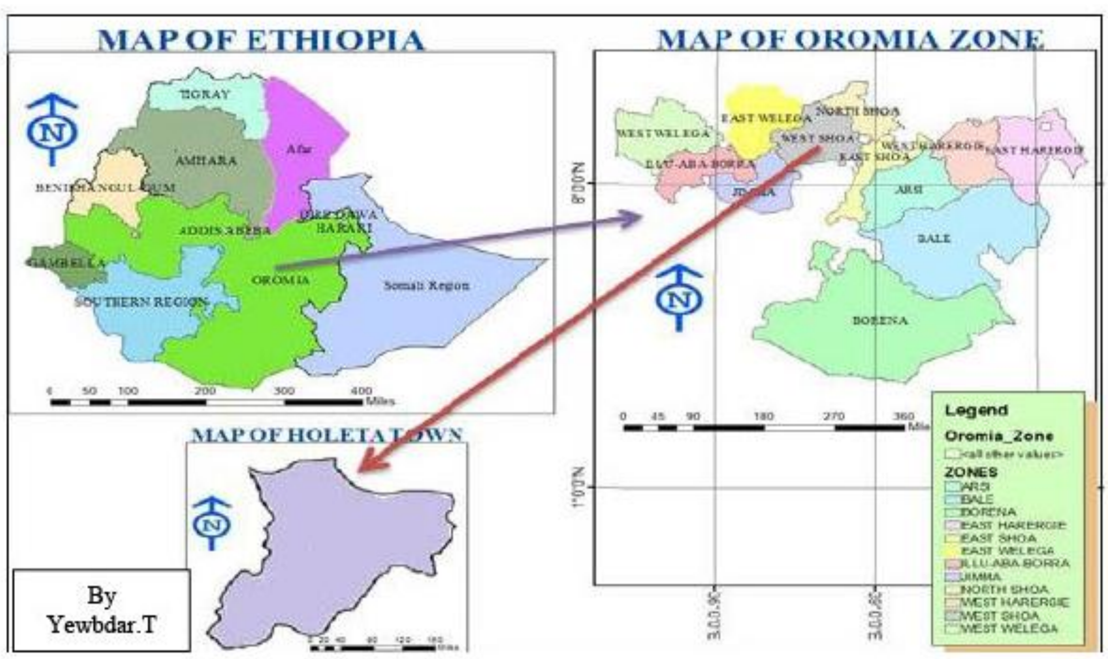


Figure 3-1 Map of the Study Area

3.2. Source and Method of Data Collection

In this study, both primary and secondary data sources were used to collect data for addressing the research questions. The study involved interviews, field observation, focus group discussions, sample preparation and laboratory experiment. The secondary sources of data from published materials and books, official documents, reports, journal articles, and research findings were also used.

Primary Sources of Data: The primary data was collected through systematic and scientific data collection techniques. The study used interviews, field observation, focus group discussions, and sample preparation to collect primary data**.**

Secondary Sources of Data: In this study, used secondary data sources from published materials and books. Published sources like books, journals, articles, and research documents were used. Information from these works of literature is used to construct theoretical frameworks and support the data gained from primary sources.

3.3. Sample Selection, Collection, and Preparation

Twelve *Acacia decurrens* wild trees were randomly selected from natural woodlands plant preservation site Manager at Holeta Town near to Addis Ababa, categorized into four diameter classes (DC): 2 to 4 cm, 4 to 6 cm, 6 to 8 cm and 8 to 10 cm. Before cutting down have to visit a site. So the sample trees have similar soil, climatic conditions and same area. Have to start too harvested from the edge to the middle. It has at the edge 2 to 4 cm and 4 to 6 cm and at the middle 6 to 8 cm, and 8 to 10 cm so by using calipers and role meters has to measure DBH (diameter at breast height). After felling, each tree was sectioned into three equal portions: bottom (lower), middle (center), and top (upper), with each segment representing approximately one-third of the total tree length. Finally, have to take green weight of a sample and given a code.

Table 3-1 Sample selection procedure on tree position and different diameter class

Tree position	Tree diameter classes based on DBH			
	2 to 4 cm	4 to 6 cm	6 to 8 cm	8 to 10 cm
Top	1/3 of L_t (2 to 4 cm)	1/3 of L_t (4 to 6 cm)	1/3 of L_t (6 to 8 cm)	1/3 of L_t (8 to 10 cm)
Medium	1/3 of L_m (2 to 4 cm)	1/3 of L_m (4 to 6 cm))	1/3 of L_m (6 to 8 cm)	1/3 of L_m (8 to 10 cm)
Bottom	1/3 of L_b (2 to 4 cm)	1/3 of L_b (4 to 6 cm)	1/3 of L_b (6 to 8 cm)	1/3 of L_b (8 to 10 cm)

Where:

- **L**: Total tree length
- **t**: Top portion
- **m**: Middle portion
- **b**: Bottom portion

Note: Twelve trees were used per replication in the experiment.

Figure 3-2 Process of sample selection, collection and preparation

3.4. Green Wood Drying and Cutting for Carbonization

The collected *Acacia decurrens* wood was dried in an oven at 105°C for three to five days, reducing moisture content to 13 to 17%. The dried wood was then take dry weight and to do the next step charcoal production to use barrel kiln. These processes have to done in Forest Products Innovation Center of Excellence in Addis Ababa.

Figure 3-3 Wood drying process

3.5. Carbonization and Charcoal Production

Dried *Acacia decurrens* wild logs, sorted by diameter class, were carbonized in a barrel kiln under low-oxygen conditions for 10 hours. The process was monitored by observing changes in smoke color from the kiln's chimneys. When the smoke turned light blue, carbonization was deemed complete (Pennise *et al*., 2001; Kammen and Lew., 2005). The charcoal was then removed, cooled, and weighed to determine the wood-to-charcoal yield. It performed at Ethiopia Ministry of water and energy under national biogas coordination program.

Figure 3-4 Carbonization and charcoal production from *Acacia decurrens*

3.6. Study variables

Independent variables of the study: a) *Acacia decurrens* different diameter class 2 to 4 cm, 4 to 6 cm, 6 to 8 cm and 8 to 10 cm diameter class is the main independent variable under diameter class.

Also we have second independent variables that is height differences (top, middle, bottom). It means I have 2 factors diameter and tree position.

Dependent variables of the study are: moisture content, volatile matter, ash content, fixed carbon and calorific value. Basic density and sulfur content (S).

3.7. Experimental design

This experiments have performed as a completely randomized design (CRD) with a total of two factors.

3.8. Materials and their purposes

Tape measured is an essential tool for layout work, marking cut lines, and verifying measurements during sample preparation.

Figure 3-5 Tape measured

Caliper is a precision measuring instrument used to measure diameter of a sample.

Figure 3-6 Caliper

Analytical balances are an extremely accurate laboratory balance created to precisely measure the mass of an object. Offering a readability up to 0.00001 grams (0.01 mg), analytical balances are frequently used in laboratories. We have to use this material for density.

Figure 3-7 Analytical balances

Sensitive balances (often called top-loading balances) provide less precise measurements for larger quantities (e.g., 0.001g). It is used for measuring green weight, dry weight and charcoal weight of a sample.

Figure 3-8 Sensitive balances

Water bucket is advice used to contain the water for measure the volume of wood by immersing.

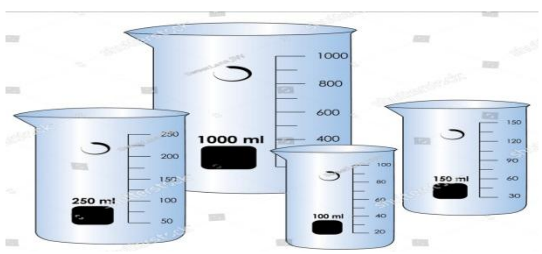


Figure 3-9 Water bucket

Bow saw it is hand tools use to cut the log.

Figure 3-10 *Bow saw*

Laboratory equipment like crucible, pair of tongs, cooling desiccator, electric furnace oven 1 (muffle furnace700±50^{0}C) and Electric furnace oven 2(950^{0}C) are used for performing laboratory activities of energy content and physiochemical properties of *Acacia decurrens* charcoal.

Figure 3-11 charcoal preparation laboratory equipment

Figure 3-12 Laboratory equipment for analyzes

3.9. Physical Properties of Green Wood

3.9.1. Moisture Content Determination

The moisture content (MC) of green wood was determined using the standard oven-drying method (ASTM, 2017). Samples were dried until a constant weight was achieved, and MC was calculated as follows:

$$\mathbf{MC}(\%) = \frac{\mathbf{W1-W2}}{\mathbf{W2}} \times \mathbf{100} \text{ --------------- } \mathbf{Equation\ 1}$$

Where:

- **W_1** = Initial weight
- **W_2** = Weight after drying

3.9.2. Basic Density Determination

Basic density (BD) was measured using Archimedes' principle. The oven-dry mass of a wood sample was divided by its green volume, which was measured using water displacement in a graduated cylinder (ASTM, 2017).

