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TESI DI LAUREA

Carbon Footprint Assessment Of Biochar Production From Biomass Via Pyrolysis

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Dedication

To my family, whose unwavering support and encouragement have been my guiding light throughout this journey. Your love and belief in me have given me the strength to persevere and achieve this milestone.

To my professors and mentors, thank you for your guidance, wisdom, and the invaluable knowledge you have imparted. Your dedication to the pursuit of knowledge has inspired me to push my boundaries and strive for excellence.

To my friends and colleagues, your camaraderie and shared experiences have made this academic endeavor not only manageable but also enjoyable. Your friendship has been a constant source of motivation.

To all those who have touched my life in some way, whether big or small, I extend my heartfelt gratitude. This thesis is a culmination of the collective support and encouragement I have received.

With deep appreciation,

Kareem Osama Al-Twal

DEDICATION

Declaration

Il candidato dichiara che il presente lavoro è originale e non è già stato sottoposto, in tutto o in parte, per il conseguimento di un titolo accademico in altre Università italiane o straniere.
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Kareem Osama Al-Twal

DECLARATION

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ABSTRACT

Abstract

Considering the pressing concern of climate change, growing global need for energy, huge increase of waste generation due to the increase of the population all around the globe, it is crucial that we explore innovative ways to handle waste and energy to aid in the fight against climate change and build a better future for upcoming generations. This research aims to investigate the process of biomass waste pyrolysis with a focus on producing biochar. The main objective of this thesis is to evaluate biomass waste pyrolysis carbon footprint taking into consideration the potential of biochar, a product of the process, to act as a carbon sink when applied to soil while also considering the avoided emissions due to the use of bio-oil and syngas which are also a product of pyrolysis, as an energy source. By doing so we hope to contribute towards mitigating climate change while also decreasing our dependence on non-renewable energy sources.

As the world continues to show a growing interest in green energy solutions, there is a focus on utilizing waste as a valuable source of energy. One specific area that has caught attention is the process of pyrolysis which involves converting biomass waste into biochar, biooil and syngas. Our analysis will cover the carbon emissions generated throughout the process including pyrolysis, transportation, and handling of products. Through this examination, we aim to gain insights into the carbon emissions involved in transforming biomass into biochar, bio-oil, and syngas. Furthermore, we will explore how this technique can contribute to mitigating climate change by storing carbon over long periods, resulting in a general negative carbon footprint.

ABSTRACT

To make choices and develop plans in the fields of bioenergy and waste management, it is crucial to evaluate the carbon emissions related with these practices. This study's findings offer information on the effects of biomass pyrolysis and such knowledge will assist stakeholders in determining their priorities and improving their manufacturing methods accordingly. Additionally, by comprehending the scale of carbon emissions, this research supports the development of innovative green solutions that can be used for energy production and waste management techniques. It's crucial to highlight that this study underscores the importance of biochar in terms of its ability to store carbon and improve soil quality. Biochar is seen also as a land management technique because it can capture carbon for a long time while also enhancing soil health. The goal of the study is to encourage the adoption of this technology as an eco-approach, by providing insight into the carbon footprint associated with biochar production. This evaluation offers insight into the sustainability of the process enabling us to understand the carbon emissions associated with it. Armed with this knowledge, stakeholders can make decisions that promote friendly practices in the energy and waste management sectors, so let's join hands and strive towards creating a better world for future generations.

CHAPTER ONE: INTRODUCTION

1. Introduction

1.1. Background

Pyrolysis is gaining more attention as a technology for converting waste into energy. This process involves breaking down waste such as biomass, polymers and other organic materials using heat without the presence of oxygen. The result is the production of outputs such as bio-oil, biochar, and syngas. It offers a technique for waste management methods and has the potential to address significant environmental challenges that we face today. Biomass holds promise for producing bioenergy while also producing biochar through pyrolysis process.

Traditional waste handling methods, such as direct combustion, incineration, and landfilling have drawbacks and environmental challenges. Landfills require amounts of space on the ground, which can lead to the emission of greenhouse gases and potentially harm soil and water quality. On the contrary, incineration and direct combustion they both have an impact on efforts to mitigate climate change by releasing pollutants and greenhouse gases into the atmosphere. However, pyrolysis offers an alternative as it allows for the recovery of energy from waste materials without causing environmental impacts when compared to other methods but rather have a positive environmental impact.

Pyrolysis plays a role by converting waste into resources aligning with the core principles of the circular economy. It has the potential to decrease reliance, on fossil fuel reserves while also promoting resource preservation and contribute to mitigating climate change. Through pyrolysis various types of waste can be transformed into biofuels and other valuable products, like biochar, syngas, and bio-oil. To fully understand the long-term potential and sustainability of this technology it is important to focus on understanding the impact of pyrolysis, from a carbon footprint perspective. Investigating greenhouse gas emissions caused by pyrolysis including aspects such as the energy usage and end-of-life scenarios for the generated materials, can provide insights. This assessment methodology helps us make decisions, about waste management practices that prioritize preservation.

In our analysis of the carbon footprint, we primarily concentrate on evaluating the emissions related to the pyrolysis process while accounting both the avoided emissions due to the use of biochar in soil and the avoided emissions due to the use of bio-oil and syngas as an energy source when compared to traditional sources of energy.

The assessment of the carbon footprint associated with creating biochar from biomass waste using the pyrolysis method offers insights, into the carbon emissions throughout the entire lifecycle of the process. This assessment includes evaluating greenhouse gas emissions at every stage considering not emissions from pyrolysis itself only but also indirect emissions resulting from energy usage, transportation, and the complete supply chain based on my system boundaries. Additionally, it is crucial to consider how biochar produced through pyrolysis can act as a carbon sink when added to soil enhancing its capacity, for carbon storage.

The upcoming sections of this dissertation will delve into the literature available, at present on pyrolysis focusing on what we currently know, areas where more research is needed and the importance of addressing its environmental impacts. We will provide explanations of the research structure, system boundaries, data collection methods, inventory analysis approaches for assessing carbon footprint used in this assessment.

In a nutshell the main goal of this dissertation is to evaluate the effects of pyrolysis from the perspective of carbon footprint. This study contributes to our understanding of approaches, for managing waste. Offers valuable information for decision makers and stakeholders in the fields of waste management and energy. It presents an analysis of the advantages and disadvantages of pyrolysis as a technology for converting waste into energy well as its potential, as a strategy to mitigate climate change.

1.2. Research Topic

This thesis will mainly focus on investigating the effects of pyrolysis on the environment in terms of carbon footprint. The aim is to assess and analyze the environmental viability of pyrolysis as a waste to energy method from a carbon emissions perspective. Our main objective is to assess the greenhouse gas emissions throughout the life cycle of the pyrolysis process. We aim to achieve this by conducting an in-depth evaluation of its carbon footprint, which will provide insights into the environmental feasibility and potential advantages of using pyrolysis as an energy solution, for managing waste.

1.3. Research Objectives

The following are the research objectives of this master's thesis:

1. Assessing the impact of pyrolysis as a waste to energy technology using carbon footprint approach.

2. To state the advantages and limitations of pyrolysis as a waste management and energy recovery approach.

3. To gain insight into technologies that converts waste into energy and their significance in achieving environmental sustainability.

4. To assist individuals in the waste management sector and other relevant parties in making decisions that improves operational efficiency by establishing regulations and standards for pyrolysis and determining carbon footprint standards.

5. To ensure that the research findings are, in line, with the Sustainable Development Goals, Goal 12 focusing on consumption and production Goal 13 addressing climate action and Goal 7 emphasizing affordable and clean energy.

6. To enhance our understanding of the ways pyrolysis can contribute to circular economy and potential enhancement in sustainable waste management while also addressing climate change by capturing and reducing carbon emissions.

7. Identifying possible methods in technology that can be used to minimize the carbon footprint related to the pyrolysis process.

1.4. Significance of the Research

The investigation of the environmental impact of pyrolysis from a carbon footprint viewpoint is of the utmost importance for various reasons:

- **Addressing Environmental Concerns:** As the world grows more aware of pollution, resource depletion and climate change the need for innovative waste disposal methods becomes increasingly important. Pyrolysis presents an approach which reduces emissions of greenhouse gases while simultaneously generating energy. We are actively working to safeguard our environment and minimize the consequences of climate change by implementing these measures.

- **The Transition to a Circular Economy:** The concept of the circular economy focuses on improving resource efficiency and reducing waste generation. It promotes the reuse and recycling of materials while also emphasizing the significance of waste to energy technologies such as pyrolysis. This research aims to contribute to the advancement of circular economy practices related to pyrolysis by examining its impacts and potential benefits.

- **Informed Decision Making:** Accurate and reliable information is of paramount importance for government decision-makers, waste management experts, and all stakeholders engaged in development. Having access to information empowers them to make informed decisions that will ultimately have positive impacts on the environment. The findings from this investigation will be of value to policymakers as they work towards creating regulations, laws and guidelines that promote the adoption of pyrolysis as a means of managing waste and recovering energy. By shedding light on the environmental consequences and tradeoffs associated with pyrolysis these regulations will effectively minimize any potential harm.

- **Knowledge Expansion and Research Advancements:** The research, on pyrolysis and its effects on the environment contributes to our understanding by compiling data from studies. This study improves our knowledge of pyrolysis technologies, types of feedstocks methods for recovering energy and the creation of products. This is achieved through a comprehensive review of existing literature and the utilization of the SimaPro software to assess the carbon footprint for specific stages of our lifecycle. Additionally, the study identifies key areas necessitating further investigation and development, such as the optimization of feed materials, the implementation of pollution control measures, and enhancements in process efficiency.

- **Sustainable Development Goals (SDGs):** The study's findings support Development Goals (SDGs) particularly Goal 12 (Responsible Consumption and Production) Goal 13 (Climate Action) and Goal 7 (Affordable and Clean Energy). According to this research pyrolysis has the potential to play a role, in achieving these sustainability objectives by promoting responsible waste management resulting in reduction in greenhouse gas emissions and facilitating the generation of clean energy.

- **Economic Implications and Industrial Applications:** Studying the impact of pyrolysis on the environment is vital and presents new opportunities in various industries. This research offers insights for businesses aiming to implement waste management strategies by evaluating the environmental performance of pyrolysis throughout its life cycle. It explores benefits such, as reducing waste disposal costs, recovering energy, and creating value added products. The findings of this study can help organizations assess the cost effectiveness and feasibility of adopting pyrolysis technologies, ultimately contributing to the development of economies and innovative waste management practices.

- **International Policy and Regulatory Frameworks:** The research findings presented in this study contribute to the development of policy frameworks aimed at addressing climate change and promoting sustainable development. These results can be used to establish regulations, guidelines, and best practices for using pyrolysis as a waste management technique. Additionally, by assessing the impacts associated with pyrolysis processes this research supports the improvement of legislation ensuring consistent environmental evaluations. It also encourages collaboration and technology transfer in the field of waste management.

1.5. Research Methodology

To assess the impact of converting biomass waste into biochar using the pyrolysis method this master's thesis utilizes a research approach that incorporates various important elements:

- **Literature Review:** To gain an understanding of our research subject and guide our data collection methods we start by conducting a review of relevant literature. This examination covers an exploration of published works and research efforts focused on topics such as pyrolysis, carbon footprints analysis of pyrolysis, waste to energy technologies, and sustainable waste management. By analyzing the existing body of literature in these areas we hope to gather insights that will enhance our study.

- **Data Collection:** Collecting data is an important step in our study as it helps us assess the carbon footprint. To fully understand the carbon emissions associated with converting biomass waste into biochar through pyrolysis we will primarily gather information from sources such as scientific articles, research papers and other publications. Moreover, when selecting these literature sources for data collection we will use a specific criterion to ensure accuracy and credibility. We will only include sources and studies that align with the goals and methods of our study to maintain its reliability.

- **Carbon Footprint Assessment:** To determine the greenhouse gas emissions related to producing biochar from biomass waste we will use an established method which is carbon footprint assessment. This assessment will also cover end of life scenarios. We will thoroughly examine every step of the pyrolysis process starting from biomass waste from waste facilities transportation to our pyrolysis plant, to applying biochar to soil and also the usage of biooil and syngas as a source of energy. Our study will carefully evaluate both indirect emissions, including those produced by energy usage and transportation. Additionally, we'll incorporate software tools, such as Sima Pro to enhance our evaluation methodology for specific life cycle stages.

- **Impact Assessment:** Understanding the results of the carbon footprint evaluation is crucial, for gaining insight into the impacts of pyrolysis. This includes analyzing data on emissions pinpointing areas with emissions and taking into consideration the benefits of carbon sink using biochar produced.

- **Comparative Analysis:** The study evaluates the impact and carbon footprint of converting biomass waste into biochar through pyrolysis. It compares this method with other energy production methods by taking into consideration the avoided emissions due to the usage of energy from bio-oil and syngas instead of traditional fossil fuels. The findings, from this research will provide insights into the sustainability of pyrolysis and its potential role in achieving environmental sustainability objectives.

- **Recommendations and Conclusion:** The investigation provided herein offers several recommendations for methods to increase sustainability while also reducing the carbon footprint involved with the pyrolysis of biomass to create biochar. These recommendations propose digging deeper into more energy-effective pyrolysis technologies that make use of carbon usage and collecting techniques, resulting into the development of policies to support and conduct out additional studies into the stability and carbon sink capacity of biochar, and through setting the regulations in place we can encourage the use of biochar for improving soil and also reducing greenhouse gas emissions while also advancing environmentally friendly waste disposal techniques.

CHAPTER TWO: LITERATURE REVIEW

2. Literature Review

2.1. Introduction Pyrolysis as a Waste-to-Energy Technology

Due to the rapid increase of the globe's population size, our need for electricity is growing at a rate that is unsustainable which poses a huge challenge to the sustainability of conventional energy sources (De Cian & Sue Wing, 2016). Moreover, Increased releases of greenhouse gases to the atmosphere in addition to the decreasing supply of fossil fuel supplies demonstrate the desire for environmentally friendly and green renewable energy alternatives. Pyrolysis of biomass is a promising innovative source of green sustainable energy and also it can be utilized as a climate mitigation strategy due to the fact that biochar a product of the process acts as a carbon sink (Kalak, 2023).

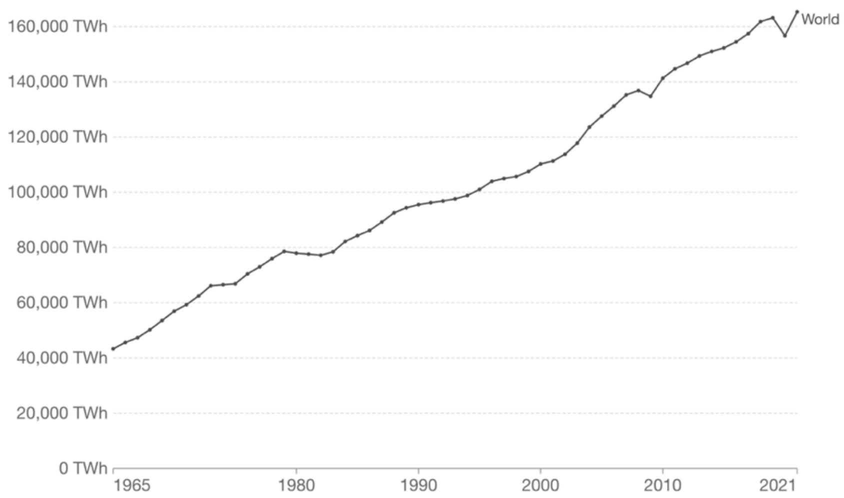

Figure 1: *Primary Energy Consumption measured in terawatt-hours (TWh) From 1965 till 2021 (BP statistical review of world energy ;and EIA)*

Among the sources of environmentally friendly energy used internationally involves biomass that may be utilized biologically or thermochemically to generate electrical power in a range of phases (solid, liquid, and gas). In comparison to petroleum and coal, emissions of carbon dioxide from bio-based fuel possess a less significant effect. In cases where petroleum and coal undergo combustion, they emit carbon that has been buried for millions of years, while whenever biofuels are burnt, they emit carbon which is a component of the natural carbon cycle which means that burning of biomass operates and generates carbon within the natural system while burning of fossil fuel increases the overall quantity of carbon in the environment (Peterson & Hustrulid, 1998).

Pyrolysis refers to the thermochemical transformation activity which generates bio-oil, biochar, and syngas using biomass. In absence of oxygen the biomass is subjected to very high temperatures leading to high molecular vibrations at which the molecules are stretched and shaken to such an extent that they start breaking down into smaller molecules. An absence of oxygen within the pyrolysis compartment prevents the organic parts from complete combustion leading to the generation of valuable compounds. Organic materials have been most frequently pyrolyzed. It's fundamentally a carbonation operation whereby a highly molecular-weight organic material is broken down or fragmented resulting in a solid product having a substantial amount of carbon and some volatile components (Maschio et al., 1992).

Pyrolysis often falls under three phases: drying, devolatilization, and char production. These stages happen progressively as the organic substance breaks down thermally:

Drying Phase

The drying phase initiates the pyrolysis process, and it is the initial stage where biomass is subjected to elevated temperatures in the absence of oxygen. During this phase, the primary objective is to remove moisture from the biomass. As the temperature rises, the heat energy drives off the water content present within the biomass. The water molecules, which were trapped within the biomass structure, begin to evaporate, turning into water vapor. This phase is crucial as it prepares the biomass for the subsequent stages by eliminating moisture and preventing interference with thermal decomposition (Glushkov et al., 2021).

Devolatilization Phase

Following the drying phase, we enter the devolatilization phase. This is a pivotal stage in the pyrolysis process where the remaining organic components of the biomass, including cellulose, hemicellulose, and lignin, undergo thermal decomposition. Operating at high temperatures and in an oxygen-free environment, these complex organic molecules start to break down into smaller, volatile compounds. This breakdown leads to the release of gases known as syngas, consisting of carbon monoxide, carbon dioxide, hydrogen, methane, and others. Additionally, bio-oil is generated, which is a liquid product containing a diverse array of organic compounds. The devolatilization phase is responsible for producing valuable bio-based chemicals and fuels (Glushkov et al., 2021).

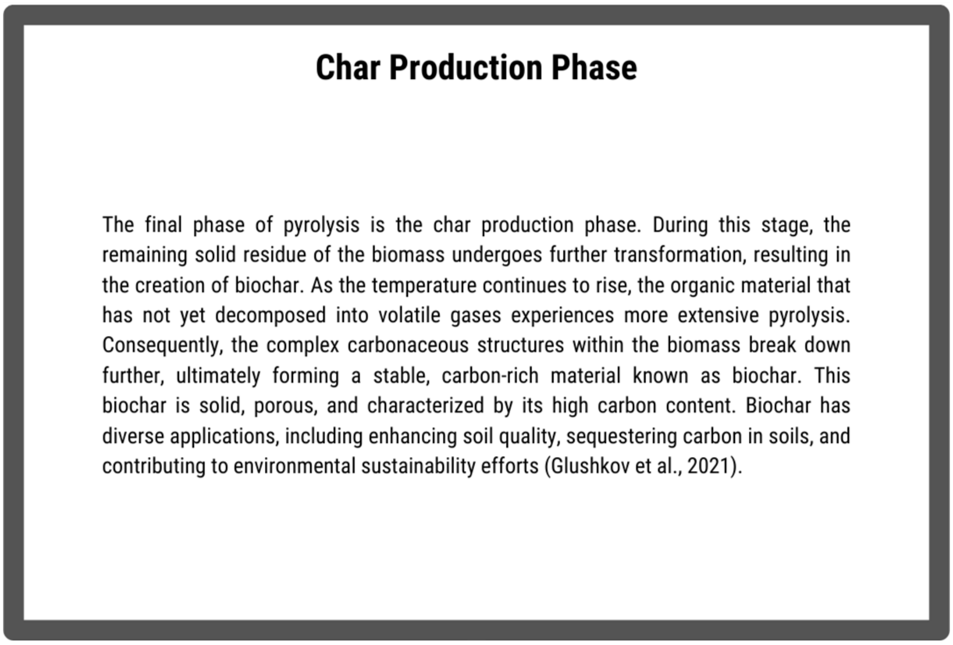

Figure 2: *Phases of Pyrolysis with description for each phase (Glushkov et al., 2021).*

2.2. Main Pyrolysis Process Products

2.2.1. Bio-oil:

Bio-oil, also known as pyrolysis oil, is an eco-friendly substance obtained by heating biomass without oxygen in a process called pyrolysis. This process breaks down matter into compounds and bio-oil is one of the valuable outcomes. Bio oil possesses a composition that comprises an array of organic molecules that include oxygenated particles, hydrocarbons, and water. This varied composition presents possibilities for its application across many sectors rendering it an appealing environmentally sustainable energy source (Bridgwater, 2012).

Bio oil has caught the interest of many as a substitute for fossil fuels in the transportation industry. When properly refined and processed it can serve as a fuel option for vehicle with a capacity to lower greenhouse gas emissions and reduce reliance on fuels making it a good solution for achieving sustainable transportation. Moreover, bio-oil has the potential to be utilized for generating electricity by burning it in power plants while also minimizing environmental effects. Its sustainable characteristics and decreased carbon footprint play a role in promoting clean energy production (Bridgwater, 2012).

Furthermore, bio-oil can be utilized in the chemical sector where it can be used as a material for manufacturing valuable chemical compounds resulting in a decrease on the dependency of petrochemical resources and encouraging the growth of an economy wherein biomass waste is transformed into valuable commodities. To put it simply bio-oil that is obtained through biomass pyrolysis shows potential in addressing environmental and energy concerns. Its versatility as a fuel for vehicles, a source of electricity and a raw material for chemicals highlights its importance in moving towards a greener energy and chemical industry (Bridgwater, 2012).

***Figure 3**: Bio-oil Produced from the Pyrolysis of Biomass (Lee et al., 2013).*

2.2.2. Syngas:

Syngas, also known as synthesis gas, is a gas mixture that forms when biomass undergoes pyrolysis. It mainly consists of carbon monoxide (CO) hydrogen (H2) carbon dioxide (CO2) methane (CH4) and other minor gases. Syngas has potential, as an energy source and can be used as a raw material, for chemical synthesis (Yaman, 2004).

Table 1: *Pyrolysis Syngas composition (Fantozzi et al., 2010).*

Composition (%vol)	
CH_4	21
CO	29
CO_2	38
H_2	7
N_2	5

One of the primary applications of syngas is in energy production. When combusted in power plants or used in gas turbines, syngas can generate electricity efficiently. This makes it a valuable resource for clean and sustainable energy generation, reducing the reliance on fossil fuels and mitigating greenhouse gas emissions. Syngas can also be utilized as a heating source in industrial processes. Its high-energy content and versatility make it suitable for various heating applications, further contributing to energy efficiency and reducing environmental impacts (Yaman, 2004).

In addition to its role in generating energy syngas plays a part in the production of chemicals as it can be used as a material to synthesize important compounds like ammonia, methanol, and other valuable substances. This versatility in chemical production does not only reduce our reliance on petrochemical materials but also supports the growth of a circular economy by utilizing renewable resources.

Moreover, syngas can be utilized in the production of biofuels by employing catalytic processes resulting into its conversion into sustainable alternatives, like bioethanol and biodiesel offering environmentally friendly options instead of traditional fossil fuels (Simanungkalit et al., 2023).

To sum up syngas which is produced through the process of biomass pyrolysis has uses in energy generation, industrial operations, and the production of chemicals. Its adaptability and ability to reduce greenhouse gas emissions make it an asset in moving towards an environment friendly energy and chemical industry.

2.2.3. Biochar:

Biochar is a carbon-rich material that remains after the volatile components of biomass have been subjected to pyrolysis. This stable and porous substance is garnering attention for its various applications, particularly in agriculture and environmental management (Webera & Quickerb, 2018). Biochar stands out for its carbon content which makes it a powerful tool for storing carbon. When biochar is added to soil, it can securely store carbon for long periods of time, thereby decreasing the levels of carbon dioxide in the atmosphere, and this supports our efforts to tackle climate change by boosting carbon capture and storage in land ecosystems (Webera & Quickerb, 2018).

Furthermore, biochar has been found to have beneficial effects on the soil fertility as its porous composition creates an environment for microorganisms resulting in improving the soil aeration. Additionally, it serves as a long-term source of nutrients gradually supplying elements to plants. The combination of enhancing soil structure and promoting availability makes biochar an invaluable beneficial addition to the soil enabling us to utilize it in sustainable land management strategies. Biochar is also recognized for its capacity to retain water in the soil due to its porous composition that allows it to retain moisture which in result can decrease the need for irrigation. This characteristic is especially valuable in areas where water is scarce as it helps conserve this resource and enhances crop yields (Kamali et al., 2022).

Moreover, biochar offers an opportunity to address the issue of greenhouse gas emissions especially in sustainable agricultural approaches. By incorporating biochar into systems alongside eco-friendly methods like reduced tillage and organic farming we witness its remarkable ability to make a significant impact, on reducing nitrous oxide ($N2O$) emissions (Lehmann et al., 2010). Nitrous oxide is a potent greenhouse gas with a much higher global warming potential than carbon dioxide ($CO2$). It is primarily produced through microbial activities in soils, especially in situations where nitrogen-based fertilizers are used and where soil conditions favor its generation. These emissions significantly contribute to the overall greenhouse gas burden in the atmosphere, exacerbating climate change.

Biochar offers benefits due to its ability to store carbon and mitigate greenhouse gas emissions as when biochar is added to soil it securely stores carbon over long periods of time converting it into a long-lasting form. This process helps reduce the concentration of carbon dioxide (CO2) which is a major contributor to global warming and climate change. By serving as a carbon sink biochar plays a role in maintaining a carbon cycle and facilitating sustainable land management practices ultimately aiding in the fight against climate related challenges (Lehmann et al., 2010).

To sum up biochar is becoming increasingly recognized as an environmentally friendly tool that holds promise in the fields of agriculture, carbon storage and water conservation. Its ranging advantages make it an asset for tackling environmental and agricultural issues while promoting more sustainable practices in land management.

Figure 4: *Biochar from American Farmland Trust (Photo courtesy of Kristin Trippe, USDA ARS).*

2.3. Key Influences on Pyrolysis Product Formation

2.3.1. Biomass Feedstock:

The type of biomass used in the pyrolysis process has an impact on the composition of the resulting product as shown in figure 6 and table 2. Different types of biomasses including wood, agricultural residues and energy crops can influence both the quantity and characteristics of the by products produced during pyrolysis (Chen et al., 2018). The most popular type of biomass used for pyrolysis is known as lignocellulosic biomass and it consists of three components: cellulose, hemicellulose, and lignin. Cellulose is a chain like molecule made up of glucose units. Hemicellulose on the hand is a polymer with branches composed of glucose units. Lignin is an interconnected polymer that gives wood its strength and rigidity (Chen et al., 2018).

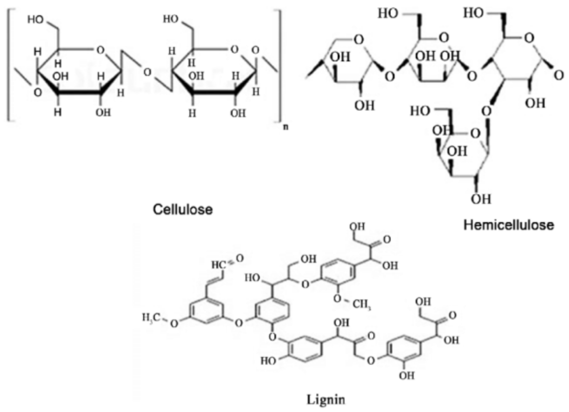

Figure 5: *Lignocellulosic biomass structural components (cellulose, hemicellulose, and lignin) (Muktham et al., 2016).*

Cellulose is an element of plant cell walls which is an abundant organic material found on Earth and due to its ability to break down into particles quickly cellulose serves as a source of fuel for pyrolysis. This process yields bio-oil a fuel, with different applications. (Chen et al., 2018).

Hemicellulose may not be as prevalent as cellulose, but it still plays a role in biomass. One of its advantages is that it can be readily broken down into molecules making it an excellent choice for pyrolysis. When hemicellulose undergoes pyrolysis, it produces bio-oil and syngas which is a combination of carbon monoxide and hydrogen.

