

**WATER TREATMENT USING BIOCHAR FROM PYROLYSIS OF SAWDUST**

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**APRIL, 2024**

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**A PROJECT SUBMITTED TO THE DEPARTMENT OF CHEMICAL ENGINEERING,  
UNIVERSITY OF BENIN, BENIN CITY.**

**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF  
BACHELOR OF ENGINEERING (B.ENG) DEGREE OF THE UNIVERSITY OF  
BENIN.**

**APRIL, 2024**

## CERTIFICATION

This is to certify that this research work was carried out by ERIBO, OSASERE BENEDICTA with Matriculation number ENG1804633 in the Department of Chemical Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State.

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## **DEDICATION**

This project is dedicated to Almighty God, my source of life, my ultimate protector and provider. I also dedicate this work to my beloved parents, Engr. & Mrs. O.B.J Eribo whose contribution in every way has been immeasurable and their unwavering support, love, and guidance have been a constant source of inspiration throughout my academic journey.

## ACKNOWLEDGEMENT

Firstly, I would like to express my heartfelt gratitude to my project supervisor, Engr. Dr. (Mrs.) E.A Oyedoh, for her relentless support and advice. Her knowledge, commitment, and astute observations have been crucial in molding this project.

With profound gratitude, I extend my sincerest appreciation to the Head of Department, Engr. Dr. (Mrs.) E.T Akhiehiero, esteemed professors, lecturers, and the dedicated staff of the Chemical Engineering Department. Their invaluable guidance and support have nurtured my academic and personal growth.

I also thank Engr. F.O Oshomogbo and the entire staff of Luco Scientific Laboratory for providing an exceptional learning and research environment. The accessibility to resources and facilities has significantly enhanced the quality of this project.

To my beloved parents, Engr. & Mrs. O.B.J Eribo, I am grateful for their unwavering love, encouragement, and patience. Their support has been a constant source of strength. I am eternally grateful to my siblings, Eribo Osarume (Miss), Eribo Edoghogho (Miss), and Eribo Osaro (Master), for their unwavering support, encouragement, and understanding throughout this endeavor.

My deepest thanks to Mr. Bright Samson, Alale Vanessa (Miss), Aganbi Emmanuel, Evbade Glory (Miss), Efosa Favour (Miss), and Odjemudia Nero for their valuable insights, shared perspectives, and unwavering encouragement. Their camaraderie has made this journey not only successful but also enjoyable and memorable.

Lastly, this project would not have materialized without the combined efforts of all those mentioned and countless others who contributed in countless ways. I express my sincere gratitude for your invaluable contributions to this endeavor.

## ABSTRACT

The main goal of this research was to explore the effectiveness of slow pyrolysis of sawdust in generating high-quality biochar with beneficial characteristics for different uses, such as soil improvement and water purification. By adjusting the pyrolysis temperature and duration, the study sought to identify the ideal conditions for producing biochar with improved physicochemical properties.

Sawdust, an abundant byproduct of the timber industry, underwent slow pyrolysis in a low-oxygen environment. The process was carried out at various temperatures, ranging from 400°C to 700°C, to evaluate how temperature affects both the yield and characteristics of the resulting biochar.

The produced biochar was analyzed through several techniques, such as surface area measurement, pH analysis, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), Brunauer-Emmett-Teller (BET) analysis, iodine number assessment, and yield percentage evaluation.

The research revealed that slow pyrolysis of sawdust produced high-quality biochar with desirable characteristics. The biochar showed elevated carbon content, a porous structure, and an almost neutral pH, making it well-suited for use in agriculture and water purification. Both laboratory and field experiments confirmed that biochar effectively enhanced soil quality, boosted water retention, and improved nutrient availability. The research also showed that up to 55% of the material could be converted into solid biochar, while the rest was produced as bio-oil and syngas. These results emphasize the sustainable and versatile advantages of utilizing slow pyrolysis of sawdust for biochar production.

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## CHAPTER ONE

### INTRODUCTION

#### 1.1 BACKGROUND OF STUDY

Given the growing environmental challenges worldwide, it's crucial to explore innovative approaches to protect our planet. Biochar presents a promising solution with the ability to store carbon, improve soil quality, and minimize waste.

Although biochar has only recently gained attention in research, its roots go far back. In the Amazon Basin, Terra preta soils, which contain charred organic material, have been found. These soils are known for their exceptional ability to retain nutrients and maintain a neutral pH, even in acidic environments. Biochar is a carbon-rich solid organic byproduct produced through the pyrolysis of biomass (Oni et al., 2019). It is created from sources like grasses, agricultural waste such as corn stalks or straw, forest residues like sawdust or wood chips, and municipal solid waste, including paper or food scraps. These substances break down at elevated temperatures without the presence of oxygen, through a process called pyrolysis. In this process, the physical and chemical characteristics of the plant material change, resulting in the formation of a highly porous, stable, carbon-dense substance called biochar. It is a flexible renewable energy resource capable of generating heat, electricity, and liquid biofuels (Xie et al., 2015). Biochar, a type of charcoal created through pyrolysis (Singh Yadav et al., 2023; Talberg et al., 2009), possesses a well-preserved porous structure, containing sufficient functional groups, various inorganic nutrients, and stable carbon elements (L. Wang et al., 2022). Compared to other organic nutrients, biochar is a stable soil nutrient that plays a crucial role in adsorption and mineralization (Clough & Condon, 2010; Kulyk, 2012; Singh Yadav et al., 2023). It has the

ability to enhance the availability of nutrients in the soil and improve the quality of the surrounding environment (Clough & Condon, 2010). It is a carbon-dense substance that enhances soil in farming regions and lowers the risk of pollution and environmental damage (Kulyk, 2012; Ulusal et al., 2021). The production of biochar depends on three key factors: manufacturing methods (techniques and temperature), biomass sources (such as rice hulls, food waste, animal byproducts, and solid waste), and production technologies (including pyrolysis, thermal carbonization, and gasification) (Kulyk, 2012). Biochar can be divided into the following categories:

1) low-ash feedstock (3–5%), such as bamboo and nut shells; 2) medium-ash feedstock (3–5 to 10–13%), such as agricultural residues, tree bark, and green waste; 3) high-ash feedstock (>13%), such as waste paper, manures, industrial effluent, and municipal solid waste. The global transformation of biomass into carbon-based compounds is increasing, with the goal of restoring degraded soils (Karimi et al., 2020; Shakya & Agarwal, 2020). The sustainable production of biochar mainly relies on woody feedstock, such as oak sawdust (Ulusal et al., 2021). Recent studies emphasize biochar's potential as a soil conditioner and container substrate additive in agriculture and horticulture, offering improvements in the physical, chemical, and biological properties of soil (Jahromi et al., 2021). Potential uses include soil amendments to improve quality and crop productivity, enhance water and nutrient retention in soils, and lower greenhouse gas emissions (Ghosh, 2013; Jahromi et al., 2021). Additionally, biochar can serve as a remediation agent, capturing both organic and inorganic pollutants in soil or water. It can attach to heavy metals, toxic chemicals, pesticides, and nutrients, preventing them from moving through the soil profile. This could be applied at abandoned mine sites, roadside runoff areas, tile line effluent, or stormwater basins to capture pollutants and water-soluble nutrients. It also has

industrial uses in polymer product formulation, the development of electronic components, or as a catalyst in industrial processes. It is also being evaluated as a filler in concrete and asphalt, as well as a livestock feed supplement due to its ability to absorb ammonia in the digestive tract, improving digestion (Preta et al., 2023). Additionally, carbon sequestration through biochar is significant because of its potential to recycle waste, retain soil nutrients, and reduce greenhouse gas emissions (Singh Yadav et al., 2023). Overall, biochar is an intriguing material with numerous potential applications and significant potential, not only as a substitute for fossil fuel carbon products but also as a foundation for various innovative and sustainable solutions (Oni et al., 2019; Preta et al., 2023).

Biochar has the capability to tackle issues in water treatment and agriculture through various methods;

Biochar can be utilized for treating wastewater from both point sources and diffuse sources in agricultural systems. Also, it can improve water retention in sandy agricultural soils, helping to alleviate drought conditions (Ndede et al., 2022), Biochar can be applied for on-farm wastewater treatment, reducing pathogens in irrigation water to support safer food production in developing countries (Gwenzi et al., 2017), Biochar can be utilized in constructed wetlands and soil to enhance water quality (X. Wang et al., 2020), Biochar's highly stable structure allows it to endure over time and effectively capture and filter pollutants from water, including metals (W. I. Biochar, 2022), Biochar can enhance soil quality and fertility by boosting water retention, improving soil stability, and promoting microbiome populations, while also decreasing the need for fertilizers and minimizing fertilizer runoff (W. I. Biochar, 2022; Bolan et al., 2023; Ndede et al., 2022). Biochar can serve as a carrier for microbes, promoting plant growth and aiding in the remediation of soil

contaminated with organic pollutants (Bolan et al., 2023), Biochar can function as an eco-friendly fertilizer, enhancing farm productivity and improving the quality of agricultural products (Gwenzi et al., 2017). Biochar can enhance crop growth and yields, making it a valuable resource for sustainable agriculture (X. Wang et al., 2020).

The most effective way to produce biochar is through slow pyrolysis, which can generate an average of 35.0% of the dry biomass weight as biochar (Yaashikaa et al., 2020b). Slow pyrolysis is a process where biomass decomposes at a low heating rate (0.1°C to 0.8°C per second) with an extended residence time of more than 30 minutes (Tomczyk, 2020). Sawdust is a common biomass feedstock used for producing biochar through slow pyrolysis.

Some advantages of slow pyrolysis compared to other pyrolysis methods include:

**Higher solid char yield:** Slow pyrolysis, defined by its slower heating rate, lower temperature, and longer residence time, optimizes the production of solid char (Basu, 2018a). This is advantageous for applications like soil improvement and water treatment, where biochar is the desired product.

**Utilization of low-grade feedstock:** Slow pyrolysis has the benefit of being able to handle low-quality feedstocks, like sawdust and other waste materials, which may not be suitable for other pyrolysis methods (Jonsson, 2016). This creates economic potential by making use of materials that would otherwise be discarded.

**Simple construction and operation of reactors:** Slow pyrolysis reactors are easier to build and operate compared to more complex pyrolysis methods (Brown, 2021). This simplicity enhances the economic feasibility of slow pyrolysis for specific applications.

**Carbon neutral and environmental potential:** Similar to other pyrolysis methods, slow pyrolysis enables the use of renewable resources in a carbon-neutral process, providing environmental benefits. It can aid in lowering greenhouse gas emissions and support the development of a more sustainable energy system.

Some disadvantages of slow pyrolysis compared to other pyrolysis methods include:

**Lower bio-oil and gas yields:** While slow pyrolysis maximizes solid char production, it usually yields less bio-oil and gas compared to fast pyrolysis. This can be a disadvantage for applications where bio-oil or gas is the preferred product, such as biofuel production.

**Lower profitability:** In certain situations, slow pyrolysis is less profitable than fast pyrolysis because it produces lower amounts of higher-value products like bio-oil (Brown, 2021). This economic disadvantage can vary based on the specific application and market conditions.

**Longer processing time:** The slower heating rate and extended residence time of slow pyrolysis can lead to longer processing times compared to other pyrolysis methods (Basu, 2018a). This may negatively impact overall process efficiency and productivity.

The potential of slow pyrolysis to produce high-quality biochar with desirable characteristics can be emphasized through the following points:

**Optimal operating conditions:** Slow pyrolysis, operating within a moderate temperature range of 350-650°C and with an extended residence time, enables the production of biochar with desirable properties (J. J. Manyà et al., 2018a). Optimal conditions for pyrolysis are 500°C and 30 minutes, which produce biochar with excellent characteristics, including an appropriate C:N ratio, porosity, surface area, key elements, cation exchange capacity (CEC), pH, and fixed carbon

(Nkomo et al., 2021).

**Enhanced nutrient content:** Biochar created via slow pyrolysis at 500°C showed high phosphorus levels, suggesting its potential as an effective phosphorus source for soil amendment and water treatment (Nkomo et al., 2021). This nutrient enrichment can enhance plant growth and improve water quality.

**Mesoporous structure for water and nutrient holding capacity:** The isotherms for biochar produced at 500°C revealed that it is a mesoporous material, indicating effective water and nutrient retention (Nkomo et al., 2021). This characteristic is advantageous for soil amendment and water treatment, as the biochar can hold and release water and nutrients as required.

**Higher carbon content and lower ash content:** Biochar produced via slow pyrolysis typically has higher carbon content, heating value, and surface area, with lower ash content, compared to biochar made through fast pyrolysis (Abdullah et al., 2023). These characteristics make slow pyrolysis biochar more suitable for uses like soil amendment and water treatment, where a stable, carbon-rich material is preferred.

**Utilization of various feedstock types:** Slow pyrolysis can efficiently handle various types of biomass feedstock, including low-quality and waste materials (Tomczyk, 2020). This adaptability enables the production of high-quality biochar from diverse sources, enhancing the sustainability and economic feasibility of the process.

Sawdust is a potential feedstock for slow pyrolysis, providing multiple benefits and opportunities for generating high-quality biochar. Sawdust, a byproduct from different wood processing industries, is a readily available and plentiful feedstock for biochar production (Trada et al., 2022). Its widespread availability supports the sustainability and economic feasibility of using sawdust in slow pyrolysis.