Water displacement is the physical phenomenon that occurs when an object is placed in water, pushing the water out of the way to make room for wood science, water displacement is the standard method used to calculate **wood density**. The formula used:

$$\boldsymbol{BD = \frac{M}{V}} \text{ --------------- } \mathbf{Equation\ 2}$$

Where:

- **BD** = Basic density (g/cm^3)
- **M** = Oven-dry mass (g)
- **V** = Green volume (cm^3)

Figure 3-13 Green wood density measurements

3.10. Proximate Analysis of Charcoal

3.10.1. Moisture Content Determination

Percentage moisture content (MC_{ch}) on dry basis was determined using the standard method ASTM, 2017). One gram of charcoal sample (W1) was weighed and oven dried at 105^{o} C until mass of the sample was constant. The change in weight (W1 − W2) after 1.30 h was then used to determine the sample’s PMC using eq, 3.

$$\boldsymbol{MCch = \left(\frac{W1 - W2}{W1}\right) * 100 - - - - - - - - - - - Equation\ 3}$$

Where

- **W1 = initial weight**
- **W2 = weight after drying, and**
- **MC_{ch} =** the percentage charcoal moisture content.

3.10.2. Volatile Matter Determination

The percentage volatile matter (PVM) was determined using the standard method (ASTM, 2018). Two-gram sample of pulverized charcoal was taken and heated at 950^{0}C for 6 minutes, subsequently cooled in desiccators, and weighed until a constant mass was achieved. The VM was calculated using eq, 4:

$$\mathbf{PVM = (w1 - w2/w1) * 100) - - - - - - - - - - - - - - Equation\ 4}$$

Where,

- **VM** = percentage of volatile matter
- $\mathbf{W_1}$ = original weight of sample
- $\mathbf{W_2}$ = weight of the sample after cooling.

3.10.3. Ash Content Determination

The percentage of ash content (PAC) was determined using standard (ASTM, 2012).The PAC was also determined by heating 1 gm of the pulverized sample in the furnace at a temperature of 550^{o} C for 4 hours and weighed after cooling in a desiccator to obtain the weight of ash. The PAC was determined using eq, 5

$$\mathbf{ASH = (W1 - W2/W1) * 100} - - - - - - - - - - - - - - \boldsymbol{Equation}\ \mathbf{5}$$

Where,

- **W2** = weight of cooled ash
- **W1** = original weight of dry sample
- **ASH** = percentage of ash content.

3.10.4. Fixed Carbon Determination

The percentage of fixed carbon (FC) was determined using (ASTM, 2018) standard by subtracting the sum of VM, AC and MC content from 100 as in eq.6.

$$\boldsymbol{FC} = \mathbf{100\%} - (\boldsymbol{ASH + MCch + VM}) - - - - - - - - - - - - - - \boldsymbol{Equation}\ \mathbf{6}$$

3.11. Ultimate Analysis of Charcoal

3.11.1. Calorific Value Determination

The caloric value (CV) of the produced charcoal was determined by using parr Oxygen bomb calorimeter in accordance with (ASTEM, 2013) standard method. The parr Oxygen bomb Calorimeter was first calibrated using a standard sample of benzoic acid whose known calorific value is 6.32 Kcal/gm. Two gram of the produced charcoal samples were placed in the crucibles and further the bomb calorimeter was operated based on the instruction. The maximum deflection obtained in the galvanometer was converted to energy value of the sample material by comparing the rise in galvanometer deflection with that obtained when a sample of known calorific value of benzoic acid is combusted. Adiabatic calorimeter was used for this process.

3.11.2. Sulfur Content Determination

Sulfur content (S) was determined using the method described by Eschka (ASTM, 2007) standard. One-gram sample was put into a porcelain crucible and mixed with 3 gm of Eschka mixture. The mixture was then covered with 1 gm of Eschka mixture. The crucibles were then put in a cold muffle furnace and heated gradually to 800°C for 60 minutes. The total Sulphur content was calculated using eq.7.

$$\boldsymbol{Total\ sulphur} = (\boldsymbol{A} - \boldsymbol{B}) * \left(\frac{\mathbf{13.738}}{\boldsymbol{C}}\right) - - - - - - - - - - - - - - \boldsymbol{Equation}\ \mathbf{7}$$

Where,

- A = the mass of barium sulphate from the sample
- B = the mass of barium sulphate from the blank
- C = the mass of sample.

3.12. Data Analysis

Data were analyzed using SAS Software (Version 9) and Microsoft Excel (2010). Statistical differences were tested using the Least Significant Difference (LSD) method at $P < 0.001$ (Gomez and Gomez, 1995).

CHAPTER FOUR

Results and Discussions

4.1.1. Characterization of *Acacia decurrens* Wood and Charcoal

The study examined how different diameter classes (DDC) and tree positions (TP) affect charcoal yield (CY) and various wood properties. The findings revealed that the main effects of both DDC and TP significantly influenced CY at $p = 0.0001$. Specifically, DDC notably affected green wood moisture content (MC_{gw}) and the moisture content of *Acacia decurrens* trees' charcoal products (MC_{coal}) at $p = 0.05$.

However, various wood properties such as basic density (BD), volatile matter (VM), fixed carbon (FC), ash content (ASH), caloric value (CV), and sulfur content (S) were not significantly impacted by DDC and TP at $p = 0.05$.

Regarding the interaction effects between DDC and TP, all tested parameters showed no significant effects at $p = 0.05$, except for CY and MC_{gw}, which exhibited significant effects at $p = 0.001$ and $p = 0.05$, respectively (Table 4.1).

These results align with previous research indicating that tree diameter can influence charcoal yield. For instance, a study on *Leucaena leucocephala* found that diameter at breast height (DBH) did not significantly affect bio-char production or its calorific value, suggesting that factors other than diameter may play a more critical role in determining charcoal yield and quality (Syed *et al.*, 2015).

Additionally, research on the impact of wood moisture content has shown that while moisture levels can affect charcoal properties, species and moisture content have little effect on charcoal yield and longitudinal shrinkage but are important for cross-sectional shrinkage (Fernando *et al.*, 2018).

These findings suggest that while DDC and TP can influence certain aspects of charcoal production, other factors, such as wood species and moisture content, also play significant roles in determining the overall quality and yield of charcoal. Generally basic density significantly influenced volumetric shrinkage of wood, the ash content and the apparent density of the charcoal.

Table 4-1 Analysis of variance (ANOVA) for physical properties of green wood, proximate and ultimate analysis on charcoal making with different diameter classes from *Acacia decurrens* trees

Sorce of Varation	DF	Mean Square								
		BD	$MC_{g\ w}$	MC_{coal}	CY	VM	FC	ASH	CV	S
Different Diameter classe	3	0.009 ns	3.63*	1.45 *	289 ***	13.17 ns	8.8 ns	0.7 ns	46231 ns	0.023 ns
Tree Position	2	0.001 ns	1.43 ns	0.19 ns	80 ***	0.36 ns	0.044 ns	0.56 ns	2485 ns	0.028 ns
Interaction Effect	6	0.007 ns	4.53 **	0.51 ns	112.5 ***	4.27 ns	3.57 ns	0.48 ns	15399 ns	0.025 ns
CV		17.45	6.39	27.18	11.51	11.61	4.11	20.7	2.46	189.4
R2		0.29	0.67	0.32	0.92	0.27	0.17	0.52	0.2	0.39
LSD		0.099	1.05	0.75	2.16	2.4	2.96	0.49	183.4	0.15

***= Significant at $p < 0.0001$; **= Significant at $p < 0.01$; *= Significant at $p < 0.05$; ns= non-significant at $p < 0.05$; CV= coefficient variation; LSD= list significant difference

4.2. The main effect of different tree diameter classes and type of tree position on charcoal making process for BD, MC_{coal}, VM, FC, ASH, CV and S

4.2.1. Basic Density (BD) of *Acacia decurrens* Trees

The study examined the main effects of DDC and TP on the BD of *Acacia decurrens* trees have shown that no significant variation in BD across DDCs, with recorded values of 0.62 g/cm³ (4 to 6 cm), 0.58 g/cm³ (2 to 4 cm), 0.58 g/cm³ (8 to 10 cm), and 0.54 g/cm³ (6 to 8 cm), respectively. Similarly, BD remained relatively consistent across TP, with values of 0.58 g/cm³at the top(T) 0.59 g/cm³ at the middle (M) sections, and 0.56 g/cm³ at the bottom (B) (Table 4.2 and Figure 4.1).These findings indicate that neither DDC nor TP had a significant impact on BD in *Acacia decurrens* trees.