Although lignin is not the most widespread chemical in biomass it is an important part. Lignin is an outstanding pyrolysis fuel given that it can be turned into biochar, which is a solid, charcoal-like material having an assortment of uses including soil improvement and carbon storage potential (Chen et al., 2018).

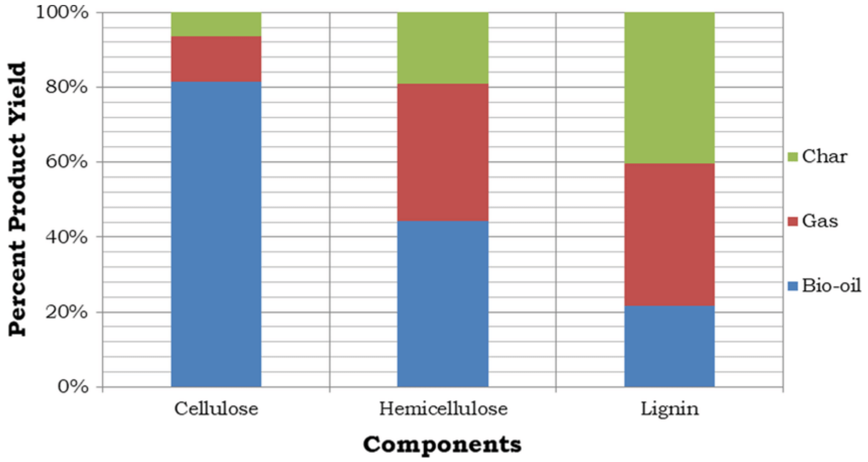

Figure 6: *Effect of biomass composition on yield of pyrolysis products (Chen et al., 2018)*

Table 2: *Composition of feedstocks and yields of pyrolysis products for different biomass (dry basis) (Chen et al., 2018)*

Sr. no	Biomass	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Species	Bio-oil (wt%)	Biochar (wt%)	Syngas (wt%)
1	Pine	40.90	30.40	28.7	-	49.5	24.9	25.6
2	Poplar	47	22	20	-	60.9	8.8	17.5
3	Acacia	41	24	15	-	45.31	35.08	19.61
4	Oak	35.38	35.55	27.10	-	58.9	16.7	24.4
5	Eucalyptus	37.14	10.44	26.73	-	42.4	37.1	14.3
6	Beech wood	46.40	31.70	21.90	-	46.1	17.8	34
7	Hardwood	45–50	20–25	20–25	Mixture of various Eastern tree species	50–55	25–27	-
					Hardwood shavings	63.3	12.7	24.0
					Aspen poplar + white birch	53.9	26.2	19.9
8	Softwood	35–40	20–25	27–30	De-barked lodgepole pine and Douglas Fir	50–55	25–27	-
					White spruce + balsam fir + larch	45	27.6	27.4
					Spruce wood	39.7	32.4	28.9
9	Lignin-containing crop residues (corn stover, wheat straw	38	26–29	15–19	Corn stover	61.6	17	21.9
					Wheat straw	46	47	7
10	Lignin-free crop residues (soybean, rye straw)	31–42	15–25	-	Soybean cake	57	38	5

2.3.2. Pyrolysis Conditions:

The temperature, rate at which heat is applied and duration of heating are factors that affect the composition and properties of pyrolysis products. These variables have an influence on the amount of bio-oil, biochar and syngas produced as well as their respective proportions.

One of the factors that significantly influences the results of pyrolysis is temperature as depicted in figure 7. When pyrolysis temperatures increase it promotes the formation of substances thereby leading to higher yields of bio-oil. At high temperatures biomass polymers, like cellulose and hemicellulose undergo thermal decomposition resulting in the production of smaller and more reactive molecules. (Ben Hassen-Trabelsi et al., 2014). On the other hand, excessive heat can cause improved break down and cracking reactions. Cracking of the substances resulting in more char production and gasification of bio-oil components. That's why finding the perfect pyrolysis temperature is crucial for achieving the desired substance composition and quality (Ben Hassen-Trabelsi et al., 2014).

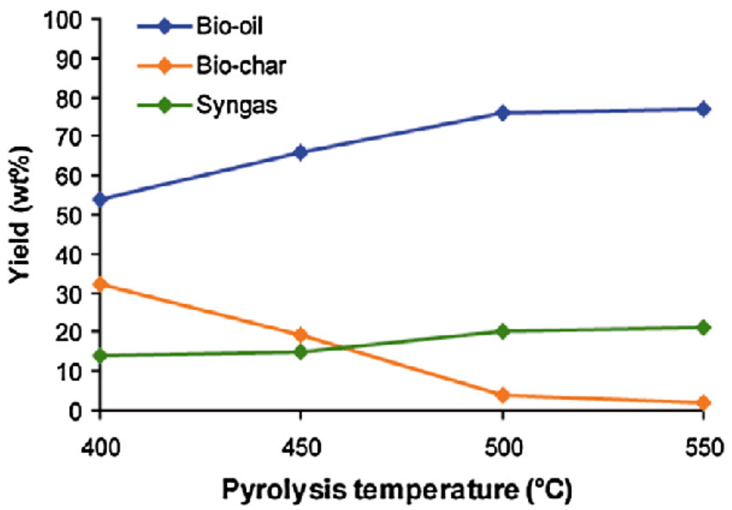

Figure 7: *Effect of pyrolysis temperature on the yield of pyrolysis products (Ben Hassen-Trabelsi et al., 2014)*

The rate at which the temperature rises during pyrolysis is commonly known as the heating rate. This rate affects how quickly primary and secondary reactions take place. When the heating rate is slower it allows time for pyrolysis reactions to complete leading to control over the composition of the result. Additionally slower heating rates have been observed to reduce degradation of oil components and enhance the synthesis of biochar with a carbon concentration. The impact of heating rate can be seen in figure 8 (Pranoto et al., 2020).

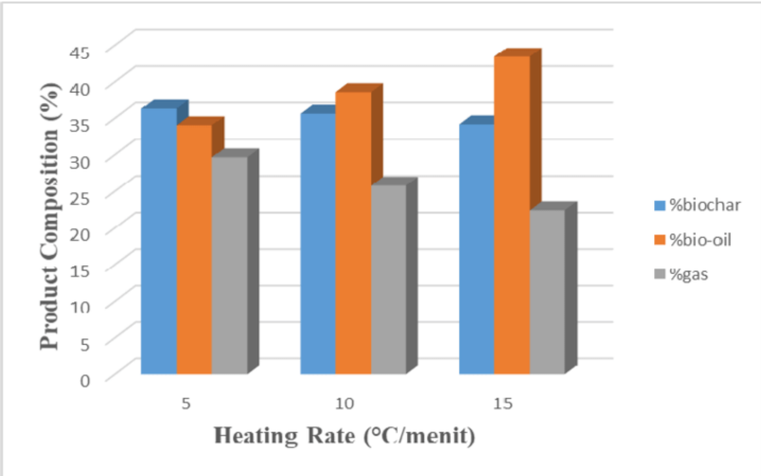

Figure 8 : *Effect of heating rate on yield of pyrolysis products (Pranoto et al., 2020)*

The length of time that the biomass stays in the pyrolysis plant, also known as residence time, has an impact on the makeup of the product. When residence durations are extended, additional reactions like vapor phase cracking and condensation can take place potentially leading to the formation of larger molecules. These processes can influence both the quantity and stability of the resulting bio-oil as shown in figure 9 (European Biomass Industry Association, 2023).

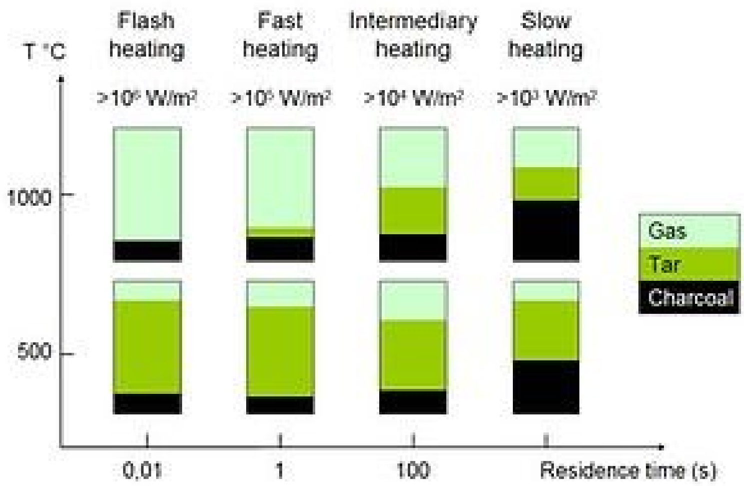

Figure 9: *Effect of residence time onyield of pyrolysis products (European Biomass Industry Association, 2023)*

2.3.3. Catalysts and Additives:

When catalysts and additives are used in pyrolysis, there are ways to modify the composition and maximize the production of substances. By speeding up chemical reactions without relying on catalysts, it is possible to increase the amount quality and selectivity of desired pyrolysis products while also minimizing the production of byproducts. Zeolites, which are transition metal oxides and mixed metal catalysts are among the catalysts that have been extensively researched for their use in pyrolysis processes. These catalysts play a role by enabling chemical reactions and providing optimal reaction conditions thereby influencing the pathways and distribution of products. For instance, the open pores and acidic regions of zeolites may promote the breaking down of biomass components enhancing the generation of lightweight fraction like bio-oil (Laougé et al., 2022).

Certain metal oxides such as catalysts based on iron, nickel or cobalt have shown the ability to enhance the breakdown of biomass and promote the creation of chemicals or fuels used in transportation. These catalysts have proven effective in piloting the outcome towards desired products such as hydrocarbons or hydrogen rich gases while minimizing the formation of byproducts like char.

The presence of substances such as acids or bases can also influence the distribution of products and the pathways of reactions during pyrolysis. For example, specific acids can enhance the removal of water from biomass while facilitating the formation of oxygen containing compounds in the bio-oil. Conversely bases can accelerate deoxygenation reactions resulting in a decrease the oxygen content of the bio-oil thereby enhancing its fuel characteristics (Laougé et al., 2022).

Specific objectives as well as expected outcomes of the result will influence the selection of the suitable catalysts and additives and to attain the intended product makeup while improving entire efficiency of the process the optimization of catalyst types, loading, and reaction conditions must be performed.

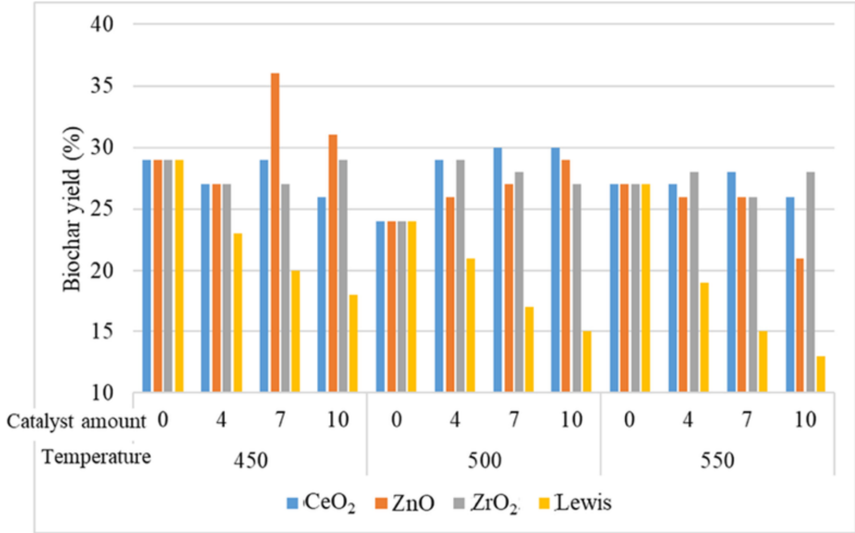

Figure 10: *Effects of temperature and catalyst type and amount on biochar yield (Laougé et al., 2022)*

2.3.4. Pre-Treatment Methods:

Pre-treatment is processes performed for biomass before pyrolysis can have a huge impact on the composition as well as the features of the pyrolysis products. Various pre-treatment methods influence the biomass's physical make-up by elimination of or addition of elements resulting in influencing the subsequent pyrolysis reactions.

1. **Dry torrefaction:** which is a technique used to process biomass by subjecting it to controlled heat conditions in the presence of oxygen between 200 and 300 °C. The main objective of this method is to improve the formation of biomass to produce high quality biofuel and make the entire production process economically feasible. During this process the composition of fibers within the biomass undergoes changes that result in a reduction in the energy needed for pyrolysis. Dry torrefaction has shown to be quite useful in improving the characteristics of biomass by modifying its properties and boosting its carbon content. When we employ torrefied biomass in the pyrolysis process we obtain bio-oil with enhanced aromatics and calorific value. The analysis proved that using dry torrefaction has improved the bio-oil quality by reducing oxygen which resulted in an increase in heating value and enhance the content of hydrocarbons in the bio-oil (Kumar et al., 2020).

2. **Steam explosion:** which is an alternative pre-treatment method involving exposing biomass to steam under high pressure followed by rapidly decompressing it. Biomass structure is disturbed by steam explosion resulting in cellulose depolymerization and lignin alteration among other physical and chemical changes. These changes could influence the flow of the outcomes and subsequent pyrolysis reactions, and it was recently observed that employing a steam explosion as a pre-treatment boosts bio-oil yields and reduces biochar formation during pyrolysis (Kumar et al., 2020).

3. **Acid treatment of biomass:** treating biomass with acid not only during the process but also before pyrolysis is a technique to enhance the quality of biooil produced and improve overall efficiency of the process. This method involves using acids such as sulfuric acid or phosphoric acid or hydrochloric acid on the biomass with a main goal to remove minerals and improve the properties of the feedstock. The pretreatment process reduces alkaline earth metals which're catalysts for undesirable reactions during the pyrolysis process resulting in a bio-oil obtained from acid treated biomass that has better characteristics like higher heating values and increased carbon content. These improvements happen because ash content is removed and due to the disruption of specific chemical bonds including C-O bonds within cellulose, hemicellulose, and lignin, as well as alkyl-aryl ether bonds within lignin. However, there are challenges associated with pretreatment including handling acidic leachate and the potential for the reactor corrosion (Kumar et al., 2020).

4. **Biological pre-treatment of lignocellulose biomass:** biological pretreatment of biomass is a friendly and cost-effective method that stands out as an appealing alternative to physical or chemical approaches. This process can be carried out at room temperature and at atmospheric pressure eliminating the need for energy or chemicals which leads to cost savings. The main goal of pretreatment is to break down components in biomass especially lignin into smaller building blocks. Microorganisms such as fungi are used for this purpose because they have enzyme systems containing laccases and peroxidases that efficiently oxidize the structure of lignin. Sometimes mediators, which are small organic compounds are employed to enhance this process by assisting enzymes in reaching inaccessible areas due to their size and selectivity.

   White rot fungi have gained recognition for their effectiveness in breaking down lignin. They are known to produce a huge number of laccases and peroxidases making them a preferred choice for treating biomass. For instance, there was a study conducted by (Yang et al.) that showcased the use of the white rot fungus Echinodontium taxodii to treat corn stover biomass. This treatment resulted in enhancements in the pyrolysis process of cellulose, hemicellulose and lignin leading to enhancement in the production of valuable pyrolytic products. Additionally, researchers also combined rot fungus (Trametes orientalis) with rot fungus (Fomitopsis pinicola) to treat corncob lignin and this combination used to pretreat the biomass showed promising outcomes in lignin and generating compounds during pyrolysis where the proportions of phenols and alkyl phenols were significantly increased (You et al., 2019).

These findings highlight the potential of using treatment methods to enhance biomass conversion processes. However, it is important to note that this approach may be time consuming and could result in some biomass being consumed by microorganisms causing yields. More research is required to explore the scalability and impact of pretreatment on biomass and its subsequent influence on pyrolysis behavior and bio-oil quality.

The specific objectives and anticipated outcomes for the result will define the pre-treatment process to use and to achieve suitable modifications in biomass structure and consequent pyrolysis product composition, pre-treatment variables such as temperature, residence duration, and reactant concentration must be adjusted.

2.3.5. Scale and Reactor Design:

The scale of the pyrolysis process and the reactor structure are key variables which may have a big impact on the composition and features of the pyrolysis products. Changes in the outputs and compositions may arise from modifications to heat transfer mechanisms, residence periods and general process parameters based on the reactor design and scale of operation. Diverse reactor concepts including fluidized bed, fixed bed as well as fast pyrolysis reactors have distinctive features that impact the method by which the products get distributed.

Because of the suspended state of biomass particles in a fluidized medium, fluidized bed reactors allow efficient heat and mass transfer resulting in shorter residency intervals and improved mixing promoting the creation of light gases and bio-oil. The production of biochar and additional reactions may be encouraged by fixed bed reactors with prolonged residence durations. Increasing the amount produced of bio-oil can be accomplished using fast pyrolysis reactors that feature rapid heating rates and shorter vapor residence durations. Variations in product yields and compositions are possible whenever pyrolysis techniques undergo scaling upwards from laboratory- to commercial-scale operations. The pyrolysis processes and consequent distribution of the products may be influenced by scale-dependent variables such as feedstock management, heat and mass transfer limits, and reactor dynamics and ignorer to maintain desired output compositions all through scale-up assessment and optimization of reactor structure and operational parameters is thus required.

2.4. Main Types of Pyrolysis

A sustainable and abundant resource biomass offers plenty of opportunities for producing environmentally friendly green electricity while lowering greenhouse gas emissions. A versatile technique for turning complex biomass feedstocks into valuable goods is pyrolysis, which is the thermal breakdown of biomass at high temperatures without the presence of oxygen. This section of the thesis will investigate several pyrolysis technology types, as well as their working environments, mechanisms, and product yields.

Table 3: *Summary for different operating parameters and products for pyrolysis processes (Chen et al., 2018)*

Operating parameters	Slow pyrolysis	Fast pyrolysis	Flash pyrolysis
Temperature (K)	550–950	850–1250	1050–1300
Heating rate (K/s)	0.1–1	10–200	> 1000
Solid residence time (s)	450–550	(0.5–10)	< 0.5
Particle size (mm)	5–50	< 1	< 0.5
Product			
Biochar (%)	35	20	12
Bio-oil (%)	30	50	75
Gas (%)	35	30	13

2.4.1. Slow Pyrolysis

Slow pyrolysis is a type of chemical process that transforms biomass into biochar, bio-oil, and syngas without the presence of oxygen. This procedure is carried out at temperatures that ranges from 550 – 950 K and with heating rates ranging from 0.1 to 1 K per second with a long residence time up to several days. As a result, repolymerization reactions occur leading to the production of larger amount of biochar (Fahmy et al., 2018). Slow pyrolysis has been primarily focused on producing biochar. Additionally, the byproducts of bio-oil and biogas are utilized as an energy source. (Fahmy et al., 2018).

Slow pyrolysis offers the following advantages:

- **Increased biochar output:** Slow pyrolysis yields an increased amount of biochar compared to other conversion methods. This is because the gradual heating rate and extended residence time allow for carbonization of the biomass.

- **Enhanced biochar quality:** Slow pyrolysis results in biochar with higher carbon content and lower ash content. This makes it particularly suitable for applications such as soil improvement, water filtration and carbon storage.

2.4.2. Fast Pyrolysis

Fast pyrolysis shows potential as a conversion method that can turn different types of biomasses, such as wood, agricultural leftovers, and energy crops into valuable resources without the need for oxygen. This technique operates at elevated temperatures, between 850 – 1250 K, with heating rates ranging from 10 to 200 K per second. The products obtained through pyrolysis are influenced by factors such, as the composition of the feedstock material, the temperature used during pyrolysis and how long it takes for the process to complete (Bridgwater, 2000).

The main result of this procedure is bio-oil, which can be obtained with efficiency reaching weights of, up to 50% based on the input. Furthermore, the process also produces char and gas as by products. Both are effectively utilized within the procedure ensuring there are no leftover waste streams.

Fast pyrolysis is an eco-sustainable technology that can help decrease greenhouse gas emissions while effectively converting biomass into fuels and chemicals. It has the potential to play a role in advancing the economy especially in the field of biomass and renewable energy. While more research and development are needed to refine and expand the process for purposes, fast pyrolysis shows potential in supporting the shift towards a more sustainable circular future (Bridgwater, 2000).

2.4.3. Flash Pyrolysis

Flash pyrolysis is a highly efficient and quick thermal transformation technology that requires subjecting biomass to exceptionally high temperatures ranging from 1050 to 1300 K accompanied by extraordinarily short residence times ranging from milliseconds to seconds. This quick heating and being subjected to pyrolysis conditions allows rapidly thermal breakdown of biomass, resulting in the generation of useful gases such as hydrogen and methane as primary products while limiting the formation of non-condensable gases and reducing amount of char yield and increase the generation of oil yield (Ighalo et al., 2022).

Table 4:*Product yields of different biomasses after flash pyrolysis (Ighalo et al., 2022)*

Biomasses	Temp (°C)	Char yield (wt%)	Oil yield (wt%)	Gas yield (wt%)	References
Linseed	550	11.5	68.8	4.5	Acikgoz and Kockar (2007)
Sewage sludge	500	–	–	–	Alvarez et al. (2015)
Pinewood waste	500	15	75.33	7.5	Amutio et al. (2011)
Pinewood sawdust	500		75.33	–	Amutio et al. (2012b)
Woody biomass	500	18.4	9.4	30.2	Imran et al. (2014)
H–ZSM5 catalysed biomass	500	16.3	14.9	46.7	Imran et al. (2016)
Cotton shell	450	–	52.5	–	Madhu et al. (2016)
Populous nigra sawdust	455	–	69	16	Makibar et al. (2015)
Chlorella vulgaris	800	21.36	60.22	18.42	Maliutina et al. (2017)
Palm kernel shell	600	20.89	73.74	5.37	Maliutina et al. (2017)
Activated sludge	500	35.6	43.1	21.3	Pokorna et al. (2009)
Dewatered digested sludge	500	56.0	26.7	17.3	Pokorna et al. (2009)
Dried activated sludge	500	42.6	28.5	28.9	Pokorna et al. (2009)
Wood bark	450	23.13	49.5	–	Sowmya Dhanalakshmi and Madhu (2021)
Crop stems	500	23	52	25	Stals et al. (2010)
Beech woods	–	23.01	60.23	16.72	Stephanidis et al. (2011)
Broom species	500	16.6	79.5	4.0	Amutio et al. (2013)
Acacia dealbata	500	23	72.1	–	Amutio et al. (2013)
Pterospartum tridentatum	500	–	75.1	–	Amutio et al. (2013)

The primary goal of flash pyrolysis is to enhance the generation of beneficial gases and most particularly hydrogen and methane which have high energy densities and can be employed as clean energy sources or feedstocks in an array of chemical processes. The short residence times associated with flash pyrolysis minimize the production of non-condensable gases such as carbon dioxide and carbon monoxide which are generally undesired due to their lower energy content and potential environmental implications. Flash pyrolysis holds great potential for hydrogen production and as a clean energy carrier, contributing to the sustainable utilization of biomass resources (Ighalo et al., 2022).

2.4.4. Vacuum Pyrolysis

Vacuum pyrolysis is a promising technique in the field of biomass conversion. Unlike pyrolysis processes that take place under atmospheric pressure vacuum pyrolysis happens within a controlled environment with low pressure. This unique characteristic gives vacuum pyrolysis benefits making it a highly promising method for effectively utilizing biomass resources (Carrier et al., 2011).

The fundamental idea behind vacuum pyrolysis is to heat biomass such as wood or other natural materials at elevated temperatures in a low-pressure environment. By lowering the pressure, the volatile compounds in the biomass can vaporize at lower temperatures. There are benefits to using vacuum pyrolysis of traditional pyrolysis methods. Firstly, it allows for higher oil yields by preventing the volatile matter from recondensing on the char. Secondly the bio-oil produced through vacuum pyrolysis is of higher quality as it contains less water and impurities. Lastly vacuum pyrolysis is a greener process compared to traditional methods since it generates fewer greenhouse gases and other harmful pollutants (Carrier et al., 2011).

***Table 5**: Experimental conditions for the vacuum and slow pyrolysis of the sugar cane bagasse as an example (Carrier et al., 2011).*

Process	Temperature (°C)	Heating rate (°C min^{-1})	Hold time (min)	Residence time of gases	Pressure (kPa abs)	Flow rate of N_2 (L min^{-1})
Vacuum	350–530	9–23	60	2 s	8	–
Slow	261–570	5–29	60	2.8 min	101	1

CHAPTER THREE: REVIEW OF BIOCHAR PELLET CARBON FOOTPRINT CASE STUDY

3. Review of Biochar Pellet Carbon Footprint Case Study

3.1. Abstract

The pressing need to tackle the issue of climate change has sparked interest in finding approaches to decrease greenhouse gas (GHG) emissions and foster sustainable agriculture. One strategy that has gained attention is the use of biochar as a soil amendment. Biochar, which is derived from pyrolysis and contains carbon holds promise not only for improving soil health but also for capturing carbon from the atmosphere.

In this chapter we will delve into a review of the case study titled "Biochar Pellet Carbon Footprint," which was originally conducted by Pietro Bartocci, Gianni Bidini, Pierluigi Saputo and Francesco Fantozzi in 2016. The study took place at the University of Perugia, in Italy. They utilized the life cycle assessment (LCA) methodology along with SimaPro software following ISO 14067 standards. The primary aim of this research was to evaluate the carbon footprint associated with biochar pellets made from miscanthus, which's a type of herbaceous energy crop.

The case study findings provide information about how carbon's managed in every stage of biochar production starting from cultivation to its use in soil. It's worth noting that the carbon footprint of biochar pellets was found to be - 737 kg CO2 eq / t of dried feedstock indicating an effect of sequestering carbon. This study emphasizes the importance of biochar not only in

helping in the combat against climate change but as a potential source of revenue for companies through carbon credits scheme.

The case study discussed in the research paper adds insights to the scientific community by providing a thorough analysis of the environmental impact of biochar pellets. Specifically, it focuses on miscanthus as the material used for producing these pellets which's an area that hasn't been extensively studied before. Furthermore, the chapter critically examines the findings in relation to research on biochar. Emphasizes the significance of sustainable production and use of biochar in addressing climate change challenges.

3.2. Introduction

Given the increasing urgency of the climate crisis, it has become extremely important to address the problem of greenhouse gas (GHG) emissions. As countries and industries work towards finding ways to reduce their carbon footprint and combat the impacts of climate change, there is a growing interest in biochar. Biochar, which is a type of carbon material produced through pyrolysis offers a solution, as it can improve soil quality and increase productivity. Additionally, it can also play a role, in capturing carbon dioxide (CO2), thereby helping to mitigate the adverse effects of global warming.

The primary focus of this chapter is to explore a case study named "Biochar Pellet Carbon Footprint." Conducted in 2016 by Pietro Bartocci and his research team, at the University of Perugia in Italy the study investigates the effects and carbon storage potential capabilities of biochar pellets. The importance of biochar cannot be overstated, as it serves as a soil enhancer and an effective method, for capturing carbon. Along with its benefits biochar also provides organizations with the opportunity to earn carbon credits in the growing carbon markets. This aspect is particularly attractive in our world that is grappling with carbon emissions restrictions.

Understanding the importance of addressing climate change, it is crucial to not only explore strategies but also gain a thorough understanding of their environmental consequences. That's why this chapter guides readers through a case study called "Biochar Pellet Carbon Footprint " offering an overview of its methods, discoveries, and implications. By examining this research our goal is to contribute to the existing understanding of biochar production, carbon storage and the role that biochar plays in mitigating climate change.

3.3. Methodology

In the "Biochar Pellet Carbon Footprint" case study, they used a methodology to evaluate the carbon footprint linked to the production of biochar pellets using miscanthus as the source material. They adopted the following aspects to guide their approach:

Life Cycle Assessment (LCA) Case Study:

- **Objective:** To evaluate the complete GHG emissions balance throughout the life cycle of biochar pellets.
- **Scope:** Covered all stages from feedstock cultivation to biochar application.
- **Functional Unit:** One ton of dry miscanthus biomass.
- **Allocation:** System expansion approach.
- **Time Reference:** Carbon storage potential considered for at least 100 years.
- **Cut-off:** Processes with less than 1% impact were excluded.
- **System Boundary:** Included cultivation, pyrolysis, pelletization, packaging, distribution, and biochar use in soil.
- **Data Collection and Quality :** Data sourced from miscanthus cultivation, the Integrated Pyrolysis Regenerated Plant (IPRP), and pelletization tests.
- **Software and Norms:** Utilized SimaPro software and adhered to ISO/TS 14067 standards. And developed Product Category Rules (PCR) based on established guidelines.