Sawdust has been effectively utilized as a feedstock in slow pyrolysis, with researchers examining how process parameters impact yield and product characteristics (Varma et al., 2019). This indicates that sawdust can be successfully transformed into biochar through slow pyrolysis, potentially yielding high-quality biochar with favorable properties. Along with biochar, slow pyrolysis of sawdust can also produce valuable byproducts like bio-oil and gases (Varma et al., 2019). This approach of generating multiple products increases the economic value of using sawdust as a feedstock, as these byproducts can be applied in various ways.

Sawdust from various wood sources can serve as a feedstock for slow pyrolysis, providing flexibility in feedstock selection (Rahmat et al., 2023). This flexibility enables the production of biochar with tailored properties and applications, depending on the intended use. Utilizing sawdust as a feedstock for slow pyrolysis provides environmental benefits by making use of a waste material that would otherwise be thrown away (Rahmat et al., 2023). This enhances the sustainability and carbon neutrality of the slow pyrolysis process, making it a more appealing choice for biochar production.

## **1.2 RESEARCH GAP**

There is a scarcity of research on how co-pyrolysis of sawdust with other feedstock affects the properties of the resulting biochar (Ali et al., 2022). Although some studies have examined the characteristics of biochar produced from sawdust alone, there has been limited exploration of the potential benefits of co-pyrolysis with different feedstock. Co-pyrolysis can improve biochar's properties, such as porosity, surface area, and nutrient content, depending on the combination of feedstock and process conditions (Ali et al., 2022). Consequently, further research is needed to explore how co-pyrolysis of sawdust with other feedstock impacts the physicochemical properties of biochar produced via slow pyrolysis. This information is essential for refining the slow pyrolysis process and producing biochar with the desired properties for particular uses.

### **1.3 PROBLEM STATEMENT**

Although there is increasing interest in producing biochar from waste biomass, there is a deficiency of thorough studies on the slow pyrolysis of sawdust for biochar production (Amalina et al., 2022; J. Manyà, 2012; Yaashikaa et al., 2020a). While many studies have concentrated on the characterization and properties of biochar from various feedstock, there has been limited research specifically examining how the slow pyrolysis of sawdust, including factors like temperature and residence time, affects the physicochemical properties of biochar (Jalalabadi et al., 2019; Tomczyk, 2020). This information is vital for improving the slow pyrolysis process and producing biochar with the desired characteristics for specific uses. Therefore, research is needed to explore the potential applications of biochar produced from sawdust through slow pyrolysis, especially in soil amendment and water treatment (Amalina et al., 2022; J. Manyà, 2012; Yaashikaa et al., 2020a). Such research is essential for assessing the economic and environmental feasibility of using sawdust as a feedstock for slow pyrolysis.

### **1.4 AIM AND OBJECTIVES**

The aim of this study is to investigate the potential of biomass pyrolysis for producing biochar, with the aim of advancing its application as a soil amendment and water treatment agent.

The objectives of this study are:

- To evaluate the potential of Biochar as a water treatment agent, assessing its effectiveness in removing different pollutants/contaminants from water sources.
- To investigate the potential of Biochar as a soil amendment, assessing its impact on soil fertility, water retention and nutrient availability.
- To access the physiochemical properties of Biochar produced through slow pyrolysis of sawdust including surface porosities and functional groups to understand its potential

application.

- To understand the effect of slow pyrolysis conditions on the yield and quality of Biochar produced from sawdust.
- To refine the slow pyrolysis process by optimizing operating conditions such as temperature, heating rate, and duration, in order to obtain the desired biochar properties and maximize its yield.
- Evaluating the economic feasibility of biochar.

### **1.5 SCOPE OF STUDY**

- The study seeks to evaluate how effectively slow pyrolysis can produce biochar from sawdust for use in water treatment and soil amendment.
- The study will concentrate on analyzing the characteristics, stability, and potential applications of biochar produced from the slow pyrolysis of sawdust.
- The study will cover the application of Biochar for water treatment and soil amendment.
- The study will evaluate the effect of slow pyrolysis conditions, such as temperature and residence time, on the properties of Biochar produced from sawdust.
- The study will use different analytical techniques, such as SEM-EDS (Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy), BET (Brunauer-Emmett-Teller), to characterize the Biochar produced through slow pyrolysis of sawdust.
- The study will be conducted in a laboratory setting, using controlled conditions.

### **1.6 RELEVANCE OF STUDY**

The importance of this study on slow pyrolysis of sawdust for biochar production is in expanding current knowledge and insight into the process and its potential uses. In particular, the study will

provide valuable contributions in the following areas:

Improved understanding of the slow pyrolysis method for producing biochar from sawdust, particularly regarding how different process conditions impact the properties of the resulting biochar.

Identification of the possible uses for biochar derived from sawdust, with a focus on its applications in water treatment and soil amendment.

Assessment of the efficiency of biochar produced from sawdust in eliminating contaminants from water and wastewater, as well as enhancing soil properties..

Provision of a basis for further research on the utilization of Biochar produced from sawdust for a range of applications.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 ENERGY

In basic terms, energy is the capacity to perform work. Energy, derived from the Ancient Greek word "enérgeia" meaning "activity," refers to a measurable property transferred to an object or system, evident through the ability to do work or through forms like heat and light. Energy is a conserved property, meaning it can change form but cannot be created or destroyed, as outlined by the law of conservation of energy. In the International System of Units (SI), energy is measured in joules (J).

The various types of energy include kinetic, potential, elastic, chemical, radiant, solar, thermal, nuclear, electrical, and internal energy.

Energy plays a vital role in environmental and sustainability studies, as its generation and use greatly affect the environment and human health.

Energy sources are categorized into renewable and non-renewable types.

##### 2.1.1 RENEWABLE ENERGY

Renewable energy is energy that comes from natural sources that are replenished faster than they are used. Examples of renewable energy sources are sunlight, wind, water, geothermal heat, and biomass (EIA, 2014). Renewable energy is commonly utilized for generating electricity, heating and cooling spaces and water, and for transportation. Its benefits are extensive and impact various areas, including the economy, environment, national security, and public health. These benefits include increased reliability and resilience of the power grid, lower greenhouse gas emissions and air pollution, greater energy independence and reduced reliance on imported oil,

job creation and economic growth in the renewable energy sector, decreased water usage and pollution, and improved public health along with reduced healthcare costs.

### **2.1.2 NON RENEWABLE ENERGY**

Non-renewable energy refers to sources of energy that are depleted faster than they can be naturally replenished. These resources are limited and will eventually be exhausted. The most prevalent forms of non-renewable energy are fossil fuels, which consist of coal, oil, and natural gas. Fossil fuels are derived from the remains of ancient plants and animals that have decomposed over millions of years and are extracted from the earth. Nuclear energy, on the other hand, is generated through nuclear reactions involving the nucleus of an atom.

Non-renewable energy sources are utilized for various applications, including industrial processes and residential needs.

### **2.1.3 BIO ENERGY**

Bioenergy is a type of renewable energy obtained from organic materials that were recently alive, referred to as biomass. Biomass is a renewable energy source originating from plant and algae materials, such as wood, food crops like corn, energy crops, and waste from forests, gardens, or farms. Bioenergy derived from biomass can be utilized for producing fuels for transportation, heat, electricity, and other products.

The use of bioenergy is generally categorized into two types: “traditional” and “modern.”

Traditional bioenergy use involves burning biomass in forms like wood, animal waste, and traditional charcoal. Modern bioenergy technologies encompass various methods, including the production of liquid biofuels from materials such as bagasse, bio-refineries, biogas generated

through anaerobic digestion of organic residues, wood pellet heating systems, and other advanced technologies (*Bioenergy & Biofuels About Bioenergy Data Biomass Has Significant Potential and Can Be Directly Burned for Heating or Power*, 2022).

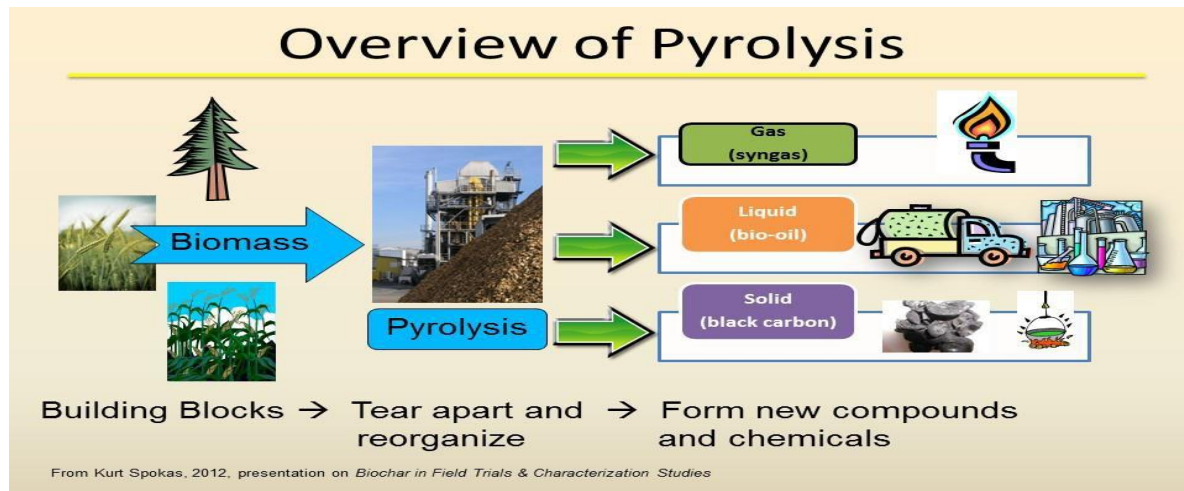
Bioenergy offers numerous advantages, such as enhancing energy security, promoting sustainability, and supporting economic stability. It achieves this by providing clean, domestic energy sources, generating electricity for homes, and creating job opportunities, among other benefits.

## **2.2 PYROLYSIS OVERVIEW**

The term "pyrolysis" originates from Greek, with "pyro" meaning "fire," "heat," or "fever," and "lysis" meaning "separation." Thus, pyrolysis refers to the process of separating materials through heat (Ibrahim, 2020). It is a method of thermally breaking down solid or liquid substances into smaller volatile compounds without using oxygen or other chemicals. Organic substances like biomass, plastics, rubber, or organic waste are subjected to high temperatures (generally ranging from 300°C to 800°C) in a controlled setting. This process provides sufficient heat to break down the strong biopolymers, resulting in the formation of solids (char), condensable liquids (such as light and heavy oils and tar), and non-condensable gases. The applied thermal energy disrupts the chemical bonds in the organic material, causing the release of volatile components.

Pyrolysis stands apart from processes like combustion and hydrolysis because it typically does not require additional reagents such as oxygen or water. It is a well-established and energy-efficient chemical technology widely utilized in the chemical industry (Ibrahim, 2020). Pyrolysis can be categorized into different types, such as fast pyrolysis, slow pyrolysis, and intermediate

pyrolysis. Pyrolysis offers several benefits compared to other treatment methods, such as quick start-up and shut-down times, and it provides a sustainable means of producing energy from waste. Nevertheless, it has some drawbacks, including a low gas yield, which diminishes the overall energy value of the gas, and a high tar content in the liquid byproducts (Ibrahim, 2020).



**Plate 2. 1: Overview of Pyrolysis**

## 2.3 TYPES OF PYROLYSIS

### SLOW PYROLYSIS

Slow pyrolysis is a thermochemical process where organic materials are heated slowly in the absence of oxygen or with a limited amount of oxygen. This process breaks down the materials into various valuable products. This method is distinguished by its relatively slow heating rates, extended residence times, and lower temperatures compared to other pyrolysis methods. Rather than burning, the volatiles from the organic material are emitted as gases, leaving a solid byproduct known as Biochar.

Slow pyrolysis is an optimal method for producing Biochar, involving the thermal breakdown of materials in a controlled, inert environment at a gradual heating rate ( $\sim 10^{\circ}\text{C}/\text{min}$ ). Organic materials

like biomass, wood, or agricultural residues are heated to temperatures generally between 300°C and 500°C (Bridgwater, 2012). The process is milder in terms of operating conditions, utilizing lower temperatures (~350-450°C) and longer residence times for coarser biomass (> 1 mm). Slow pyrolysis primarily focuses on producing Biochar, which can constitute up to around 60 wt.% of the output, with 25-30 wt.% as bio-oil and the remainder as gas (Cai et al., 2020). This process is designed to maximize the production of solid char.

Biochar produced through slow pyrolysis can be analyzed for its elemental composition, structure, surface area, and pore distribution (Lee et al., 2013). This method offers a sustainable approach to energy generation from waste and provides several benefits compared to other treatment processes, such as rapid start-up and shut-down times. This process can generate chars with energy content comparable to that of coal, making them suitable for various combustion applications.

The amount and quality of Biochar obtained from slow pyrolysis are influenced by the type of feedstock and the conditions of the pyrolysis process (Ronsse et al., 2013).

In summary, slow pyrolysis is a promising method for producing Biochar from organic materials and holds potential to play a significant role in a sustainable energy future.

## **FAST PYROLYSIS**

Fast pyrolysis is a process where organic material undergoes rapid thermal breakdown in the absence of oxygen. This method operates at high temperatures (600-1200°C) over a short duration, typically around 10 seconds. The process primarily produces bio-oil, or pyrolysis oil, which is a complex blend of organic compounds with potential uses as a biofuel or chemical feedstock.

Additionally, it produces some amounts of char and gas. Fast pyrolysis of biomass provides the benefit of producing a liquid product that is easy to transport and store. This liquid can also serve as a feedstock for producing biofuels and chemicals (Czernik & Bridgwater, 2004).