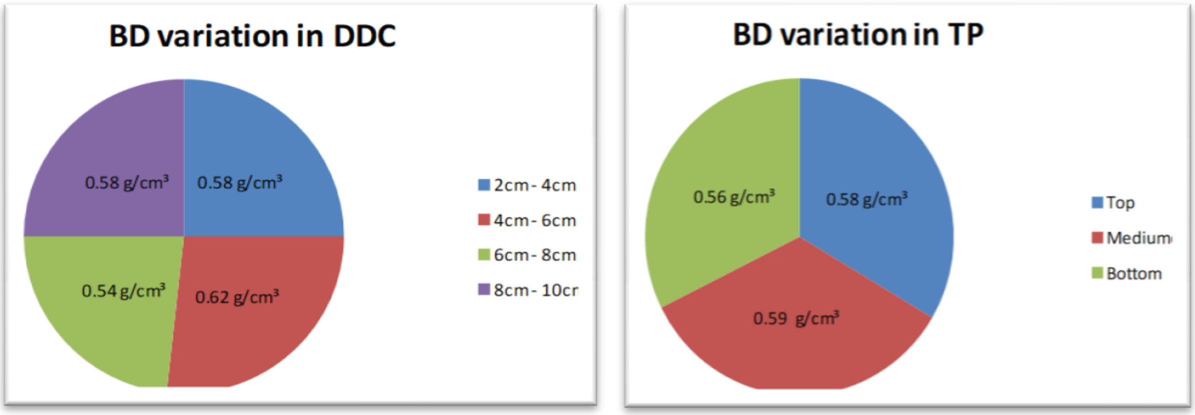


Figure 4-1 BD (g/cm^3) Variation in DDC and TP

The consistency of BD across DDC and TP in this study contrasts with some previous research where variations in BD have been observed due to changes in tree diameter or position. For example, studies by Smith and Johnson, 2020) Fifamè *et al.,* 2022) and Mengistu *et al.*, 2025) reported that tree diameter significantly influenced the basic density of other tree species. Additionally, the effect of TP on BD has been shown to vary depending on environmental conditions and species-specific characteristics. In contrast, the findings in this study align with those of Brown and Clark, 2017 and Chen *et al*., 2017)they found no significant variation in BD with changes in DDC or TP for other species, suggesting that *Acacia decurrens* may not be as sensitive to these factors as some other tree species.

4.2.2. The Moisture Content of Charcoal

The moisture content (MC) of charcoal is a critical factor in determining its quality and combustion efficiency. Research has shown that when the moisture content exceeds 10%, charcoal becomes brittle and tends to break into fine particles upon heating. In contrast, lower moisture content enhances the handling and transportation of charcoal, as it is less prone to breaking. Moreover, increased moisture in firewood charcoal can delay ignition and reduce burning efficiency. This is because higher moisture content leads to an increase in density and a reduction in porosity, which in turn causes slower ignition times (Jarawi and Jusoh, 2023).

In the present study, the moisture content of charcoal (MC_{coal}) was assessed based on tree diameter at breast height (DBH) and tree position (TP). The highest MC_{coal} was observed in trees with a DBH of 2 to 4 cm, which recorded a value of 3.25%. This value was statistically similar to those for

DBH classes of 8 to 10 cm (2.77%) and 4 to 6 cm (2.96%). The lowest MC_{coal} was found in trees with a DBH of 6 to 8 cm, which was 2.29% lower than the maximum value recorded (Table 4.2 and Figure 4.2).

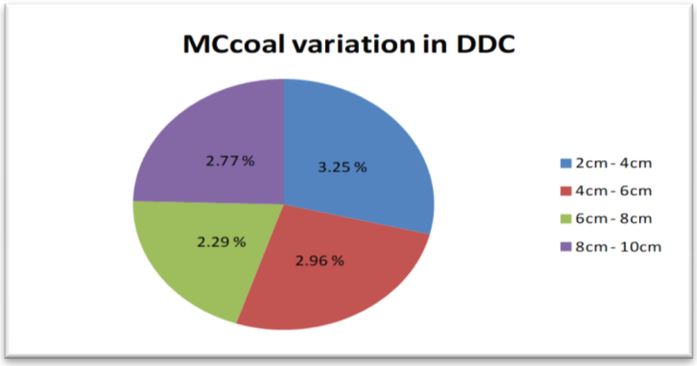


Figure 4-2 MC $_{coal}$ Variation in DDC

These findings suggest that tree size influences the moisture content of charcoal, with smaller diameter trees showing higher moisture content. Additionally, when analyzing the moisture content based on tree position (TP), the values remained relatively consistent across different sections of the tree: 2.71% at the top, 2.79% at the middle, and 2.96% at the bottom. This suggests that TP had a minimal effect on the moisture content of the charcoal.

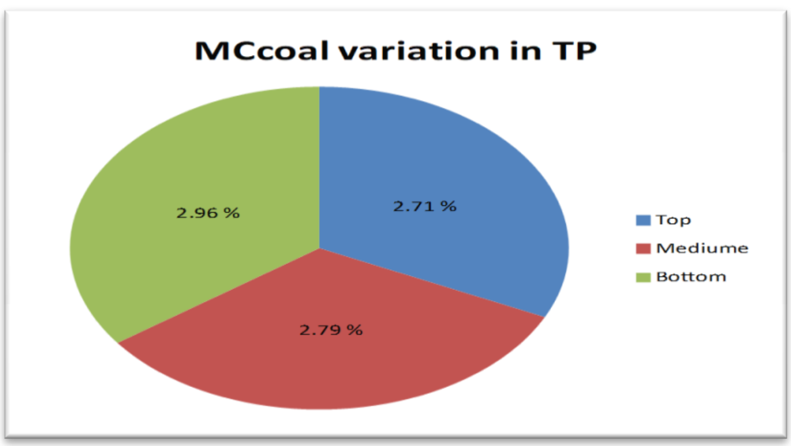


Figure 4-3 MC $_{Coal}$ Variation in TP

These findings are consistent with previous studies on the moisture content of charcoal. For instance,(Jarawi and Jusoh 2023) noted that higher moisture levels in charcoal reduce ignition efficiency and combustion performance. However, unlike some studies that have found more significant variation in moisture content with changes in tree diameter or position (e.g., Smith and

Johnson, 2020), this study observed only a slight variation in moisture content across tree position and a more noticeable effect of DBH.

Smith and Johnson (2020) reported that charcoal from smaller diameter trees tends to have higher moisture content, similar to the present study's findings. They also suggested that moisture content significantly impacts the burning efficiency of charcoal, with values exceeding 10% leading to inefficient combustion. Furthermore, studies by Leonello *et al.,*(2024) have emphasized that a reduction in moisture content improves the handling and transportation of charcoal, a conclusion that aligns with the results observed in this study.

4.2.3. Volatile mater

Several studies have analyzed the impact of volatile matter on charcoal quality and its implications for combustion efficiency. Research suggests that volatile matter content varies depending on the wood species, carbonization conditions, and production methods (Antal and Grønli, 2003; Akowuah *et al.*, 2012; Njenga *et al.*, 2013). High volatile matter charcoals are preferred for applications requiring easy ignition, whereas low volatile matter charcoals are better suited for industrial applications requiring prolonged burn time and minimal smoke emissions.

The results of this study indicate that the effect of volatile matter (VM) on charcoal production from different diameter sections (DS) of *Acacia decurrens* trees was not statistically significant at $p = 0.05$. The highest VM content (22.53%) was recorded in firewood charcoal from the 8 to 10 cm DS, followed by 21.71% and 20.35% in the 4 to 6 cm and 6 to 8 cm DS, respectively. The lowest VM content (19.91%) was observed in the 2 to 4 cm diameter class. Additionally, when comparing VM content across tree positions (TP), statistically uniform values were observed: 20.92% at the top, 21.23% in the middle, and 21.22% at the bottom of the tree.

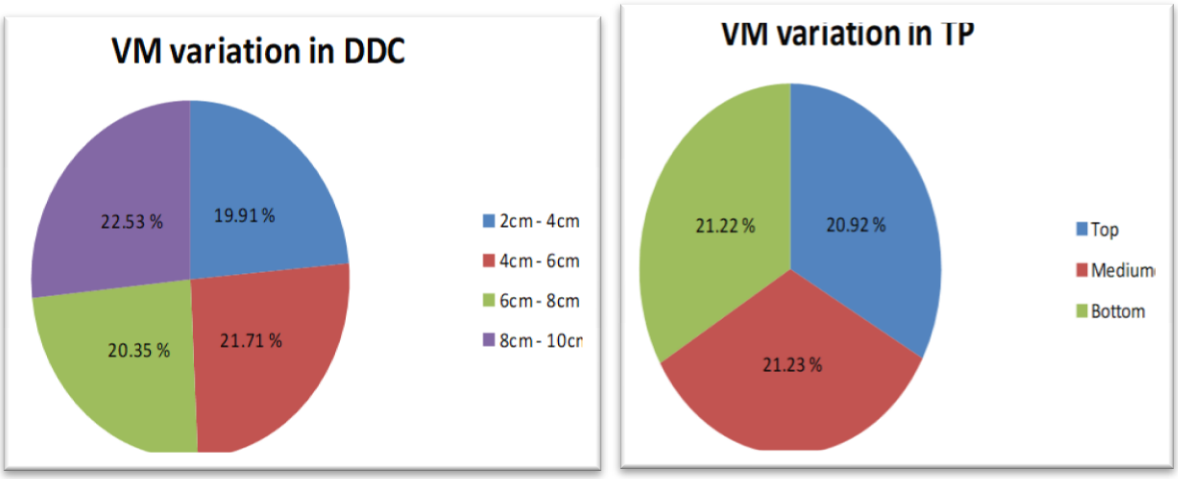


Figure 4-4 VM Variation in DDC and TP

These findings align with previous studies indicating that diameter class and tree position have minimal impact on volatile matter content under controlled carbonization conditions (FAO, 1985; Mencarelli *et al*., 2022).