- **Carbon Footprint Calculation :** Analyzed contributions from cultivation, pyrolysis, pelletization, packaging, biochar's role as a carbon sink, and avoided heat and electricity use.

Table 6: *Product category rules for the carbon footprint of pelletized biochar adopted.*

Stage	Rule	Description
Scope and Functional Unit	Scope of the study	Calculate PCF of biochar (expressed in kg CO2eq/t feedstock dried), based on ISO 14067
	System boundary	The following phases are considered: cultivation, transformation, packaging, distribution and use
	Functional unit	The functional unit considered is 1 ton of dry matter of feedstock.
	Allocation	Allocation is particularly important in the pyrolysis process. System Expansion is the approach to be chosen
	Time reference	Cultivation operation are refferred to the growing season 2011, while the time reference for biochar action in soil is supposed to be at least 100 years.
	Cut-off on LCA processes	The threshold of 1% is chosen
Product definition	Biochar	Biochar in this analysis is defined as the solid product of a slow pyrolysis process to be pelletized and used as soil amendment
Data collection & quality	Cultivation	The following processes are comprised: fertilization, harvest, weeding, irrigation, haying and baling, ploughing
	Pyrolysis	Pyrolysis data are taken from the Integrated Pyrolysis Regenerated Plant (IPRP) of the University of Perugia
	Use	It is assumed that the biochar is pelletized, packed and then spread in the soil. Data on pellettization are collected through experimental tests
Carbon Footprint calculation	Software	Simapro software is used to design process tree, and calculate PCF, the method used is IPCC 2013
	Norm	ISO TS 14067
Results communication	Label	A carbon footprint label is designed for the package

3.4. Results

In this section we will share the findings from the evaluation of the carbon emissions associated with biochar pellets. Our main emphasis will be, on how miscanthus, as the material used affects the carbon footprint.

3.4.1. Cultivation: Mass and Energy Balances

Based on the observations in the fields it was found that the average biomass productivity per hectare was 66 tons. When the biomass is harvested it had a moisture content of around 40% which means that the total amount of matter obtained from the harvest was estimated to be 39.6 tons per hectare. These findings are crucial, in understanding the properties and yields of the feedstock.

3.4.2. Transformation: Mass and Energy Balance

Table 7 provides data, on the materials used in constructing the IPRP plant. These materials have been a part of the biochar supply chain for over a year. As a result, it is estimated that one fifteenth of the plants materials will be replaced each year considering a lifespan of 15 years.

Table 7 : *Materials used to produce the IPRP plant.*

Material	Weight (kg)
Steel	17,547
Concrete	5,411
Copper	95
Cast Iron	8
Aluminium	208
Iron	580
Rockwool	33
Plastic	147
Total	24,029

According to Bartocci et al research, in 2016, it is estimated that cultivating one hectare of miscanthus can yield 13 tons of biochar along, with 14,000 MJ of electricity and 24,000 MJ of heat. To pelletize one kilogram of biochar experimental tests have shown that around 0.05 kWh/kg of energy is required.

3.4.3. Carbon Footprint Calculation Results

The total carbon footprint calculated for biochar pellets derived from miscanthus was found to be -737 kgCO2eq/t of feedstock dried. This negative value implies that biochar production and application result in a net reduction of GHG emissions, indicating its potential as a carbon storage strategy.

Table 8 : *Contribution of single phases to the Carbon footprint of biochar.*

Life cycle stage	Contribution (kg CO2eq/t feedstock dried)	Contribution (%)
Cultivation	199	-27
Pyrolysis	52	-7
Pelletizing	22	-3
Packaging	7	-1
Use in soil as a carbon sink	-368	50
Avoided use of heat	-251	34
Avoided use of electricity	-398	54
Total	-737	100

3.5. Discussion and conclusion

The findings of the assessment, on the carbon footprint of biochar pellets specifically focusing on miscanthus as the raw material have significant implications for sustainable biochar production and its role in mitigating climate change. The calculated carbon footprint of -737 kgCO2eq/t of dried feedstock aligns with existing research highlighting the potential of biochar as a approach for climate mitigation strategies. This result reinforces the idea that when produced sustainably and using materials biochar can contribute to a net reduction in greenhouse gas (GHG) emissions. Similar to studies, which have shown carbon footprints for biochar from different biomass sources this study demonstrates how biochar can effectively capture and store carbon. Additionally by focusing on miscanthus a energy cropthe study adds valuable scientific insights into various feedstock options for biochar production. This expands our knowledge about how suited biochar is for agricultural contexts and its potential as a long term solution, for storing carbon in soils.

The findings underscore the importance of the carbon sink effect, which contributes significantly to the positive impact of biochar. Accounting for 50% of the total carbon footprint reduction, this effect highlights biochar's dual role as a soil amendment and a carbon storage tool. As biochar enhances soil health, nutrient availability, and water retention capacity, it acts as a mechanism for long-term carbon storage in soils, contributing to both agricultural sustainability and climate change mitigation. Additionally, the study emphasizes the substantial contributions of avoided heat and electricity generation through the pyrolysis combined heat and power (CHP) process, further showcasing the multifaceted advantages of biochar production systems. These findings offer valuable insights for researchers, policymakers, and practitioners interested in harnessing biochar as a means of mitigating climate change and enhancing agricultural practices. By recognizing the significance of the carbon sink effect and the broader implications of biochar production, stakeholders can better strategize the integration of biochar into sustainable land management practices.

In conclusion, this study underscores the viability of biochar production, particularly with miscanthus feedstock, as a potent strategy for addressing climate change. The negative carbon footprint confirms that, when produced sustainably, biochar not only reduces greenhouse gas emissions but actively sequesters carbon. The focus on miscanthus enriches our understanding of biochar's applicability in diverse agricultural contexts and its potential for long-term carbon storage in soils, with the carbon sink effect accounting for a substantial 50% of the footprint reduction. Moreover, the study highlights the economic and environmental advantages of avoiding heat and electricity generation through pyrolysis CHP. These findings are pivotal for policymakers, researchers, and practitioners, emphasizing the multifaceted benefits of biochar integration into sustainable land management practices. Biochar emerges as a powerful ally in the pursuit of a greener, more sustainable future.

CHAPTER FOUR: EXPLORING BIOMASS WASTE

4. Exploring Biomass Waste

4.1. Introduction

Effective management of biomass waste plays a role, in promoting resource utilization. In this chapter we will explore the conventional most used techniques used for handling types of biomass waste ranging from agricultural and forestry residues to municipal solid waste and industrial byproducts. These organic materials offer potential, for generating energy in the form of electricity, heat and biofuels. However the conventional methods of managing biomass waste mainly focus on direct combustion, incineration, and landfilling which come with their difficulties and points of contention.

The responsible management and utilization of biomass waste have become increasingly important specially in developing countries. The growing amount of biomass waste along with the need for sustainable recycling methods has gained attention. Biomass is a source of energy that plants capture through photosynthesis. It includes a range of materials, from plant and animal sources. This versatile resource can be converted into forms of bioenergy making it the largest energy source globally following coal, oil and natural gas (Tong, 2019).

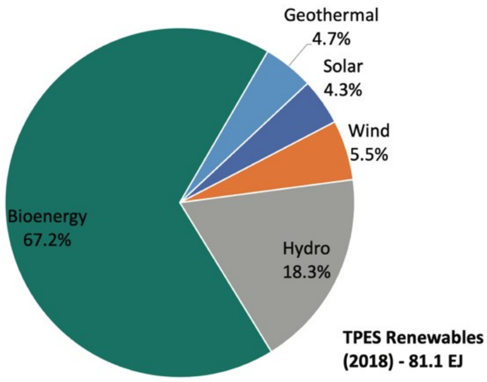

***Figure 11**: Total Primary energy supply globally in 2018 (World Bioenergy Association)*

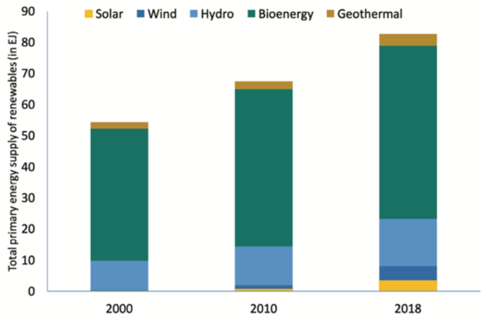

***Figure 12:** Total Primary energy supply of renewables globally (World Bioenergy Association)*

Based on data provided by the World Bioenergy Association bioenergy has become a major player, in the energy sector worldwide making a significant contribution to the overall primary energy supply. In 2018 renewable energy sources accounted for an 81.1 EJ of energy supply with biomass-based sources alone responsible for 55.6 EJ which represents a percentage of around 67% as shown in figure 11.

These statistics offer evidence of how crucial bioenergy's, in the worldwide shift towards renewable and sustainable energy sources. In a time marked by an increasing understanding of environmental issues and the pressing demand to decrease carbon emissions, bioenergy emerges as a leading contender in the quest, for a greener and sustainable energy future.

Incineration, landfilling and direct combustion are three ways to handle biomass waste and each have its own characteristics and outcomes. Incineration involves controlled burning of biomass waste to produce energy, for generating electricity and heat. On the other hand landfilling involves disposing of biomass waste in designated areas where it decomposes and releases methane, a greenhouse gas. Direct combustion focuses on burning biomass waste like wood or agricultural residues to generate heat and electricity. Each method has its pros and cons. In this chapter we will thoroughly explore these aspects. Additionally we will discuss approaches, to managing biomass waste that highlight the changing landscape of waste management practices.

4.2. Utilizing Biomass Waste for the Synthesis of Functional Materials

Over the last years, significant research efforts have been dedicated to different types of biomass waste, encompassing agricultural and forestry residues, animal waste, industrial waste, and municipal solid waste (MSW). It's important to highlight that merely a small portion of these biomass resources is presently harnessed for energy and material purposes, signifying a substantial reserve that remains untapped (Tripathi et al., 2019).

4.2.1. Agricultural and Forestry Wastes

A significant volume of biomass waste is derived from agricultural and forestry activities. Notably, rice straw, wheat straw, corn straw, sugarcane bagasse, and rice husk are among the most abundant agricultural waste materials.

Table 9 : *Most abundant agricultural waste materials, with annual generation estimates (Cho et al., 2020).*

Agricultural Waste	Annual generation estimates
Rice straw	731 million tons
Wheat straw	354 million tons
Corn straw	204 million tons
Sugarcane bagasse	181 million tons
Rice husk	110 million tons

On a global scale, the production of wood biomass waste is truly astonishing, with an annual output estimated at a staggering 4.6 gigatons (Gt) as reported by Tripathi et al. in 2019. This vast quantity of wood biomass waste underscores the pressing need for efficient and sustainable strategies to harness its untapped potential for various applications, including energy production and material synthesis.

Furthermore it's crucial to take into account the amounts of waste produced by other industries. A prime example is the olive oil industry, which generates a 30 million tons (Mt) of waste every year. This waste consists of byproducts and residues and finding proper disposal methods becomes quite challenging due, to its sheer volume. By exploring approaches to convert olive oil waste into resources we can greatly improve the sustainability of this industry while minimizing its impact, on the environment (Tripathi et al., 2019).

Similarly, the coffee industry is a major contributor to agricultural waste, producing approximately 7.4 Mt of waste annually. This waste consists of used coffee grounds, coffee pulp and cherry husks, which are often not fully utilized or disposed of without maximizing their potential, as resources. Exploring approaches to repurpose and recycle these coffee related waste materials can lead to the creation of products and processes that benefit both the coffee industry and the environment (Tripathi et al., 2019).

Given the amount of waste produced by these industries it is clear that finding ways to tackle disposal challenges and make better use of resources is essential, for creating a sustainable and environmentally conscious global economy. Both researchers and businesses are now prioritizing solutions that can uncover the value in these waste materials leading to a more sustainable and circular approach, to managing resources.

4.2.2. Animal Wastes

Animal waste is mainly generated from activities such, as fisheries, meat and leather processing and poultry industries. Some notable sources of animal waste include waste from fish, shrimp and crabs as manure, from livestock and poultry feathers. Seafood waste, which includes shells, heads, skins, tails, fins and bones is an biomaterial resource.

For instance, India's fish production in 2016–2017 exceeded 11.41 Mt, with up to 80% of marine fish being processed, resulting in 20–80% of fishing waste. These inedible waste materials have often been discarded near harbors or into the sea, contributing to environmental issues such as oxygen depletion, toxic hydrogen sulfide (H2S) production, pathogen dissemination, and foul odors (Govindharaj et al., 2019).

The poultry and meat sectors responding to increased consumer demand generate large amounts of byproducts such, as bones, feathers, tendons and skins. These waste materials present a challenge because they may carry pathogens making it crucial to address them promptly and effectively. Given these circumstances it is essential to consider how we manage these waste materials (Li et al., 2021).

Methods commonly used to handle waste, such, as incineration and composting play a role in dealing with this waste problem. However they do have some challenges. Incineration, although it effectively reduces waste volume. Destroys pathogens, has drawbacks like high energy consumption and the emission of carbon dioxide. These concerns can have impacts, on the environment.

However, when it comes to composting although it is a green method, for handling these waste materials there are difficulties that need to be addressed. One such challenge is the emission of hydrogen sulfide gas, which can produce odors during the process. This not raises concerns but also has the potential to become a nuisance, for the neighboring communities.

The research carried out by Li and colleagues in 2021 serves as a reminder of the importance of taking an comprehensive approach, to handling the substantial byproducts produced by the poultry and meat sectors. It highlights the necessity, for finding a balance that not focuses on controlling pathogens effectively but also considers the significant environmental and community impacts associated with waste management strategies (Li et al., 2021).

4.2.3. Municipal Solid Wastes

Textiles and paper waste play roles, in solid waste (MSW) and contribute significantly to the overall waste stream. In the year 2014 the United States alone generated a 16 million tons (Mt) of textile waste while globally wastepaper production reached 400 Mt (Tong XC, et al., 2019). It is surprising to note that despite their importance the recycling rates for these materials remain relatively low. Textiles make up 5% of landfill waste , with a global recycling rate of only 13% which is in contrast to wastepaper and cardboard, with an impressive recycling rate of 58% (Hole G, Hole AS, 2020).

There are generally two ways to handle MSW (Municipal Solid Waste); landfilling and incineration. However both of these methods have impacts, on the environment. For example they can lead to groundwater contamination and the release of greenhouse gases when the waste decomposes (McKendry P, 2002). To tackle these challenges considerable efforts have been made to discover approaches for reusing wastepaper and cardboard. Some of these approaches involve recycling cellulose for packaging, creating biochar and bio oil through pyrolysis, and extracting cellulose nanocrystals (Yu F, et al. 2016).

When it comes to the pyrolysis process of biomass it's important to consider how this challenge, in waste management relates to this thesis. Biomass pyrolysis shows promise as a way to convert waste, such as textiles, paper waste and other materials found in solid waste (MSW) into valuable products while also addressing environmental concerns tied to traditional disposal methods. This connection serves as a backdrop for this thesis on biomass pyrolysis.

CHAPTER FIVE: CARBON FOOTPRINT ASSESSMENT OF BIOCHAR PRODUCTION FROM BIOMASS VIA PYROLYSIS

5. Carbon footprint assessment of biochar production from biomass via pyrolysis

5.1. Introduction

In this research a detailed assessment is conducted to measure the impact of carbon emissions, in the production of biochar from biomass through pyrolysis. The study follows the guidelines provided in ISO 14067 focusing on determining the amount of CO2 equivalent emitted per Kg of feedstock. By using a scenario-based anticipatory life cycle assessment approach to assess the environmental impact specifically its contribution to climate change is thoroughly evaluated. Moreover, the analysis also explores how biochar can potentially store carbon when applied to soil.

According to the guidelines stated in ISO 14067 the term "carbon footprint" (CF) concerns to quantifying the greenhouse gas (GHG) emissions and GHG removals linked to a product system. These values are measured in carbon dioxide equivalents (CO2eq). The evaluation of the carbon footprint is conducted through a Life Cycle Assessment (LCA) with a focus, on the impact of climate change. The main goals of this research are to measure the carbon emissions throughout the process of producing biochar and examine how biochar helps reduce greenhouse gas emissions. Additionally, it investigates the enduring effects of biochar, on soil, which are thought to last for at least a century.

Ensuring the quality of data is of importance. This research heavily relies on reliable sources that meet standards. The study highlights the significance of pyrolysis, in converting biomass waste into products such as biochar, bio-oil and syngas. This process does not help in reducing waste disposal only but also plays a crucial role in mitigating greenhouse gas emissions. The findings from this study are anticipated to provide knowledge on practices, for managing biomass waste and addressing climate change.

5.2. Goal and Scope

- **Goal and scope of the Study:**

  Intended Application: The main goal of this research project is to calculate the carbon footprint of biochar production by measuring the amount of CO2 equivalent emitted per Kg of feedstock used. Following the guidelines set by ISO 14067 the study will begin the analysis from the transportation of the collected biomass waste. The focus will be, on examining the emissions produced and mitigated during both slow pyrolysis and fast pyrolysis processes in biochar production to understand which process is more beneficial to the environment.

  The study will particularly emphasize the evaluation of emissions generated and reduced during slow pyrolysis and fast pyrolysis, with a specific focus on energy usage from bio-oil and syngas derived from biomass. This comparison will contrast the potential emissions that would have occurred if traditional fossil fuels were used for energy usage in both pyrolysis methods therefore estimating the avoided emissions due to the energy usage from bio-oil and syngas.

  Moreover, the analysis will include an assessment of the carbon storage potential of biochar when applied to soil, considering the differences between biochar generated from slow and fast pyrolysis methods. The comparison will shed light on the distinct carbon footprints associated with these different biochar production techniques.

- **The CFP study is being conducted with these main objectives:**

  1. Measuring the carbon emissions at every stage of the pyrolysis process which is important to understand its impact on the environment.

  2. Considering the extent to which the production of biochar contributes to or helps in reducing greenhouse gas emissions.

  3. Quantifying the avoided emissions achieved by utilizing bio-oil and syngas for energy usage when compared to traditional fossil fuel energy.

  4. Taking into consideration the potential of biochar to store carbon and the role it plays in maintaining the carbon balance.

  5. In addition to these objectives, the analysis will encompass both slow pyrolysis and fast pyrolysis methods. This comparison is essential for understanding the distinct carbon footprints and environmental impacts associated with each biochar production technique. By evaluating both methods, the study aims to provide a comprehensive understanding of the environmental implications and benefits associated with slow and fast pyrolysis in biochar production.

- **Intended Audience**: The findings of this CFP analysis are meant to be shared with groups involved in the process including but not limited to:

  1. Environmental regulatory authorities.
  2. Biochar producers and manufacturers.
  3. Research institutions and scientists involved in sustainability and climate change studies.
  4. Environmental organizations and advocacy groups.
  5. Businesses and individuals interested in assessing the environmental impact of biochar and its role in reducing carbon emissions.

- **Functional unit:** 1 Kg of biomass feedstock input.
- **System boundary:**

  The stages considered for the assessment in this study are as follows:

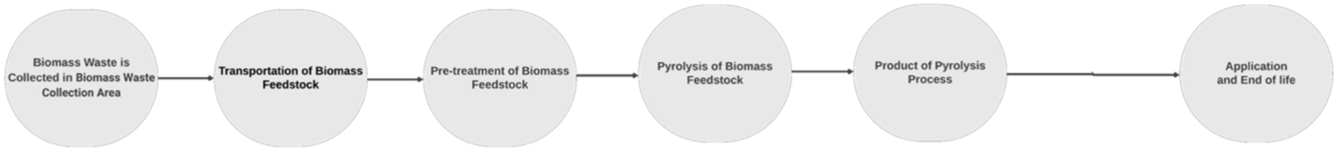

Figure 13: *System boundaries of my analysis.*

- **Allocation:** Mass allocation.
- **Impact Category:** Climate Change.
- **Time reference:** The recommended time frame, for the effects of biochar, on soil is believed to be a minimum of 100 years.
- **Cut-off:** 1%.
- **Data and Data Quality Requirements:** We will gather the data, for this study exclusively from trustworthy sources. Our data quality criteria will comply with ISO standards to ensure reliability and comprehensiveness.

- **Assumptions for Scenario A which is Slow Pyrolysis:**

1. The System boundary of the life cycle assessment for the Pyrolysis of biomass.
2.

Operating Parameters	**Slow Pyrolysis**
Temperature (K)	550 – 950
Heating Rate (K/s)	0.1-1
Solid Residence time (s)	450 - 550
Particle Size (mm)	5-50
Product	**Slow Pyrolysis**
Biochar (%)	35
Bio-oil (%)	30
Syngas (%)	35

3. The total GHG emissions related to pyrolysis process considered is only the GHG emissions due to the production of the electricity needed to run this process of pyrolysis which is 0.5 kWh per kg of product.
4. In our study, biomass transportation and also biochar transportation are key elements in our life cycle assessment. We use heavy-duty lorries meeting EURO5 emissions standards to transport biomass and biochar each for a standardized 100 km distance.
5. Hammer milling is used for biomass size reduction and based on data from literature of energy use that ranges from 5-60 kWh/ton we will assume the worst-case scenario of 60 kWh/ton.
6. The initial global warming potential of the biomass drying process is specified at 9.2 kg CO2-e per ton (t) of oven-dry biomass. Considering it takes 1.68 tons of raw biomass to produce 1 ton of oven-dry biomass, a calculation is performed to determine the carbon footprint per kilogram of raw biomass which results in 0.0055 kg CO2-e per kilogram of raw biomass processed.
7. 2.46 t CO2eq per t BC is the Carbon storage potential of the use of biochar in soil based on an average of the available data to represent the status of our biomass waste.
8. Average calorific value for bio-oils produced, which is set at 27.5 MJ/kg.
9. Average calorific value for syngas produced, which is set at 19.1 MJ/kg.

- **Assumptions for Scenario B which is Fast Pyrolysis:**
  1. The System boundary of the life cycle assessment for the Pyrolysis of biomass.
  2.

Operating Parameters	Fast Pyrolysis
Temperature (K)	850 – 1250
Heating Rate (K/s)	10-200
Solid Residence time (s)	0.5 - 10
Particle Size (mm)	Less than 1
Product	**Fast Pyrolysis**
Biochar (%)	20
Bio-oil (%)	50
Syngas (%)	30
Source: (Chen et al., 2018)	

3. The total GHG emissions related to pyrolysis process considered is only the GHG emissions due to the production of the electricity needed to run this process of pyrolysis with heat required equal to 1.45 MJ/kg of dry feedstocks taken from an average value from this range: 1.30–1.60 MJ/kg of dry feedstocks.
4. In our study, biomass transportation and also biochar transportation are key elements in our life cycle assessment. We use heavy-duty lorries meeting EURO5 emissions standards to transport biomass and biochar each for a standardized 100 km distance.
5. Hammer milling is used for biomass size reduction and based on data from literature of energy use that ranges from 5-60 kWh/ton we will assume the worst-case scenario of 60 kWh/ton.
6. The initial global warming potential of the biomass drying process is specified at 9.2 kg CO2-e per ton (t) of oven-dry biomass. Considering it takes 1.68 tons of raw biomass to produce 1 ton of oven-dry biomass, a calculation is performed to determine the carbon footprint per kilogram of raw biomass which results in 0.0055 kg CO2-e per kilogram of raw biomass processed.
7. 2.46 t CO2eq per t BC is the Carbon storage potential of the use of biochar in soil.
8. Average calorific value for bio-oils produced, which is set at 27.5 MJ/kg.
9. Average calorific value for syngas produced, which is set at 19.1 MJ/kg.

Why does the pyrolysis of waste exist?

The primary purpose of biomass waste pyrolysis is to transform waste materials into substances, like biochar, bio oil and syngas. This process helps in reducing waste disposal while also offering energy sources and contributing to the mitigation of greenhouse gas emissions.

How much?

The amount of biomass waste processed in a pyrolysis system will differ based on its size and capability. It can range from setups that handle a few kilograms, per batch to industrial systems capable of processing several tons of biomass waste every day. However for the purpose of our analysis we will consider one kilogram of feedstock, as our functional unit.

How well?

The conversion efficiency refers to the proportion of waste that is successfully transformed into biochar, bio oil and syngas and this based on the process we adopt and analyze.

For how long?

- Taking care of maintenance and following the recommended operating procedures can help prolong the lifespan of the system.

- The quality of the equipment plays a role, in determining how long the system will last. Using high quality components and materials can significantly increase the lifespan of the system.

- Environmental factors can have an impact, on the lifespan of the system especially when it comes to being exposed to harsh conditions.

- According to research biochar is believed to have a lasting impact, on soil lasting for a minimum of 100 years.

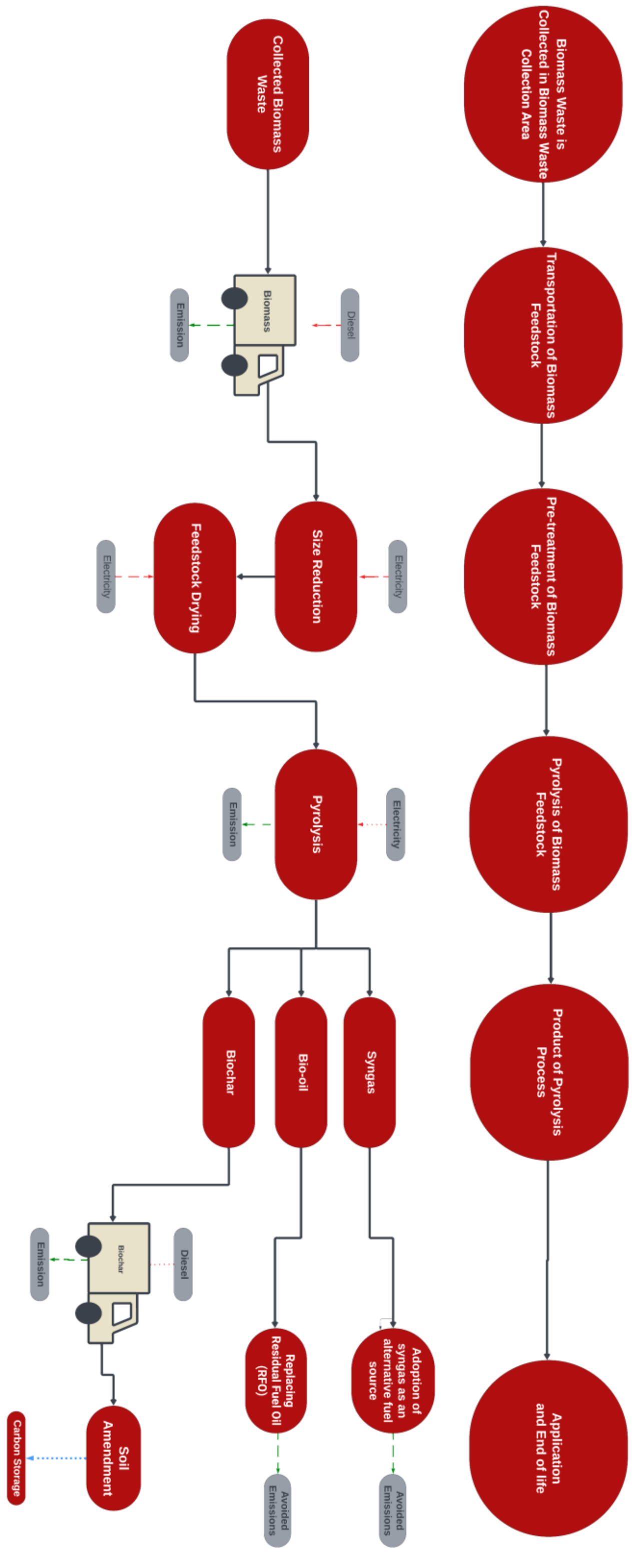

***Figure 14**: System boundary for the Pyrolysis of biomass.*

5.3. Carbon footprint: Life Cycle Assesment Approach

To effectively address climate change it is important to examine how pyrolysis impacts carbon emissions. Pyrolysis provides a solution for transforming materials into products which has the potential to reduce carbon emissions compared to traditional disposal methods and energy production methods. This chapter will specifically focus on evaluating the carbon footprint of pyrolysis in relation to climate change. It will emphasize the measurement of carbon emissions and explore the potential for carbon storage potential associated with biochar while also assessing the avoided emissions due to the energy usage from biooil and syngas.