Fast pyrolysis is a promising technology for converting biomass into bio-oil and holds the potential to play a key role in a sustainable energy future. An overview of the technology indicates that the process is viable for scaling up and commercialization (Singh-Morgan et al., 2022).

The amount and quality of bio-oil produced through fast pyrolysis are influenced by the type of feedstock and the conditions of the process (Bridgwater et al., 1999). Fast pyrolysis can lower greenhouse gas emissions by converting organic materials into useful products, reducing reliance on fossil fuels, and offering a sustainable solution for managing biomass and organic waste.

Controlling the rapid heating rates and temperature variations within the reactor, along with upgrading and stabilizing bio-oil to enhance its quality and storage stability, presents technical challenges in fast pyrolysis.

## **INTERMEDIATE PYROLYSIS**

Intermediate pyrolysis is a process where organic material undergoes thermal decomposition without oxygen. It operates at intermediate temperatures and heating rates, producing a combination of Biochar, bio-oil, and syngas (Basu, 2018b).

Intermediate pyrolysis is considered an efficient and eco-friendly method for treating waste, particularly low-value, high-ash biomass. It can process various types of biomass while simultaneously producing bio-oil and adsorption Biochar (Kazawadi et al., 2021).

The heating rates in intermediate pyrolysis are significantly lower than those in fast pyrolysis,

typically falling between 100-500°C/min (Hornung, 2012).

Intermediate pyrolysis is a promising technology for producing biofuels and chemicals from biomass and has the potential to play a key role in a sustainable energy future. A study has evaluated the performance, economic viability, and environmental impact of intermediate pyrolysis systems (Yang et al., 2017). Intermediate pyrolysis helps decrease greenhouse gas emissions by transforming organic materials into useful products and reducing dependence on fossil fuels. Additionally, it offers a sustainable approach for managing biomass and organic waste.

## **FLASH PYROLYSIS**

Flash pyrolysis is a thermal process where biomass feedstock, like wood or straw, is swiftly heated for a brief duration, usually between 0.5 and 3 seconds, without the presence of oxygen (L. Li et al., 2013). Flash pyrolysis is an exceptionally fast process with very short residence times, ranging from milliseconds to seconds. It operates at extremely high temperatures, typically over 1000°C. This method mainly produces gases, such as hydrogen and light hydrocarbons, with minimal amounts of liquid or solid products. It is utilized in applications where rapid gas production is essential.

Fast or flash pyrolysis is particularly effective for the pyrolytic liquefaction of biomass. This endothermic process requires the feedstock to be dry, with small particle sizes (< 3 mm), and is generally done at atmospheric temperature with rapid cooling of the products. The resulting yields include liquid condensates (30-60%), gases (such as CO, H<sub>2</sub>, CH<sub>4</sub>, CO<sub>2</sub>, and light hydrocarbons), and char.

Flash pyrolysis is a key method for converting biomass into environmentally friendly biofuels. The process occurs under a dynamic vacuum, where the hot zone must heat the gaseous molecules

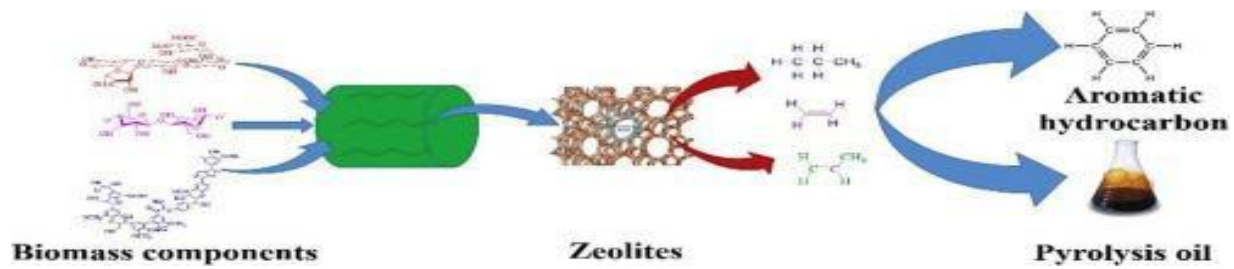
effectively, often by including solids to promote gas-solid interactions. The precursor is volatilized with mild heating under vacuum conditions. In the hot zone, the precursor either fragments or rearranges, and the final products are collected through rapid cooling.

## **CATALYTIC PYROLYSIS**

Catalytic pyrolysis is a process that employs a catalyst to break down biomass or plastic waste into liquid hydrocarbon oil (Miandad et al., 2019; Pattiya, 2018). The catalyst increases the yield of the desired products while minimizing the creation of undesirable byproducts (Dada et al., 2023). In catalytic pyrolysis, catalysts aid in the decomposition of complex organic molecules by lowering the activation energy needed for the reactions. They can alter the distribution of products by encouraging particular chemical pathways. Commonly used catalysts include zeolites, metal oxides, and supported metal catalysts.

Catalytic pyrolysis can be classified into two types: ex-situ and in-situ. In ex-situ catalytic pyrolysis, the catalyst is introduced into the reactor after the feedstock has been heated, whereas in in-situ catalytic pyrolysis, the catalyst is combined with the feedstock before heating (Pattiya, 2018). This process is done at high temperatures (300-900°C) without the presence of oxygen (Miandad et al., 2019). The liquid oil produced can serve as a raw material for producing biofuels or chemicals. Catalytic pyrolysis has proven to be an efficient technique for transforming biomass into high-quality bio-oil (Dada et al., 2023).

Recent studies have concentrated on employing catalysts for catalytic fast pyrolysis (CFP) of biomass and the hydro-deoxygenation (HDO) of biomass pyrolysis vapors (Eschenbacher et al., 2021). The catalyst utilized in catalytic pyrolysis can be analyzed to identify its deactivation, which varies depending on the feedstock (Luna-Murillo et al., 2021).



**Plate 2. 2: Schematic diagram of catalytic pyrolysis**

## **HYDROTHERMAL PYROLYSIS**

Hydrothermal pyrolysis, also referred to as hydrothermal carbonization (HTC) or wet pyrolysis, is a thermochemical depolymerization process that breaks down wet biomass, organic waste, or other organic materials into carbon-rich products under high temperatures and pressures, with water present. This process produces hydro char or hydrothermal carbon, a solid material similar to Biochar. The process is also referred to as hydrous pyrolysis (Toor et al., 2019). Hydrous pyrolysis involves the thermal decomposition of biomass in hot water. It serves as an alternative to dry pyrolysis, commonly called hydrothermal carbonization (Titirici & Emmerich, 2017). This method is a depolymerization process that reduces large molecules into smaller fragments. This thermal process operates under high temperature and pressure, enabling the conversion of wet biomass into oil similar to crude. Hydrothermal pyrolysis occurs in a water-rich environment, generally at temperatures ranging from 180°C to 250°C and pressures between 5 and 50 bar (500 to 5,000 kPa). It is especially effective for processing wet or moisture-rich feedstock, such as sewage sludge, algae, food waste, or other biomass with high water content. The use of high temperature and pressure in hydrothermal conditions speeds up the breakdown of organic matter. This process could play an important role in the formation of fossil fuels, distinguishing itself from pyrolysis by its ability to handle wet biomass (Toor et al., 2019).

Hydrothermal pyrolysis offers potential uses for producing solid biofuels through either conventional or microwave heating methods (Nizamuddin et al., 2018). Additionally, it can be employed to convert waste biomass into char (Sivaprasad et al., 2021).

### **MICROWAVE PYROLYSIS**

Microwave pyrolysis is an advanced and rapidly developing thermal technique that employs the electric field of electromagnetic waves to heat biomass (Kurian, 2022). Also referred to as microwave-assisted pyrolysis, this method provides a moderate heating rate, falling between that of conventional pyrolysis and slower processes. It can be used to diminish biomass waste volume and transform these wastes into energy-rich products (Singh et al., 2022).

It is an eco-friendly energy recovery technology with significant potential for advancing sludge resource management (S. Li et al., 2022). The process can produce solid fuel with high energy density (Nizamuddin et al., 2018). In contrast to traditional heating methods, microwaves can heat polar or electrically conductive molecules in organic materials, leading to fast and even heating. By adjusting microwave power levels and exposure times, specific temperature profiles can be attained within the material. Microwave radiation penetrates the material, causing polar molecules to vibrate rapidly and produce heat internally. This distinctive heating method allows for rapid and effective pyrolysis with accurate temperature control. Like traditional pyrolysis, microwave pyrolysis yields various valuable products: Biochar, a solid material rich in carbon; Bio-oil, a liquid that can be used in biofuels and chemicals; and Gases, including hydrogen, carbon monoxide, methane, and other byproducts.

The quantity and quality of the products are influenced by factors such as the pyrolysis temperature, heating rate, microwave absorbers, characteristics of the sludge, and the presence of catalysts (S. Li et al., 2022; Nizamuddin et al., 2018).

This process can be applied to pyrolyze materials such as cellulose, lignin, algae, plastic waste, and coal (Suresh et al., 2021). Microwave pyrolysis holds promise for creating solid fuel from biomass waste (Singh et al., 2022). It can also be utilized to treat sludge and transform it into energy-rich products (S. Li et al., 2022). This process is capable of producing high-quality products with significant energy density (Nizamuddin et al., 2018).

## **2.4 BIOMASS**

Biomass is a renewable energy source originating from organic materials from plants and animals. It is a clean energy source generated through photosynthesis, which transforms sunlight into plant matter (McKendry, 2002). Biomass serves as a crucial fuel source in numerous countries, particularly for cooking and heating in developing countries. It can be used directly for generating heat or transformed into renewable liquid and gaseous fuels through various methods.

Energy biomass sources include plants, wood, waste, and municipal solid waste. Trees, crops, and municipal solid waste are reliably available and can be managed in a sustainable manner. Key biomass feedstock for power generation are paper mill residues, lumber mill scraps, and municipal waste.

The most frequently used feedstock for biomass fuels today are corn grain, which is utilized for ethanol production, and soybeans, which are used for producing biodiesel.

Nevertheless, biomass has a lower energy density compared to fossil fuels, and up to 50% of biomass consists of water, which is lost during the energy conversion process.

## **2.4.1 BIOMASS SOURCES**

### **WOODY BIOMASS:**

- Wood from trees and forestry byproducts: Logs, branches, tree trimmings, and wood chips.
- Sawdust and wood shavings generated from sawmills and woodworking activities.
- Wood pellets and wood briquettes produced from compressed wood particles.

### **AGRICULTURAL BIOMASS:**

- Crop Residues: Leftover plant material from agricultural crops, such as corn Stover, wheat straw, rice husks, and sugarcane bagasse.
- Energy Crops: Specifically grown for biomass energy production, including switch grass, miscanthus, and willow.
- Crop Byproducts: Parts of plants not used for food, such as corn cobs and wheat bran.

### **MUNICIPAL SOLID WASTE (MSW):**

- Organic Fraction: Food scraps, yard waste, and other organic materials from household and municipal waste.
- Green Waste: Leaves, grass clippings, and other organic yard waste.

### **ALGAE:**

- Microscopic aquatic plants grown in controlled environments such as ponds or bioreactors for biomass production. Algae can be utilized to produce biofuels, such as biodiesel or bioethanol.

### **ANIMAL MANURE:**

- Organic waste from animal farming, such as cow dung, poultry litter, and pig manure, can be processed through anaerobic digestion to generate biogas for energy production.

#### **INDUSTRIAL BIOMASS:**

- Biomass residues produced by different industries, such as the pulp and paper industry, sawmills, and food processing plants. Examples include black liquor from pulp mills and fruit pomace from fruit processing.

#### **AQUATIC BIOMASS:**

- Organic matter from aquatic sources, such as seaweed, water hyacinth, and other aquatic plants. It can be utilized for biofuel production or as a feedstock for bio-based products.

#### **URBAN AND YARD WASTE:**

- Organic materials collected from urban areas and residential yards. These materials can be utilized for composting, mulching, or generating energy.

#### **ENERGY CROPS:**

Specific energy crops like jatropha, switchgrass, miscanthus, and elephant grass are cultivated exclusively for biomass energy generation.

#### **FOREST RESIDUES:**

- Organic material remaining in forests following timber harvesting, such as logging debris and slash.

### **DEDICATED ENERGY CROPS:**

- Some plants are cultivated specifically for biomass energy production, such as switchgrass, miscanthus, and giant reed.

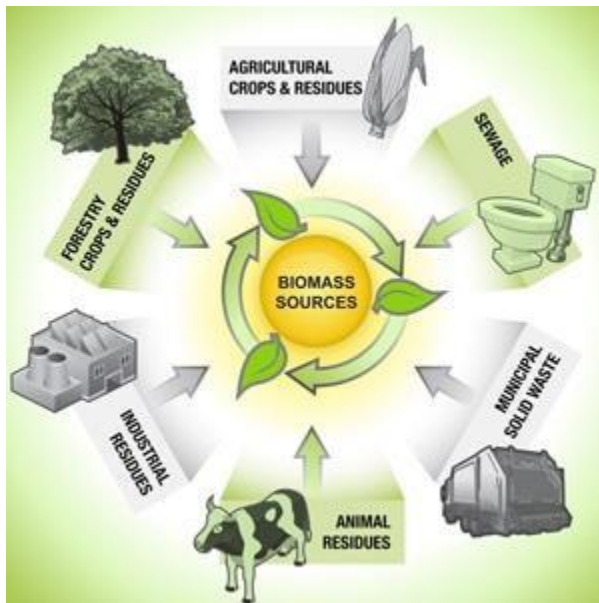
### **ALCOHOL FUELS:**

- Ethanol and methanol derived from biomass sources, usually grains, sugarcane, or lignocellulosic feedstock.