4.2.4. Fixed Carbon

Fixed carbon (FC) content is a critical determinant of charcoal quality, as it directly affects energy density, combustion duration, and overall fuel performance. Higher fixed carbon levels generally result in longer-lasting combustion, greater heat output, and reduced smoke emission—characteristics that are highly valued in both domestic and industrial fuel applications (Mencarelli *et al.*, 2022). However, charcoal with elevated FC content often contains reduced volatile matter, making it more difficult to ignite initially (Njenga *et al*., 2013).

The FC content of charcoal is primarily influenced by factors such as wood species, carbonization temperature, and pyrolysis duration. Higher carbonization temperatures tend to enhance FC concentration by progressively eliminating volatile compounds and non-carbon constituents, thereby yielding a denser, carbon-rich product (Antal and Grønli, 2003; Akowuah *et al.*, 2012). Species variability also plays a role, as hardwood species typically produce charcoal with higher FC content than softwood counterparts due to their denser lignocellulose structure (FAO, 1985).

In the current study, the FC content of *Acacia decurrens* charcoal was examined across different diameter size classes (DS) and tree parts (TP). The statistical analysis revealed that differences in FC content were not significant at $p = 0.05$. Among the diameter classes, the FC content ranged from 72.65% (8 to 10 cm) to 74.68% (6 to 8 cm), with intermediate values of 72.94% (4 to 6 cm) and 74.25% (2 to 4 cm). Similarly, FC values across different tree positions, top (73.7%), middle (73.62%), and bottom (73.58%), were statistically uniform.

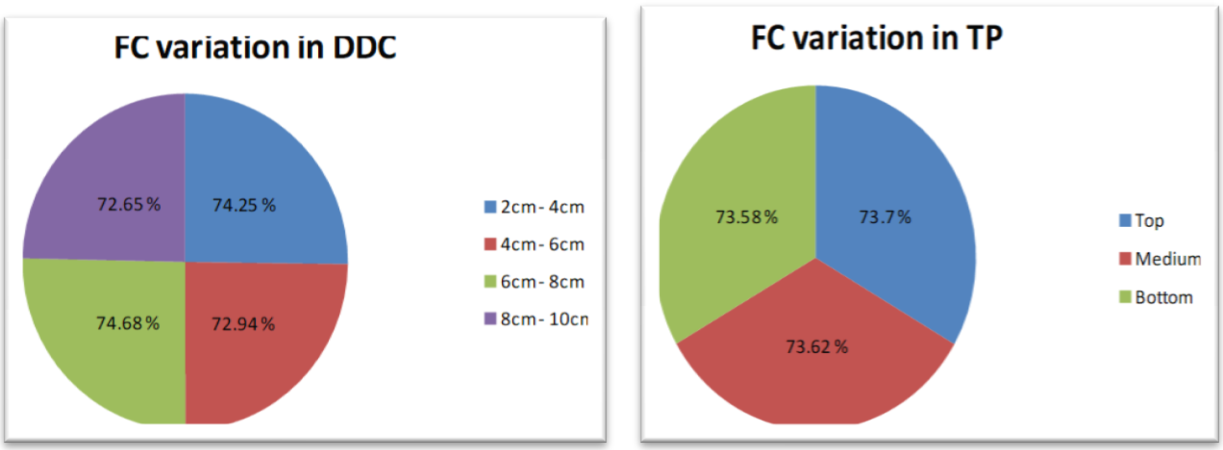


Figure 4-5 FC Variation in DDC and TP

These findings support previous research suggesting that, under standardized carbonization conditions, the influence of tree diameter and position on FC content tends to be negligible (Mencarelli *et al.*, 2022; Austine *et al.*, 2022). Such consistency in FC levels across different tree components enhances the suitability of *Acacia decurrens* for uniform charcoal production and efficient fuel use.

4.2.5. Ash Content

Ash content is a key quality indicator in biomass-based fuels, including charcoal. It refers to the inorganic mineral residue left behind after the complete combustion of the organic matter. High ash content in charcoal is generally undesirable, as it lowers combustion efficiency, increases the amount of unburned residue, and can clog stoves or furnaces, thereby reducing overall user satisfaction (Antal and Grønli, 2003; Mencarelli *et al*., 2022).

Several studies emphasize that reducing ash content enhances fuel quality, especially in domestic and industrial applications. According to Shafizadeh *et al.*,(1981) and Imeh *et al.*,(2007), lower ash content improves the calorific performance and reduces the frequency of stove maintenance. Furthermore, ash content is influenced by multiple factors, including species type, tree part, and carbonization conditions. Generally, hardwood species produce charcoal with lower ash content than softwoods (FAO, 1985; Njenga *et al.*, 2013). Uniform and optimized carbonization processes can also minimize the ash content regardless of tree part or size class (Mencarelli et al., 2022).

In the current study, the ash content of charcoal produced from different diameter size classes (DS) and tree parts (TP) of *Acacia decurrens* was found to be statistically non-significant at $p = 0.05$. Among the diameter classes, the lowest ash content was recorded in the 8 to 10 cm DS (2.05%), although this was not significantly different from the 4 to 6 cm DS (2.39%). The highest ash contents were observed in the 6 to 8 cm DS (2.67%) and 2 to 4 cm DS (2.59%). Similarly, ash content was statistically uniform across tree parts, with values of 2.67% at the top (T), 2.36% at the middle (M), and 2.25% at the bottom (B).

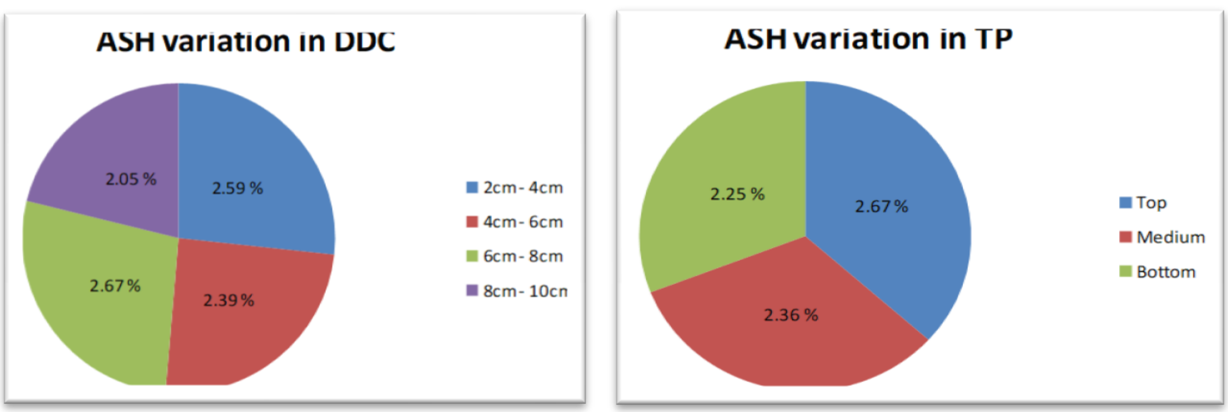


Figure 4-6 ASH Variation in DDC and TP

These findings are consistent with earlier literature, which notes that tree position and diameter class exert minimal influence on ash content under consistent pyrolysis conditions (Imeh *et al.*, 2007; Mencarelli *et al.*, 2022). The relatively low and uniform ash levels observed in this study affirm the suitability of *Acacia decurrens* as a clean and efficient biofuel source, particularly when processed using standardized carbonization techniques.

4.2.6. Calorific Value

The calorific value, also known as the heating value, is a critical parameter in evaluating the energy potential of biomass fuels, particularly charcoal. It represents the amount of heat energy released when a given quantity of a substance undergoes complete combustion under standard conditions. A higher calorific value corresponds to more energy output, making the fuel more efficient for heating and cooking applications (FAO, 1985; Antal and Grønli, 2003).