The purpose of carbon footprint assessment is to measure the greenhouse gas emissions linked to a process or product. When it comes to pyrolysis assessing the carbon footprint involves monitoring how carbon moves throughout each step of the process starting from transporting the materials from waste facilities to using the end products of pyrolysis.

5.3.1. Life Cycle Stages analysis – Slow Pyrolysis

5.3.1.1. Transportation of biomass waste feedstock to the plant

In our study, biomass transportation is a key element in our life cycle assessment. We use heavy-duty lorries meeting EURO5 emissions standards to transport biochar over a standardized 100 km distance. We assessed the carbon dioxide equivalent (CO2e) emissions for this transportation using SimaPro software, ensuring accurate environmental impact analysis with an input unit of KgKm which results in:

Carbon footprint = 0,0137 Kg CO2eq / Kg of feedstock.

5.3.1.2. Biomass Pre-treatment : Size Reduction

Note that: *the emissions due to the hammer mill's machinery production was not within the analysis.*

Hammer milling is widely used for biomass comminution due to its high size reduction ratio and easy adjustment of the particle size range. Usually, the grinding energy for a hammer mill varies between 5 and 60 kWh/ton and we will assume the worst-case scenario of 60 kWh/ton (Paraschiv et al., 2021). Additionally, based on data from Entsoe the current emissions based on the energy mix in Italy is = 389 g CO2eq/kWh which means that for each kWh used 0,389kg of CO2eq is emitted. Therefore, the emissions are 0,389 x 60 = 23,34 kg of CO2eq for every ton of feedstock = **0,02334 Kg CO2eq / Kg of feedstock.**

5.3.1.3. Biomass Pre-treatment : Feedstock Drying

Note that: *the emissions due to the dryer's machinery production was not within the analysis.*

The carbon footprint estimation of approximately **0.00547619** kg CO2-e per kilogram (kg) of raw biomass processed to yield the final oven-dry biomass is derived from the provided data (Haque & Somerville, 2013). The initial global warming potential of the biomass drying process is specified at 9.2 kg CO2-e per ton of oven-dry biomass. Considering it takes 1.68 tons of raw biomass to produce 1 ton of oven-dry biomass, a calculation is performed to determine the carbon footprint per kilogram of raw biomass. By dividing the initial global warming potential (9.2 kg CO2-e) by the total quantity of raw biomass used to obtain the final product (1.68 tons equating to 1680 kilograms), an approximation of **0.00547619 kg CO2-e per kilogram of raw biomass processed is derived,** reflecting the carbon emissions associated with each kilogram of the initial feedstock throughout the processing and drying stages to produce the final oven-dry biomass (Haque & Somerville, 2013).

5.3.1.4. Pyrolysis Process

The total GHG emissions related to this step considered is only the GHG emissions due to the production of the electricity needed to run this process of pyrolysis (Gahane et al., 2022).

When conducting our research, it is important to consider the amount of electricity used in biomass pyrolysis processes. A valuable study titled "Life cycle assessment of biomass pyrolysis " conducted by Gahane, Biswal and Mandavgane in 2022 and published in Bioenergy Research provided us with insights, on this topic. According to their investigation most pyrolysis processes typically consume between 0.4 to 0.6 kWh per kilogram of the product produced. To analyze electricity usage in biomass pyrolysis processes for our study we have adopted a value of 0.5 kWh per kilogram of product produced based on the research. This reference will be essential as a foundation for our examination (Gahane et al., 2022). Additionally, based on data from Entsoe the current emissions based on the energy mix in Italy is = 389 g CO2eq/kWh which means that for each kWh 0,389 kg of CO2eq is emitted.

Therefore, to calculate the emissions we assume that Pyrolysis is 100% efficient and the amount of electricity usage for 1 Kg of product is the same for 1 Kg of feedstock:

0.5 kWh per kilogram of feedstock x 0,389kg of CO2eq/kWh = **0,1945 Kg CO2eq / Kg of feedstock**

5.3.2. Transportation of Biochar to Land

In our study the transportation of biochar plays a role, in our assessment of its life cycle. To transport biochar, we use heavy duty freight lorries with load capacities ranging from 16 to 32 tons for a standardized distance of 100 Km. These lorries meet the EURO5 emissions standards outlined in the {RER} guidelines. We take this transportation process seriously.

The Carbon footprint is 0,0137 Kg CO2eq / Kg of biochar transported and since for the production of 1 Kg of biochar we need 2,8571 Kg of feedstock we can calculate the Carbon footprint for 1 Kg feedstock by dividing the 0,0137 Kg CO2eq / Kg of biochar transported by 2,8571 Kg of feedstock to have a carbon footprint which is **0,004795 Kg CO2eq / Kg of feedstock.**

5.3.3. Application of Biochar to Land and Carbon Storage Potential

In our research we extensively reviewed studies to evaluate how biochar could help reduce carbon dioxide (CO2) emissions. We collected data from multiple sources, including studies, on methods of producing biochar and the materials used. To determine the value of 2.46 t CO2eq per t BC we added up values from multiple studies and divided them by the number of data points. This average value is an important parameter, in our analysis as it allows us to adjust the carbon footprint of pyrolysis processes and accurately account for the carbon storage potential of biochar produced. By subtracting this storage potential from the emissions associated with pyrolysis we obtain a more precise representation of the net carbon footprint, which highlights how biochar can effectively help mitigate greenhouse gas emissions.

Table 10: *Summary of CO2 Storage Potential for Different Biochar Sources.*

Biochar Source	CO2 Storage Potential (t CO2eq per t BC)	References
Sugarcane Residues in São Paulo	1.64 ± 0.11	(Lefebvre et al., 2021)
Willow Wood in Belgian Plantation	2.2	(Rajabi Hamedani et al., 2019)
Spanish Poplar Wood	3.9	(Peters et al., 2015)
Switchgrass for Canadian Wheat	2.3	(Brassard et al., 2018)
Average Value	**2.46**	**Calculated from the available data**

Therefore, to calculate the CO2 storage potential (Kg CO2eq per Kg feedstock) we can multiply the 2.46 (t CO2eq per t BC) by 0.35 as for each 1 Kg of feedstock we produce 0.35 Kg of biochar having a CO2 storage potential (Kg CO2eq per Kg feedstock) = **0,861 Kg CO2eq per Kg feedstock.**

5.3.4. Bio-oil energy production and their effect on the CF

The study assesses the carbon emissions reduction resulting from the utilization of bio-oil as a fuel source in the context of a pyrolysis process. The specific focus is on a functional unit of 1 kg of feedstock, of which 30% is transformed into bio-oil. The analysis considers the average calorific value of bio-oils within the range of 20-35 MJ/kg to calculate the emissions reduction and in the study, we will employ an average calorific value for bio-oils produced, which is set at 27.5 MJ/kg. This value represents the midpoint of the range of typical calorific values observed for bio-oils (Steele et al., 2012).

The research examines the environmental impact of substituting bio-oil for an alternative fuel, Residual Fuel Oil (RFO), in a pyrolysis process. One of the key objectives is to quantify the reduction in carbon dioxide (CO2) emissions associated with this substitution.

Furthermore, using data that states a reduction of 0.0749 kg CO2 per MJ of fuel consumption, this study aims to provide a quantitative assessment of the reduction in carbon dioxide (CO2) emissions achieved by the adoption of bio-oil as an alternative fuel source (Ben et al., 2019).

1. Energy content (MJ) = 0.30 kg (bio-oil) * 27.5 MJ/kg (average calorific value)
2. Energy content (MJ) = 8.25 MJ

Now that we have the energy content of the 0.30 kg of bio-oil as 8.25 MJ, we can calculate the emissions reduction using the original value of 0.0749 kg CO2 per MJ of fuel consumption:

3. Emissions Reduction = 8.25 MJ * 0.0749 kg CO2 per MJ
4. Emissions Reduction ≈ 0.618 kg CO2 Per Kg of Feedstock

So, using an average calorific value of 27.5 MJ/kg for bio-oil, you can estimate that the production of 0.30 kg of bio-oil reduces CO2 emissions by approximately 0.618 kg of CO2 when considering the energy content of the bio-oil. This is the emissions reduction associated with your functional unit of 1 kg of feedstock and 30% bio-oil production.

5.3.5. Syngas energy production and their effect on the CF

The study assesses the carbon emissions reduction resulting from the utilization of syngas as a fuel source in the context of a pyrolysis process. The specific focus is on a functional unit of 1 kg of feedstock, of which 35% is transformed into syngas. The analysis considers the average calorific value of syngas, which is determined to be between 10.4 MJ/Kg and 27.8 MJ/Kg, but we will use an average value of 19.1 MJ/kg (Ghenai, 2010).

In the study, we will employ this average calorific value to calculate the emissions reduction associated with the use of syngas as an alternative fuel source.

Furthermore, using data that states a reduction 350 gCO2-eq/kWh is equivalent to 0.0972 kg CO2 per MJ of fuel consumption, this study aims to provide a quantitative assessment of the reduction in carbon dioxide (CO2) emissions achieved by the adoption of syngas as an alternative fuel source (Bachmann et al., 2023).

1. Energy content (MJ) = 0.35 kg (syngas) * 19.1 MJ/kg (average calorific value)
2. Energy content (MJ) = 6.685 MJ

Now that we have the energy content of the 0.35 kg of syngas as 6.685 MJ, we can calculate the emissions reduction using the original value of 0.0972 kg CO2 per MJ of fuel consumption:

3. Emissions Reduction = 6.685MJ * 0.0972 kg CO2 per MJ
4. Emissions Reduction ≈ 0.6498 kg CO2 Per Kg of Feedstock

So, using an average calorific value of 19.1 MJ/kg for syngas, you can estimate that the production of 0.35 kg of syngas reduces CO2 emissions by approximately 0.6498 kg of CO2 when considering the energy content of the syngas. This is the emissions reduction associated with your functional unit of 1 kg of feedstock and 35% syngas production.

Total Emission reduction due to the use of bio-oil and syngas as an alternative source of energy = 1.2678 kg CO2 Per Kg of Feedstock

5.4. Results Based on Life cycle of the Process.

Table 11: *Data collected Based on Life cycle of the Process – Slow Pyrolysis*

Life Cycle Stage	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	**0,0137**
Biomass Pre-treatment : Size Reduction	**0,02334**
Biomass Pre-treatment : Feedstock Drying	**0.00547619**
Pyrolysis Process	**0,1945**
Transportation of Biochar to Land	**0,004795**
Carbon storage potential of biochar when applied to soil	**-0,861**
Avoided emissions due to syngas and bio-oil energy generation.	**-1,267**

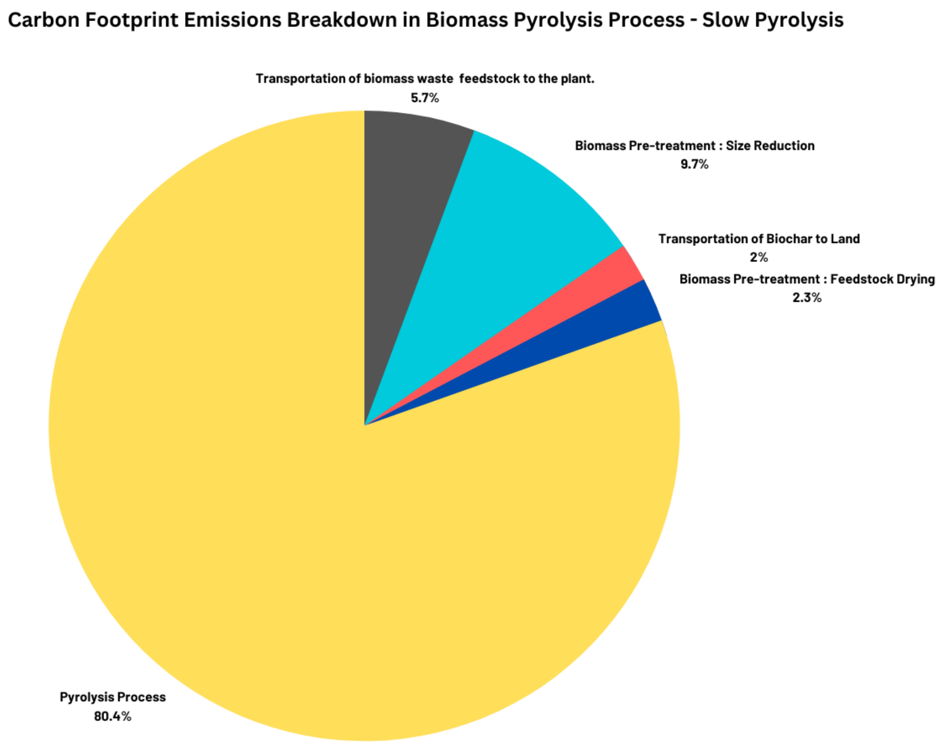

Figure 15 : *Carbon Footprint Emissions Breakdown in Biomass Pyrolysis Process - Slow Pyrolysis*

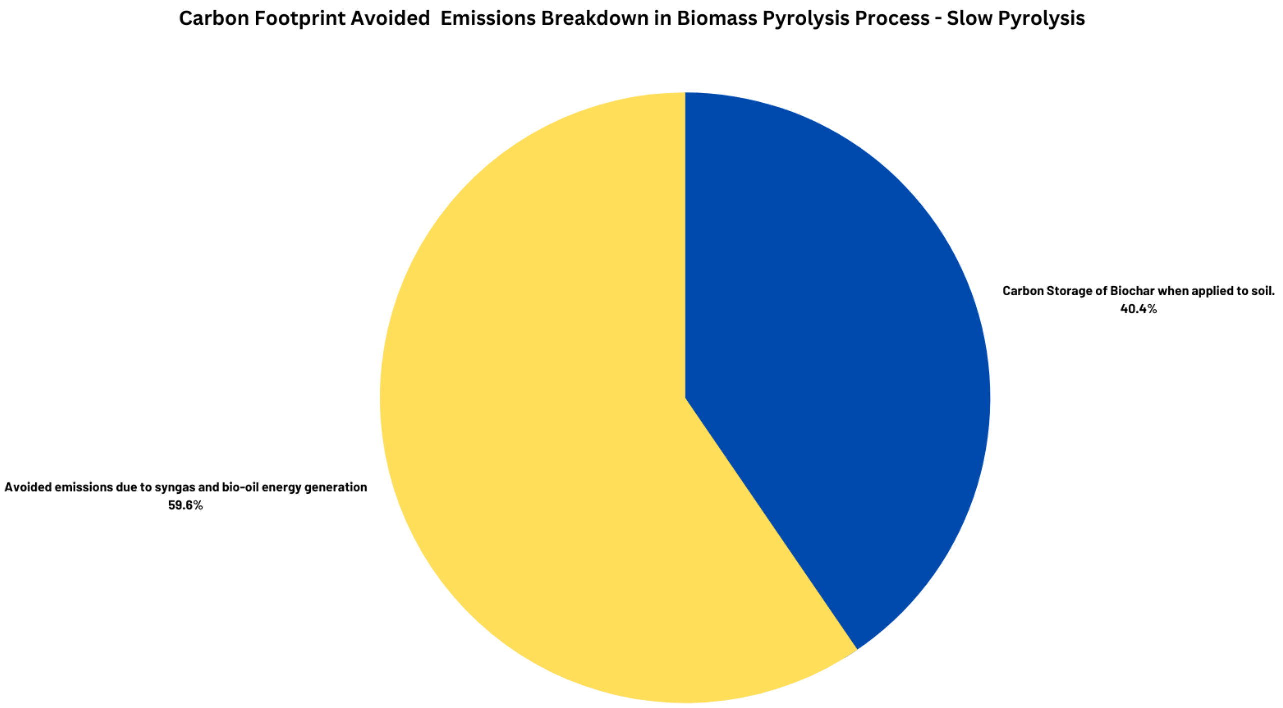

Figure 16: *Carbon Footprint Avoided Emissions Breakdown in Biomass Pyrolysis Process - Slow Pyrolysis*

5.5. Analysis and Results

Scenario X1: Carbon footprint of Pyrolysis Process taking into consideration both carbon storage potential of biochar and avoided emissions due to the use of biooil and syngas as an energy source.

Table 12: *Carbon Footprint of Slow Pyrolysis Process for Scenario X1.*

Life Cycle Stage - Scenario X1	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	**0,0137**
Biomass Pre-treatment : Size Reduction	**0,02334**
Biomass Pre-treatment : Feedstock Drying	**0,00547619**
Pyrolysis Process	**0,1945**
Transportation of Biochar to Land	**0,004795**
Carbon storage potential of biochar when applied to soil	**-0,861**
Avoided emissions due to syngas and bio-oil energy usage	**-1,2678**
Total Carbon Footrpint	**-1,8861**

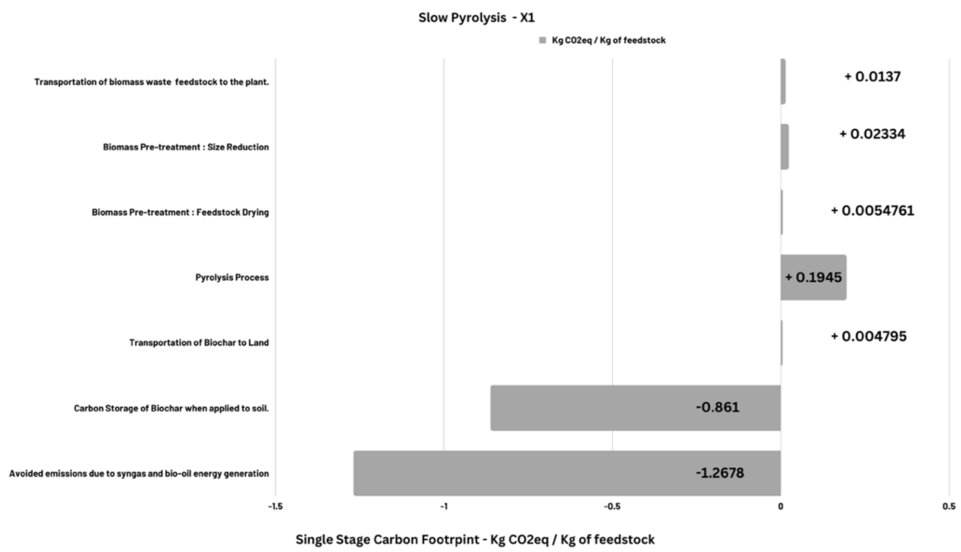

Figure 17 : *Single Stage Carbon Footrpint - Kg CO2eq / Kg of feedstock – Slow Pyrolysis X1.*

Scenario X2: Carbon footprint of Pyrolysis Process taking into consideration the carbon storage potential of biochar without taking into consideration the avoided emissions due to the use of biooil and syngas as an energy source.

Table 13:*Carbon Footprint of Slow Pyrolysis Process for Scenario X2.*

Life Cycle Stage - Scenario X2	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137
Biomass Pre-treatment : Size Reduction	0,02334
Biomass Pre-treatment : Feedstock Drying	0,00547619
Pyrolysis Process	0,1945
Transportation of Biochar to Land	0,004795
Carbon storage potential of biochar when applied to soil	-0,861
Total Carbon Footrpint	-0,61918

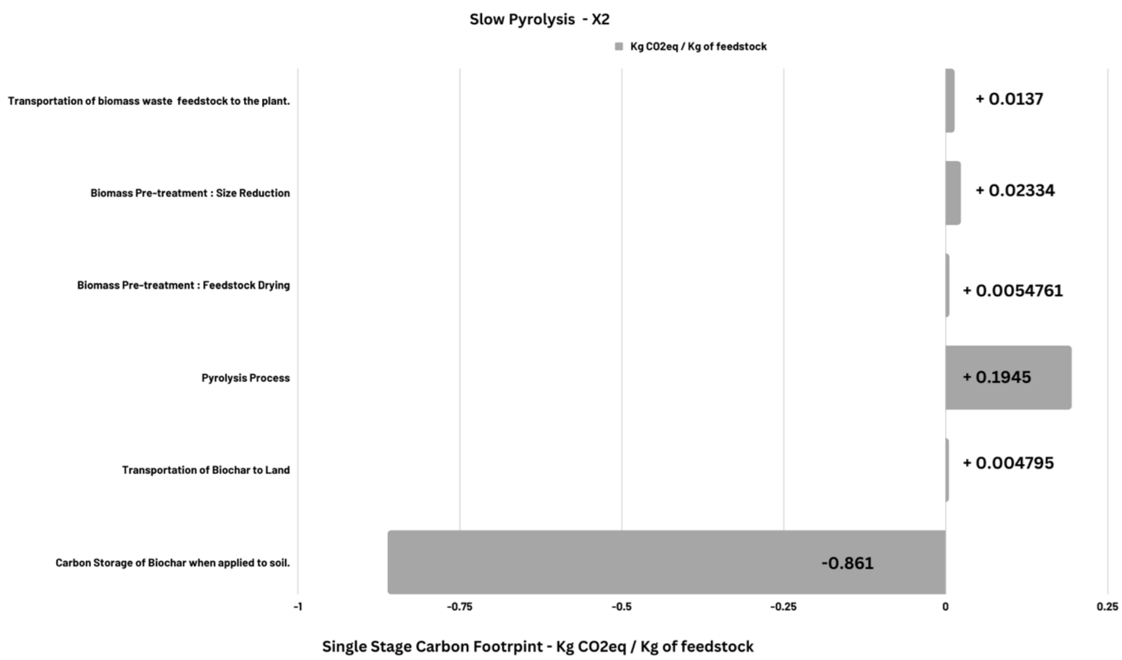

Figure 18: *Single Stage Carbon Footrpint - Kg CO2eq / Kg of feedstock – Slow Pyrolysis X2.*

Scenario X3: Carbon footprint of Pyrolysis Process without taking into consideration the carbon storage potential of biochar while taking into consideration the avoided emissions due to the use of biooil and syngas as an energy source.

Table 14: *Carbon Footprint of Slow Pyrolysis Process for Scenario X3.*

Life Cycle Stage - Scenario X3	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137
Biomass Pre-treatment : Size Reduction	0,02334
Biomass Pre-treatment : Feedstock Drying	0,00547619
Pyrolysis Process	0,1945
Transportation of Biochar to Land	0,004795
Avoided emissions due to syngas and bio-oil energy usage	-1,2678
Total Carbon Footrpint	-1,0259

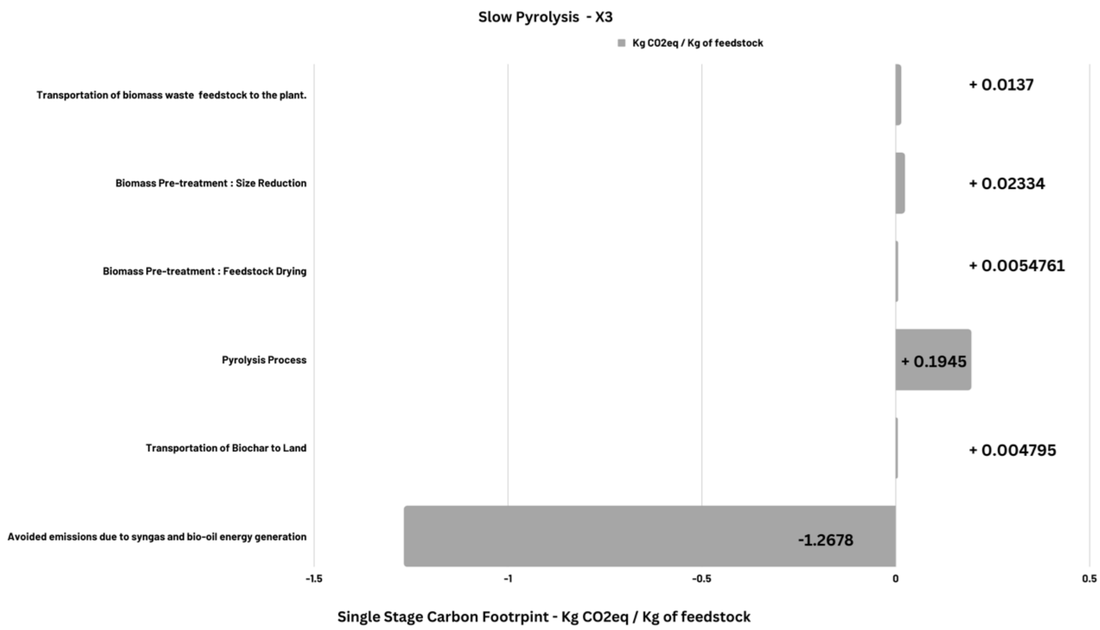

Figure 19: *Single Stage Carbon Footrpint - Kg CO2eq / Kg of feedstock – Slow Pyrolysis X3.*

5.5.1. Life Cycle Stages analysis – Fast Pyrolysis (Biochar transportation)

5.5.1.1. Transportation of biomass waste feedstock to the plant

In our study, biomass transportation is a key element in our life cycle assessment. We use heavy-duty lorries meeting EURO5 emissions standards to transport biochar over a standardized 100 km distance. We assessed the carbon dioxide equivalent (CO2e) emissions for this transportation using SimaPro software, ensuring accurate environmental impact analysis with an input unit of KgKm which results in:

Carbon footprint = 0,0137 Kg CO2eq / Kg of feedstock.

5.5.1.2. Biomass Pre-treatment : Size Reduction

Note that: *the emissions due to the hammer mill's machinery production was not within the analysis.*

Hammer milling is widely used for biomass comminution due to its high size reduction ratio and easy adjustment of the particle size range. Usually, the grinding energy for a hammer mill varies between 5 and 60 kWh/ton and we will assume the worst-case scenario of 60 kWh/ton (Paraschiv et al., 2021). Additionally, based on data from Entsoe the current emissions based on the energy mix in Italy is = 389 g CO2eq/kWh which means that for each kWh used 0,389kg of CO2eq is emitted. Therefore, the emissions are 0,389 x 60 = 23,34 kg of CO2eq for every ton of feedstock = **0,02334 Kg CO2eq / Kg of feedstock.**

5.5.1.3. Biomass Pre-treatment : Feedstock Drying

Note that: *the emissions due to the dryer's machinery production was not within the analysis.*

The carbon footprint estimation of approximately **0.00547619** kg CO2-e per kilogram (kg) of raw biomass processed to yield the final oven-dry biomass is derived from the provided data (Haque & Somerville, 2013). The initial global warming potential of the biomass drying process is specified at 9.2 kg CO2-e per ton of oven-dry biomass. Considering it takes 1.68 tons of raw biomass to produce 1 ton of oven-dry biomass, a calculation is performed to determine the carbon footprint per kilogram of raw biomass. By dividing the initial global warming potential (9.2 kg CO2-e) by the total quantity of raw biomass used to obtain the final product (1.68 tons equating to 1680 kilograms), an approximation of **0.00547619 kg CO2-e per kilogram of raw biomass processed is derived,** reflecting the carbon emissions associated with each kilogram of the initial feedstock throughout the processing and drying stages to produce the final oven-dry biomass (Haque & Somerville, 2013).

5.5.1.4. Pyrolysis Process

The total GHG emissions related to this step considered is only the GHG emissions due to the production of the electricity needed to run this process of pyrolysis (Gahane et al., 2022).

The total heat required for fast pyrolysis, according to Daugaard and Brown (2003), ranges from 1.30 to 1.60 MJ/kg of dry feedstocks. For this analysis, I will use the average value, which is 1.45 MJ/kg, as a reference. Converting the energy value to kilowatt-hours (kWh), 1 MJ is equivalent to 0.27778 kWh. Therefore, 1.45 MJ/kg is approximately 0.4021 kWh/kg.

Using the information that each kWh of electricity in Italy emits 0.389 kg based on data from Entsoe the current emissions based on the energy mix in Italy of CO2 equivalent, the carbon emissions associated with the energy consumption in fast pyrolysis can be estimated.