### **WASTE COOKING OIL:**

- Used cooking oil and grease can be transformed into biodiesel via a process called Trans esterification.

The composition, moisture content, and energy content of these biomass sources can differ, making them suitable for various applications and conversion technologies. To maintain their long-term availability and environmental benefits, it is crucial to source and manage biomass resources sustainably and responsibly.



**Plate 2. 3: Different Biomass sources**

## **2.5 BIOMASS PYROLYSIS PROCESS**

### **DRYING**

Biomass is typically dried to decrease moisture levels, as high moisture content can lower pyrolysis efficiency and reduce the yield of the desired products.

### **HEATING**

The dried biomass is subsequently heated to high temperature, usually between 300°C and 800°C, in an oxygen-free environment. This lack of oxygen prevents combustion and facilitates the decomposition of biomass through thermal cracking and other chemical reactions.

### **DECOMPOSITION**

As the biomass is heated, it experiences a series of complex chemical reactions, including fragmentation, depolymerization, and vaporization. These processes break down the complex organic molecules in the biomass into simpler forms, such as gases, liquids, and solids.

## **PRODUCT FORMATION**

The products obtained from biomass depend on factors such as temperature, heating rates, and the duration of the process. The primary outputs of pyrolysis usually include biochar, bio-oil, and syngas. Biochar is a solid byproduct composed of carbon-rich material. It is a stable form of carbon that can be used to enhance soil fertility and contribute to carbon sequestration.

Bio-oil, also referred to as pyrolysis oil or bio-crude, is a liquid product comparable to crude oil. It can be further refined and processed to produce biofuels, chemicals, and other valuable products.

Syngas, or synthetic gas, is a blend of hydrogen, carbon monoxide, and other gases. It can be utilized as an energy source or further processed to create chemical fuels and other products.

## **CONDENSATION AND COLLECTION**

The vapors generated during biomass pyrolysis are condensed into liquid products like bio-oil, which are then collected and separated from the solid and gas products.

## **RESIDUE DISPOSAL**

The solid byproduct, or biochar, can be utilized as a soil amendment or as an energy source through combustion or gasification.

### **2.6 BIOCHAR**

Biochar is a carbon-dense solid substance produced by burning organic material from agricultural and forestry wastes, known as biomass, through a regulated process called pyrolysis (Spears,

2018).

It is produced via a method known as pyrolysis, where organic materials, usually biomass, undergo thermal decomposition in an environment with little to no oxygen.

Biochar is distinguished by its unique characteristics and is used in various agricultural, environmental, and energy-related fields. This stable, solid material is high in pyrogenic carbon and can persist in soil for thousands of years.

It is a form of black carbon derived from biomass sources like wood chips, plant residues, manure, or other agricultural waste, intended to convert the biomass carbon from these materials into a more stable form (carbon sequestration). The chemical composition of biochar varies based on the feedstock used in its production. Biochar technology holds potential for addressing climate change, enhancing soil quality, reducing waste, and generating energy as a byproduct (Spears, 2018).

### **2.6.1 CHARACTERISTICS OF BIOCHAR**

**Carbon-Rich:** Biochar is mainly made up of carbon and has a stable, highly porous structure.

**High Surface Area:** Its porous structure gives biochar a large surface area, which improves its capacity to retain water and nutrients.

**Stability:** Biochar is resistant to decomposition and can persist in soil for centuries to millennia, serving as a long-term carbon storage solution.

**Soil Amendment:** When incorporated into soil, biochar can boost soil quality by improving water retention, increasing nutrient availability, and promoting microbial activity.

**Reduced Greenhouse Gas Emissions:** Producing biochar through pyrolysis helps lower greenhouse gas emissions by capturing carbon that would otherwise be released during the

natural decomposition of biomass.

## **2.6.2 ADVANTAGES OF BIOCHAR**

**Carbon Sequestration:** Biochar is a potent method for carbon sequestration. When incorporated into soil, it traps carbon for a long time, aiding in climate change mitigation by lowering atmospheric carbon dioxide (CO<sub>2</sub>) levels. Biochar and bioenergy co-production can aid in combating global climate change by replacing fossil fuel use and capturing carbon in stable soil carbon pools (Dhyani, 2022).

**Reduced Greenhouse Gas Emissions:** Producing biochar through pyrolysis can lead to reduced greenhouse gas emissions compared to other waste disposal methods, as it captures carbon that would otherwise be emitted as CO<sub>2</sub> during the decomposition of biomass.

**Water Retention:** Biochar's porous structure enhances soil's ability to retain water, decreasing the need for irrigation and making it beneficial in areas prone to drought. Additionally, it supplies nutrients to the microbial communities within the soil (Pakistan, 2021).

**Improved Soil Fertility:** Biochar can improve soil fertility by boosting nutrient retention and availability. It creates a stable environment for beneficial microorganisms, enhances soil structure, and supports plant growth. Additionally, it promotes soil health by increasing the activity of soil organisms (Pakistan, 2021), reduces fertilizer runoff, and may lower the need for fertilizers (Nancy, 2021).

**Nutrient Management:** Biochar can aid in the gradual retention and release of nutrients, thereby minimizing the risk of nutrient runoff into water bodies and the leaching of harmful substances.

**Reduction in Soil Erosion:** Applying biochar can enhance soil structure, which helps decrease soil erosion, especially on sloped terrain.

**Soil Remediation:** Biochar can be used to clean up contaminated soils by adsorbing heavy metals and organic pollutants, thereby immobilizing them and decreasing their bioavailability.

**Waste Management:** Biochar can be made from organic waste materials, diverting them from landfills or incineration and transforming them into a valuable resource.

## 2.6.2 DISADVANTAGES OF BIOCHAR

**Initial Cost:** Producing and applying biochar can be expensive, due to the energy needed for pyrolysis and the associated transportation costs.

Biochar can become spontaneously combustible when exposed to air, meaning it has the potential to self-heat and even ignite (Dhyani, 2022).

**Feedstock Availability:** The supply and long-term viability of biomass for Biochar production may be constrained, and competing demands for the same feedstock can increase expenses.

**Long-Term Effects Uncertain:** Although Biochar can store carbon for extended periods, its long-term effects on soil and ecosystems are still being investigated. There are some concerns about how it might influence soil pH and microbial populations.

**Regulation and Certification:** The absence of uniform regulations and certification for Biochar quality and production methods can result in variable product quality and reduced market acceptance.

**Potential Release of Harmful Substances:** If Biochar is not produced and managed correctly, it

may hold onto contaminants from the feedstock, which could potentially be released into the environment.

**Transportation and Distribution:** The logistics involved in producing and distributing Biochar to rural or remote areas can be difficult, restricting its availability to those who could benefit the most from it.

## **2.7 PRODUCTION OF BIOCHAR THROUGH SLOW PYROLYSIS**

Biochar produced from the slow pyrolysis of sawdust has become recognized as an alternative way to transform waste biomass into a valuable product. This slow pyrolysis technique provides a controlled and effective method for producing Biochar. The characteristics of Biochar made from the slow pyrolysis of sawdust can differ based on the pyrolysis conditions and the type of sawdust utilized. Biochar has potential uses in water treatment, soil enhancement, and carbon storage.

Comprehending the properties of Biochar produced via the slow pyrolysis of sawdust is crucial for refining the production process and creating effective uses for this valuable material. The process operates within a temperature range of 300 to 700 °C and varies in residence time (Youngsang et al., 2021). Slow pyrolysis is the most efficient technique for producing Biochar, yielding about 35.0% from the weight of dry biomass (Y. Li et al., 2023; Tomczyk, 2020). This method retains the biomass's carbon content and transforms it into a stable, carbon-dense, and porous material.

The process of producing Biochar through slow pyrolysis involves the following steps:

**Feedstock preparation:** The first step involves preparing the feedstock, which can include various biomass materials such as wood chips, plant residues, manure, or other agricultural waste products (J. J. Manyà et al., 2018b; Ronsse et al., 2013).

**Feedstock Size:** Depending on the pyrolysis system, the feedstock might need to be cut or shredded into uniform pieces to ensure consistent heating.

**Loading the Reactor:** Load the prepared feedstock into a pyrolysis reactor, which must be designed to regulate temperature, residence time, and gas flow while maintaining an oxygen-limited environment (J. J. Manyà et al., 2018b).

**Heating:** The reactor is gradually heated to a temperature between 300 and 700°C (572 to 1292°F) at a slow rate (J. J. Manyà et al., 2018b). Slow pyrolysis carefully raises the temperature over an extended period, allowing for the controlled breakdown of the biomass.

**Pyrolysis:** The feedstock undergoes thermal decomposition in an oxygen-free environment, resulting in a mixture of solid Biochar, liquid bio-oil, and gas (syngas) products (Cai et al., 2020; J. J. Manyà et al., 2018b).

**Char Formation:** The pyrolysis process produces carbon-rich char as a solid byproduct. This char is porous and stable, making it ideal for a range of applications.

**Cooling:** Following the pyrolysis process, the hot gases and char move through a cooling zone, where the gases are condensed, and the char is cooled down.

**Char Collection:** The cooled Biochar is gathered for further processing, packaging, and storage. It can then be used as a soil amendment or for various other applications (J. J. Manyà et al., 2018b; Ronsse et al., 2013).

## **2.8 FACTORS AFFECTING THE YIELD OF BIOCHAR**

The amount of Biochar produced through pyrolysis is affected by multiple factors, and understanding such factors is crucial for optimizing the production process. The following are

key factors that can influence Biochar yield:

**Feedstock Type and Composition:** The type of organic material used greatly impacts Biochar yield, as different feedstock have varying carbon content and levels of volatile matter. For instance, hardwood biomass typically produces more Biochar than softwood because of its higher lignin content.

**Feedstock Moisture Content:** The moisture content of the feedstock affects the yield, as energy is first needed to remove the moisture before pyrolysis can begin. Wet feedstock may demand more energy, leading to reduced Biochar yields.

**Pyrolysis Temperature:** The temperature at which pyrolysis occurs is critical. Higher temperatures typically produce more Biochar but can also increase gas output while reducing the amount of liquid bio-oil.

**Residence Time:** The residence time of the feedstock in the pyrolysis reactor impacts Biochar yield. Generally, longer residence times result in higher yields, but excessively prolonged times can cause over-pyrolysis and degrade the Biochar.

**Heating Rate:** The heating rate, or the speed at which the temperature is increased during pyrolysis, affects both the yield and properties of Biochar. Slower heating rates generally result in higher Biochar yields but may lengthen the overall processing time.

**Oxygen Concentration:** Biochar is usually made in an environment with little to no oxygen to avoid combustion. Even minimal oxygen can lower the Biochar yield and increase the production of ash.

**Reactor Design:** The design of the pyrolysis reactor can affect the yield of Biochar. Aspects like reactor geometry, insulation, and heating techniques influence heat transfer efficiency and, therefore, the yield.

**Feedstock Size and Preparation:** The yield can be influenced by the size and treatment of the feedstock. Using smaller particles might lead to more even heating and increased yields. Additionally, ensuring the feedstock is adequately dried is crucial.

**Catalysts and Additives (if used):** Utilizing catalysts or additives during pyrolysis can impact both the yield and characteristics of the Biochar. Certain additives might encourage Biochar production, while others can improve specific attributes.

**Operating Conditions (e.g., pressure, gas flow rate):** Different operating conditions in the pyrolysis reactor, including pressure and gas flow rate, can impact the yield and quality of Biochar.

**Cooling and Condensation Efficiency:** The effectiveness of the cooling and condensation systems in collecting condensable products like bio-oil can impact the overall mass balance and yield of Biochar.

## **2.9 PHYSIOCHEMICAL PROPERTIES OF BIOCHAR**

Biochar is a carbon-rich solid created by pyrolyzing organic materials. Its diverse physicochemical properties make it useful for many applications. These properties can differ based on the type of feedstock, the conditions during pyrolysis, and any subsequent processing methods. Here are some important physicochemical properties of Biochar:

**Carbon Content:** Biochar mainly consists of carbon (C), which typically makes up 50% to 90% of its total composition. The high carbon content is a key characteristic of Biochar.

**Surface Area:** Biochar has a large surface area resulting from its porous structure formed during pyrolysis. This feature is crucial for its adsorption capacity and reactivity.

**Porosity:** Biochar is defined by its porous nature, consisting of both micro- and mesopores. This porosity enhances its high surface area and adsorption ability.

**pH Level:** Biochar generally has a pH ranging from neutral to alkaline, though this can vary based on the feedstock and pyrolysis conditions. Its pH level can affect how it alters soil acidity or alkalinity when applied as a soil amendment.

**Cation Exchange Capacity (CEC):** Biochar can exchange cations (positively charged ions) with its environment. Its cation exchange capacity (CEC) varies depending on the feedstock, which can improve nutrient retention in soils.

**Electrical Conductivity:** Biochar can display electrical conductivity, which is affected by both its carbon content and the mineral composition of the original feedstock.

**Ash Content:** The ash content in Biochar differs depending on the feedstock used. It is made up of inorganic minerals and elements found in the original organic material.

**Density:** Biochar's bulk density can differ based on the feedstock and production method. Lower-density Biochar tends to be more porous.

**Thermal Stability:** Biochar is highly resistant to heat and can endure elevated temperatures without breaking down, making it ideal for use in high-temperature environments.