The calorific value of charcoal depends on multiple factors, including the type of biomass feedstock, carbonization conditions, and moisture content. Numerous studies have investigated the calorific potential of various wood species and their derived charcoals. For instance, Akowuah *et al.*,2012 reported high calorific values for *Anogeissus leiocarpus* charcoal, demonstrating its suitability for domestic energy use. Similarly, Njenga *et al.*,(2013) found that agroforestry tree prunings produced charcoal with consistent heating performance. Mencarelli *et al.*,(2022) emphasized that controlled pyrolysis and uniform carbonization procedures help maintain stable calorific values across different wood sections.

In the present study, the main effects of diameter size classes (DS) and tree parts (TP) on the calorific value of *Acacia decurrens* charcoal were found to be statistically non-significant at the p = 0.05 probability level. The calorific values across the selected DS were comparable, recorded as 7738 cal/g for 2 to 4 cm, 7595 cal/g for 4 to 6 cm, 7596 cal/g for 6 to 8 cm, and 7592 cal/g for 8 to 10 cm. Similarly, tree part values were closely clustered: 7643 cal/g for the top (T), 7632 cal/g for the middle (M), and 7615 cal/g for the base (B) sections.

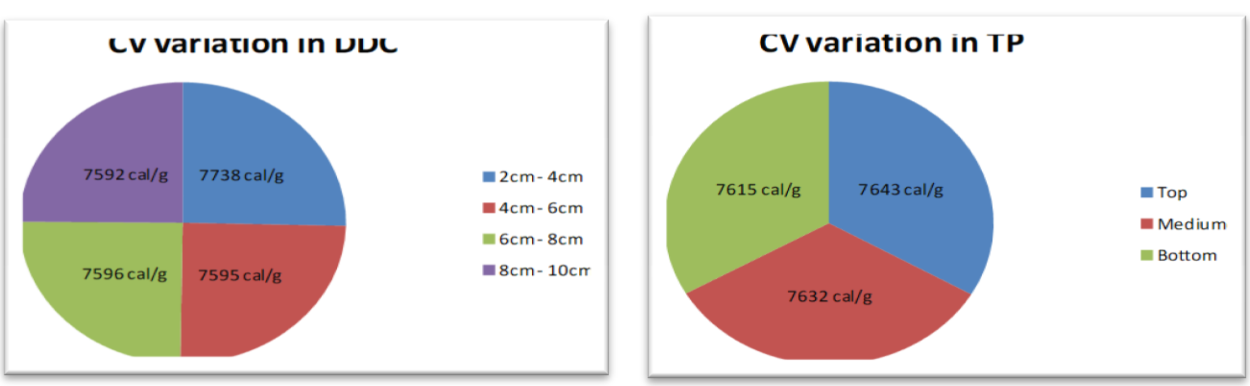


Figure 4-7 CV cal/g Variation in DDC and TP

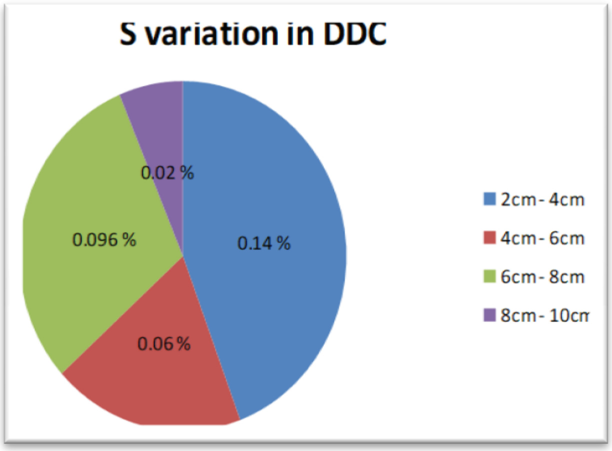
These findings align with previous research indicating that when carbonization is performed under consistent and optimized conditions, the calorific value of charcoal remains relatively uniform across different parts and sizes of the same tree species (FAO, 1985; Mencarelli *et al*., 2022). This reinforces the suitability of *Acacia decurrens* as a viable bioenergy source and highlights the reliability of its energy output regardless of minor physical differences in feedstock.

4.2.7. Sulfur Content

Sulfur content in charcoal refers to the concentration of sulfur compounds originating from the raw biomass and retained in the final product following carbonization. Elevated sulfur levels are undesirable as they can result in the emission of sulfur dioxide (SO_2) during combustion, a major pollutant that contributes to environmental issues such as acid rain and atmospheric contamination (FAO, 1985; Njenga *et al.*, 2013). SO_2 emissions also have serious public health implications, including respiratory and cardiovascular conditions, particularly in indoor environments where charcoal is commonly used (Akowuah *et al.*, 2012).

The selection of biomass with inherently low sulfur content is critical for the production of cleaner-burning charcoal. Studies have shown that sulfur levels in charcoal are influenced by both the type of feedstock and the carbonization conditions (Antal and Grønli, 2003; Njenga *et al*., 2013). According to the FAO (1985), monitoring sulfur content is essential in charcoal quality assessment, especially for charcoal intended for domestic or industrial use where emissions standards may apply.

In the current study, the main effects of sulfur content across different diameter size classes (DS) and tree parts (TP) of *Acacia decurrens* were found to be statistically non-significant at the $p = 0.05$ probability level. The recorded sulfur content ranged from 0.02% to 0.14% across diameter classes and from 0.03% to 0.13% across tree parts.



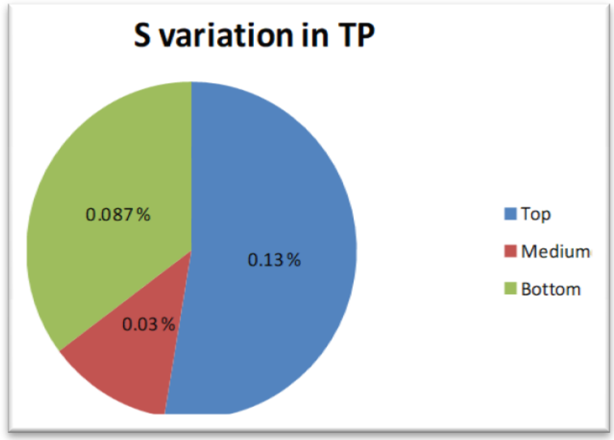


Figure 4-8 Sulfur Variation in DDC and TP

These values fall within the acceptable thresholds for clean charcoal production and suggest that *Acacia decurrens* is a suitable feedstock in terms of environmental safety and emission control.

These findings are consistent with prior studies highlighting the low sulfur emission potential of certain agroforestry and native species used in bioenergy systems (Akowuah *et al.*, 2012; Njenga *et al.*, 2013). The relatively narrow range and low percentages observed in this study reaffirm the role of species selection in minimizing environmental impact during biomass energy conversion.

Table 4-2 Main effects of different diameter class and tree position on charcoal making process for basic density, green wood moisture content, volatile matter, fixed carbon, ash content, caloric value and Sulphur content.

Treatments	Mean Separation						
Diameter classe	**BD**	**MC_{coal}**	**VM**	**FC**	**ASH**	**CV**	**S**
2cm - 4cm	0.58 ^{a}	3.25 ^{a}	19.91 ^{b}	74.25 ^{a}	2.59 ^{a}	7738 ^{a}	0.14 ^{a}
4cm - 6cm	0.62 ^{a}	2.96 ^{ab}	21.71 ^{ab}	72.94 ^{a}	2.39 ^{ab}	7595 ^{a}	0.06 ^{a}
6cm - 8cm	0.54 ^{a}	2.29 ^{b}	20.35 ^{ab}	74.68 ^{a}	2.67 ^{a}	7596 ^{a}	0.096 ^{a}
8cm - 10cm	0.58 ^{a}	2.77 ^{ab}	22.53 ^{a}	72.65 ^{a}	2.05 ^{b}	7592 ^{a}	0.02 ^{a}
Tree position							
Top	0.58 ^{a}	2.71 ^{a}	20.92 ^{a}	73.7 ^{a}	2.67 ^{a}	76.43 ^{a}	0.13 ^{a}
Mediume	0.59 ^{a}	2.79 ^{a}	21.23 ^{a}	73.62 ^{a}	2.36 ^{a}	7632 ^{a}	0.03 ^{a}
Bottom	0.56 ^{a}	2.96 ^{a}	21.22 ^{a}	73.58 ^{a}	2.25 ^{a}	7615 ^{a}	0.087 ^{a}
t- Value	2.07	2.07	2.07	2.07	2.07	2.07	2.07

Note; BD Basic Density, MC_{coal} Moisture Content of Charcoal, VM Volatile Matter, FC Fixed Carbon, ASH Ash Content, CV Caloric value and S Sulfur Content

4.3. Interaction effect of different tree diameter classes and type of tree position on green wood moisture content and charcoal yield from *Acacia decurrens* trees

4.3.1. Green Wood Moisture Content

Green wood moisture content refers to the amount of water present in freshly cut wood prior to any drying or seasoning process. This property is a critical factor in charcoal production, as it directly influences both the yield and quality of the final product. High moisture content in wood reduces carbonization efficiency and leads to poor-quality charcoal with lower calorific value (FAO, 1987). Therefore, it is generally recommended that would be dried to a moisture content of 20% or less before undergoing carbonization to ensure optimal results (Bridgewater *et al.*, 2000; Antal *et al.*, 2003).