For 1 kg of dry feedstock processed through fast pyrolysis, the energy requirement is about 0.4021 kWh. Multiplying this by the carbon emissions per kWh (0.389 kg CO2eq/kWh) indicates an emission of **0.15641 kg of CO2 equivalent for the energy utilized in the pyrolysis process per kilogram of feedstock.**

5.5.2. Transportation of Biochar to Land

In our study the transportation of biochar plays a role, in our assessment of its life cycle. To transport biochar, we use heavy duty freight lorries with load capacities ranging from 16 to 32 tons for a standardized distance of 100 Km. These lorries meet the EURO5 emissions standards outlined in the {RER} guidelines. We take this transportation process seriously.

The Carbon footprint is 0,0137 Kg CO2eq / Kg of biochar transported and since for the production of 1 Kg of biochar we need 5 Kg of feedstock we can calculate the Carbon footprint for 1 Kg feedstock by dividing the 0,0137 Kg CO2eq / Kg of biochar transported by 5 Kg of feedstock to have a number which is **0,00274 Kg CO2eq / Kg of feedstock.**

5.5.3. Application of Biochar to Land and Carbon Storage Potential

In our research we extensively reviewed studies to evaluate how biochar could help reduce carbon dioxide (CO2) emissions. We collected data from multiple sources, including studies, on methods of producing biochar and the materials used. To determine the value of 2.46 t CO2eq per t BC we added up values from multiple studies and divided them by the number of data points. This average value is an important parameter, in our analysis as it allows us to adjust the carbon footprint of pyrolysis processes and accurately account for the carbon storage potential of biochar produced. By subtracting this storage potential from the emissions associated with pyrolysis we obtain a more precise representation of the net carbon footprint, which highlights how biochar can effectively help mitigate greenhouse gas emissions.

Table 15: *Summary of CO2 Storage Potential for Different Biochar Sources.*

Biochar Source	CO2 Storage Potential (t CO2eq per t BC)	References
Sugarcane Residues in São Paulo	1.64 ± 0.11	(Lefebvre et al., 2021)
Willow Wood in Belgian Plantation	2.2	(Rajabi Hamedani et al., 2019)
Spanish Poplar Wood	3.9	(Peters et al., 2015)
Switchgrass for Canadian Wheat	2.3	(Brassard et al., 2018)
Average Value	**2.46**	**Calculated from the available data**

Therefore, to calculate the CO2 storage potential (Kg CO2eq per Kg feedstock) we can multiply the 2.46 (t CO2eq per t BC) by 0.2 as for each 1 Kg of feedstock we produce 0.2 Kg of biochar having a CO2 storage potential (Kg CO2eq per Kg feedstock) = **0,492 Kg CO2eq per Kg feedstock.**

5.5.4. Bio-oil energy production and their effect on the CF

The study assesses the carbon emissions reduction resulting from the utilization of bio-oil as a fuel source in the context of a pyrolysis process. The specific focus is on a functional unit of 1 kg of feedstock, of which % 50 is transformed into bio-oil. The analysis considers the average calorific value of bio-oils within the range of 20-35 MJ/kg to calculate the emissions reduction and in the study, we will employ an average calorific value for bio-oils produced, which is set at 27.5 MJ/kg. This value represents the midpoint of the range of typical calorific values observed for bio-oils (Steele et al., 2012).

The research examines the environmental impact of substituting bio-oil for an alternative fuel, Residual Fuel Oil (RFO), in a pyrolysis process. One of the key objectives is to quantify the reduction in carbon dioxide (CO_2) emissions associated with this substitution.

Furthermore, using data that states a reduction of 0.0749 kg CO_2 per MJ of fuel consumption, this study aims to provide a quantitative assessment of the reduction in carbon dioxide (CO_2) emissions achieved by the adoption of bio-oil as an alternative fuel source (Ben et al., 2019).

5. Energy content (MJ) = 0.50 kg (bio-oil) * 27.5 MJ/kg (average calorific value)
6. Energy content (MJ) = 13.75 MJ

Now that we have the energy content of the 0.50 kg of bio-oil as 13.75 MJ, we can calculate the emissions reduction using the original value of 0.0749 kg CO_2 per MJ of fuel consumption:

7. Emissions Reduction = 13.75 MJ * 0.0749 kg CO_2 per MJ
8. Emissions Reduction ≈ 1.029875 kg CO_2 Per Kg of Feedstock

So, using an average calorific value of 27.5 MJ/kg for bio-oil, you can estimate that the production of 0.50 kg of bio-oil reduces CO_2 emissions by approximately 1.029875 kg of CO_2 when considering the energy content of the bio-oil. This is the emissions reduction associated with your functional unit of 1 kg of feedstock and 50% bio-oil production.

5.5.5. Syngas energy production and their effect on the CF

The study assesses the carbon emissions reduction resulting from the utilization of syngas as a fuel source in the context of a pyrolysis process. The specific focus is on a functional unit of 1 kg of feedstock, of which 30% is transformed into syngas. The analysis considers the average calorific value of syngas, which is determined to be between 10.4 MJ/Kg and 27.8 MJ/Kg, but we will use an average value of 19.1 MJ/kg (Ghenai, 2010).

In the study, we will employ this average calorific value to calculate the emissions reduction associated with the use of syngas as an alternative fuel source.

Furthermore, using data that states a reduction 350 gCO2-eq/kWh is equivalent to 0.0972 kg CO2 per MJ of fuel consumption, this study aims to provide a quantitative assessment of the reduction in carbon dioxide (CO2) emissions achieved by the adoption of syngas as an alternative fuel source (Bachmann et al., 2023).

5. Energy content (MJ) = 0.30 kg (syngas) * 19.1 MJ/kg (average calorific value)
6. Energy content (MJ) = 5.7 MJ

Now that we have the energy content of the 0.3 kg of syngas as 5.7 MJ, we can calculate the emissions reduction using the original value of 0.0972 kg CO2 per MJ of fuel consumption:

7. Emissions Reduction = 5.7 MJ * 0.0972 kg CO2 per MJ
8. Emissions Reduction ≈ 0.55404 kg CO2 Per Kg of Feedstock

So, using an average calorific value of 19.1 MJ/kg for syngas, you can estimate that the production of 0.3 kg of syngas reduces CO2 emissions by approximately 0.55404 kg of CO2 when considering the energy content of the syngas. This is the emissions reduction associated with your functional unit of 1 kg of feedstock and 30% syngas production.

Total Emission reduction due to the use of bio-oil and syngas as an alternative source of energy = 0.55404 +1.029875 = 1.583915 kg CO2 Per Kg of Feedstock

5.6. Results Based on Life cycle of the Process.

***Table 16**: Data collected Based on Life cycle of the Process – Fast Pyrolysis*

Life Cycle Stage	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137
Biomass Pre-treatment : Size Reduction	0,02334
Biomass Pre-treatment : Feedstock Drying	0,00547619
Pyrolysis Process	0,15641
Transportation of Biochar to Land	0,00274
Carbon storage potential of biochar when applied to soil	-0,492
Avoided emissions due to syngas and bio-oil energy usage	-1,583915

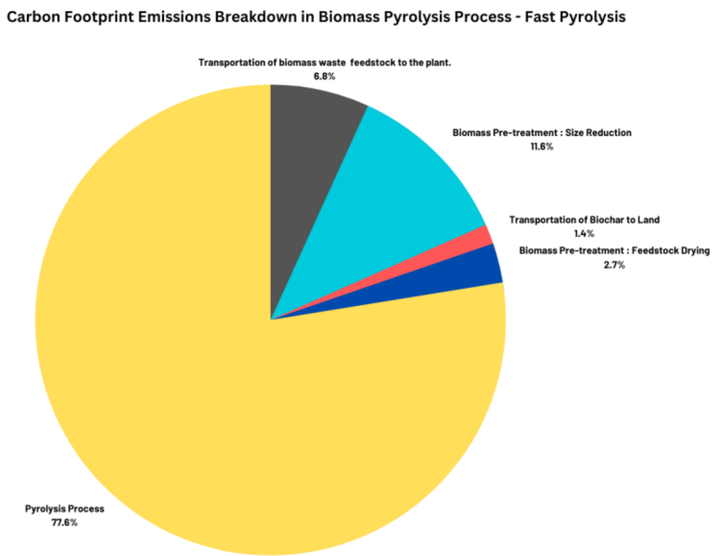

***Figure 20:** Carbon Footprint Emissions Breakdown in Biomass Pyrolysis Process - Fast Pyrolysis*

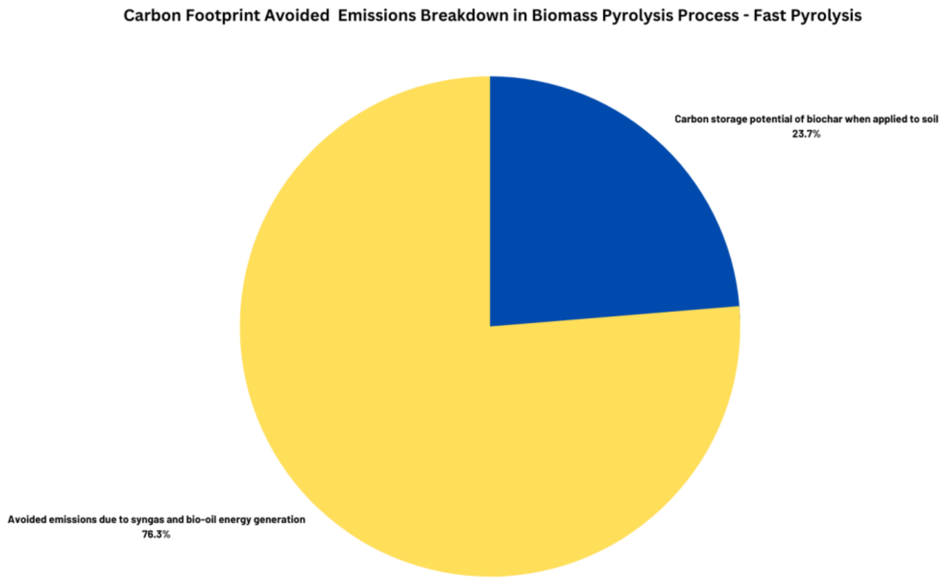

Figure 21: *Carbon Footprint Avoided Emissions Breakdown in Biomass Pyrolysis Process - Fast Pyrolysis*

5.7. Analysis and Results

Scenario Y1: Carbon footprint of Pyrolysis Process taking into consideration both carbon storage potential of biochar and avoided emissions due to the use of biooil and syngas as an energy source.

Table 17:*Carbon Footprint of Fast Pyrolysis Process for Scenario Y1.*

Life Cycle Stage - Scenario Y1	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137
Biomass Pre-treatment : Size Reduction	0,02334
Biomass Pre-treatment : Feedstock Drying	0,00547619
Pyrolysis Process	0,15641
Transportation of Biochar to Land	0.00274
Carbon storage potential of biochar when applied to soil	-0,492
Avoided emissions due to syngas and bio-oil energy usage	-1,583915
Total Carbon Footrpint	-1,87424881

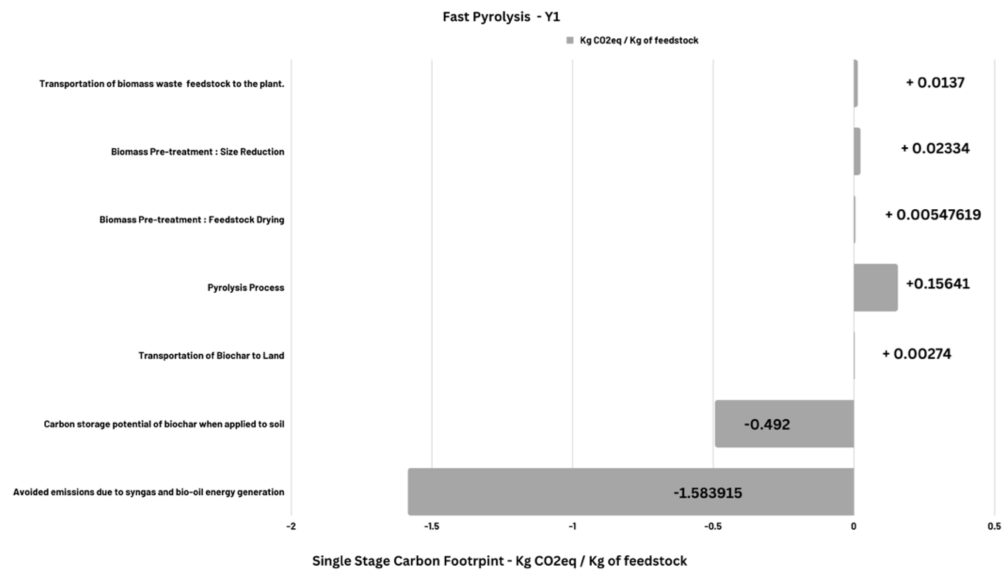

Figure 22 :*Single Stage Carbon Footrpint - Kg CO2eq / Kg of feedstock – Fast Pyrolysis Y1.*

Scenario Y2: Carbon footprint of Pyrolysis Process without taking into consideration the carbon storage potential of biochar while taking into consideration the avoided emissions due to the use of biooil and syngas as an energy source.

Table 18: *Carbon Footprint of Fast Pyrolysis Process for Scenario Y2.*

Life Cycle Stage - Scenario Y2	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137
Biomass Pre-treatment : Size Reduction	0,02334
Biomass Pre-treatment : Feedstock Drying	0,00547619
Pyrolysis Process	0,15641
Transportation of Biochar to Land	0.00274
Carbon storage potential of biochar when applied to soil	-0,492
Total Carbon Footrpint	-0,29033381

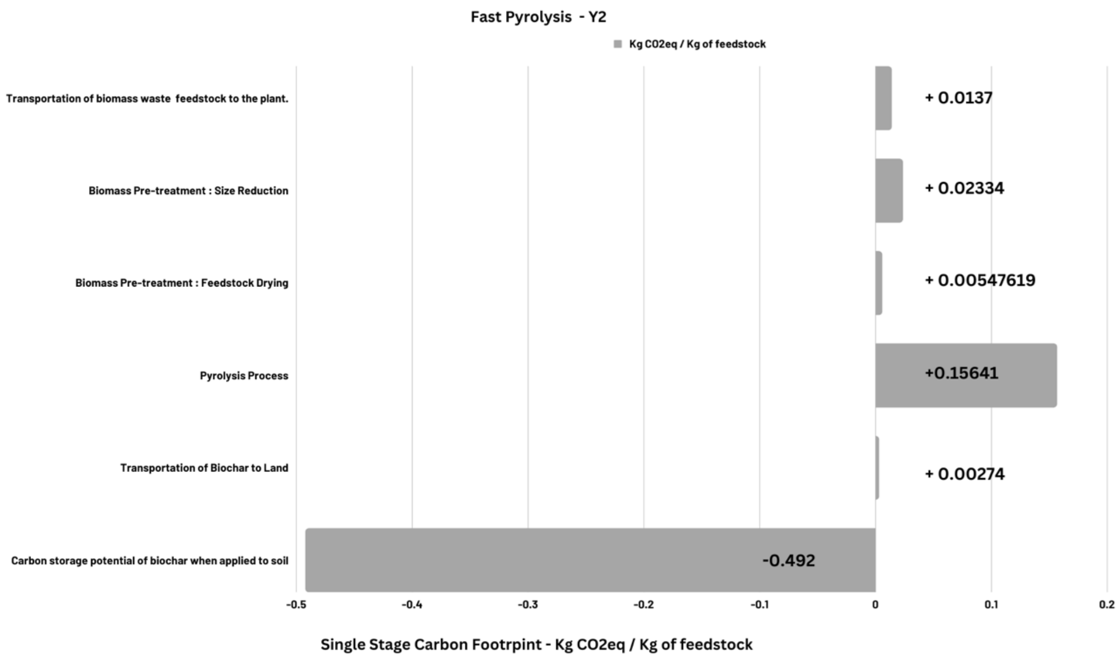

Figure 23:*Single Stage Carbon Footrpint - Kg CO2eq / Kg of feedstock – Fast Pyrolysis Y2.*

Scenario Y3: Carbon footprint of Pyrolysis Process taking into consideration the carbon storage potential of biochar without taking into consideration the avoided emissions due to the use of biooil and syngas as an energy source.

Table 19:*Carbon Footprint of Fast Pyrolysis Process for Scenario Y3.*

Life Cycle Stage - Scenario Y3	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	**0,0137**
Biomass Pre-treatment : Size Reduction	**0,02334**
Biomass Pre-treatment : Feedstock Drying	**0,00547619**
Pyrolysis Process	**0,15641**
Transportation of Biochar to Land	**0.00274**
Avoided emissions due to syngas and bio-oil energy usage	**-1,583915**
Total Carbon Footrpint	**-1,38224881**

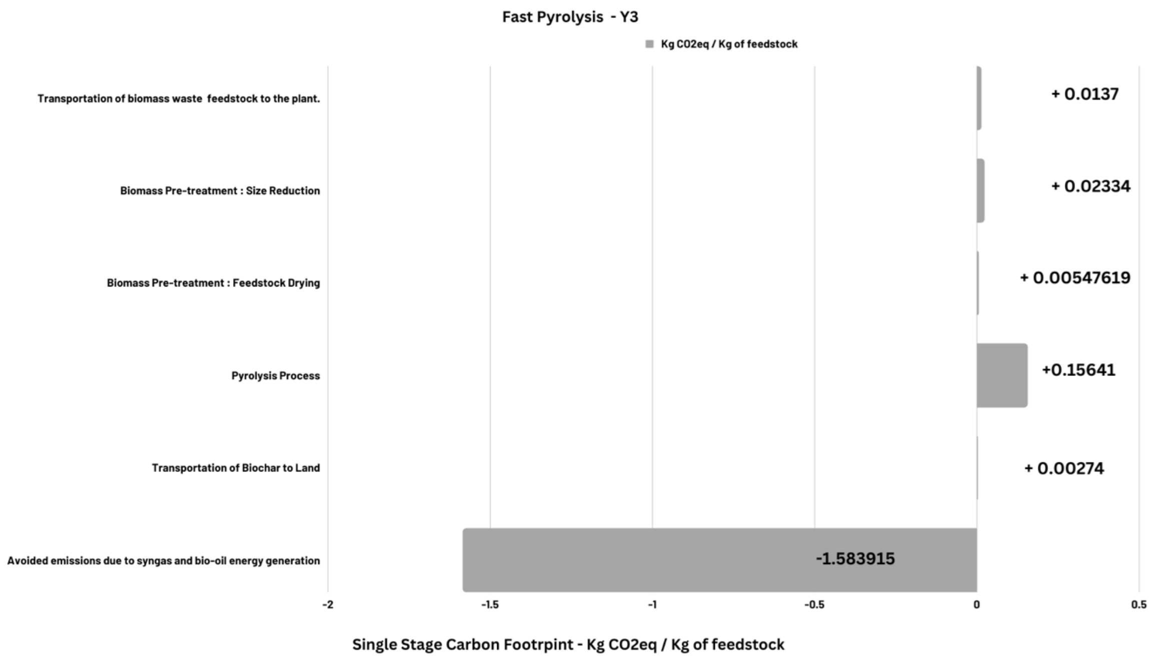

Figure 24 :*Single Stage Carbon Footrpint - Kg CO2eq / Kg of feedstock – Fast Pyrolysis Y3.*

5.8. Slow Pyrolysis Vs Fast Pyrolysis Carbon Footprint

Table 20: *Life Cycle stage emissions Slow Pyrolysis Vs Fast Pyrolysis*

Life Cycle Stage - Emissions	Slow Pyrolysis	Fast Pyrolysis
	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137	0,0137
Biomass Pre-treatment : Size Reduction	0,02334	0,02334
Biomass Pre-treatment : Feedstock Drying	0.00547619	0,00547619
Pyrolysis Process	0,1945	0,15641
Transportation of Biochar to Land	0,004795	0.00274

Table 21: *Carbon Footprint of Slow Pyrolysis X1 Vs Fast Pyrolysis Y1.*

Life Cycle Stage - Scenario X1 | Y1	Slow Pyrolysis	Fast Pyrolysis
	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137	0,0137
Biomass Pre-treatment : Size Reduction	0,02334	0,02334
Biomass Pre-treatment : Feedstock Drying	0.00547619	0,00547619
Pyrolysis Process	0,1945	0,15641
Transportation of Biochar to Land	0,004795	0.00274
Carbon storage potential of biochar when applied to soil	-0,861	-0,492
Avoided emissions due to syngas and bio-oil energy usage	-1,2678	-1,583915
Total Carbon Footrpint	-1,892465	-1,87424881

Table 22: *Carbon Footprint of Slow Pyrolysis X2 Vs Fast Pyrolysis Y2.*

Life Cycle Stage - Scenario X2 | Y2	Slow Pyrolysis	Fast Pyrolysis
	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137	0,0137
Biomass Pre-treatment : Size Reduction	0,02334	0,02334
Biomass Pre-treatment : Feedstock Drying	0.00547619	0,00547619
Pyrolysis Process	0,1945	0,15641
Transportation of Biochar to Land	0,004795	0.00274
Carbon storage potential of biochar when applied to soil	-0,861	-0,492
Total Carbon Footrpint	-0,624665	-0,29033381

Table 23:*Carbon Footprint of Slow Pyrolysis X3 Vs Fast Pyrolysis Y3.*

Life Cycle Stage - Scenario X3 | Y3	Slow Pyrolysis	Fast Pyrolysis
	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
Transportation of biomass waste feedstock to the plant.	0,0137	0,0137
Biomass Pre-treatment : Size Reduction	0,02334	0,02334
Biomass Pre-treatment : Feedstock Drying	0.00547619	0,00547619
Pyrolysis Process	0,1945	0,15641
Transportation of Biochar to Land	0,004795	0.00274
Avoided emissions due to syngas and bio-oil energy usage	-1,2678	-1,583915
Total Carbon Footrpint	-1,031465	-1,38224881