**Hygroscopicity:** Biochar's porous structure allows it to absorb and retain water, helping improve water retention in soils when used as a soil amendment.

**Absorption and Adsorption:** Biochar can both absorb and adsorb a variety of substances, such as organic compounds, heavy metals, and pollutants. This makes it valuable for environmental cleanup and water treatment applications.

**Surface Functional Groups:** Biochar surfaces may have functional groups like hydroxyl (-OH), carboxyl (-COOH), and phenolic groups, which can affect its reactivity and ability to adsorb substances.

**Specific Surface Area (SSA):** The specific surface area of Biochar indicates the total surface area available per unit mass. A higher specific surface area enhances its adsorption capability.

**Particle Size and Distribution:** The size and distribution of Biochar particles can differ based on processing techniques and feedstock. The particle size can influence its effectiveness for various applications.

**Color:** Biochar can vary in color from black to dark brown, depending on the type of feedstock, pyrolysis conditions, and ash content.

**Nutrient Content:** Biochar may retain residual nutrients from the feedstock, which can affect its effectiveness as a soil amendment.

## **2.10 BIOCHAR USED FOR WATER TREATMENT**

Water treatment involves eliminating contaminants and unwanted substances from water to ensure it is safe and suitable for its intended use. Water treatment may include multiple stages such as coagulation, sedimentation, filtration, disinfection, and ion exchange. The specific water treatment procedures can differ based on the quality of the source water and the intended use.

Water treatment is used in various contexts, such as for drinking water, industrial processes,

irrigation, and water recreation. The success of water treatment depends on factors like the nature of the contaminants, the conditions under which treatment occurs, and the methods used.

Biochar has proven effective in treating water and wastewater because of its distinctive properties. Here are some methods in which Biochar can be applied for water treatment:

- **Adsorption:** Biochar's large surface area allows it to adsorb pollutants like heavy metals, organic compounds, and pathogens from water and wastewater (Xiang et al., 2020). Biochar filters have been utilized to eliminate contaminants from urban stormwater runoff, which can otherwise cause microbial contamination of vegetables (X. Wang et al., 2020).
- **Reduction of runoff:** Biochar can enhance soil moisture retention, leading to reduced runoff and better water quality.
- **Long-lasting:** Biochar's highly stable structure ensures its durability and effectiveness in water treatment.
- **Hybrid materials:** Hybrid materials combining Biochar with metal oxides, like titanium dioxide, have proven effective in removing contaminants from water (Weidner et al., 2022).

## 2.11 BIOCHAR USED FOR SOIL AMENDMENT

A soil amendment is any substance added to soil to enhance its physical or chemical characteristics, such as water retention, permeability, infiltration, drainage, aeration, and structure. The aim is to create a more favorable environment for root development. Soil amendments can be either organic or inorganic, originating from living or non-living sources. Organic amendments consist of materials like compost, wood chips, Biochar, and manure, while

inorganic amendments include substances such as sand, gravel, and vermiculite.

Soil amendments can enhance soil aggregation, boost porosity and permeability, and improve aeration, drainage, and rooting depth. They also increase the water and nutrient retention of sandy soils. These amendments are applied to improve soil texture and structure, enrich nutrient content, enhance drainage or water retention, and adjust the soil's pH level. The effectiveness of soil amendments can be influenced by factors such as the type of amendment, the rate at which it is applied, and the type of soil. Biochar, a finely ground charcoal made from the pyrolysis of organic material, is used as a soil amendment to enhance soil quality and increase crop yields. Here are several ways for using Biochar as a soil amendment:

- **Improved soil quality:** Biochar can enhance soil quality by boosting water retention, minimizing nutrient loss, and improving the efficiency of nutrient use by crops (Lamichhane et al., 2023; Melissa, 2021).
- **Increased crop yield:** Biochar can boost crop yields by promoting plant growth and enhancing nutrient availability (Enhances et al., 2023; Lamichhane et al., 2023).
- Biochar can lessen the reliance on commercial fertilizers by enhancing soil fertility and overall health.
- **Long-lasting:** Biochar's highly stable structure ensures its durability and effectiveness as a soil amendment.
- **Application methods:** Biochar can be applied to root zones using air tools, injected into soil as a liquid slurry, employed for deep drainage through vertical mulching, or spread on newly-aerated lawns mixed with compost.

## 2.12 PROPERTIES OF BIOCHAR USED FOR SOIL AMENDMENT AND WATER TREATMENT

### SOIL AMENDMENT

- **Physical Properties:** Biochar should possess a high surface area and porosity to enhance the soil's water retention and minimize nutrient leaching (Lamichhane et al., 2023).
- **Chemical Properties:** Biochar should have a neutral pH and minimal contamination levels (Adhikari et al., 2023).
- **Biological Properties:** Biochar should contain few microorganisms to avoid competing with soil microbes (Guo, 2020).

### WATER TREATMENT

- **Physical Properties:** Biochar should possess a large surface area and porosity to enhance water retention and decrease the loss of water and nutrients (Lamichhane et al., 2023).
- **Chemical Properties:** Biochar should have a strong capacity to adsorb contaminants like heavy metals (Rawat et al., 2019).
- **Biological Properties:** Biochar should contain few microorganisms to avoid contaminating the treated water (Asirifi et al., 2023).

## 2.13 OTHER USES/APPLICATION OF BIOCHAR

Biochar has many potential applications beyond soil amendments. Here are some additional uses of Biochar:

**Sanitation of human and kitchen wastes:** Biochar can be utilized to sanitize human and kitchen waste, lowering the risk of disease transmission.

**Composting agent:** Biochar can be incorporated into compost to enhance its quality and decrease greenhouse gas emissions (Hans-Peter & Kelpie, 2014).

**Reduction of odors:** Biochar can be mixed with silage, litter, slurry, and manure to minimize the odors generated by decomposing material (Schmidt & Wilson, n.d.).

**Feed additive/supplement:** Biochar can be used as a feed additive or supplement for livestock to enhance their health and growth. \_

**Air pollution control:** Biochar can be applied to capture pollutants like mercury from power plant emissions and to remediate contaminated soils (Hertsgaard, 2014).

**Building materials:** Biochar can be utilized as a construction material, including in the manufacturing of bricks and concrete.

**Livestock Bedding:** Biochar can serve as bedding for livestock, helping to absorb moisture, control odors, and enhance animal comfort in barns and stables.

**Carbon Capture and Sequestration (CCS):** Biochar can be employed as a method for carbon capture and storage, sequestering carbon from the atmosphere for long durations.

**Bioenergy Production:** Biochar can be utilized as a solid fuel for heating and energy production. When burned, it generates heat that can be used for residential or industrial heating purposes.

**Composting Enhancer:** Incorporating Biochar into compost piles can accelerate the composting process by boosting aeration, moisture retention, and microbial activity.

**Biodegradable Plastics:** Biochar can be added to biodegradable plastics to enhance their structural strength and water resistance.

**Fire Mitigation:** Biochar can be used in forests or landscapes to lower the risk of wildfires by enhancing soil moisture and decreasing the flammability of vegetation.

**Odor Control:** Biochar can help minimize odors in composting operations, wastewater treatment facilities, and livestock environments.

**Livestock Feed Additive:** In certain situations, Biochar is mixed into livestock feed to enhance digestive health and lower methane emissions from ruminant animals.

**Concrete Additive:** Biochar can serve as a partial replacement for cement in concrete mixtures, helping to decrease the carbon footprint of construction materials.

**Landfill Cover:** Biochar can be used as a cover material for landfills to minimize odors and gas emissions, as well as to enhance the stability of landfill surfaces.

**Environmental Remediation:** Biochar can be applied to clean up contaminated soils, sediments, and water bodies by adsorbing and trapping pollutants.

**Desalination:** Biochar has been investigated for use in desalination, especially when combined with other desalination techniques, to extract salts and minerals from brackish water.

**Biogas Production:** Biochar can boost the effectiveness of anaerobic digesters in biogas production by offering a substrate for microorganisms that produce methane.

## **2.14 BIOCHAR ECONOMIC VIABILITY**

The economic feasibility of Biochar production and use depends on several factors, including feedstock costs, production methods, revenue opportunities, and market rates. Despite existing challenges, Biochar systems have the potential to be profitable, particularly when adapted to local conditions and production scales.

## **2.15 IODINE NUMBER**

The iodine number, also referred to as the iodine value or iodine absorption number, indicates how much iodine (in grams) a substance can absorb or chemically bind per 100 grams. It is used to gauge the surface area of activated carbon or Biochar, though it only directly relates to the surface area of certain activated carbons.

The iodine number is calculated based on the amount of iodine adsorbed by the activated carbon or Biochar. Specifically, it measures the adsorption of the triiodide ion ( $I_3^-$ ). Since surface oxides on activated carbon repel the triiodide ion, a higher concentration of surface oxides results in a lower iodine number.

A higher iodine number doesn't always indicate greater adsorption capacity for the specific molecules we aim to adsorb. The iodine number can be influenced by variables like temperature and pyrolysis conditions.

## CHAPTER THREE

### METHODOLOGY AND MATERIALS

The aim of this study is to investigate the potential of biomass pyrolysis for producing Biochar, with the goal of encouraging its application as a soil amendment and its use in water treatment.

#### 3.1 MATERIALS

##### EXPERIMENTAL SETUP

- **Pyrolysis Reactor:** A pyrolysis reactor will be used for the slow pyrolysis process.
- **Sawdust Preparation:** Sawdust was collected from a sawmill in Isihor Ugbowo, Benin City, Edo State, Nigeria, and dried in an oven to reduce its moisture content to below 10%.
- **Pyrolysis Temperature:** The pyrolysis process was conducted at different temperatures, (400, 450,500,550,600,650, 700) °C
- **Holding Time:** The sawdust underwent pyrolysis for a total of 1 hour and 30 minutes, with the process divided into 30-minute intervals, followed by 15-minute breaks at each temperature stage (Shaaban et al., 2013).

##### APPARATUS AND EQUIPMENT USED

**Table 3.1: Apparatus/Equipment Used During This Study and Their Functions**

S/N	Apparatus /Equipment	Function
1	Weighing balance	It was used to weigh the mass of the sawdust before and after pyrolysis.

2	Stopwatch	It was used to monitor the holding time of the process.
3	Crucible with lid	It was used to feed the sawdust to the reactor and also trap gasses that was released during the pyrolysis process.
4	Pyrolysis reactor	It was used for the slow pyrolysis process.
5	Heating source (Electricity)	It was used to heat the pyrolysis reactor to the desired temperature.
6	Temperature controller	It was used to maintain the desired temperature in the pyrolysis reactor.
7	Thermocouple	It was used to monitor and record the temperature during the pyrolysis process.
8	Gas collection system	It was used to capture and collect the gases produced during pyrolysis.
9	Oven	It was used to dry the feedstock (sawdust).
10	Grinder	It was used to grind the sawdust into smaller particle to ensure uniform particle size.
11	ASTM 250 $\mu$ m sieve	It was used to remove large particles or debris. Used to reduce the size of the sawdust before activation.
12	Conical flask Jinotech instruments	Used to collect filtrate during the washing out process.
14	Electric muffle furnace	Used for carbonization of char.

	PEC Medical USA (Model-SX-5-12)	
15	Electro-heating Standing Temperature Controlled Pyrolysis Reactor	Used for pyrolysis of saw dust
16	Desiccator	Used during cooling processes to prevent moisture gain.
17	Whatman filter paper	Used to separate washed char residue from the filtrate
18	Plastic dropper	Used to add minute quantities of sample solutions or reagents.
19	Plastic funnels	Used during process for filtration.
20	Glass beakers Jinotech instruments	Used to hold samples for analysis.
21	Electronic Compact Scale	Used to weigh samples and reagents
22	Crucibles	Used to hold the sawdust during carbonization
23	Volumetric flask S.Pryex	Used for making standard solutions
24	Burette Jinotech instruments	Used to hold titrant during titration process.
25	Retort stand and clamp	Used to hold the burette in place during titration.

26	Measuring cylinder Jintoech instruments	Used to measure volumes of liquids
27	Cycling vibrator HY-4A PEC MEDICAL, USA	Used for adequate mixing of liquid samples

**Table 3.2: Reagents Used and its Application**

S/N	Reagents Used	Source(s)	Application
1.	Distilled Water	Luco chemical laboratories	Used for preparation of solutions.
2.	Potassium hydroxide (KOH)	Trust Chemical Laboratories	Used as activating agent for the char activation.
3.	Sulfuric Acid (H <sub>2</sub> SO <sub>4</sub> ) solution	LOB chemie laboratory reagents	Used to facilitate neutralization of carbonized char.
4.	Hydrochloric acid (HCl) solution		Used during determination of surface area.
5.	Sodium thiosulfate (Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> ) powder		Used as titrant during titration to determine the surface area.
6.	Potassium iodide (KI) powder		Used for the preparation of iodine solution.
7.	Iodine (I <sub>2</sub> ) crystals		Used for the preparation of iodine solution.

8.	Cassava starch powder		Used for preparation of starch indicator.
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### 3.2 METHODOLOGY

#### EXPERIMENTAL PROCEDURE

- Collect a representative sample of sawdust and use a sieve to eliminate impurities or foreign materials.



**Plate 3. 1: Sample of sawdust**

- The sawdust was thoroughly sieved to ensure a uniform particle size.



**Plate 3. 2: Sample of sawdust been sieved**

- The sawdust was oven-dried at approximately 100-105°C for 24 hours to eliminate any remaining moisture (Shaaban et al., 2013).
- An empty crucible was weighed on the weighing balance.