Several studies emphasize the importance of pre-drying wood to improve pyrolysis efficiency and product consistency. For instance, Antal *et al*.,(2003) demonstrated that lower moisture levels result in higher fixed carbon content and improved charcoal structure. Similarly, (FAO, 1987; Bridgewater *et al.*, 2000 ; Mengistu *et al*., 2025) have highlighted moisture reduction as a critical pre-treatment step in biomass-to-energy conversion systems.

In the present study, the interaction effect of diameter class (DC) and tree part (TP) on the green wood moisture content of *Acacia decurrens* showed statistically significant differences at the p = 0.05 level. The lowest green wood moisture content was observed in the 4 to 6 cm diameter class (T branch section), with a recorded value of 13.6%. This was followed by the 2 to 4 cm diameter class (M section), which showed a moisture content of 15.82%.

Conversely, the highest moisture content was found in the 6 to 8 cm diameter class (M section), reaching 18.14%, followed by the 8 to 10 cm class (B and M sections), with moisture contents of 16.94% and 17.54%, respectively—values that were not statistically different. Overall, the 4 to 6 cm diameter class demonstrated the lowest green wood moisture content, at 25.03%, which is notably lower than the maximum recorded value, confirming the significant variability of moisture distribution across tree parts and size classes (Table 4.3 and Figure 4.9).

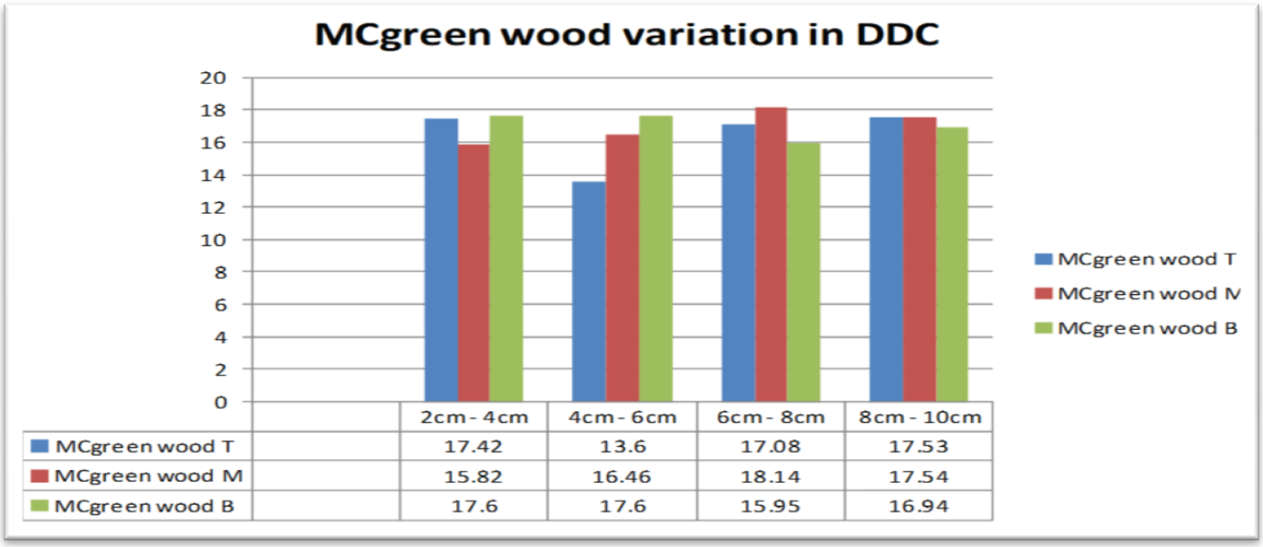


Figure 4-9MC $_{\text{green wood}}$ Variation in DDC

These findings align with existing literature, reinforcing the principle that smaller diameter classes and certain tree parts tend to retain less moisture and are, therefore, more suitable for efficient charcoal production.

4.3.2. Charcoal Yield

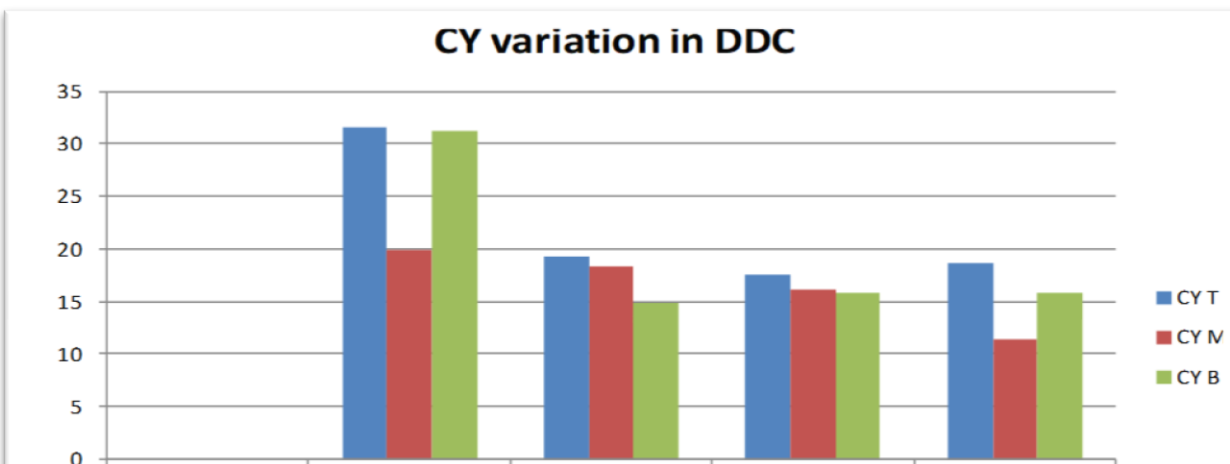
Charcoal yield—the proportion of solid charcoal obtained from a given amount of dry wood—is a key indicator of the efficiency of the carbonization process and the suitability of feedstock for fuel production. Multiple factors influence charcoal yield, including wood species, initial moisture content, carbonization temperature, method used, and post-carbonization handling (FAO, 1987; Bridgwater *et al*., 2000; Antal and Grønli, 2003).

The type of wood used is among the most critical determinants. Hardwoods, due to their dense structure, generally produce a higher yield and denser charcoal than softwoods. The moisture content of wood before carbonization significantly affects both efficiency and quality. It is recommended that the wood air-dried to moisture content of 20% or lower to ensure higher carbonization efficiency and minimize energy loss during drying (FAO, 1987; Antal and Grønli, 2003).

Carbonization temperature is another vital factor. Lower temperatures (around 300°C) tend to yield more volatile matter and tars, resulting in lower fixed carbon and increased smoke, while higher temperatures (500 to 600°C) facilitate greater fixed carbon retention, enhancing the overall quality and energy density of the charcoal (FAO, 1987; Antal and Grønli, 2003).

The carbonization method also plays a key role—modern kilns like retorts typically produce more uniform and energy-dense charcoal than traditional methods such as earth pits, which are often less efficient and result in higher material loss (FAO, 1987). Furthermore, post-carbonization handling—including cooling and storage practices—can significantly affect charcoal quality, as improper handling may lead to moisture absorption and reduced combustion efficiency (FAO, 1987).

In the current study, the interaction between diameter class (DC) and tree part (TP) significantly affected the charcoal yield of *Acacia decurrens*. The highest statistically uniform yields were recorded at the top (T) and middle (M) tree positions for the 2 to 4 cm DC, with values of 31.55% and 31.24%, respectively. This was followed by a yield of 19.90% observed at the middle and bottom positions for DCs of 2 to 4 cm and 4 to 6 cm, respectively. The lowest charcoal yield was recorded at the 8 to 10 cm DC, specifically from the middle tree section, at 11.48%. Overall, the highest charcoal yield in this study reached 63.61%, associated with the smallest diameter class (2 to 4 cm), underscoring the influence of wood size and tree part on charcoal productivity. It is calculated by Yield = (charcoal dry weight / initial dry wood weight) × 100".



	2cm - 4cm	4cm - 6cm	6cm - 8cm	8cm - 10cm
CY T	31.55	19.22	17.56	18.7
CY M	19.9	18.35	16.17	11.48
CY B	31.24	14.9	15.82	15.79

Figure 4-10 CY Variation in DDC

These findings align with existing literature, which indicates that smaller diameter wood and upper tree parts, due to their lower density and moisture retention, often carbonize more completely and efficiently (FAO, 1987; Antal and Grønli, 2003). Understanding such relationships is essential for optimizing charcoal production systems for both fuel efficiency and sustainability.