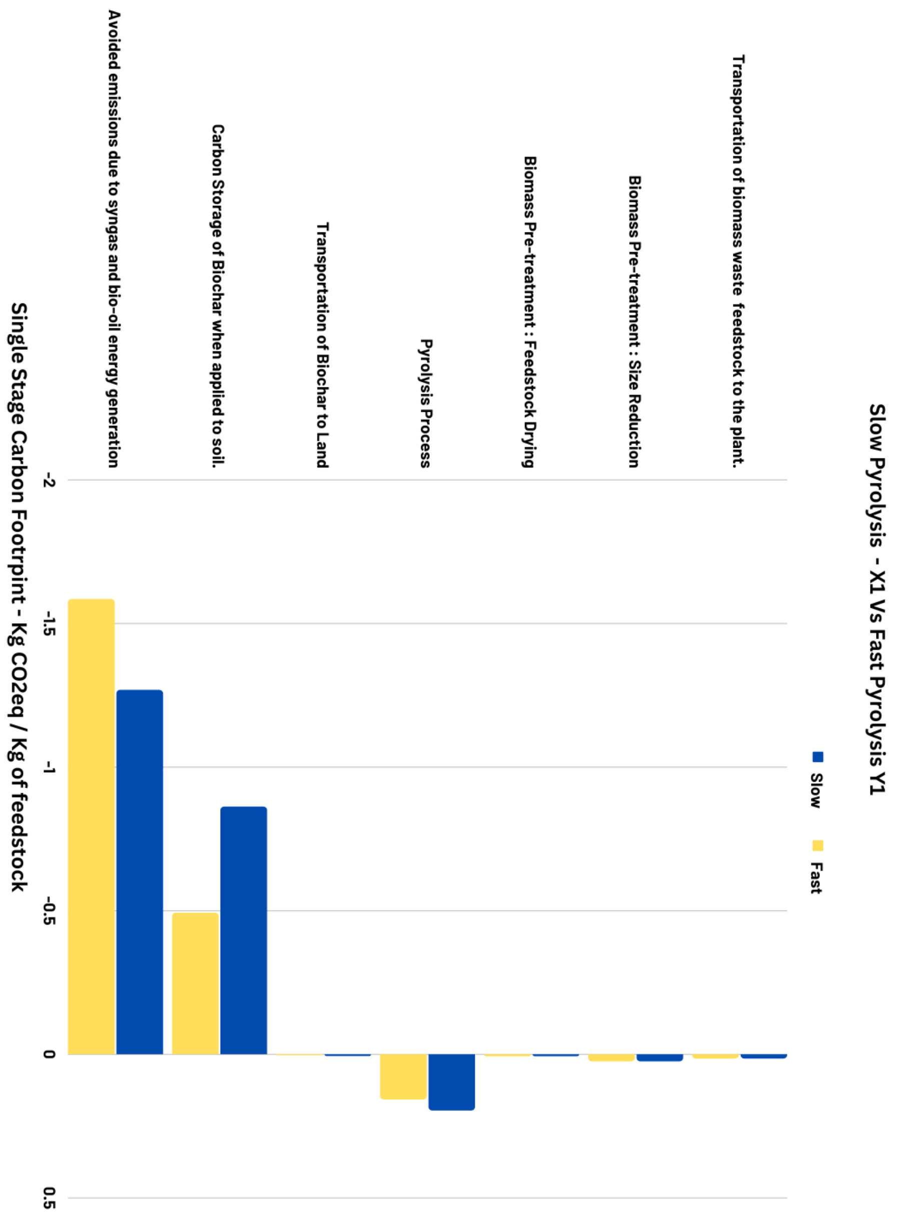

Figure 25:*Carbon Footprint of Slow Pyrolysis X1 Vs Fast Pyrolysis Y1.*

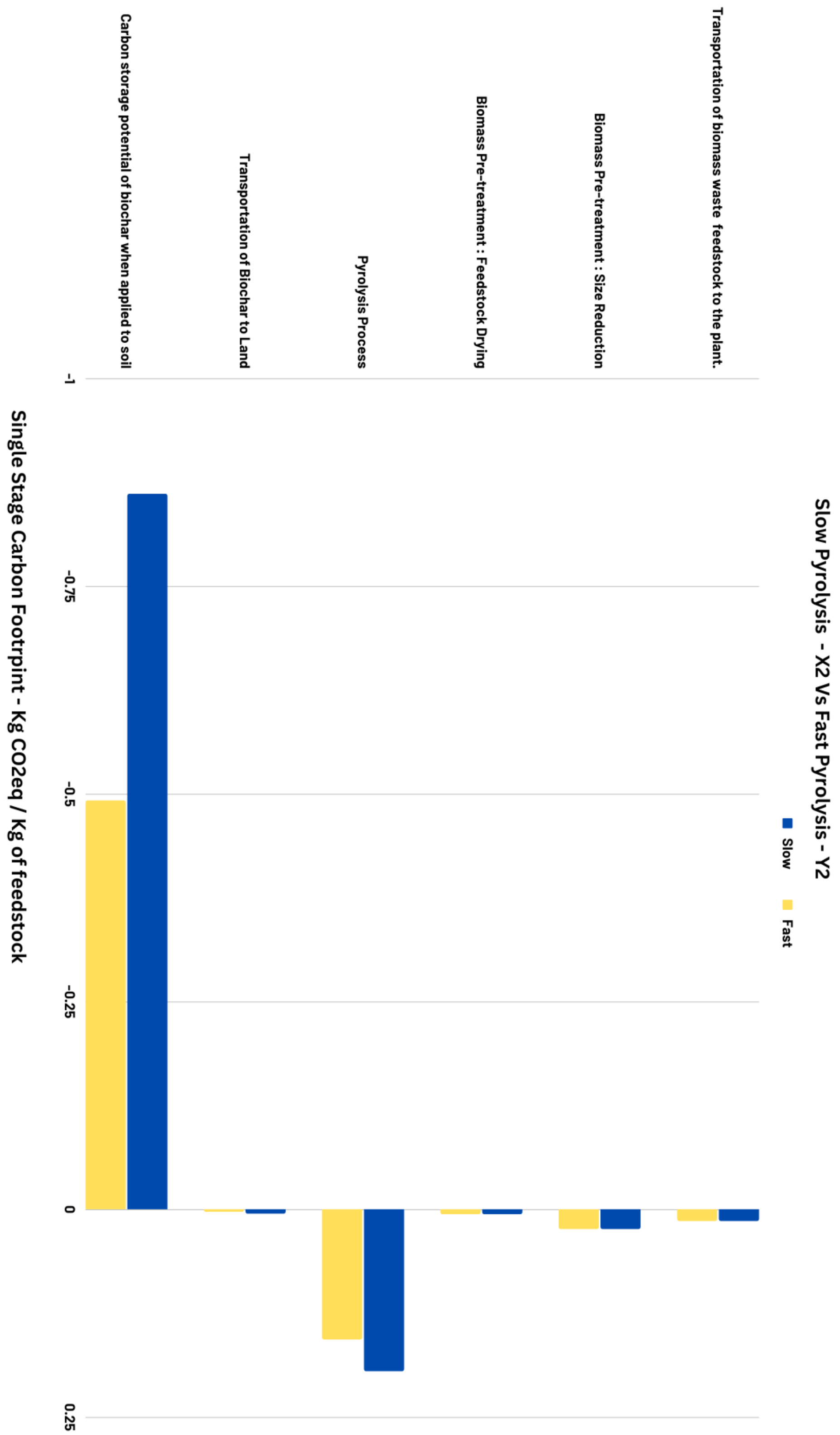

Figure 26:*Carbon Footprint of Slow Pyrolysis X2 Vs Fast Pyrolysis Y2.*

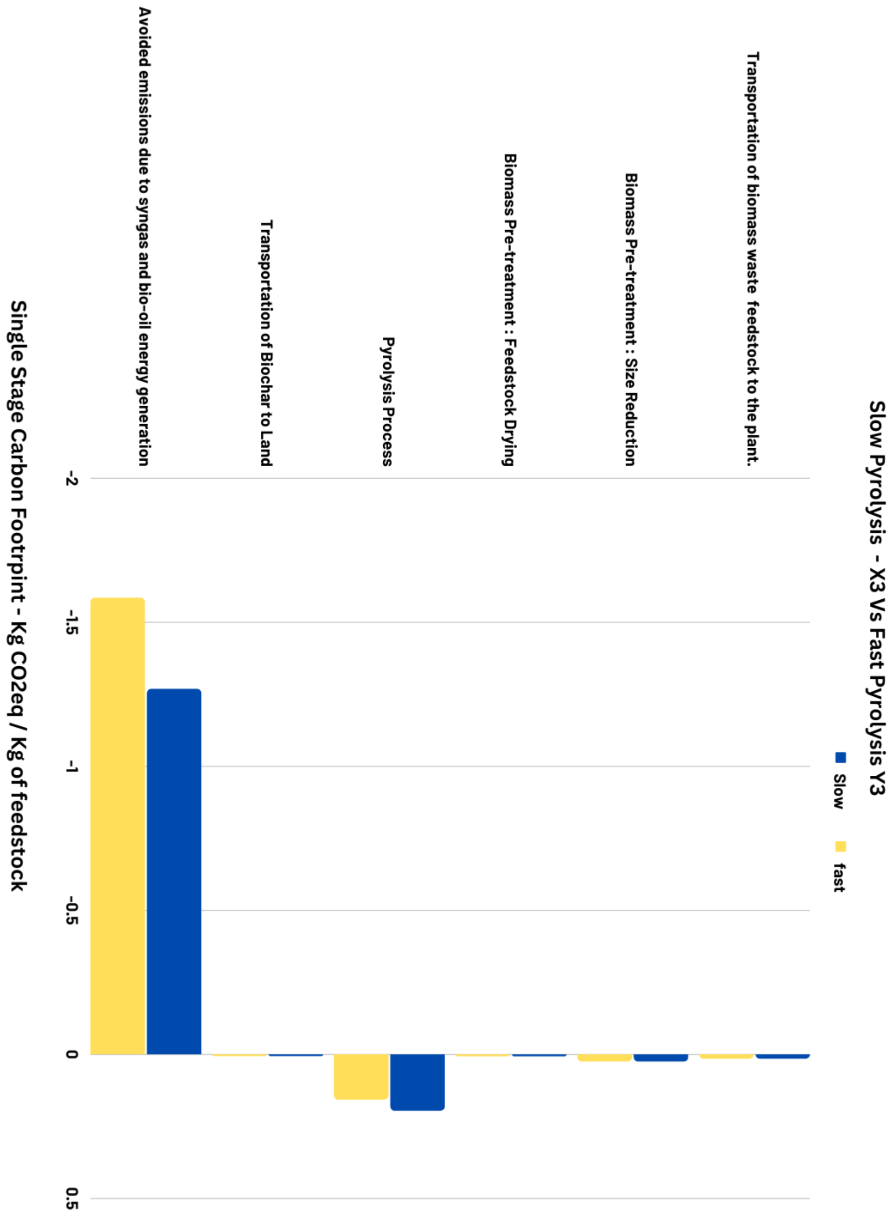

Figure 27:*Carbon Footprint of Slow Pyrolysis X3 Vs Fast Pyrolysis Y3.*

5.9. Conclusion

5.9.1. Slow Pyrolysis

From the data provided it is evident that the slow pyrolysis process has impacts at various stages of its life cycle. The carbon footprints vary during transportation, pretreatment and the pyrolysis process indicating the complexity of emissions linked to this method. However, there is an aspect to consider regarding biochar's ability to store carbon when used in soil. This showcases a negative carbon footprint which offers an environmentally advantageous outcome.

Moreover, the process brings about advantages by mitigating the emissions that arise from generating energy through fossil fuel sources. By utilizing syngas and bio-oil as an energy source it doesn't only decreases carbon emission but also takes a proactive approach, in substituting traditional energy sources with environmentally friendly alternatives.

The overall impact indicates that some steps, in the pyrolysis process may release emissions but the overall result is environmentally positive. This method shows potential for reducing greenhouse gas emissions by storing carbon in biochar and using pyrolysis byproducts, for energy production.

When we analyze scenarios involving X1, X2 and X3 in relation to the pyrolysis process we gain insights into the factors that affect the carbon footprint. As we examine the elements, within these scenarios several interesting observations become apparent.

In Scenario X1, when we consider both the carbon storage potential of biochar and the emissions that can be reduced through syngas and bio-oil energy utilization there is a decrease, in the carbon footprint. Specifically, it demonstrates a value of -1.8861 kg CO2eq per Kg of feedstock. This particular scenario emphasizes the significance of utilizing biochar in soil and generating electricity from syngas and biooil.

Scenario X2 isolates the impact of biochar's carbon storage potential without considering energy generation, resulting in a negative carbon footprint of -0.61918 kg CO2eq per Kg of feedstock. This demonstrates the significant role of biochar in emission reduction, highlighting its importance even without the consideration of energy-related contributions.

In Scenario X3 when we only consider the emissions avoided from energy production and we don't consider biochar's ability to store carbon the total carbon footprint is calculated as -1.0259 kg CO2eq per kg of feedstock. This scenario highlights how energy generation plays a role, in reducing emissions. It overlooks the valuable contribution of biochar, in sequestering carbon.

In addition, the analysis clearly demonstrates that the avoided emissions from the utilization of syngas and bio-oil as an energy source (-1.267) have a greater adverse impact on reducing emissions compared to the soil-applied biochar's capacity to store carbon (-0.861). This highlights how using syngas and bio-oil as an energy source during the slow pyrolysis process may decrease emissions substantially and significantly. As a result, we can observe a reduction, in the carbon footprint when we combine the carbon storage capacity of biochar with the avoided emissions from utilizing syngas and bio-oil as an energy source. While biochar has an important function, using syngas and bio-oil as an energy source directly results in a more meaningful emission reduction in this particular scenario.

5.9.2. Fast Pyrolysis

The analysis of the fast pyrolysis process, considering the carbon footprint across its life cycle stages, reveals critical insights into the environmental impact of each stage.

The data that has been gathered and analyzed provides information, about the carbon footprint during stages of the fast pyrolysis process. This includes emissions from transportation, pretreatment, pyrolysis itself and the subsequent transportation of biochar. It is clear that the pyrolysis process plays a role in determining the carbon footprint with emissions standing at 0.15641 kg CO2eq per kg of feedstock. However, it should be noted that there are stages, such as the transportation of biomass waste and biomass pretreatment which also contribute to emissions but, to a lesser extent.

Furthermore, the potential for carbon storage through biochar application to soil displays a negative value of -0.492, indicating the process's capacity to store carbon. This showcases a positive environmental aspect, contributing to the reduction of overall emissions.

Furthermore, the utilization of syngas and bio-oil, for energy purposes leads to a decrease in emissions as evidenced by the negative value of 1.583915. This highlights the potential of this process, in mitigating greenhouse gas emissions.

The analysis shows that the fast pyrolysis process is quite complex as emissions are produced at stages during pyrolysis, transportation, and pretreatment. However, it is worth noting that the carbon storage potential of biochar and the reduction in emissions from energy generation have an impact, on mitigating greenhouse gas emissions.

This comprehensive evaluation offers valuable insights into the environmental impact of the fast pyrolysis process, highlighting both areas for emissions and substantial opportunities for emission reduction through carbon storage and energy generation. It emphasizes the importance of considering and optimizing different stages for a more environmentally sustainable process.

Analyzing scenarios, Y1, Y2 and Y3 related to the fast pyrolysis process provides valuable insights, into the factors that impact the carbon footprint. When examining elements within these scenarios several noteworthy observations come to light.

In Scenario Y1 the carbon footprint is calculated to be - 1.87424881 kg CO2eq per kg of feedstock considering the potential of biochar to store carbon and the reduced emissions, from syngas and bio-oil energy generation. This analysis demonstrates how energy production and the ability of biochar to store carbon work to greatly reduce greenhouse gas emissions.

In Scenario Y2, which solely focuses on the carbon storage potential of biochar without considering energy generation, the total carbon footprint stands at -0.29033381 kg CO2eq per kg of feedstock. This scenario emphasizes the role of biochar in emission reduction, disregarding the contributions of energy-related emissions reduction.

Scenario Y3 exclusively considers the avoided emissions from energy production, excluding biochar's carbon storage potential, resulting in a less negative total carbon footprint of -1.38224881 kg CO2eq per kg of feedstock. This underlines the influence of energy generation in reducing emissions while neglecting the contribution of biochar to carbon sequestration.

Moreover, it's notable from the data that the combination of the avoided emissions due to syngas and bio-oil electricity usage (-1.583915) significantly contributes to a more negative total carbon footprint than the carbon storage potential of biochar when applied to soil (-0.492) as the amount of biochar generated from the process accounts only for 20% of the total output while the amount of syngas and biooil accounts for the rest 80%.

These scenarios highlight the role of biochar, in storing carbon and the significant impact of reducing emissions from energy use in lowering the carbon footprint during the fast pyrolysis process. Taking an approach that considers both aspects leads to a noticeable reduction, in the carbon footprint. This emphasizes the importance of optimizing stages to create a sustainable process highlighting the significance of considering and utilizing both biochar’s carbon storage capacity and energy use to reduce emissions within fast pyrolysis.

5.9.3. Slow Pyrolysis Vs Fast Pyrolysis

The comparison of carbon footprints between slow and fast pyrolysis methods across various life cycle stages provides valuable insights into their environmental impacts.
In the evaluated stages:

Transportation of Biomass Waste Feedstock: Both the slow and fast pyrolysis techniques have carbon footprints when it comes to transporting biomass waste feedstock to the plant. This means that both methods have impacts, at this particular stage mainly because the transportation of biomass happens before the pyrolysis process it is similar for both. The consistent carbon footprints at this stage indicate that the emissions produced during biomass transportation, which's similar, for both methods contribute equally to the environmental impact before moving on to the next pyrolysis stage.

Biomass Pre-treatment (Size Reduction and Feedstock Drying): The carbon footprints appear to be similar indicating that both pyrolysis methods result in similar emissions during the pretreatment stages of biomass. This similarity can be attributed to the use of similar pretreatment methods, in both cases.

Pyrolysis Process: It is noteworthy that slow pyrolysis shows a higher carbon footprint during the pyrolysis phase, in comparison, to fast pyrolysis. This discrepancy arises from the increased electricity consumption associated with the slow pyrolysis method as opposed to fast pyrolysis.

Transportation of Biochar to Land: While both methods produce emissions during biochar transportation, slow pyrolysis appears to have higher emissions in this stage compared to fast pyrolysis as more biochar per functional unit is generated when compared to fast pyrolysis and since we are reporting the emissions in regard to our functional unit of 1 Kg of feedstock this difference emerges.

Carbon Storage Potential of Biochar: Slow pyrolysis has shown a carbon storage potential of -0.861 Kg CO2eq per Kg of feedstock when biochar is applied to soil while fast pyrolysis exhibits a value of -0.492 Kg CO2eq per Kg of feedstock. This suggests that slow pyrolysis might have a higher capacity for carbon storage through the application of biochar in soil. It's important to note that slow pyrolysis tends to generate more biochar per 1 kg of feedstock compared to fast pyrolysis, which likely contributes to its higher potential for carbon storage, in this particular context.

Avoided Emissions due to Syngas and Bio-oil Energy Usage: In terms of avoiding emissions due to the utilization of biooil and syngas as an energy source slow pyrolysis shows a reduction of 1.2678 Kg CO2eq per Kg of feedstock while fast pyrolysis has a higher reduction value of around 1.583915 Kg CO2eq per Kg of feedstock. This comparison suggests that fast pyrolysis has a higher ability to reduce emissions through the use of syngas and bio-oil as energy sources. The reason, for this difference can be attributed to the production of bigger amounts of bio-oil and syngas in the fast pyrolysis process. The increased production of these energy sources likely contributes to its more efficient avoidance of emissions, thus indicating its potential superiority in reducing emissions through syngas and bio-oil generation.

After considering both carbon storage potential of biochar and avoided emissions due to biooil and syngas, slow pyrolysis appears to have a carbon footprint of -1.892465 which is slightly better, than fast pyrolysis which has a footprint of 1.87424881. Slow pyrolysis is preferred because it shows emissions slightly higher reduction throughout the process indicating a more effective way to reduce emissions overall. Although slow pyrolysis does generate emissions in certain stages but its ability to store more carbon and its superior emissions reduction throughout the entire process make it a slightly more environmentally friendly choice compared to fast pyrolysis. In my opinion and based on my analysis this nuanced advantage of slow pyrolysis signifies a more environmentally friendly option when considering the entire lifecycle of the process.

5.10. Sensitivity Analysis for Slow Pyrolysis

Table 24 *Sensitivity Analysis - Original input and output*

Stage Name	Original Input		Original Output
Transportation of biomass waste feedstock to the plant	**Distance**	100	0,0137
		Km	Kg CO2eq / Kg of feedstock.
Biomass Pre-treatment: Size Reduction	**Electricity**	60	0,02334
		kWh/ton feedstock	Kg CO2eq / Kg of feedstock.
Biomass Pre-treatment: Feedstock Drying	**Data from literature**	Data from literature	0,00547619
			Kg CO2eq / Kg of feedstock.
Pyrolysis Process	**Electricity**	0,5	0,1945
		kWh/Kg feedstock	Kg CO2eq / Kg of feedstock.
Transportation of Biochar to Land	**Distance**	100	0,004795072
		Km	Kg CO2eq / Kg of feedstock.
Application of Biochar to Land and Carbon storage	**Data from literature**	Data from literature	0,861
			Kg CO2eq / Kg of feedstock.
Bio-oil energy utilization	**Calorific value**	27,5	0,617925
		MJ/kg	Kg CO2eq / Kg of feedstock.
Bio-oil energy utilization	**Avoided Emissions**	0,0749	0,617925
		kg CO2 per MJ of fuel consumption	Kg CO2eq / Kg of feedstock.
Syngas energy utilization	**Calorific value**	19,1	0,649782
		MJ/kg	Kg CO2eq / Kg of feedstock.
Syngas energy utilization	**Avoided Emissions**	0,0972	0,649782
		kg CO2 per MJ of fuel consumption	Kg CO2eq / Kg of feedstock.

Table 25 : *Sensitivity Analysis – Input +10% and Output+10%*

Stage Name	Input 2 (+10%)	Output 2 (+10%)
Transportation of biomass waste feedstock to the plant	110	0,01507
	Km	Kg CO2eq / Kg of feedstock.
Biomass Pre-treatment: Size Reduction	66	0,025674
	kWh/ton feedstock	Kg CO2eq / Kg of feedstock.
Biomass Pre-treatment: Feedstock Drying	Data from literature	0,006023809
		Kg CO2eq / Kg of feedstock.
Pyrolysis Process	0,55	0,21395
	kWh/Kg feedstock	Kg CO2eq / Kg of feedstock.
Transportation of Biochar to Land	110	0,005274579
	Km	Kg CO2eq / Kg of feedstock.
Application of Biochar to Land and Carbon storage	Data from literature	0,9471
		Kg CO2eq / Kg of feedstock.
Bio-oil energy utilization	30,25	0,6797175
	MJ/kg	Kg CO2eq / Kg of feedstock.
Bio-oil energy utilization	0,08239	0,6797175
	kg CO2 per MJ of fuel consumption	Kg CO2eq / Kg of feedstock.
Syngas energy utilization	21,01	0,7147602
	MJ/kg	Kg CO2eq / Kg of feedstock.
Syngas energy utilization	0,10692	0,7147602
	kg CO2 per MJ of fuel consumption	Kg CO2eq / Kg of feedstock.

***Table 26 :** Sensitivity Analysis – Input -10% and Output -10%*

Stage Name	Input 3 (-10%)	Output 3(-10%)
Transportation of biomass waste feedstock to the plant	90	0,01233
	Km	Kg CO2eq / Kg of feedstock.
Biomass Pre-treatment: Size Reduction	54	0,021006
	kWh/ton feedstock	Kg CO2eq / Kg of feedstock.
Biomass Pre-treatment: Feedstock Drying	Data from literature	0,004928571
		Kg CO2eq / Kg of feedstock.
Pyrolysis Process	0,45	0,17505
	kWh/Kg feedstock	Kg CO2eq / Kg of feedstock.
Transportation of Biochar to Land	90	0,004315565
	Km	Kg CO2eq / Kg of feedstock.
Application of Biochar to Land and Carbon storage	Data from literature	0,7749
		Kg CO2eq / Kg of feedstock.
Bio-oil energy utilization	24,75	0,5561325
	MJ/kg	Kg CO2eq / Kg of feedstock.
Bio-oil energy utilization	0,06741	0,5561325
	kg CO2 per MJ of fuel consumption	Kg CO2eq / Kg of feedstock.
Syngas energy utilization	17,19	0,5848038
	MJ/kg	Kg CO2eq / Kg of feedstock.
Syngas energy utilization	0,08748	0,5848038
	kg CO2 per MJ of fuel consumption	Kg CO2eq / Kg of feedstock.

***Table 27 :** Sensitivity Analysis Results*

Carbon footrpint Base Scenario	**Original Output**	**1,886895738**
	New Output	**Percentage Change in Output (%)**
Carbon footrpint considering (Transportation of biomass waste feedstock to the plant +10%)	1,885525	-0,073
Carbon footrpint considering (Transportation of biomass waste feedstock to the plant -10%)	1,888265	0,073
Carbon footrpint considering (Biomass Pre-treatment : Size Reduction +10%)	1,884561	-0,124
Carbon footrpint considering (Biomass Pre-treatment : Size Reduction -10%)	1,889229	0,124
Carbon footrpint considering (Biomass Pre-treatment : Feedstock Drying +10%)	1,886348	-0,029
Carbon footrpint considering (Biomass Pre-treatment : Feedstock Drying -10%)	1,887443	0,029
Carbon footrpint considering (Pyrolysis Process +10%)	1,867445	-1,031
Carbon footrpint considering (Pyrolysis Process -10%)	1,906345	1,031
Carbon footrpint considering (Transportation of Biochar to Land +10%)	1,886416	-0,025
Carbon footrpint considering (Transportation of Biochar to Land -10%)	1,887375	0,025
Carbon footrpint considering (Application of Biochar to Land and Carbon storage +10%)	1,972995	4,563
Carbon footrpint considering (Application of Biochar to Land and Carbon storage -10%)	1,800795	-4,563
Carbon footrpint considering (Bio-oil energy utilization +10%) - Calorific Value	1,948688	3,275
Carbon footrpint considering (Bio-oil energy utilization -10%) - Calorific Value	1,825103	-3,275
Carbon footrpint considering (Bio-oil energy utilization +10%) - Avoided Emissions	1,948688	3,275
Carbon footrpint considering (Bio-oil energy utilization -10%) - Avoided Emissions	1,825103	-3,275
Carbon footrpint considering (Syngas energy utilization +10%) - Calorific Value	1,951873	3,444

Carbon footrpint considering (Syngas energy utilization -10%) - Calorific Value	1,821917	-3,444
Carbon footrpint considering (Syngas energy utilization +10%) - Avoided Emissions	1,951873	3,444
Carbon footrpint considering (Syngas energy utilization -10%) - Avoided Emissions	1,821917	-3,444

Based on the sensitivity analysis performed on various stages of the process with changes in inputs and outputs, several crucial findings and conclusions can be derived:

- **Transportation of Biomass Waste Feedstock:**
  A variation of ±10%, in the distance traveled had an insignificant influence on the total carbon footprint resulting in a percent change of around ±0.073%. This implies that modifications in transportation distance only have a limited impact on the carbon footprint, as a whole.

- **Biomass Pre-treatment (Size Reduction and Feedstock Drying):**
  Variations of around ±10% in electricity consumption for size reduction and feedstock drying had a noticeable impact but not a drastic impact on the carbon footprint. The percentage changes observed were approximately ±0.124%. ±0.029% respectively.

- **Pyrolysis Process:**
  A variation of, around ±10% in electricity consumption during the pyrolysis process had a substantial effect demonstrating a percentage shift of approximately 1.031%. This suggests that adjustments made during this stage have a notable impact, on the carbon footprint.

- **Transportation of Biochar:**
  When altering the transportation of biochar alone by ±10%, the carbon footprint exhibited a change of around ±0.025%. This indicates that the transport phase has a relatively minor impact on the overall carbon footprint, suggesting that changes in the distance or method of transportation might have limited effects on the environmental impact.

- **Application to Land and Carbon Storage:**
  Modifying the use of biochar, on the land and carbon storage by ±10% led to a variation of 4.563% in the carbon footprint. This emphasizes the important role that the approach to carbon storage plays in exerting a significant influence, on the overall carbon footprint.

- **Bio-oil and Syngas Energy utilization:**
  Changes in calorific value and avoided emissions for bio-oil and syngas energy utilization by ±10% exhibited significant impacts, resulting in considerable percentage changes of approximately ±3.275% to ±3.444%.

To sum up, the analysis emphasizes how various stages of the process are influenced by changes, in inputs and outputs. The pyrolysis process, the use of biochar in land application and the utilization of biooil and syngas in energy production have significant impacts on the carbon footprint. While certain stages may be more sensitive than others the overall carbon footprint is shaped by the combined effect of all stages. Therefore, effectively improving stages such as pyrolysis, biochar's ability to store carbon and energy production methods for biooil and syngas will be crucial, in minimizing the carbon footprint of the process. A comprehensive plan that focuses on these areas will be necessary to achieve sustainability goals and reduce environmental impacts.

5.11. Data Quality Analysis

Based on Product environmental footprint guidance category Rules Guidance:

Within the environmental footprint context, the data quality of each dataset and the total EF study shall be calculated and reported. The calculation of the DQR shall be based on 4 data quality criteria:

3453 $$DQR = \frac{TeR+GR+TiR+P}{4}$$ [Equation 20]

TeR: Technological-Representativeness
GR: Geographical Representativeness
TiR: Time-Representativeness
P: Precision/uncertainty

Table 28: *Reference Table for Calculating DQR Variables based on Product environmental footprint guidance category Rules Guidance*

P: Precision/uncertainty	
1	Measured/calculated and externally verified
2	Measured/calculated and internally verified, plausibility checked by reviewer
3	Measured/calculated/literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer
4 to 5	Not applicable
TiR: Time-Representativeness	
1	The EF report publication date happens within the time validity of the dataset
2	The EF report publication date happens not later than 2 years beyond the time validity of the dataset
3	The EF report publication date happens not later than 4 years beyond the time validity of the dataset
4	The EF report publication date happens not later than 6 years beyond the time validity of the dataset
5	The EF report publication date happens later than 6 years after the time validity of the dataset

TeR: Technological-Representativeness	
1	The technology used in the EF study is exactly the same as the one in scope of the dataset
2	The technologies used in the EF study is included in the mix of technologies in scope of the dataset
3	The technologies used in the EF study are only partly included in the scope of the dataset
4	The technologies used in the EF study are similar to those included in the scope of the dataset
5	The technologies used in the EF study are different from those included in the scope of the dataset.
GR: Geographical Representativeness	
1	The process modelled in the EF study takes place in the country the dataset is valid for
2	The process modelled in the EF study takes place in the geographical region (e.g., Europe) the dataset is valid for
3	The process modelled in the EF study takes place in one of the geographical regions the dataset is valid for
4	The process modelled in the EF study takes place in a country that is not included in the geographical region(s) the dataset is valid for, but sufficient similarities are estimated based on expert judgement.
5	The process modelled in the EF study takes place in a different country than the one the dataset is valid for
Data is from Product Environmental Footprint Category Rules Guidance Version 6.3 – May 2018	

1. Transportation of biomass waste feedstock to the plant

- **Precision/Uncertainty (P):** Score: 1

  Using SimaPro software demonstrates a validated method for analysis with the findings being calculated. This suggests that the data utilized and the results obtained are reliable and conclusive.

- **Time Representativeness (TiR):** Score: 1

  Based on the ecoinvent database, which undergoes updates yearly and includes, over 18,000 dependable life cycle inventory datasets therefore I will assign a rating of 1 for Time Representativeness. The database is regularly updated with enhanced data along, with advancements.

- **Technological Representativeness (TeR):** Score: 1

  The investigation outlines the deployment of heavy-duty lorries that meet EURO5 emissions standards, granting clarity on transportation technology. This corresponds to the dataset properly, demonstrating a high level of technological representativeness.

- **Geographical Representativeness (GR):** Score: 2

  There is a specific distinction between the country where my analysis is conducted (Italy) and the geographical region specified in the study (EU), even though both the dataset and my analysis are within the EU. The difference raises a few concerns regarding how closely the study's methodology matches the unique circumstances in Italy. As a result, a score of 2 is given, meaning that while the process the study models occurs in the EU, the dataset's validity is guaranteed but there is no guarantee of its precise alignment with Italy.

Data Quality Rating = 1.25

2. Biomass Pre-treatment: Size Reduction

- **Precision/Uncertainty (P):** Score: 2

  The information regarding energy consumption and emissions are derived from secondary data based on literature. Although this approach suggests a systematic way of gathering information using secondary data but it introduces some level of uncertainty. Consequently the study is assigned a score of 2, which reflects the degree of uncertainty associated with relying on secondary data.

- **Time Representativeness (TiR):** Score: 1

  Based on the publication information provided by (Paraschiv et al., 2021), the study originates from an identifiable source. Since this data was published in 2021 it satisfies the Time Representativeness requirements. Consequently it receives a score of 1 indicating that it comes from an unique recent source.

- **Technological Representativeness (TeR):** Score: 1

  In the field of processing, hammer milling is a popular technique to reduce the size of biomass and also by considering the worst case scenario the dataset demonstrates a high level of technological representation and aligns, with a conservative approach.

- **Geographical Representativeness (GR):** Score: 2

  Italy and Romania are both part of the European Union and the research conducted in Romania aligns, with the framework of the EU. Even though there might be some variations, the proximity and shared EU membership between these two countries suggest a certain level of representativeness. As a result a score of 2 is assigned to indicate that the studys process is conducted within the European Union (EU) region, for the dataset used.

Data Quality Rating = 1.5

3. Biomass Pre-treatment: Feedstock Drying

- **Precision/Uncertainty (P):** Score: 1

  The calculation of the carbon footprint relies on data from Somerville & Haque (2013). The systematic and validated approach is evident in the calculation process, which considers the initial global warming potential and the quantity of raw biomass needed. The utilization of data points and transparent calculations reflects a high level of accuracy and confidence, in the analysis.

- **Time Representativeness (TiR):** Score: 5

  The EF report publication date happens later than 6 years after the time validity of the dataset.