**Plate 3. 3: Weighing balance**

- A measured quantity of the prepared sawdust was placed into the crucible and weighed.
- The pyrolysis reactor was pre heated to a temperature of 400 °C.



**Plate 3. 4: Pyrolysis reactor**

- Once the reactor was heated, 5 crucibles with the sawdust was carefully put into the pyrolysis reactor.
- The sawdust underwent pyrolysis with little to no oxygen in the reactor. The crucibles were removed at different intervals: the first after 30 minutes, the second after 45 minutes, the third after 60 minutes, the fourth after 75 minutes, and the fifth after 90 minutes.
- After pyrolysis the crucible was allowed to cool to room temperature and was weighed.
- Repeat procedure for temperatures (450-700) °C.

#### **SAMPLE COLLECTION**

The sawdust collected from Isihor Ugbowo, Benin City, Edo State, was thoroughly sieved to ensure uniform particle size. The sample was then sun-dried before being placed in an oven at approximately 100-105°C for 24 hours to eliminate moisture.

### CHARACTERIZATION OF THE ACTIVATED CARBON

To measure the effectiveness of the produced activated carbon for its intended use, various chemical tests were performed. The iodine number test was used to characterize the activated carbon, for the purpose of liquid phase adsorption, while other methods for product characterization included measuring the percentage yield, ash content, and bulk density.

**Ash Content (%):** Ash content was measured by weighing 1g of powdered carbon (sieved to <250µm) into a porcelain crucible and heating it at 115°C for 6 hours. The carbon was then heated in a muffle furnace at 650°C for 2.5 hours. After cooling, the crucible was transferred to a desiccator and weighed. The ash content was calculated as:

$$Ash (\%) = \frac{Final\ solids\ weight\ (g) \times 100}{Initial\ carbon\ weight\ (g)} \dots\dots\dots 3.1$$

**% Yield:** The AC yield will be defined as the final weight of the product after activation, washing and drying. The percent yield will be determined from Eq 3.2:

$$Yield\% = \frac{M_{final}}{M_{initial}} * 100\% \dots\dots\dots 3.2$$

Where  $M_{final}$  is the mass activated carbon of and  $M_{initial}$  is the mass of precursor.

**Total Surface Area (m<sup>2</sup>/g):** The total surface area of the activated carbons was determined using the BET method for specific surface area analysis, as described by Pendyal et al. (1999).

**pH of Activated Carbons:** To measure the pH, one gram of carbon was suspended in 100 ml of distilled water with a pH of 7.0 and heated at 90°C for 20 minutes. After cooling, the pH was measured using an Orion 410 pH meter (Orion Research Inc., Cambridge, MA). The pH meter was calibrated with standard buffers within the expected pH range before the measurement.

### **3.3 SAMPLE CHARACTERIZATION STUDIES**

#### **3.3.1 BET (BRUNAUER-EMMETT-TELLER) SURFACE AREA**

The BET method is a specialized technique for measuring the surface area of a material. It uses gas adsorption to determine the surface area of a solid substance.

The surface area will be determined through nitrogen (N<sub>2</sub>) adsorption at -196 °C using an automatic adsorption instrument (ASAP 2010, Micrometrics).

#### **3.3.2 FTIR ANALYSIS**

The surface functional groups of the prepared activated carbon will be identified using Fourier Transform Infrared (FTIR) spectroscopy (Perkin Elmer), and the resulting spectra will be recorded.

#### **3.3.3 SEM-EDS (SCANNING ELECTRON MICROSCOPY WITH ENERGY-DISPERSIVE X-RAY SPECTROSCOPY) ANALYSIS**

SEM-EDS is a technique used to study the surface morphology and chemical composition of Biochar. It integrates scanning electron microscopy (SEM), which reveals the material's surface topography, with energy-dispersive X-ray spectroscopy (EDS), which determines the elemental

composition of the Biochar.

Surface morphology of the activated carbon sample will be examined using a scanning electron microscope.

### **3.3.4 IODINE NUMBER**

In addition to assessing the production yield of activated carbon (AC), the iodine number will also be used to evaluate the quality of ACs produced. The iodine number will be determined using the ASTM D4607-94 method.

The iodine number is the amount of iodine, measured in milligrams, that is adsorbed by 1.0 gram of carbon when the iodine concentration in the filtrate is 0.02 N (0.02 mol/L). This test is straightforward and provides a quick estimate of the internal surface area of activated carbons.

### **DETERMINATION OF SURFACE AREA BY IODINE NUMBER METHOD**

- About 10ml of 5% HCl solution was added to 0.5 gram of the activated carbon sample.

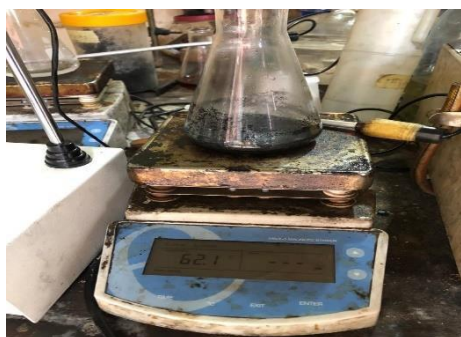


**Plate 3. 5: 10 ml of 5% HCL solution**



**Plate 3. 6: 0.5 g of Biochar sample**

- Boil for 60seconds and allow to cool.



**Plate 3. 7: HCL and Biochar solution\**



**Plate 3. 8: HCL Solution without Biochar sample (blank)**

- Thereafter, 20ml of 0.1M of iodine solution was added to each of the mixtures and then subjected to intensive shaking using an orbital shaker for 5minutes.



**Plate 3. 9: 20 ml 0.1 M iodine solution**

- The solution containing the sample was filtered using a filter paper.
- 0.2ml of starch solution was added in drops to 10ml of each HCl-Iodine solution mixture until it turned blue-black.



**Plate 3. 10: HCL-Iodine-starch solution (Sample)**



**Plate 3. 11: HCL-Iodine-starch solution (Blank)**

- The HCl-Iodine-starch solution mixture was titrated against 0.1M sodium thiosulfate solution.



**Plate 3. 12: 0.1M sodium thiosulfate solution.**

- The titer volumes obtained were recorded for each titration. Blank titration was also carried out without the sample to determine the blank titer volume. To determine the surface area, the iodine number was first calculated using the equation;

$$= \frac{Vb - V_s}{126.9} \dots \dots \dots 3.3$$

Where IN represents the iodine number

m is mass of sample = 0.5 g

N is normality (0.1N)

Vb is the titer volume of blank = 0.5 cm<sup>3</sup>

Vs is the titer volume of sample= 0.1 cm<sup>3</sup>

Vfb = 1

$$V_{fs} = 1$$

$$= \frac{0.5 - 0.1}{0.5} \times 0.1 \times 126.9 \times \frac{1}{1}$$

$$= 10.152$$

The surface area was calculated using the equation;

$$= \frac{IN \times 10^{-5}}{126.92} \times N \times W_i \dots \dots \dots 3.4$$

Where IN is the iodine number

$$m_i = 126.92 \text{ g/mol}$$

$$N = 6.023 \times 10^{23} \text{ mol}^{-1}$$

$$W_i = 0.2096 \times 10^{-18} \text{ m}^2$$

$$S_i = \frac{10.152 \times 10^{-5}}{126.92} \times 6.023 \times 10^{23} \times 0.2096 \times 10^{-18}$$

$$= 0.1010 \text{ m}^2$$

### 3.4 DETERMINATION OF POROSITY

To determine the porosity, 10 ml of each sample was placed into a measuring cylinder, followed by the addition of 10 ml of water. The mixture was then filtered to collect the volume of water that passed through the sample. Porosity was calculated for using the equation;

$$= \frac{V_L}{V_L + V_{fs}} \times 100 \dots \dots \dots 3.5$$

$V_L$  = volume of liquid that penetrates into the sample

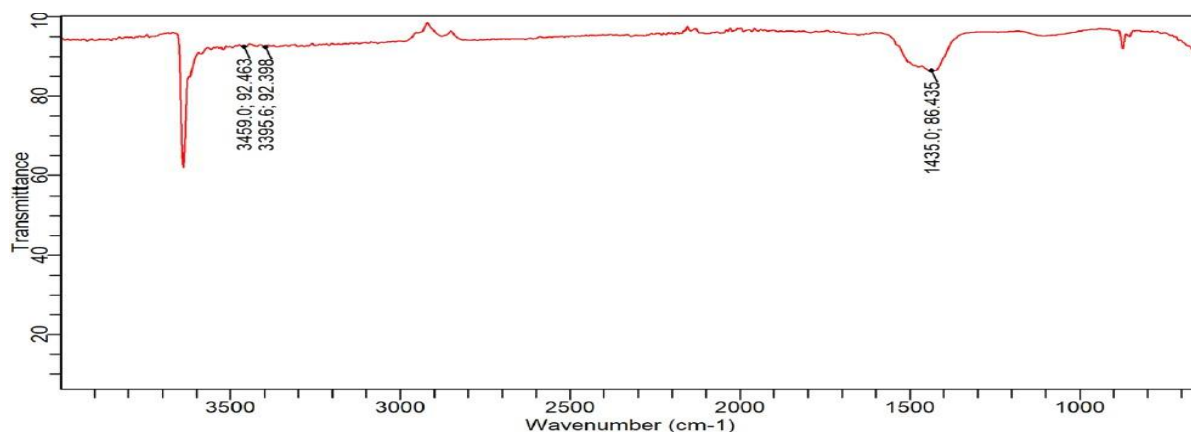
$V_s$  = volume of sample

## CHAPTER FOUR

### RESULTS AND DISCUSSION

#### 4.1 FOURIER TRANSFORM INFRARED (FTIR) SPECTRA:

Oxygen-containing surface functional groups significantly affect the surface characteristics and adsorption performance of activated carbons (Dawood & Sen, 2014). These groups can form during the activation process or be introduced through oxidation after the activated carbon is prepared. The FTIR spectra obtained for the prepared adsorbent is given in Figure 4.1. The sample showed three major absorption bands in the region  $1600 - 1400 \text{ cm}^{-1}$ . The strong band around  $1435 \text{ cm}^{-1}$  refers to the stretching vibrations of Carbonate ion ( $\text{CO}^{2-}$ ) bonds which is often found in activated carbons. Similarly, the weak peak seen at  $3395.60477 \text{ cm}^{-1}$  has been assigned to stretching vibrations of aliphatic primary amine ( $\text{N} - \text{H}$ ) bonds.