Table 4-3 Interaction effects of diameter classes and tree position on green wood moisture content and charcoal yield of *Acacia decurrens* wood charcoal

Diameter classe	$MC_{green\ wood}$			CY		
	T	M	B	T	M	B
2cm - 4cm	17.42 ^{ab}	15.82 ^{b}	17.6 ^{ab}	31.55 ^{a}	19.9 ^{b}	31.24 ^{a}
4cm - 6cm	13.6 ^{c}	16.46 ^{ab}	17.6 ^{ab}	19.22 ^{bc}	18.35 ^{bcd}	14.9 ed
6cm - 8cm	17.08 ^{ab}	18.14 ^{a}	15.95 ^{b}	17.56 ^{bcd}	16.17 ^{bcd}	15.82 ^{cd}
8cm - 10cm	17.53 ^{ab}	17.54 ^{ab}	16.94 ^{ab}	18.70 ^{bcd}	11.48 ^{e}	15.79 ^{cd}
LSD	1.82			3.74		
T- value	2.07					

Note; MC green wood; Moisture Content of Green Wood and CY; Charcoal Yield

CHAPTER FIVE

Conclusions and Recommendations

5.1. Conclusions

The findings of present study confirm that diameter class and tree position play selective but crucial roles in influencing certain characteristics or charcoal and green wood. While most chemical properties remain stable, smaller diameter classes and upper tree sections appear more favorable for achieving higher yield and improved moisture profiles, making them more suitable for efficient charcoal production. These insights can inform stainable wood harvesting and charcoal processing strategies for energy-efficient biofuel applications.

It was found that charcoal Yield (CY) was significantly influenced by both DDC and TP at $p< 0.0001$, with the highest yield (63.61%) observed in trees with a 2 to 4 cm diameter, particularly from the top and middle sections. This suggests that smaller diameter classes may be more efficient for charcoal production.

Green wood moisture content (MC_{gw}) was also significantly affected by DDC ($P < 0.05$). Moisture content varied across diameter sizes and tree positions, with lower MC_{gw} generally associated with better quality charcoal.

Conversely, basic density (BD), charcoal moisture content (MC_{coal}), volatile matter (VM), fixed carbon (FC), ash content (ASH), caloric value (CV) and sulfur content (S) showed no significant differences across DDC and TP. This indicates that these properties are relatively stable regardless of tree size or section, highlighting the robustness of *Acacia decurrens* as a charcoal source.

Notably, interaction effects between DDC and TP were statistically significant only for CY and MC_{gw} while other parameters remained unaffected. This underscores the important of considering both diameter and position simultaneously when targeting higher charcoal yield and better moisture. This study is limited to one species, one location, and barrel kiln technology.

5.2. Recommendations

The current study provides valuable insights into the fuel wood and charcoal characteristics of *Acacia* decurrens, with a focus on properties such as basic density, moisture content, volatile matter, fixed carbon, ash content, calorific value, sulfur content, green wood moisture content, and charcoal yield. While many of the evaluated parameters showed limited variation across diameter size classes (DS) and tree parts (TP), the study also highlights several key areas where further investigation is necessary. Future research should consider the following directions.

Species Comparison Under Similar Condition Comparative studies involving other native or exotic tree species, processed under identical carbonization conditions, are essential to contextualize the performance of *Acacia decurrens*.

Carbonization Process Optimization Further research should examine how variations in carbonization parameters, such as temperature, duration, and method (e.g., earth kiln vs. retort kiln), affect the physicochemical properties of *Acacia decurrens* charcoal. Controlled experiments may uncover subtle differences in fuel quality that were not evident under uniform pyrolysis conditions.

Assessment of Tree Age and Growth Conditions Since the current study did not assess the influence of tree age or site-specific growth conditions, further work could explore how these variables impact wood structure, moisture distribution, and ultimate charcoal yield and quality.

Charcoal Briquetting and Blending Potential Investigating the potential for converting *Acacia decurrens* charcoal into briquettes, or blending it with agricultural residues, could broaden its applicability and enhance fuel efficiency, especially for urban markets and institutional use.

Life Cycle Assessment (LCA) and Sustainability Metrics A full LCA, including carbon footprint analysis and sustainability metrics for harvesting, transport, processing, and end use of *Acacia decurrens*, would provide a comprehensive picture of its environmental viability as a bioenergy source. Conducting such a detailed assessment would provide clearer scientific evidence on whether *Acacia decurrens* can serve as an environmentally sustainable and economically viable alternative energy resource in the long term.

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Annex

Annex 1 Basic Density Final Result

Basic Density						
Label	Duplication	Volume in Ml	Mass 1 in gram	Mass 2 in gram	Basic Density	Average
2-4B	B1	23.00	20.90	13.66	0.59	0.54
	B2	30.00	23.35	15.11	0.50	
	B3	15.00	12.33	7.74	0.52	
2-4M	M1	20.00	20.15	12.64	0.63	0.64
	M2	20.00	19.56	12.70	0.64	
	M3	10.00	10.10	6.38	0.64	
2-4T	T1	15.00	17.02	10.71	0.71	0.58
	T2	13.00	8.42	10.32	0.79	
	T3	22.00	16.38	5.28	0.24	
4-6B	B1	60.00	61.09	37.86	0.63	0.56
	B2	80.00	54.82	33.88	0.42	
	B3	42.00	42.25	26.42	0.63	
4-6M	M1	65.00	55.68	34.04	0.52	0.61
	M2	39.00	40.74	25.46	0.65	
	M3	50.00	49.96	32.01	0.64	
4-6T	T1	47.00	54.87	33.72	0.72	0.69
	T2	34.00	36.89	23.03	0.68	
	T3	40.00	43.04	26.64	0.67	
4-8B	B1	110.00	105.08	65.33	0.59	0.58
	B2	120.00	107.33	66.14	0.55	
	B3	137.00	134.22	80.30	0.59	
4-8M	M1	100.00	86.75	52.03	0.52	0.55
	M2	89.00	82.83	51.37	0.58	
	M3	107.00	94.92	58.29	0.54	
4-8T	T1	90.00	75.92	45.18	0.50	0.49
	T2	104.00	86.26	53.00	0.51	
	T3	77.00	55.02	34.49	0.45	
8-10B	B1	186.00	183.26	105.40	0.57	0.59
	B2	173.00	170.02	106.88	0.62	
	B3	145.00	139.17	82.96	0.57	
8-10M	M1	167.00	143.53	87.10	0.52	0.57
	M2	210.00	199.40	125.06	0.60	
	M3	123.00	118.85	73.10	0.59	
8-10T	T1	137.00	122.00	74.26	0.54	0.58
	T2	104.00	101.83	61.81	0.59	
	T3	154.00	143.57	90.75	0.59	

Annex 2 Moisture Content Final Result

	Moisture content				
Label	Duplication	W1	WO	MC	Average
	B1	214.00	178.00	16.82%	
	B2	390.00	323.00	17.18%	
2-4B	B3	330.00	268.00	18.79%	17.60%
	M1	328.00	271.00	17.38%	
	M2	320.00	270.00	15.63%	
2-4M	M3	173.00	148.00	14.45%	15.82%
	T1	280.00	228.00	18.57%	
	T2	280.00	233.00	16.79%	
2-4T	T3	148.00	123.00	16.89%	17.42%
	B1	953.00	790.00	17.10%	
	B2	1030.00	853.00	17.18%	
6-4B	B3	849.00	692.00	18.49%	17.59%
	M1	942.00	794.00	15.71%	
	M2	851.00	699.00	17.86%	
6-4M	M3	804.00	677.00	15.80%	16.46%
	T1	578.00	505.00	12.63%	
	T2	709.00	613.00	13.54%	
6-4B	T3	888.00	758.00	14.64%	13.60%
	B1	1711.00	1451.00	15.20%	
	B2	1616.00	1355.00	16.15%	
6-8B	B3	1611.00	1345.00	16.51%	15.95%
	M1	1427.00	1171.00	17.94%	
	M2	1541.00	1261.00	18.17%	
6-8M	M3	1279.00	1045.00	18.30%	18.14%
	T1	1055.00	893.00	15.36%	
	T2	1259.00	1039.00	17.47%	
6-8T	T3	1396.00	1139.00	18.41%	17.08%
	B1	2116.00	1769.00	16.40%	
	B2	2168.00	1796.00	17.16%	
8-10B	B3	2823.00	2336.00	17.25%	16.94%
	M1	1875.00	1529.00	18.45%	
	M2	1876.00	1575.00	16.04%	
8-10M	M3	2588.00	2119.00	18.12%	17.54%
	T1	1770.00	1459.00	17.57%	
	T2	1677.00	1367.00	18.49%	
8-10T	T3	2264.00	1890.00	16.52%	17.53%

Annex 3 Analysis Report Final Result

GEOLOGICAL INSTITUTE OF ETHIOPIA	Doc. Number: GLD/F5.10.2	Version No: 1
Geochemical Laboratory Desk		Page 1of 1
Document Title:- Hydrocarbon Analysis Report	Effective date:	Nov. 2022

Customer Name :- Yewbdar Tilahun Haile

Sample type:-Charcoal

Sample Preparation:- 60 Mesh

Date Submitted:-17/12/2024

Issue Date:- 17/02/2025

Request No:-GLD/RN/700/25

Report No:- GLD/TR/4421/25

Number of Sample: Thirty six(36)

Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash), Calories & Sulfur.