- **Technological Representativeness (TeR):** Score: 1

  In their research paper presented at the BSME International Conference on Thermal Engineering Nawshad Haque and Michael Somerville extensively examine different types of biomass dryers and drying methods. Their study evaluates the impact, cost considerations and technological aspects involved in selecting a suitable dryer. They specifically explore how variations, in drying temperature can affect productivity and expenses. The study contributes to a high degree of technological representativeness by offering insightful information on dryer selection that takes into account both environmental and financial factors.

- **Geographical Representativeness (GR):** Score: 2

  The study provides valuable insights into biomass drying, but without explicit confirmation of the geographic scope, a perfect score is not assigned. Therefore, a score of 2 is assigned, indicating a moderate level of geographical representativeness.

Data Quality Rating = 2.25

4. Pyrolysis Process

- **Precision/Uncertainty (P):** Score: 2

  According to a research study conducted by Gahane, Biswal and Mandavgane in 2022 they provide an transparent reference regarding the electricity consumption, in biomass pyrolysis processes. The study mentions that the amount of electricity used ranges from 0.4 to 0.6 kWh per kilogram of product produced. However it's important to note that using a value of 0.5 kWh per kilogram introduces some uncertainty since it falls within a range. Additionally assuming pyrolysis has 100% efficiency adds simplicity that might jeopardize precision. As a result, a score of 2 is given, signifying a moderate degree of accuracy with some degree of uncertainty in the chosen values.

- **Time Representativeness (TiR):** Score: 1

  The use of a study conducted in 2022 ensures a recent understanding of biomass pyrolysis processes. By referencing the most recent research findings, the study aligns with current technological practices, supporting a high level of time representativeness.

- **Technological Representativeness (TeR):** Score: 1

  In our study we have included an relevant and recent source titled "Life cycle assessment of biomass pyrolysis", by Gahane, Biswal and Mandavgane in 2022. This guarantees a very high degree of technological representativeness when analyzing the amount of electricity used in biomass pyrolysis processes. To accurately evaluate the technology we have adopted a value (0.5 kWh, per kilogram of product produced) based on the research findings, which strengthens the foundation of our study.

- **Geographical Representativeness (GR):** Score: 3

  The research mentions that the evaluation of pyrolysis took place in India emphasizing the significance of the analysis. Although considering Italys energy mix and Entsoes emissions data the primary emphasis is, on India, which provides an important geographical context. This acknowledgement makes it clearer where exactly the pyrolysis study was conducted thereby enhancing the understanding of the findings. A score of three is thus given, indicating a moderate level of geographical representativeness with a distinct focus on the main study site in India.

Data Quality Rating = 1.75

5. Transportation of Biochar to Land

- **Precision/Uncertainty (P):** Score: 1

  Using SimaPro software demonstrates a validated method for analysis with the findings being calculated. This suggests that the data utilized and the results obtained are reliable and conclusive.

- **Time Representativeness (TiR):** Score: 1

  Based on the ecoinvent database, which undergoes updates yearly and includes, over 18,000 dependable life cycle inventory datasets therefore I will assign a rating of 1 for Time Representativeness. The database is regularly updated with enhanced data along, with advancements.

- **Technological Representativeness (TeR):** Score: 1

  The investigation outlines the deployment of heavy-duty lorries that meet EURO5 emissions standards, granting clarity on transportation technology. This corresponds to the dataset properly, demonstrating a high level of technological representativeness.

- **Geographical Representativeness (GR):** Score: 2

  There is a specific distinction between the country where my analysis is conducted (Italy) and the geographical region specified in the study (EU), even though both the dataset and my analysis are within the EU. The difference raises a few concerns regarding how closely the study's methodology matches the unique circumstances in Italy. As a result, a score of 2 is given, meaning that while the process the study models occurs in the EU, the dataset's validity is guaranteed but there is no guarantee of its precise alignment with Italy.

Data Quality Rating = 1.25

6. **Application of Biochar to Land and Carbon Storage Potential**

- **Precision/Uncertainty (P):** Score: 1

  The research findings reveal that the estimation of biochars ability to store CO2 is highly accurate. The research followed a precise approach, by gathering data from different studies calculating an average value of 2.46 t CO2eq per t BC and using a calculation method with an output of 0.861 Kg CO2eq per Kg feedstock. The accuracy of the analysis is further strengthened by the inclusion of references regarding the CO2 storage capacity of biochar from a variety of sources. Consequently, a score of 1 is given, signifying a high degree of accuracy in the research.

- **Time Representativeness (TiR):** Score: 3.75

  Based on the publication years of the references used we assign scores to determine the Time Representativeness (TiR) score of the research. The recent reference, from 2021 gets a score of 2 while the oldest reference from 2015 gets a score of 5. By calculating the average TiR score for all the references used we obtain a value of 3.75.The majority of the references fall within the datasets 4 year timeframe suggesting that this research utilizes relevant data to shed light on our understanding of CO2 storage potential, from different biochar sources.

- **Technological Representativeness (TeR):** Score: 1

  The study presents an examination of research conducted to assess how biochar contributes to the reduction of CO2 emissions. By gathering data from sources including research studies, on the production methods and materials used in biochar it demonstrates a strong understanding of the technological aspects involved.

- **Geographical Representativeness (GR):** Score: 2

  The research exhibits a moderate level of geographical representativeness as it considers biochar sources from diverse countries, including Spain, Canada, São Paulo, and Belgium. The inclusion of multiple countries contributes to a broader understanding of biochar's CO2 storage potential.

Data Quality Rating = 1.9375

7. **Bio-oil energy production and their effect on the CF**

- **Precision/Uncertainty (P):** Score: 1

  The research applies a well defined approach to measure the avoided emissions that occur when bio oil is used as a fuel. By using a calorific value for bio oils which is determined based on the middle point of the observed range, the analysis becomes more accurate. Moreover including a formula, for calculating emissions reduction promotes an precise approach earning a precision score of 1.

- **Time Representativeness (TiR):** Score: 3.5

  Combining data from 2019 and 2012, the study reflects a moderately diverse timeframe, with a significant gap between the two years. Assigning a score of 4 to 2012 and a score of 3 to 2019, the average TiR score = 3.5

- **Technological Representativeness (TeR):** Score: 1

  The research showcases a level of accuracy in terms of technology by including information, about the properties of bio oil the calorific value used in the analysis and the process of substituting it in a pyrolysis system. The clear explanation of how energy content's calculated and how emissions are reduced indicates an understanding of the technical aspects involved.

- **Geographical Representativeness (GR):** Score: 5

  The study does not align directly with the location under consideration (Italy), resulting in a score of 5. This indicates a significant discrepancy in geographical relevance

Data Quality Rating = 2.625

8. Syngas energy production and their effect on the CF

- **Precision/Uncertainty (P):** Score: 3

  The research methodically measures the avoided emissions from syngas as a fuel. However, it's important to note that the accuracy is influenced by the variability in the reduction factor used. We acknowledge this uncertainty, assigning a precision score of 3 to reflect the potential impact of this variability on our findings.

- **Time Representativeness (TiR):** Score: 3

  Combining data from 2010 and 2023 , the study reflects a moderately diverse timeframe, with a significant gap between the years. Assigning a score of 1 to 2023 and a score of 5 to 2010, the average TiR score = 3

- **Technological Representativeness (TeR):** Score: 1

  The study demonstrates a high level of technological representativeness by incorporating specific details on syngas properties, the calorific value used in the analysis, and the substitution process in a pyrolysis system. The clarity on the energy content calculation and emissions reduction formula indicates a detailed understanding of the technological aspects involved.

- **Geographical Representativeness (GR):** Score: 2

  There is a specific distinction between the country where my analysis is conducted (Italy) and the geographical region specified in the study (EU), even though both the dataset and my analysis are within the EU. The difference raises a few concerns regarding how closely the study's methodology matches the unique circumstances in Italy. As a result, a score of 2 is given, meaning that while the process the study models occurs in the EU, the dataset's validity is guaranteed but there is no guarantee of its precise alignment with Italy.

Data Quality Rating = 2.25

***Table 29**: Results of DQR Analysis Across Each Stage of the Study(a)*

Transportation of biomass waste feedstock to the plant				
TeR	**GR**	**TiR**	**P**	**DQR**
1	2	1	1	1.25
Biomass Pre-treatment: Size Reduction				
TeR	**GR**	**TiR**	**P**	**DQR**
1	2	1	2	1.5
Biomass Pre-treatment: Feedstock Drying				
TeR	**GR**	**TiR**	**P**	**DQR**
1	2	5	1	2.25
Pyrolysis Process				
TeR	**GR**	**TiR**	**P**	**DQR**
1	3	1	2	1.75
Transportation of Biochar to Land				
TeR	**GR**	**TiR**	**P**	**DQR**
1	2	1	1	1.25
Application of Biochar to Land and Carbon Storage Potential				
TeR	**GR**	**TiR**	**P**	**DQR**
1	2	3.75	1	1.9375
Bio-oil energy production and their effect on the CF				
TeR	**GR**	**TiR**	**P**	**DQR**
1	5	3.5	1	2.625
Syngas energy production and their effect on the CF				
TeR	**GR**	**TiR**	**P**	**DQR**
1	2	3	3	2.25

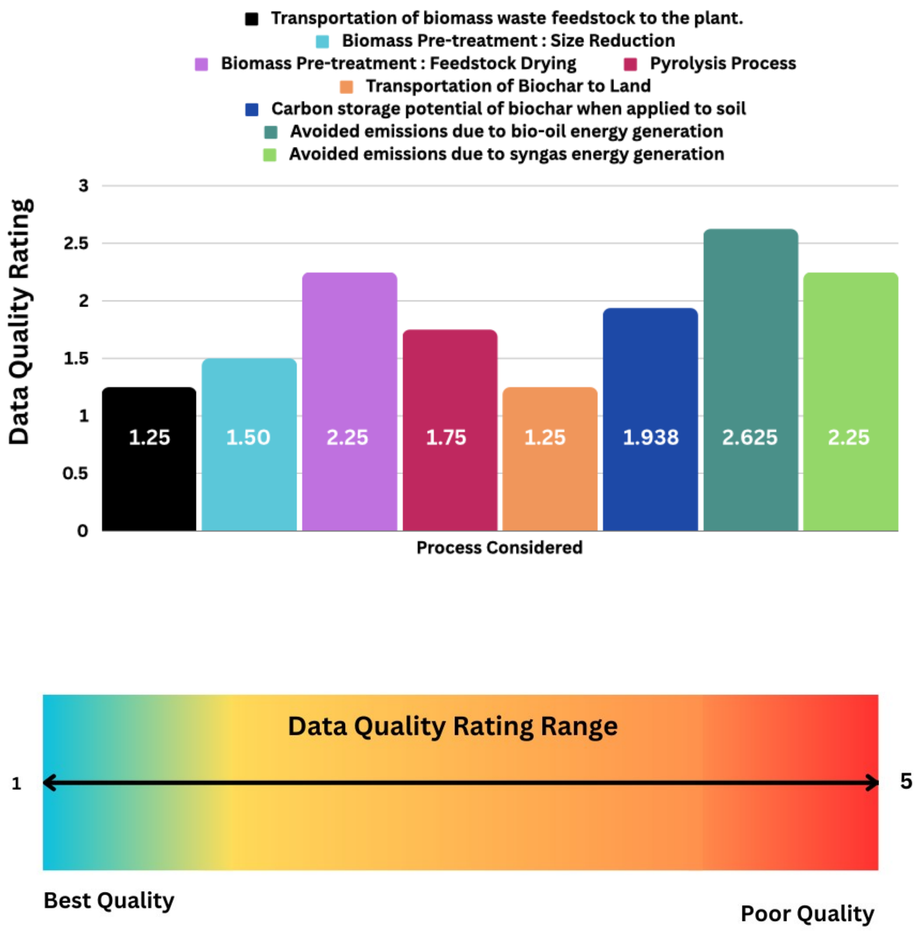

__Figure 28:__ Results of DQR Analysis Across Each Stage of the Study(b)

__Figure 29:__ Total DQR of the study

Table 30: *Results of DQR Analysis Across Each Stage of the Study and analysis of the total DQR of the study*

Life Cycle Stage - Scenario X1	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock	% Effect on Total CF	DQR	Effect on Total DQR of my Analysis
Transportation of biomass waste feedstock to the plant.	**0,0137**	**0,726**	**1,25**	**0,009075306**
Biomass Pre-treatment : Size Reduction	**0,02334**	**1,237**	**1,5**	**0,018553369**
Biomass Pre-treatment : Feedstock Drying	**0,00547619**	**0,290**	**2,25**	**0,006529677**
Pyrolysis Process	**0,1945**	**10,307**	**1,75**	**0,180379978**
Transportation of Biochar to Land	**0,004795**	**0,254**	**1,25**	**0,003176357**
Carbon storage potential of biochar when applied to soil	**-0,861**	**-45,628**	**1,938**	**0,884275514**
Avoided emissions due to Biooil energy generation	**-0,618**	**-32,751**	**2,625**	**0,859703031**
Avoided emissions due to Syngas energy generation	**-0,64980**	**-34,436**	**2,25**	**0,77481**
Total Carbon Footrpint	**-1,88698881**	**-100**	**-**	
Total DQR of my Study	**2,7365**			

In conclusion when we thoroughly evaluate the ratings, for Data Quality (DQR) at each stage in the life cycle of pyrolysis we gain insights into how reliable and precise the data used in our carbon footprint analysiss. It's worth noting that most DQRs, ranging from 1.25 to 2.625 suggest overall acceptable level of data quality. Some critical stages like biomass waste transportation, pyrolysis process and biochar transportation have lower DQRs indicating a high level of confidence in the accuracy and dependability of the data. However certain stages like biomass pre-treatment and avoided emissions due to biooil generation have high DQRs, which calls for scrutiny and validation to enhance accuracy in these areas. The Total DQR for our study stands at 2,737 which serves as a comprehensive measure of overall data quality. In our analysis higher Total DQR values imply lower data quality , emphasizing the need for continued diligence in refining our methodology and ensuring a more precise carbon footprint analysis. This reflective assessment maintains an objective and constructive tone, acknowledging strengths while candidly addressing opportunities for refinement in our ongoing pursuit of a robust environmental impact assessment.

5.12. Comparison with current literature results

When comparing my analysis findings, with those reported in existing literature regarding the stages of my analysis which are : biomass waste feedstock transport, biomass pretreatment (including size reduction and drying), pyrolysis process, biochar transportation to land, carbon storage potential when biochar is applied to soil, and the reduction in emissions due to biooil and syngas power utilization, it becomes apparent that there is variability in the results. These variations can be attributed to the assumptions made in life cycle evaluation studies. The wide range of values observed highlights the influence of factors such as feedstock type, biochar's ability to store carbon in soils, substitution effects and technical choices. The inherent complexity and sensitivity of biochar systems to these assumptions underscore the need for a careful analysis of results while acknowledging the multifaceted nature of environmental impacts, in biochar life cycle assessments.

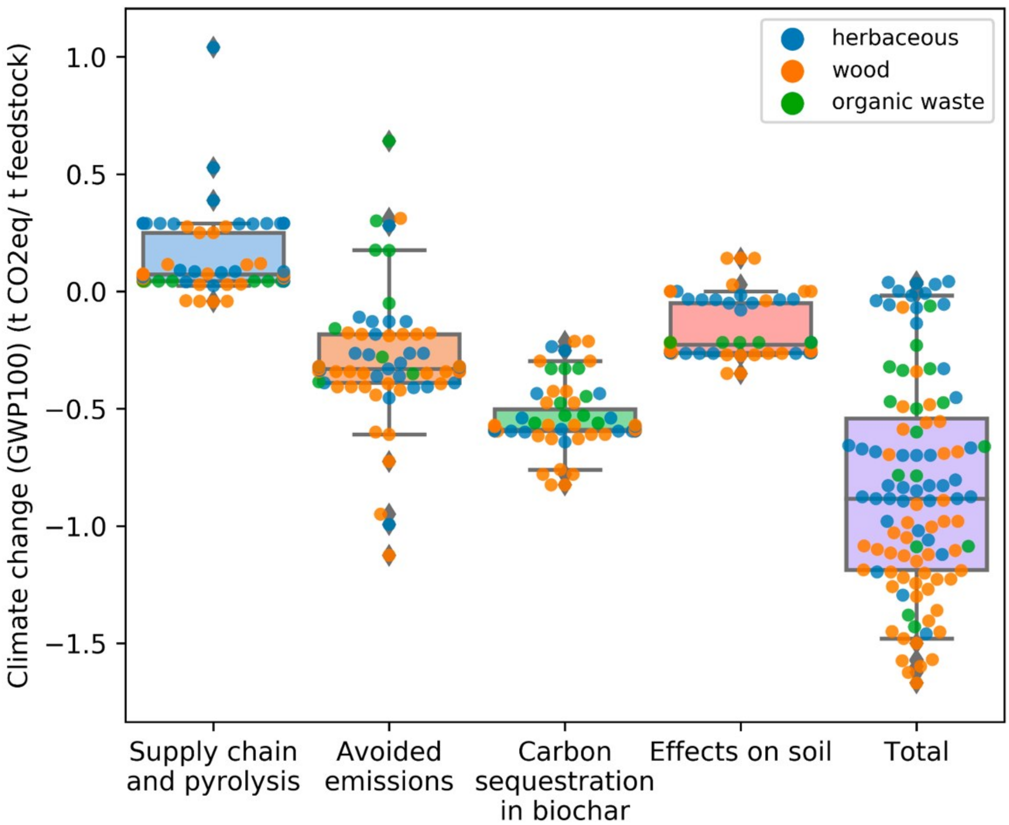

Figure 30: *A survey of climate change impacts from life-cycle studies of pyrolysis systems (Tisserant & Cherubini, 2019).*

In this study researchers conducted a survey to examine the effects of climate change resulting from pyrolysis systems that produce biochar and its application, on fields. In the context of this research positive values indicate the release of greenhouse gases (GHGs) while negative values signify the reduction, in GHG emissions or the capture of carbon.

The term ‘Supply chain and pyrolysis’ refers to feedstock provision and pretreatment, pyrolysis, and transport. The values, as depicted in the figure, range from emissions during feedstock collection, preprocessing (e.g., drying and chipping), and pyrolysis. Each dot in the figure represents one biochar-production system (Tisserant & Cherubini, 2019).

‘Avoided emissions’ account for the avoided fossil carbon emissions by using bio-oil and pyrolysis gas for energy production. In some cases, it also accounts for avoided emissions due to reduced fertilizer consumption.

‘Effects on soil’ account for biochar effects on soil emissions (e.g., priming effect on soil organic carbon and NO2 emissions) and changes in reflectivity of a surface (Tisserant & Cherubini, 2019).

Based on my calculations the transportation of biomass waste feedstock to the plant, biomass pre-treatment for size reduction and feedstock drying, and pyrolysis results in a total emission of 0.237 tons of CO2 equivalent per ton of feedstock. This value falls within the range suggested by 34 literature reviews as shown in the graph. Additionally, the result is also very close to the median value of the analysis, indicating accuracy in my calculations.

Furthermore, it was stated, based on the analysis conducted on 34 literature reviews, that transportation of feedstock and of biochar usually represents less than 10% of the GHG emissions from the supply chain. In my analysis, this also accounts for less than 10%, reflecting the accuracy of my work in comparison to the literature reviews.

When considering the reduction of emissions, through the use of syngas and bio oil as energy sources I have determined that there is a reduction of 1.267 tCO2eq/t feedstock. This falls within the range reported in the analysis of 34 papers as indicated in the graph. It is worth mentioning though that there may be differences in the results due to varying assumptions and the diverse implementation of syngas and bio oil, across studies.

In their extensive review of 34 life cycle assessment (LCA) studies encompassing carbon sequestration, supply-chain emissions, substitutions, and soil effects within biochar systems, (Tisserant & Cherubini, 2019) identified an average total carbon footprint of -0.9 tonne CO2-eq $tonne^{-1}$ biomass, with a reported range extending from -1.5 to 0 tonne CO2-eq per tonne of biomass. In my analysis, the calculated total carbon footprint of -1.8862 kg CO2eq / kg of feedstock aligns closely with this reported range, with a nuanced difference in absolute values. Methodological divergences, regional-specific considerations, and variations in underlying assumptions inherent to each study may contribute to this observed distinction. These differences warrant careful consideration and potential further exploration to elucidate the specific factors influencing the reported carbon footprints and to enhance the robustness of future assessments in the domain of biochar systems.

In summary when examining the life cycle assessments of biochar which includes stages, like transporting the feedstock, pyrolysis, applying biochar and utilizing energy we find a landscape with varying results. These differences in outcomes are influenced by assumptions, methodological choices and the inherent complexity of biochar systems. While my analysis aligns closely with values suggested in literature reviews and falls within the range it's important to recognize that other factors can also have an impact on the results. By comparing our findings with Tisserant et al.s study (2019) we can see how our research fits into the context of biochar assessments. These differences emphasize the need for exploration and improvement of methodologies to ensure more precise and reliable analyses in this evolving field of biochar research. This study contributes to the discussion, about biochar life cycle assessments. Highlights the importance of carefully considering assumptions and methodological choices to gain a more accurate understanding of the environmental impacts associated with biochar systems (Azzi et al., 2022).

5.13. Recommendation to reduce the environmental impact of pyrolysis of biomass.

After conducting an analysis of the carbon footprint associated with biomass pyrolysis used for biochar production, I have identified suggestions to minimize the environmental impact of this process and make it more sustainable. These recommendations focus on reducing greenhouse gas emissions enhancing energy efficiency and maximizing the effects of biochar as a tool, for carbon sequestration.

1. **Optimize Pyrolysis Plant Design**: To enhance the design of pyrolysis plants and minimize their carbon footprint, in biochar production it is crucial to prioritize energy efficiency during construction. This can be achieved through the utilization of materials and technologies that effectively reduce emissions. By incorporating plant designs we can successfully mitigate the carbon emissions related to the construction process.
2. **Increase Energy Efficiency:** Reducing electricity consumption during the pyrolysis process is crucial in minimizing our carbon footprint. It is important to focus on research and development to enhance the energy efficiency of pyrolysis equipment. This can be accomplished by tuning the heating process and investigating the utilization of different renewable energy sources to power pyrolysis plants.
3. **Sustainable Feedstock Sourcing:** The selection of biomass feedstock is crucial, for ensuring the sustainability of the process. Choosing biomass that comes from sources, like residues or energy crops specifically grown for fuel can effectively minimize the environmental impact. It is also essential to avoid using feedstock that requires transportation and contributes to emissions.
4. **Carbon Storage Potential and Soil Application:** To make the most of biochar's ability to store carbon it is important to encourage its use, in soil. Educating and motivating farmers and landowners to utilize biochar as a soil enhancer can have benefits. Not only it helps sequester carbon, but it also improves soil quality and boosts agricultural productivity.
5. **Waste Diversion:** We should encourage the redirection of biomass waste away from direct combustion and towards pyrolysis. By implementing policies and offering incentives we can promote the adoption of pyrolysis as an eco-approach to managing waste.

6. **Research and Development**: It is essential to continue researching pyrolysis technology. We should explore methods, materials, and process enhancements to decrease emissions and enhance the production of products, like biochar, bio-oil, and syngas.
7. **Life Cycle Assessment:** Regularly conduct life cycle assessments to monitor the impact of biomass pyrolysis. Continuously evaluating this process can help identify areas where improvements can be made and determine the effectiveness of measures that have been implemented.
8. **Regulation and Standards:** Work together with agencies to establish and enforce emissions standards and guidelines, for biomass pyrolysis. This ensures that the industry prioritizes sustainability and minimizes its impact, on the environment.
9. **Public Awareness:** Promote understanding, among businesses and individuals regarding the advantages of biomass pyrolysis and its potential for decreasing carbon emissions. Foster engagement, in initiatives and programs that help offset carbon footprints.
10. **Collaborative Efforts:** Promote cooperation, among biochar producers, research institutions, environmental organizations, and government agencies to advance sustainability efforts and foster innovation, in the biomass pyrolysis sector.

5.14. Research Opportunities

1. **Advanced Pyrolysis Technologies**: One area of research that holds potential is the advancement of pyrolysis technologies. This involves investigating designs, for reactors considering materials for feedstock and optimizing the overall process. The focus of research can be, on enhancing the energy efficiency and environmental impact of pyrolysis systems.
2. **Biochar Applications:** Exploring a range of applications, for biochar is an area of study. Biochar has the potential to be utilized not as a soil enhancer but in fields such as wastewater treatment, carbon capture and storage and even as an ingredient in construction materials. Researchers can delve into these applications. Investigate their capacity for carbon sequestration.
3. **Sustainability Metrics:** It is crucial to develop sustainability metrics to evaluate the production of biochar. Researchers should focus on developing methods that assess the economic and social impacts of biomass pyrolysis. This will provide a holistic view on the sustainability of this process.
4. **Waste Diversion Strategies:** It is important to explore approaches to divert biomass waste form traditional waste management practices and instead promote its utilization, through pyrolysis. Research efforts should concentrate on developing policies providing incentives and raising public awareness about the benefits of adopting sustainable waste management practices such as pyrolysis.
5. **Life Cycle Assessment Refinement:** Ongoing research provides an opportunity for refinement of life cycle assessment methodologies that are specific to biomass pyrolysis. This involves enhancing data collection improving modeling techniques and ensuring that assessments are kept up to date with the advancements, in technologies and sources of feedstock.
6. **Carbon Storage Potential Mechanisms:** Studying the ways in which biochar application contributes to carbon storage potential in soil is a field of research. It is crucial to explore how various types of biochar and methods of application can influence both the storage of carbon in soil and its overall health.
7. **Environmental Policy and Regulation**: Researchers can play a role, in shaping policies and regulations that foster the growth of biomass pyrolysis. This includes working with government entities and regulatory bodies to establish emissions criteria while also encouraging the adoption of eco approaches.

5.15. Research limitations

1. **Data Collection Challenges:** Collecting data to conduct an analysis of the entire life cycle can be hindered by the difficulties linked to gathering information. It might be challenging to obtain precise comprehensive data from phases of the biomass pyrolysis process including emissions from various stages of the process. This lack of data availability can lead to uncertainties in the assessment and making assumptions as seen in our research.
2. **Industry-Specific Data:** The field of biomass pyrolysis is an industry that is continually changing and requires expertise. As a result, it can be challenging to find industry data and consistent reporting methods. Researchers may encounter obstacles when trying to obtain information, from pyrolysis plant operators and companies due to concerns, about information or an unwillingness to share certain details.
3. **Heterogeneity of Biomass Feedstock**: The wide range of biomass sources available poses a challenge. Each feedstock material has its composition and properties resulting in different emissions and biochar quality. Due, to this variation it becomes challenging to draw conclusions or make statements about the outcomes.
4. **Economic Viability:** Although biochar production offers a lot of advantages, but its economic feasibility can present limitations. Further research is necessary to explore methods that can make biochar production financially competitive, in comparison to other waste management approaches and to identify opportunities for generating revenue through the sale of biochar and more specifically in terms of carbon credits.
5. **Long-Term Monitoring:** Studying the lasting impacts of biochar, in soil and its contribution to carbon storage potential might necessitate prolonged periods of observation. Researchers may encounter difficulties concerning the availability of resources and funding, for conducting these long-term studies.
6. **Regional Variability:** The impact, on the environment caused by biomass pyrolysis can differ based on factors such as the location, climate, and local circumstances. It's important to conduct research studies that're specific to each region since findings from one area may not necessarily be applicable, to others.
7. **Changing Technology:** With the advancement of pyrolysis technology, it is crucial for researchers to keep up with the developments and constantly update their knowledge to remain relevant, in their field. As technology progresses research findings may become obsolete making it necessary for researchers to adapt and stay informed.

5.16. Model Built

The model was designed and built with a comprehensive array of variables and functions. It incorporated input parameters such as calorific values of biooil and syngas, product composition, and energy usage, enabling the calculation of output of carbon footprint at different stages of the pyrolysis process.

The model's core components revolved around the incorporation of essential parameters for assessing the environmental impact of the pyrolysis process. By incorporating variables such as calorific values of resultant products, product composition percentages, and energy usage, the model could precisely estimate the carbon footprint. Moreover, the model's design included functionality to seamlessly integrate primary data, thus enhancing its accuracy for future analyses.