**Figure 4. 1: FTIR Spectrum of analysis of adsorbent**

## 4.2 RESULTS OF SCANNING ELECTRON MICROSCOPE

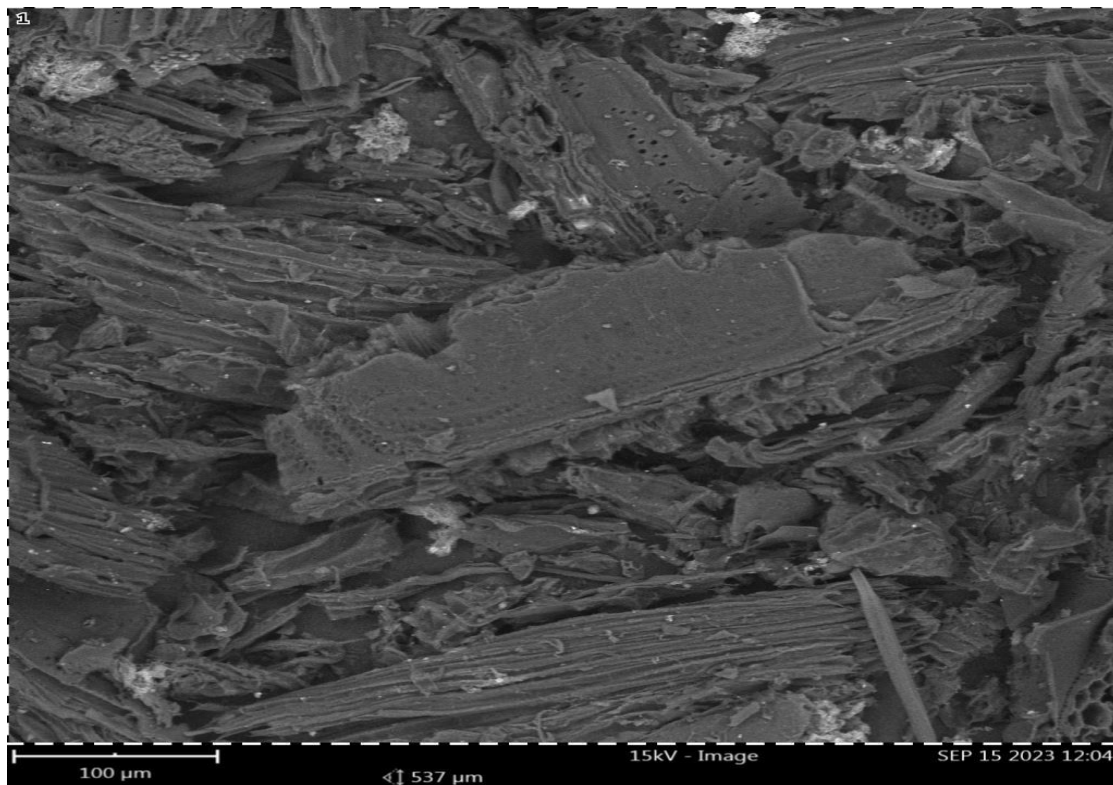


Figure 4. 2: SEM micrograph of pyrolyzed sawdust

## 4.3 SURFACE AREA STUDY OF PYROLYZED SAW DUST BY BET

### Multi-Point BET Plot

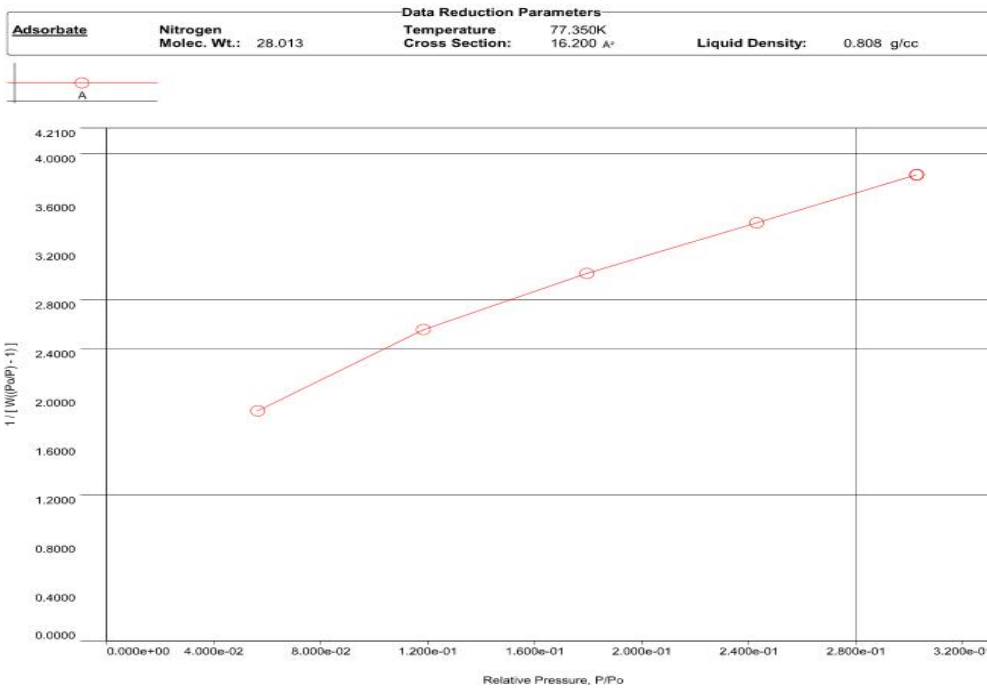


Figure 4. 3: Multi-Point BET Plot

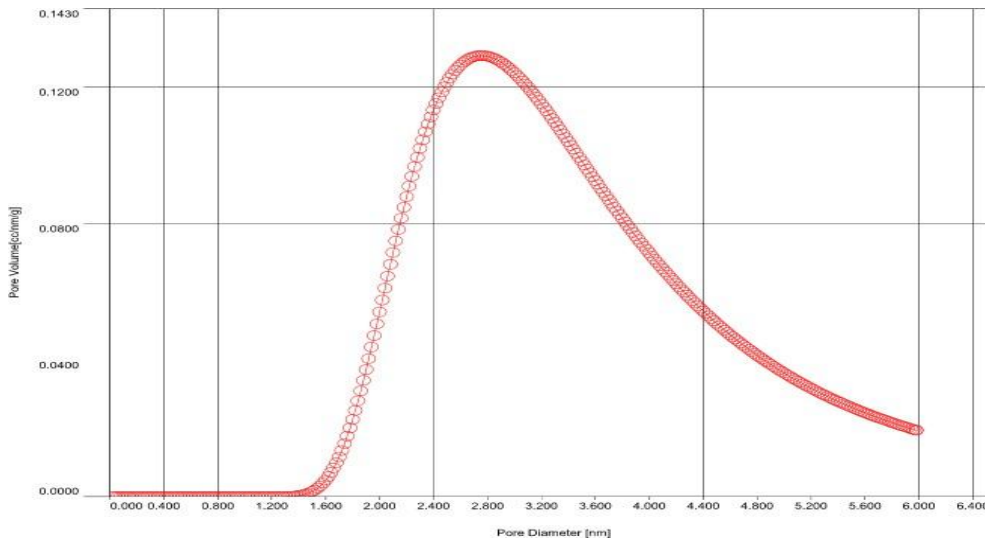


Figure 4. 4: DA Plot

### Area-Volume Summary

Data Reduction Parameters Data			
<b>t-method</b> <b>BJH/DH method</b> <b>DR method</b> <b>HK method</b> <b>SF method</b> <b>DFT method</b>	Thermal Transpiration: off Calc. method: de Boer Moving pt. avg.: off Affinity coefficient (A): 0.3300 Tabulated data interval: 1 Tabulated data interval: 1 Calc. Model: N2 at 77 K on carbon (slit pore, NLDFT equilibrium model) Rel. press. range: 0.0000 - 1.0000	Eff. mol. diameter (D): 3.54 Å Eff. cell stem diam. (d): 4.0000 mm	
<b>Adsorbate</b>	Nitrogen Molec. Wt.: 28.013 Critical Temp.: 126.200 K Carbon DR. Exp (n): 2.000	Temperature: 77.350K Cross Section: 16.200 Å² Critical Press.: 33.500 atm	Moving pt. avg: off Liquid Density: 0.808 g/cc SuperCritic. K.: 1.000
<b>Adsorbent</b>			

Surface Area Data	
SinglePoint BET.....	2.757e+02 m²/g
MultiPoint BET.....	3.765e+02 m²/g
Langmuir surface area.....	1.016e+03 m²/g
BJH method cumulative adsorption surface area.....	4.721e+02 m²/g
DH method cumulative adsorption surface area.....	5.026e+02 m²/g
t-method external surface area.....	3.765e+02 m²/g
DR method micropore area.....	4.630e+02 m²/g
DFT cumulative surface area.....	1.127e+02 m²/g

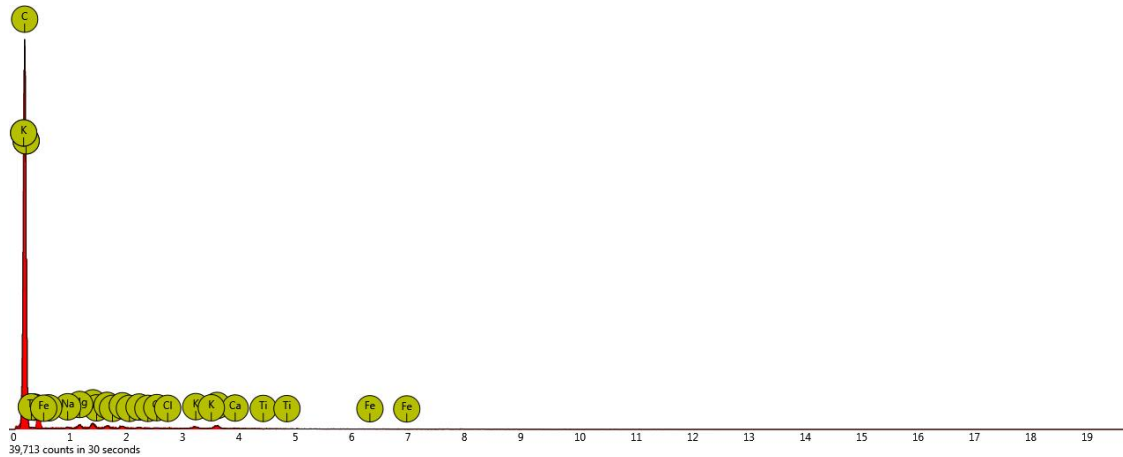
  

Pore Volume Data	
BJH method cumulative adsorption pore volume.....	2.299e-01 cc/g
DH method cumulative adsorption pore volume.....	2.353e-01 cc/g
DR method micropore volume.....	1.645e-01 cc/g
HK method micropore volume.....	7.883e-02 cc/g
SF method micropore volume.....	2.483e-02 cc/g
DFT method cumulative pore volume.....	1.303e-01 cc/g

Pore Size Data	
BJH method adsorption pore Diameter (Mode Dv(d)).....	2.118e+00 nm
DH method adsorption pore Diameter (Mode Dv(d)).....	2.118e+00 nm
DR method micropore Pore width.....	5.676e+00 nm
DA method pore Diameter (Mode).....	2.760e+00 nm
HK method pore Diameter (Mode).....	3.675e-01 nm
SF method pore Diameter (Mode).....	4.523e-01 nm
DFT pore Diameter (Mode).....	2.647e+00 nm

**Figure 4. 5: Area-Volume Summary**

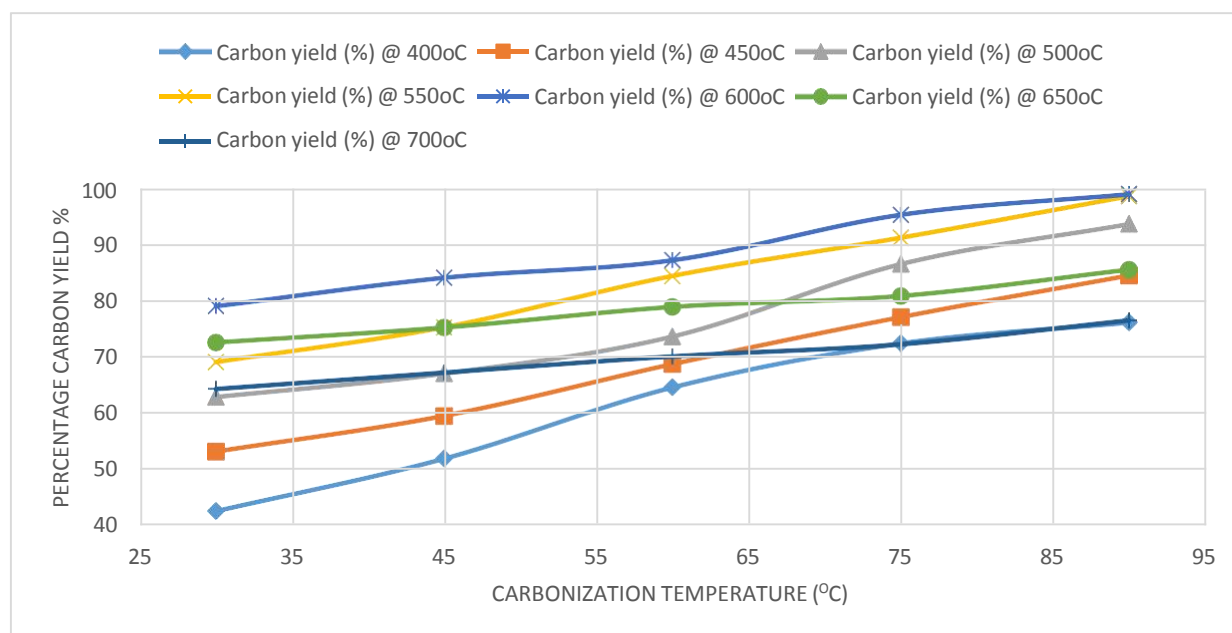


**Figure 4. 6: Elemental composition by energy dispersive spectrometer (EDS)**

**Table 4. 1: Elements compositions of pyrolyzed sawdust**

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	98.46	96.18
20	Ca	Calcium	0.25	0.83
13	Al	Aluminum	0.33	0.72
12	Mg	Magnesium	0.25	0.49
19	K	Potassium	0.13	0.41
15	P	Phosphorus	0.15	0.37
14	Si	Silicon	0.16	0.36
11	Na	Sodium	0.13	0.25
16	S	Sulfur	0.09	0.22
17	Cl	Chlorine	0.06	0.16
22	Ti	Titanium	0.00	0.00
26	Fe	Iron	0.00	0.00

#### 4.4 RESULTS OF PYROLYSIS OF WOOD SAWDUST



**Figure 4. 7: Effects of temperature of the pyrolysis of wood sawdust for carbon production**  
**KINETICS OF CARBONIZATION OF SAWDUST BY PYROLYSIS**

**Table 4. 2: Carbon yield at different temperature and time**

Pyrolysis Time (minutes)	Carbon yield (%) @ 400°C	Carbon yield (%) @ 450°C	Carbon yield (%) @ 500°C	Carbon yield (%) @ 550°C	Carbon yield (%) @ 600°C	Carbon yield (%) @ 650°C	Carbon yield (%) @ 700°C
30	42.47	53.07	62.85	69.05	79.07	72.57	64.27
45	51.85	59.45	67.03	75.26	84.14	75.24	67.19
60	64.57	68.69	73.64	84.43	87.26	78.91	70.08
75	72.43	77.08	86.57	91.25	95.37	80.86	72.24
90	76.15	84.53	93.72	98.67	99.04	85.55	76.51

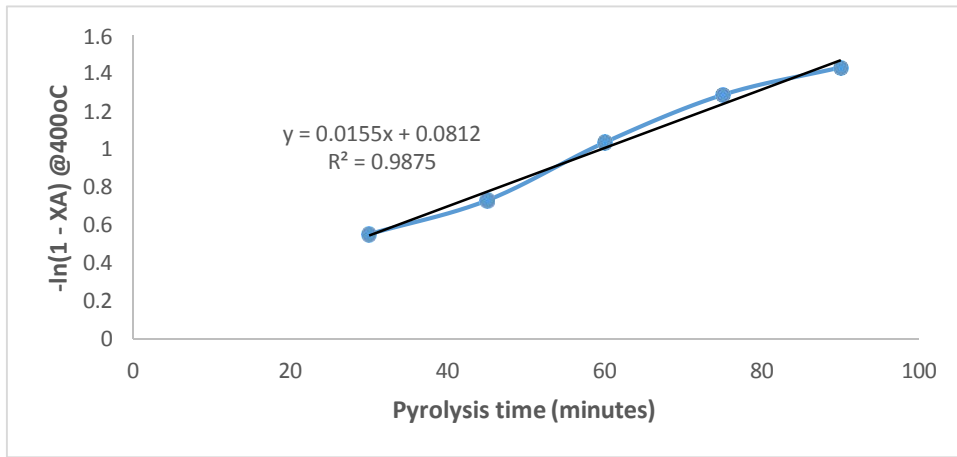
**Table 4. 3: Conversion of biomass at different temperatures**