Method of analysis:- Proximate Analysis, Adiabatic Calorie Metter and Gravimetric Method.

Collectors' Code	Moisture %	Volatile Matter %	Fixed carbon %	Ash %	Calorific Value cal/gm	sulfur%	Weight of Sample
T1-6-8	2.56	20.04	73.10	4.30	7650.03	0.09	179gm
B1-6-8	2.47	21.41	73.92	2.20	7579.75	0.35	117gm
M1-6-8	2.39	23.81	70.90	2.89	7408.94	<0.02	174gm
T2-6-8	2.27	19.08	76.18	2.46	7574.89	0.30	153gm
M2-6-8	2.01	19.72	76.39	1.87	7723.60	<0.02	123gm
B2-6-8	2.53	22.48	72.74	2.25	7405.15	<0.02	46gm
T3-6-8	2.37	20.19	74.10	3.33	7475.59	<0.02	115gm
M3-6-8	2.06	18.06	77.39	2.49	7796.35	<0.02	180gm
B3-6-8	1.98	18.34	77.43	2.25	7749.45	<0.02	191gm
T2-8-10	2.24	19.42	76.01	2.33	7624.61	<0.02	214gm
M2-8-10	3.64	25.54	67.90	2.92	7587.00	<0.02	120gm
B2-8-10	3.31	25.14	69.83	1.72	7446.60	<0.02	98gm
T1-8-10	2.54	22.43	73.12	1.91	7497.59	0.04	266gm
M1-8-10	2.47	22.56	72.88	2.08	7424.24	<0.02	169gm
B1-8-10	2.99	21.38	74.03	1.60	7609.70	<0.02	150gm
T3-8-10	2.63	23.50	71.93	1.94	7739.13	<0.02	217gm
M3-8-10	2.66	20.81	74.33	2.21	7718.53	<0.02	136gm
B3-8-10	2.48	21.98	73.82	1.72	7677.59	<0.02	163gm
T2-4-6	2.99	21.00	73.01	2.99	7785.52	<0.02	100gm
M2-4-6	2.64	23.22	71.91	2.23	7647.37	<0.02	94gm
B2-4-6	2.91	21.79	73.22	2.08	7645.29	<0.02	64gm

Geochemical Laboratory Desk

Page 1

	GEOLOGICAL INSTITUTE OF ETHIOPIA	Doc. Number: GLD/F5.10.2	Version No: 1
	Geochemical Laboratory Desk		Page 1of 1
Document Title:-	Hydrocarbon Analysis Report	Effective date:	Nov. 2022

T3-4-6	2.41	22.56	72.70	2.33	7589.52	<0.02	94gm
M3-4-6	2.28	19.44	75.72	2.56	7573.56	<0.02	135gm
T1-4-6	3.40	22.87	71.49	2.24	7492.24	<0.02	56gm
M1-4-6	4.20	23.26	70.68	1.86	7440.37	<0.02	103gm
B1-4-6	2.98	19.63	74.45	2.94	7622.62	0.42	114gm
B3-4-6	2.85	21.61	73.24	2.30	7559.87	<0.02	120gm
B3-2-4	2.85	19.90	74.34	2.91	7578.66	0.03	68gm
M3-2-4	2.50	16.86	78.00	2.64	8131.57	0.04	32gm
T3-2-4	4.07	22.17	70.92	2.84	7650.45	<0.02	25gm
T2-2-4	2.21	16.48	79.22	2.08	7907.66	0.80	40gm
B3-2-4	5.66	24.58	67.82	1.95	7451.41	0.06	37gm
M3-2-4	4.02	20.97	73.39	1.61	7442.89	0.06	16gm
B1-2-4	2.48	16.39	78.08	3.05	8049.87	0.04	42gm
M1-2-4	2.61	20.51	73.90	2.99	7694.90	0.08	53gm
T1-2-4	2.84	21.34	72.56	3.26	7730.60	0.15	46gm

Note: - This result represent only for the sample submitted to the laboratory.

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Quality Control
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Annex 4 All Final Data

R	DC	TP	BD	$MC_{green\ wood}$	MC_{carcol}	CY	VM	FC	ASH	CV	S
1	1	B	0.59	16.82	2.48	34.83	16.39	78.08	3.05	8049.87	0.04
2	1	B	0.50	17.18	2.85	29.41	19.9	74.34	2.91	7578.66	0.03
3	1	B	0.51	18.79	5.66	29.48	24.58	67.82	1.95	7451.41	0.06
1	1	M	0.63	17.38	2.61	19.56	20.51	73.9	2.99	7694.9	0.08
2	1	M	0.63	15.63	2.5	18.52	16.86	78	2.64	8131.57	0.04
3	1	M	0.64	14.45	4.02	21.62	20.97	73.39	1.61	7442.89	0.06
1	1	T	0.71	18.57	2.84	29.82	21.34	72.56	3.26	7730.6	0.15
2	1	T	0.79	16.79	2.21	26.61	16.48	79.22	2.08	7907.66	0.8
3	1	T	0.24	16.89	4.07	38.21	22.17	70.92	2.84	7650.45	0.02
1	2	B	0.62	17.10	2.98	14.43	19.63	74.45	2.94	7622.62	0.42
2	2	B	0.42	17.18	2.91	14.54	21.79	73.22	2.08	7645.29	0.02
3	2	B	0.63	18.49	2.85	15.75	21.61	73.24	2.3	7559.87	0.02
1	2	M	0.52	15.71	4.2	18.51	23.26	70.68	1.86	7440.37	0.02
2	2	M	0.65	17.86	2.64	16.60	23.22	71.91	2.23	7647.37	0.02
3	2	M	0.64	15.80	2.28	19.94	19.44	75.72	2.56	7573.56	0.02
1	2	T	0.72	12.63	3.4	19.41	22.87	71.49	2.24	7492.24	0.02
2	2	T	0.68	13.54	2.99	19.90	21	73.01	2.99	7785.52	0.02
3	2	T	0.66	14.64	2.41	18.34	22.56	72.7	2.33	7589.52	0.02
1	3	B	0.59	15.20	2.47	16.13	21.41	73.92	2.2	7579.75	0.35
2	3	B	0.55	16.15	2.53	15.50	22.48	72.74	2.25	7405.15	0.02
3	3	B	0.59	16.51	1..98	15.84	18.34	77.43	2.25	7749.45	0.02
1	3	M	0.52	17.94	2.39	15.97	23.81	70.9	2.89	7408.94	0.02
2	3	M	0.58	18.17	2.01	15.31	19.72	76.39	1.87	7723.6	0.02
3	3	M	0.54	18.30	2.06	17.22	18.06	77.39	2.49	7796.35	0.02
1	3	T	0.50	15.36	2.56	20.04	20.04	73.1	4.3	7650.03	0.09
2	3	T	0.51	17.47	2.27	16.84	19.08	76.18	2.46	7574.89	0.3
3	3	T	0.45	18.41	2.37	15.80	20.19	74.1	3.33	7475.59	0.02
1	4	B	0.57	16.40	2.99	16.34	21.38	74.03	1.6	7609.7	0.02
2	4	B	0.62	17.16	3.31	16.59	25.14	69.83	1.72	7446.6	0.02
3	4	B	0.57	17.25	2.48	14.43	21.98	73.82	1.72	7677.59	0.02
1	4	M	0.52	18.45	2.47	10.60	22.56	72.88	2.08	7424.24	0.02
2	4	M	0.59	16.04	3.64	10.73	25.54	67.9	2.92	7587	0.02
3	4	M	0.59	18.12	2.66	13.12	20.81	74.33	2.21	7718.53	0.02
1	4	T	0.54	17.57	2.54	19.74	22.43	73.12	1.91	7497.59	0.04
2	4	T	0.59	18.49	2.24	17.26	19.42	76.01	2.33	7624.61	0.02
3	4	T	0.59	16.52	2.63	17.51	23.5	71.93	1.94	7739.13	0.02

Note DC 1=2-4 cm DC2=4-6 cm, DC3=6-8cm and DC4= 8-10cm