Input Data Interface	
Product	**%**
Biochar	
Biooil	
Syngas	
Energy of Pyrolysis Used	**Kwh per Kg Feedstock**
Energy used	
Calorific Value	**MJ/kg**
Bioil	
Syngas	

Figure 31: *Model - Input Data Interface*

Output Data Interface	
Life Cycle Stage - Emissions	**Carbon footrpint of Stage Kg CO2eq / Kg of feedstock**
Transportation of biomass waste feedstock to the plant.	
Biomass Pre-treatment	
Pyrolysis Process	
Transportation of Biochar to Land	
Carbon Storage Potential of Biochar when applied to soil	
Carbon Emissions Reduction of Bio-oil and Syngas vs. Fossil Fuels	
Total Carbon Footrprint	**Kg CO2eq / Kg of feedstock**
Total Emissions	**Kg CO2eq / Kg of feedstock**
Total Avoidded Emissions	**Kg CO2eq / Kg of feedstock**

Figure 32*: Model - Output Data Interface*

The model, designed to compute the carbon footprint in pyrolysis processes, stands as a pivotal instrument for assessing and enhancing environmental sustainability. Its comprehensive integration of essential variables and functions, alongside its adaptability to incorporate primary data, underscores its significance in providing a detailed understanding of the environmental impact. Consequently, the model plays a vital role in guiding the adoption of eco-conscious practices in the pyrolysis industry while paving the way for increased accuracy in future analyses.

Here is a sample calculation using the model:

Input Data Here (Numbers Only)	
Product	**%**
Biochar	35
Biooil	30
Syngas	35
Energy of Pyrolysis Used	**Kwh per Kg Feedstock**
Energy used	0,5
Calorific Value	**MJ/kg**
Bioil	27,5
Syngas	19,1

Figure 33: *Model sample calculation- Input Data Interface*

No Error	Results	Life Cycle Stage - Emissions	Carbon footrpint of Stage Kg CO2eq / Kg of feedstock
		Transportation of biomass waste feedstock to the plant.	0,0137
		Biomass Pre-treatment	0,02881619
		Pyrolysis Process	0,1945
		Transportation of Biochar to Land	0,004795
		Carbon Storage Potential of Biochar when applied to soil.	-0,861
		Carbon Emissions Reduction of Bio-oil and Syngas vs. Fossil Fuels	-1,2677
Total Carbon Footrprint		-1,8869	Kg CO2eq / Kg of feedstock
Total Emissions		0,242	Kg CO2eq / Kg of feedstock
Total Avoidded Emissions		-2,129	Kg CO2eq / Kg of feedstock

Figure 34: *Model sample calculation- Output Data Interface*

CHAPTER SIX: BIOCHAR: A SUSTAINABLE SOLUTION FOR AGRICULTURE AND CLIMATE

6. Biochar: A Sustainable Solution for Agriculture and Climate

Biochar is a carbon-rich material produced by pyrolysis and it is created through the process of heating biomass without oxygen as discussed in detail earlier. Research has shown that biochar offers advantages for agriculture such as improving soil quality while reducing the need for fertilizers and enhancing crop yields. Additionally, biochar can contribute to addressing climate change by storing carbon in the soil acting as a carbon sink and decreasing greenhouse gas emissions.

Within this chapter we will delve into the roles that biochar plays in agriculture and its potential to aid in mitigating climate change. Furthermore, we will explore how biochar can contribute to the concept of circular economy.

6.1. The Role of Biochar in Sustainable agriculture

The extensive application of fertilizers such as nitrogen (N) phosphorus (P) and potassium (K) along with the increased use of pesticides to enhance crop growth has been on the rise. This trend is particularly noticeable in China, where they account for 90% of fertilizer usage in the world (Pan et al., 2017). Similarly, countries like Cambodia, Laos and Vietnam have also witnessed increases in pesticide application each year with escalations of 61%, 55% and 10% (Schreinemachers et al., 2015).
When agricultural practices mentioned are used extensively there is an increase in the loss of nutrients and pesticides through leaching. This situation does not only lead to a decline in soil

fertility but also contributes to environmental contamination. Additionally nutrient leaching from farmlands raises farming expenses while speeding up soil acidification and reduces crop yields (Ding et al., 2017).

The use of biochar shows promise in recovering carbon. This friendly solution not only helps in storing carbon but also provides significant advantages for soil health and agricultural productivity as supported by many reputable studies.

Biochar application offers a benefit by enhancing soil fertility. Numerous studies consistently show that when biochar is added to soil it brings about enhancements in soil structure, nutrient retention and water holding capacity. As a result, it contributes to the growth of more productive crops. Unlike soil additives that break down rapidly biochar can persist in the soil for long time usually around two to three years. This lasting presence does not bring only lasting benefits to the land but also holds promise in reducing soil contamination caused by inorganic substances (Rehman & Razzaq, 2017).

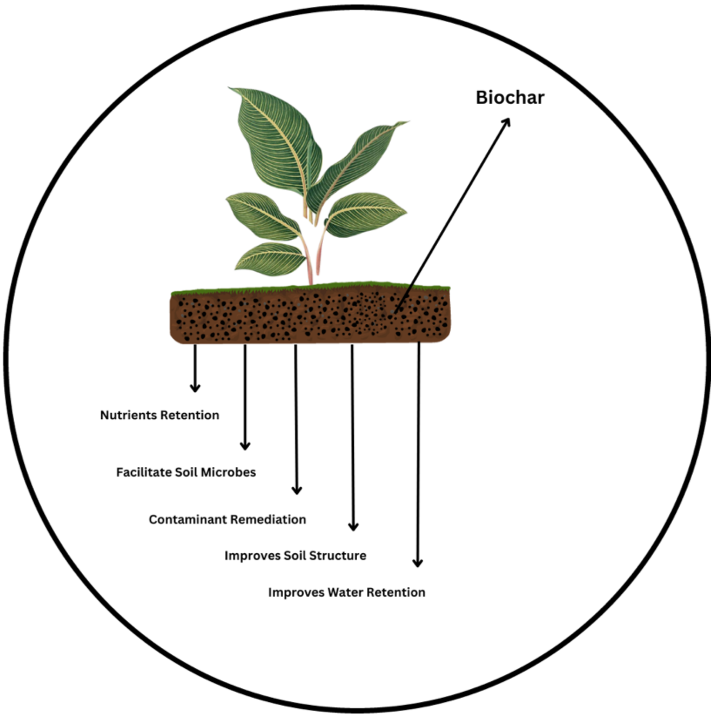

Figure 35: *Overall Agriculture benefits of Biochar.*

6.2. Biochar and Climate Change Mitigation

One of the reasons why biochar is seen as effective in addressing climate change is its slow decomposition. This distinguishes it from the raw biomass it originates from and aids in minimizing carbon release into the atmosphere. As a result, biochar becomes a tool for reducing carbon emissions and combating climate change (Woolf et al., 2018).

The key role of biochar in mitigating climate change lies in its ability to maintain carbon reserves over time compared to raw biomass. This characteristic leads to an increase in the amount of carbon stored in the soil. While the storage potential of carbon, through biochar involves redistributing existing biomass carbon than capturing carbon. Several studies have agreed that this long-term storage potential effect is the primary way biochar influences greenhouse gas balances while other factors help regulate this impact (Woolf et al., 2018).

Biochar's impact on climate change mitigation depends on several secondary mechanisms, in addition to its ability to sequester carbon in the soil. These mechanisms include:

- **Reducing nitrous oxide (N2O) emissions from soil:** Biochar can combine with nitrogen and other nutrients which reduces their accessibility to microbes which results in less N2O production (Woolf et al., 2018).

- **Altering methane emission or oxidation rates in soil:** Biochar has the potential to create a living environment, for microorganisms that can consume methane. Additionally, it can modify the chemical conditions in the soil thereby reducing the likelihood of methane production (Woolf et al., 2018).

- **Preventing the release of N2O and methane (CH4) that would have occurred from the breakdown or burning of biomass**: When biomass is transformed into biochar it does not get emitted into the atmosphere as methane or N2O gases (Woolf et al., 2018).

- **Enhancing plant growth**: Biochar can improve soil fertility and water retention, which can lead to increased plant growth. This increased growth can remove more CO2 from the atmosphere, and if the biomass is used to produce more biochar, this can create a positive feedback loop (Woolf et al., 2018).

- **Reduce greenhouse gas emissions by displacing fossil fuels:** Pyrolysis byproducts like the syngas and biooil produced have the potential to generate power and heat replacing fossil fuels such as coal and natural gas. This can result in reductions in greenhouse gas emissions which depends on the biomass utilized and the effectiveness of the pyrolysis procedure (Yang et al., 2021).

- **Reduce greenhouse gas emissions by storing carbon in soil:** Biochar is a substance produced through pyrolysis and it is made up of carbon material. When added to soil biochar aids in the removal of carbon dioxide from the atmosphere by long term storage. Scientific research has revealed that biochar can effectively store carbon in soil for hundreds of years or even thousands of years (Yang et al., 2021).

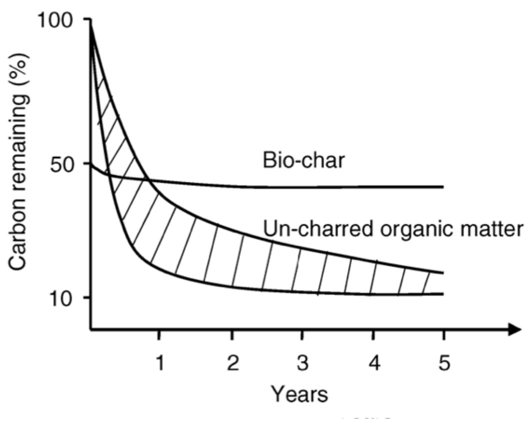

Figure 36 *Schematics for biomass or biochar remaining after charring and decomposition in soil (Lehmann et al., 2006)*

- **By reducing methane emissions:** Pyrolysis can also play a role in mitigating methane emissions originating from agriculture practices. The reason behind this lies in the ability of pyrolysis to transform byproducts including manure and crop residues into biochar and other useful substances. Given that methane is a greenhouse gas therefore, taking measures to decrease its release from agriculture can exert a substantial influence on the global climate.

In *Figure 30* we compare two systems where the first one is without Pyrolysis (a) and the other one is with Pyrolysis process adopted (b) and we can summarize the main impact as follows:

(a) Without Pyrolysis process:

- Plants remove CO2 from the atmosphere through photosynthesis.

- When plants decompose in the soil the CO2 is released back into the atmosphere.

- Some of the nitrogen in the soil is also released into the atmosphere as nitrous oxide (N2O), a potent greenhouse gas.

(b) With Pyrolysis process:

- Half of the carbon is released into the atmosphere during pyrolysis and the remaining carbon in the biochar decomposes more slowly than raw biomass, so less CO2 is released into the atmosphere overall.

- Biochar can also reduce N2O emissions from soil by up to 80%.

- Biochar can improve soil fertility and increase plant growth, which can remove more CO2 from the atmosphere.

- Biochar can be used to produce bioenergy, which can displace fossil fuels and reduce CO2 emissions.

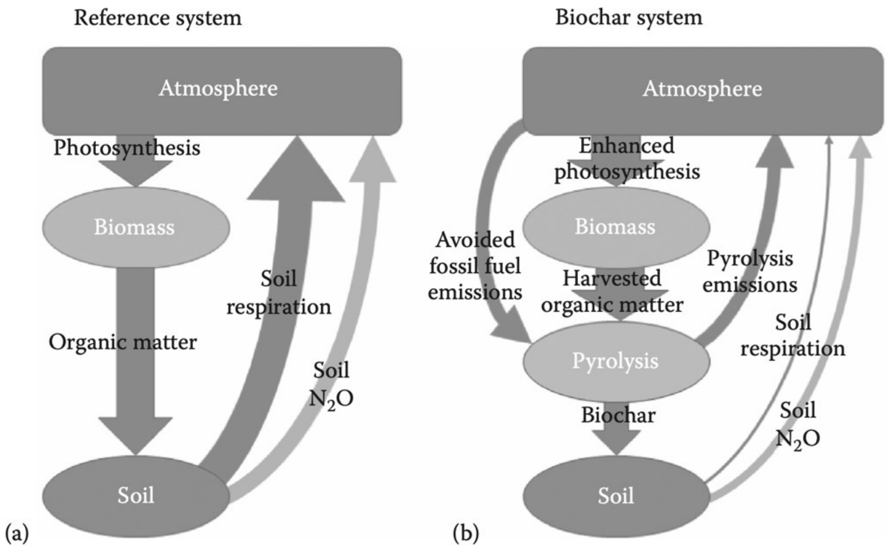

Figure 37: *Comparison between Reference System and Biochar system (Woolf et al., 2018).*

There is also an important aspect to discuss which is the PH of the soil where Lower soil pH is generally linked to higher emissions of nitrous oxide (N2O) from both nitrification and denitrification processes. Therefore, the ability of biochar to increase the PH of soil will result in lower emissions of nitrous oxide (N2O) (Woolf et al., 2018).

In a real-world experiment conducted by Hüppi et al. (2015) they examined the impact of biochar and lime amendments on soil with a pH of 6.3. Interestingly their findings revealed that biochar resulted in a 52% decrease in N2O emissions while the application of lime did not have any effect on emissions. Consequently, the researchers concluded that the reduction in N2O emissions associated with biochar cannot be solely attributed to an increase, in soil PH (Woolf et al., 2018).

In summary biochar provides an approach to address climate change mainly due to its slower decomposition rate which differentiates it from raw biomass. By preserving carbon over time biochar boosts carbon storage in the soil effectively reducing carbon emissions released into the atmosphere. While carbon storage potential is a factor biochar impact on climate change mitigation extends to important processes as well. These include decreasing oxide (N2O) emissions from soil influencing methane dynamics and preventing the release of N2O and methane that would otherwise occur from biomass breakdown or burning. Additionally, biochar enhances soil fertility which promotes plant growth while also being useful for bioenergy production. However, it's worth noting that although soil pH plays a role in biochar effectiveness in mitigating N2O emissions it is not the determining factor. Real world experiments like the one conducted by Hüppi et al. (2015) have shown how various factors interact to make biochar a versatile and valuable tool for combating climate change and improving soil management practices.

6.3. Biochar and the Circular Economy

The circular economy is a model that aims to minimize waste by maximizing the utilization of materials and resources. Biochar, a carbon substance derived from biomass waste through pyrolysis has applications such as enhancing soil quality, purifying water, and trapping carbon dioxide by acting as a carbon sink. Biochar systems provide opportunities for putting the economy into circular economy basis as it contributes to waste reduction while also enabling the production of valuable products from waste materials resulting in a total reduction in greenhouse gas emissions (Andooz et al., 2023).

Pyrolysis has the potential to decrease waste by redirecting waste from landfills and incinerators into a more environmentally friendly process. In the United States, landfills contribute significantly to methane emissions a greenhouse gas that traps heat in the atmosphere 25 times more when compared to carbon dioxide. Additionally, incinerators release greenhouse gases and other harmful pollutants like dioxins and furans (Andooz et al., 2023).

Through diverting waste from landfills and incinerators pyrolysis can play a role in reducing greenhouse gas emissions and mitigating various environmental impacts. Furthermore, it aids in conserving resources like trees and land that are often utilized to produce materials frequently discarded as waste supporting the objectives of the circular economy (Singh et al., 2022).

Moreover, using biochar in agriculture to improve soil health and productivity is a part of the circular economy. It focuses on resource efficiency, sustainability, and environmental responsibility. Biochar can enrich soil quality, retain nutrients, and reduce dependence on chemical fertilizers and pesticides. This does not help conserve resources only but also transforms biomass residues into a valuable soil amendment resulting into reduction of waste. These practices perfectly align with the principles of circular economy by prolonging the lifespan of materials and resources promoting system resilience while minimizing impacts from inputs and ultimately supporting more sustainable eco-friendly and economically viable farming methods. Moreover, biochar plays a role as a long-term carbon sink in soils contributing to carbon storage potential efforts and helping mitigate climate change.

Furthermore, pyrolysis can create and extract resources from waste, including biochar, pyrolysis oil and syngas. Biochar is a source of carbon that can enhance soil quality and help in carbon sequestration. Pyrolysis oil can serve as a fuel source and can be utilized as a substance for producing chemicals and other valuable goods. Syngas can be employed in electricity generation, and it can be also used to produce different types of fuels (Andooz et al., 2023).

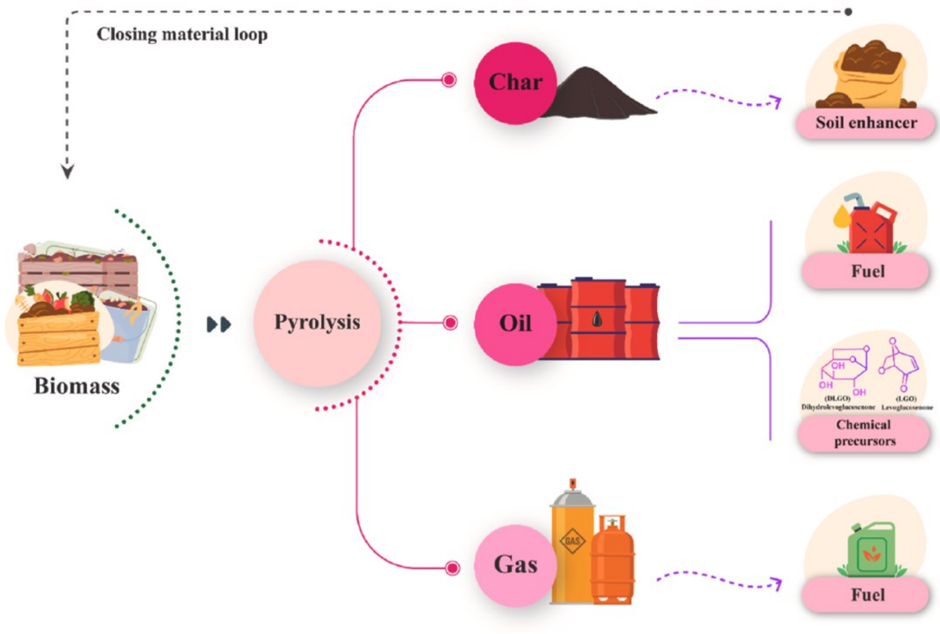

Figure 38: *Schematic representation of how biomass pyrolysis can close the material loop (Andooz et al., 2023).*

Finally, one of the wide-ranging contributions of biochar production to the circular economy and environmental sustainability is its ability to capture carbon from the atmosphere which addresses climate change, essentially biochar acts as a storage for carbon keeping it in a stored form for a long time this helps prevent its release into the atmosphere and its contribution to the greenhouse effect (Singh et al., 2022).

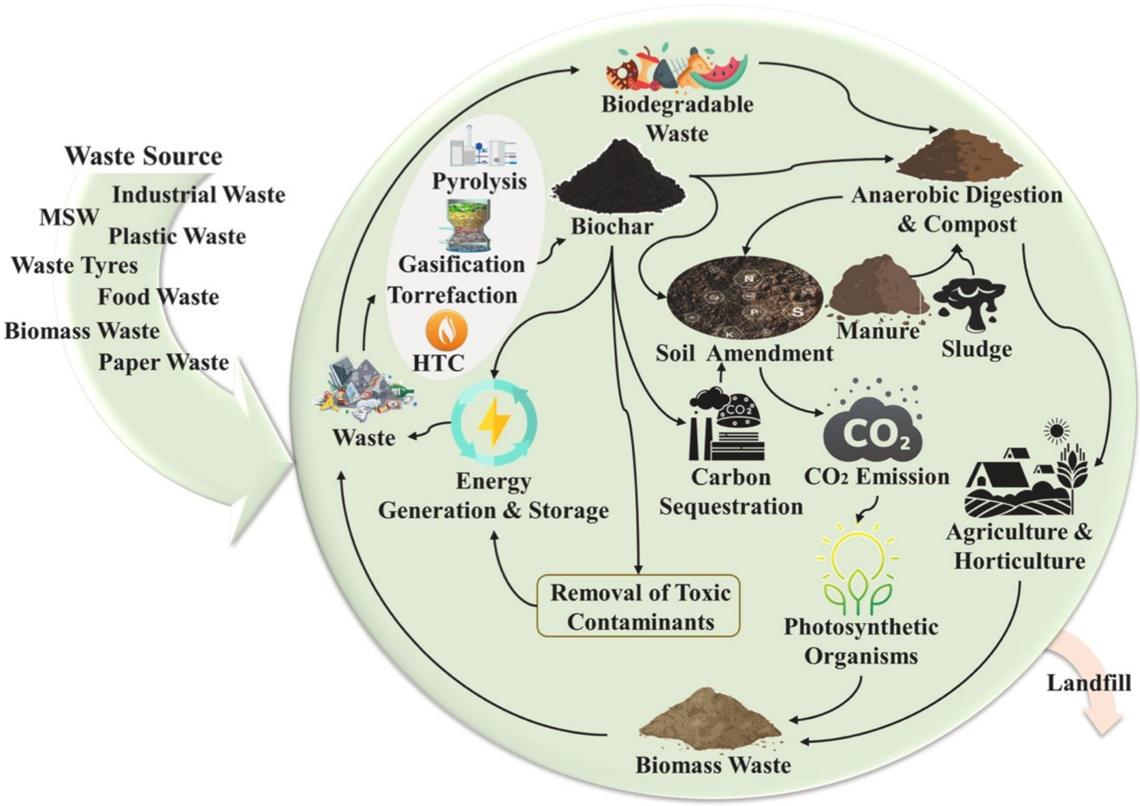

Figure 39 *: Circular Economy in Biochar Industry (Singh et al., 2022).*

CHAPTER SEVEN: PROSPECTS AND RECOMMENDATIONS FOR BIOCHAR INTEGRATION

7. Prospects and Recommendations for Biochar Integration

7.1. Prospects for Biochar Integration

Indeed, biochar has the potential to bring about changes and address a range of global challenges. These challenges include mitigating climate change ensuring food security and managing waste efficiently. However, to fully tap into this potential and effectively incorporate biochar into our systems it requires a long-term commitment, from stakeholders, across different sectors.

Certainly, the potential benefits of incorporating biochar are quite promising and span across various critical sectors. Let's explore these possibilities in detail and discuss how they can be further improved.

7.1.1. Agriculture Sector :

- **Enhanced Soil Health and Fertility:** Further research and the development of customized application techniques can enhance the effectiveness of biochar in improving soil structure and retaining nutrients. These advancements have the potential to result in enhancements, in crop yields and overall soil quality.

- **Reduced Chemical Inputs:** By encouraging the adoption of organic methods, in farming we can expedite the decrease, in the use of chemical fertilizers and pesticides. This approach does not only benefit the environment but also provides economic advantages for farmers.

- **Climate Resilience:** In areas that're susceptible, to the impacts of climate change, such as droughts and severe weather events, biochar can be incredibly valuable, in bolstering soil resilience. This ensures that agriculture can continue to thrive in harsh circumstances.

7.1.2. Energy Sector :

- **Bioenergy Innovation:** Ongoing studies, in the area of biochar have the potential to drive advancements in bioenergy generation. By developing cutting edge technologies, we can optimize the utilization of biochar energy capabilities resulting in increased production of energy.

- **Carbon-Neutral Energy Production:** By combining the use of biochar, with carbon capture and storage (CCS) technologies we can make energy production environmentally friendly by achieving carbon neutrality or even a carbon negative status. This would lead to a reduction in greenhouse gas emissions, from the energy sector.

- **Energy from Biomass Waste:** The importance of biochar, in managing biomass waste goes beyond reducing landfill waste. It also allows us to extract energy from waste materials and retrieve resources, which contributes to creating a more resilient circular economy.

7.1.3. Waste Management Sector

- **Advanced Waste Conversion:** Ongoing exploration and progress have the potential to result in eco-techniques, for transforming biomass waste into biochar thereby reducing expenses related to waste management and minimizing negative environmental effects.

- **Contaminant Remediation**: The extensive utilization of biochar, in regions facing pollution problems can greatly enhance soil quality by addressing contaminated soils and water.

- **Sustainable Waste Practices**: Promoting the implementation of eco waste management methods, such, as incorporating biochar can result in efficient and cleaner waste processing practices while conserving valuable resources.

7.2. Recommendations for Biochar Integration

- **Supportive Policy Frameworks**: Governments, at every level should establish policies that encourage and enable the production and utilization of biochar. This can encompass providing incentives, tax benefits and grants to support biochar producers and users. Moreover, setting up defined frameworks, for biochar production and application can offer stability to the industry while promoting its growth.

- **Research and Development Investment**: Governments, research organizations and private companies should continue to invest in research and development. This involves investigating different forms of biochar, improving the selection of materials, refining pyrolysis processes and enhancing application methods. Furthermore, conducting studies, on the effects of biochar, on soil quality, crop yield and environmental impact and outcomes is crucial.

- **Education and Outreach**: It is crucial for biochar to gain awareness and acceptance for it to be widely adopted. To achieve this, we need to create outreach initiatives that inform the public about the advantages and various applications of biochar. These programs should specifically target farmers, landowners, policymakers, and the general population. Additionally, organizing hands on demonstration projects can effectively showcase the benefits of biochar and motivate people to embrace its use.

- **Research Consortia**: Collaborating between research institutions government agencies and industry stakeholders can facilitate the exchange of knowledge and expertise. The establishment of research consortia has the potential to expedite progress, in biochar technology and practices.

- **Standards and Certification**: Establishing quality criteria and certification procedures, for biochar products is crucial to instilling trust in their efficacy and safety, among consumers and users. By doing so we can foster utilization of biochar across diverse applications.

- **Incentives for Farmers and Landowners**: Offering rewards, to farmers and landowners who integrate biochar into their land management methods has the potential to expedite its utilization. These incentives can be linked to storage potential of carbon improved crop yields or other quantifiable advantages.

- **Industry Collaboration**: Promoting collaboration, between biochar producers and industries, like agriculture, energy and waste management can result in customized solutions that cater to the requirements of each sector. By forming ventures and partnerships the utilization of biochar can be encouraged across a range of applications.

- **Market Development**: We should put in some effort to establish markets, for biochar products. This involves connecting biochar producers with customers in sectors like agriculture. Developing the market can help generate demand, for biochar and promote growth in production.

- **Environmental Impact Assessment**: It's important to evaluate the impact of producing and using biochar to make sure it is done in a sustainable and eco-friendly manner. These assessments help us determine the practices and regulations to follow.

- **International Collaboration**: Biochar is not constrained by borders, between countries. By working to conduct research, establish best practices, and develop standards we can establish a worldwide framework for incorporating biochar, thereby promoting its utilization, on a broader level.

To sum up, effectively integrating biochar into systems and practices requires a well-coordinated approach that encompasses various aspects. It is important to have policies, in place as they provide the regulations and financial incentives to promote the production and use of biochar. Additionally, it is crucial to conduct research and development activities that continuously improve biochar production techniques while also exploring applications and understand its long-term effects. Education and outreach programs play a role in raising awareness and gaining acceptance ultimately building trust in the effectiveness of biochar, as a viable solution.

Cooperation among sectors plays a role, in connecting these components. It is important for industries, research institutions, government agencies and environmental organizations to come together to foster innovation, exchange knowledge and align their objectives. This spirit of collaboration does not only speed up the implementation of biochar but also harnesses the combined expertise of different stakeholders to maximize its impact.

With a commitment and dedication, to this approach biochar has the potential to become a truly transformative solution on a global scale. It presents a response to the challenges posed by climate change as it can effectively capture carbon and reduce emissions. Moreover, biochar plays a role in enhancing food security by improving soil health and boosting crop yields thus contributing to the resilience of systems. Additionally, it plays a part in promoting waste management practices by diverting organic waste from traditional waste management techniques and creating a valuable resource. Furthermore, it can remediate contaminated soils and water providing benefits, for our environment.

In this time of climate urgency biochar emerges as a ray of hope offering an environmentally friendly solution that can make a significant contribution, towards a more resilient and responsible future. By joining forces, we can envision a future where biochar is embraced and integrated into systems and practices to tackle climate change, ensure food security, and improve waste management. The potential, for biochar to create lasting effects knows no bounds and adopting it reflects our forward-thinking dedication to building a better world for generations to come.

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