Pyrolysis Time (minutes)	Carbon yield @ 400°C ( $X_{A@400oC}$ )	Carbon yield @ 450°C ( $X_{A@450oC}$ )	Carbon yield @ 500°C ( $X_{A@400oC}$ )	Carbon yield @ 550°C ( $X_{A@400oC}$ )	Carbon yield @ 600°C ( $X_{A@400oC}$ )
30	0.4247	0.5307	0.6285	0.6905	0.7907
45	0.5185	0.5945	0.6703	0.7526	0.8414
60	0.6457	0.6869	0.7364	0.8443	0.8726
75	0.7243	0.7708	0.8657	0.9125	0.9537

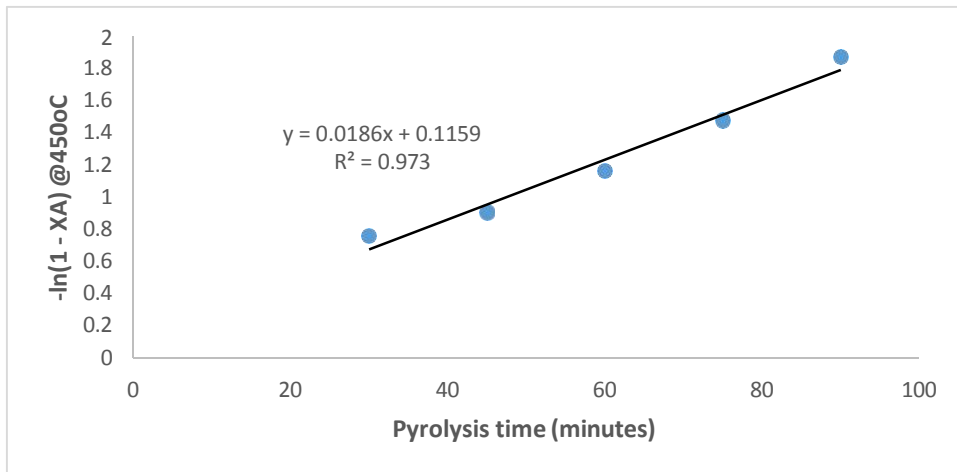
90	0.7615	0.8453	0.9372	0.9867	0.9904
----	--------	--------	--------	--------	--------

**Table 4. 4: Rate constant at plot at reaction temperatures**

Pyrolysis Time (minutes)	$-\ln(1 - X_A)$ @400°C	$-\ln(1 - X_A)$ @450°C	$-\ln(1 - X_A)$ @500°C	$-\ln(1 - X_A)$ @550°C	$-\ln(1 - X_A)$ @600°C
30	0.55286364	0.75651306	0.99020641	1.17279719	1.5639866
45	0.73084905	0.90263441	1.10957213	1.39674882	1.84137
60	1.03761127	1.16123265	1.33332248	1.8598242	2.0604235
75	1.28844196	1.47316029	2.00767918	2.43611649	3.0726133
90	1.43338597	1.86626752	2.76780021	4.31999124	4.6459922



**Figure 4. 8: Rate constant at plot at reaction temperature of 400°C**



**Figure 4. 9: Rate constant at plot at reaction temperature of 450°C**

## 4.5 REACTION KINETICS

The Rate Constant  $k$

From rate constants at various pyrolysis temperature, it could be seen from Figure 4.7 that increase in temperature also increases the conversion of biomass to carbon. The overall rate equation ( $K$ ) can be found using eqn 4.1 for first order reaction

$$kt = -\ln(1 - X_A) \dots\dots\dots 4.1$$

Where:

$X_A$  is taken as conversion of biomass.

The experimental data collected at 673K, 723K, 773K, 823K, 873K, 923K and 973 K were tested for 1st order kinetics

The results of experiment conducted at various temperatures are presented in table 4.5 as estimated using linearized Arrhenius equation. The experimental data fitted well for 1st order kinetics and were subjected to linearized Arrhenius equation.

$$k = k_0 * \exp\left(-\frac{E_a}{RT}\right) \dots\dots\dots 4.2$$

Finding the natural log of both sides of equation (4.2) produces equation (4.3)

$$\ln k = \left(-\frac{E_a}{RT}\right) + \ln k_0 \dots\dots\dots 4.3$$

Where,

$E_a$  is activation energy,

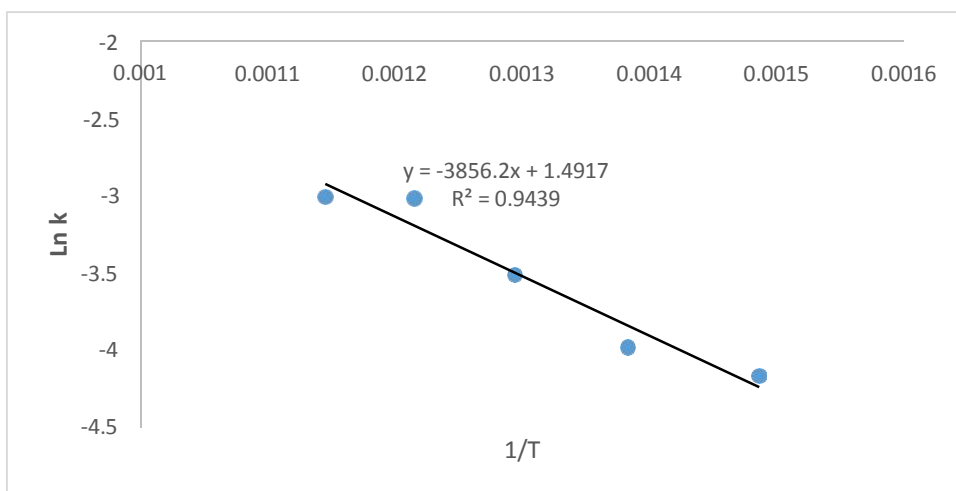
$R$  is the gas constant (8.314 J/mol.K)

$T$  is an absolute temperature, and

$k_0$  is a frequency factor.

**Table 4. 5: Results of experiment conducted at various temperatures as estimated using linearized Arrhenius equation**

Temp °C	Temp, K	1/T	Rate constant, k	Ln k
400	673	0.001486	0.0155	-4.16691526
450	723	0.001383	0.0186	-3.9845937
500	773	0.001294	0.0297	-3.51660823
550	823	0.001215	0.0489	-3.01797788
600	873	0.001145	0.0493	-3.0098312



**Figure 4. 10: Graph of  $\ln k$  vs.  $1/T$**

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATION

#### 5.1 CONCLUSION

In conclusion, the slow pyrolysis of sawdust to create Biochar represents a sustainable and promising method for utilizing biomass while promoting environmental responsibility. Through this project, we have gained valuable insights into the production process and the properties of the resulting Biochar.

Key findings and observations from the study include:

**Biochar yield:** Slow pyrolysis is an efficient technique for producing Biochar, typically resulting in up to 55% solid Biochar, with the remaining portions being bio-oil and syngas.

From the experiment it was observed that the Biochar yield was optimum at 600 °C at 90 minutes with a yield of 99.04%

**Biochar Quality:** The slow pyrolysis process successfully converted sawdust into high-quality Biochar, featuring a high carbon content, porous structure, and nearly neutral pH. These properties make it ideal for use in applications such as soil enhancement and carbon storage.

**Soil Enhancement:** A review of existing studies highlighted the beneficial effects of Biochar produced from sawdust on soil structure, nutrient retention, and water-holding capacity. Its potential to enhance soil health and boost crop yields offers significant promise for sustainable farming practices.

**Water treatment:** Biochar has demonstrated potential as an effective water treatment agent due to its capacity to filter out contaminants from water.

**Waste Utilization:** Transforming sawdust, a common waste product of the wood industry, into Biochar, helps reduce waste and promotes more efficient use of resources.

**Physiochemical properties:** Studies indicate that the physicochemical properties of Biochar, such as surface area, porosity, acid-base characteristics, surface functional groups, and elemental composition, are influenced by the pyrolysis temperature and the type of feedstock used. These factors significantly affect its effectiveness and suitability for removing specific contaminants.

**Iodine number and surface area:** Iodine number was calculated to 10.152gms and the surface area using iodine value method was calculated to be 0.1010 m<sup>2</sup>

## **5.2 RECOMMENDATIONS**

Based on the findings and outcomes of this project, the following recommendations are made:

**Environmental Impact Assessment:** Carry out a thorough environmental impact assessment to examine the sustainability and ecological effects of large-scale production of Biochar from sawdust. This will ensure that the practices are responsible and environmentally friendly.

**Market Development:** Explore and identify potential markets and industries for Biochar derived from sawdust. Collaborate with stakeholders such as agricultural organizations and environmental agencies to encourage the use of Biochar across different sectors.

**Education and Outreach:** Increase awareness and share information about the benefits of Biochar production and use among farmers, policymakers, and the general public. Educational and outreach initiatives can facilitate greater adoption.

**Policy Support:** Advocate for policy support and incentives that encourage the production and use of Biochar as a sustainable practice for agriculture and the environment. Work with policymakers to promote Biochar-friendly regulations.

**Continued Research:** Invest in ongoing research and development to broaden the uses of sawdust-derived Biochar and improve production methods. Collaborate with academic and research institutions to advance Biochar science and technology.

When selecting modification methods for Biochar, take into account its potential uses. Environmental application fields determine the modification techniques to use.

**Quality Assurance:** Develop quality assurance protocols to maintain uniformity in Biochar production. This involves overseeing the quality of feedstock, process conditions, and the characteristics of the final product.

In conclusion, the slow pyrolysis of sawdust to produce Biochar offers a multifaceted solution for tackling waste management, enhancing soil quality, and mitigating climate change. With further research, optimization, and collaborative efforts, this sustainable practice has the potential to significantly benefit agriculture, environmental protection, and resource efficiency.

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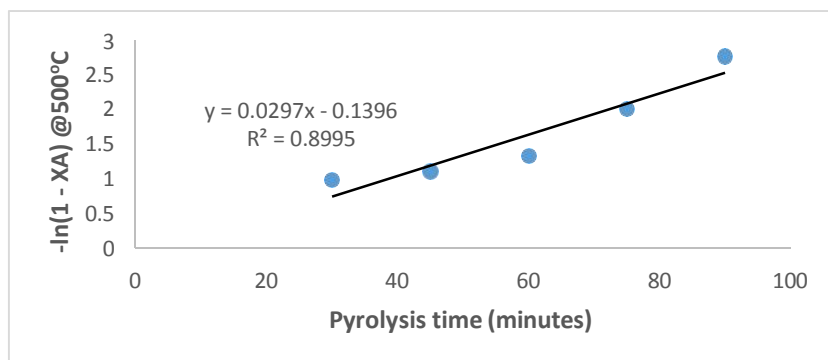
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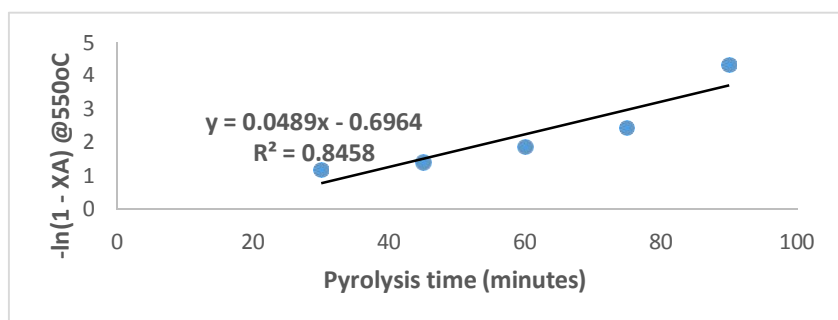
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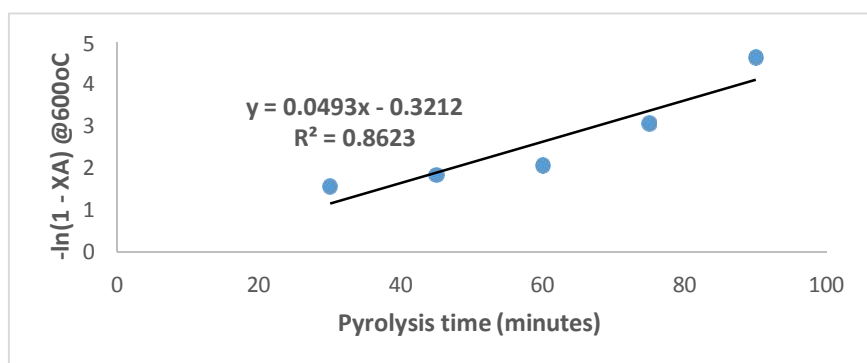
## APPENDIX



**Figure A 1: Rate constant at plot at reaction temperature of 500°C**



**Figure A 2: Rate constant at plot at reaction temperature of 550°C**



**Figure A 3: Rate constant at plot at reaction temperature of 600°C**