Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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LIFE CYCLE ASSESSMENT OF BIOCHAR IN NORWAY

Master's thesis in Master of Energy and Environmental Engineering
Supervisor: Prof Franceso Cherubini
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Background and objective

The continuing increase in emissions will present a major challenge for meeting the international goal of limiting warming to <2 °C relative to the preindustrial era, particularly if stringent climate change mitigation strategies are not introduced rapidly. To avoid warming of more than 2 °C with a >50% chance, the large-scale deployment of renewable energy options and negative emissions technologies

(NETs), that is technologies that result in the net removal of carbon dioxide (CO2) from the atmosphere, is required. As society must decide which mitigation pathways are desirable to tackle climate change, information on the technical opportunities and sustainability profile afforded by alternative renewable systems and NETs is necessary. Over the portfolio of possible options, biochar emerges as a solution that can offer a variety of benefits as a renewable energy and material source for industrial processes, and when applied to agricultural soils represents a NET with large deployment potential. For example, the use of biochar in agriculture can increase soil carbon storage (with a global potential of about 15% of current anthropogenic GHG emissions) and bring additional field benefits (higher yields, higher water and nutrient retention, lower N2O emissions, etc.). However, the variety of possible combinations in terms of biomass feedstocks, biochar conversion process, applications, and environmental impact accounting methods, lead to a variety of possible outcomes in terms of net environmental and climate benefits, requiring case-specific analysis and evaluation to benchmark the sustainability profile of the individual value chain. Further, an early environmental sustainability analysis before large-scale deployment of novel technologies is key to identify potential side-effects and quantify achievable benefits of improvement options, which can be embedded in the technological development.

Relative to other mitigation options, biochar is affected by lower impact on land competition, energy requirement and cost, so have fewer disadvantages than many NETs. However, the degree of the climate change mitigation potential and the effects on agricultural soils are largely dependent on the specific value chain configuration and geographical context, especially regarding type of feedstock, soil conditions and background climate. Environmental impact accounting methods and type of stressors considered are also key factors shaping the sustainability profile of biochar systems. Many complexities of the biochar value chain, together with the interlinkages with other sectors such as the agricultural and industrial sectors, requires advanced and holistic approaches to perform robust and informing sustainability analysis. In order to prevent possible burden-shifts of concerns, other environmental impact categories than climate change should also be factored in the assessment, such as eutrophication, acidification, primary energy consumption, and others. All these factors must be considered in the quest for environmentally friendly and sustainable systems.

This thesis work will build on the material gathered during the previous semester and other data to perform a Life-Cycle Assessment (LCA) study of producing biochar from forest residues in Norway and applying it to agricultural soils. Inputs and emissions to collect, process, transport, and convert forest residues into biochar and its transport and application to agricultural soils. Production conditions will be based on the best options for producing the biochar that can best match the specific feedstock and application to Norwegian soils. Benefits and trade-offs will be identified and discussed. Primary data of the biochar system will be based on case-specific modelling and literature sources, and up-to-date databases will be used for modelling background systems.

The following tasks are to be considered:

Perform a review of existing studies about LCA of biochar systems and summarize the key findings to be used in the introduction and background section.

1) Gather process and emission data for the biochar system under study and the application to agricultural soils

2) Compile a flow-sheet diagram and model the specific type of biochar system

3) Perform the LCA by characterizing the emission flows of the life-cycle emission inventory 5) Compare the achieved results with the findings of the studies reviewed in task 1.

6) Interpret and discuss the results, with identifications of areas of concerns and possible improvement options.

Acknowledgment

This work is the result of my master’s degree at the Department of Energy and Process Engineering, Norwegian University of Science and Technology, spring 2020.

A warm Namaste to my Lord Krishna.

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I am lucky to have Bijay Bhusal as my beloved husband, for being the backbone of my life. I owe respect and gratitude to my parents Harihar Prasad Ghimire, Bidhya Ghimire, Tank Prasad Bhusal, Bodhika Bhusal and my siblings Sharmila Phyual, Deepa, Krishna, Pragya and Sita

Baptiste, my dear friend, I am grateful to have you here at NTNU. You have helped me a lot in my study and encouraged every time as Yuna Prajapati used to do. Finally, I would like to thank my relatives, friends, and teachers for their support and encouragement throughout my study.

Abstract

Biochar is seen as a cost-effective and easy to implement negative emission technology to sequester carbon dioxide and help to mitigate climate change. A Life cycle assessment (LCA) of slow pyrolysis using forest residues was conducted to study the environmental effects of biochar in Norway. The LCA was performed for biochar production at 350°C and 650°C for comparison and analysis of potential trade-offs. Co-products formed during pyrolysis (i.e. bio-oil and syngas) were assumed to be burnt for energy recovery and displace district heating produced from natural gas. SimaPro software has been used with EcoInvent as background system for the LCA and the ReCiPe impact assessment method was used for impacts characterization at midpoint level. Pyrolysis at 650°C showed an increased stable carbon yield by 24% than 350°C. Biochar at 650°C showed lower impacts for global warming, fossil resource scarcity impacts -2.34 compared to -1.46 kg CO_2eq at 350°C and -0.037 vs 0.0024 kg oil eq. This is due to more stable carbon in the biochar produced at 650°C and more displaced district heating. For the other impact categories, biochar produced at 650°C showed slightly but larger impacts compared to 350°C, which is probably due to lower biochar yield at 650°C that requires more feedstock and more upstream inputs and emissions. The net climate mitigation potential for Norway at pyrolysis temperature 350 °C and 650 °C will be 1.1 Mt CO_2 eq/yr and 1.3 Mt CO_2 eq/yr respectively.

Keywords: **Life cycle assessment, Biochar, Pyrolysis, Carbon sequestration, Soil**

1. Contents

LIST OF FIGURES

LIST OF TABLES

Abbreviations

BECCCS	Biochar, Bioenergy Carbon Capture and Storage
CDR	Carbon dioxide Removal
GHG	Greenhouse Gas
HHV	High Heating Value
HTT	High Treatment Temperature
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCIA	Life Cycle Inventory Assessment
N_2O	Nitrous Oxide
NET	Negative Emission Technology
NH_3	Ammonia

1. Introduction

1.1 Background

The rapid change in the global climate may have catastrophic impacts on the environment. Limiting the increase of temperature has become an international cooperation goal with the ratification of the Paris agreement (Allen, 2018) aiming at limiting global warming under 1.5°C compared to the pre-industrial level by 2100.

Long term global warming is driven by an excess of carbon dioxide in the atmosphere due to its release from fossil sources. All future emission scenarios achieving the Paris agreement rely on negative emission technologies (NET) that aim at removing excess carbon dioxide from the atmosphere (IPCC, 2018). Many different NETs are available as afforestation, biochar, bioenergy carbon capture and storage (BECCS), enhanced weathering, ocean fertilization, ocean liming, soil carbon sequestration and direct air capture (Minx et al., 2018)

Among them, biochar is attracting a lot of attention. Biochar is the solid phase remaining after the thermal decomposition of biomass under anaerobic conditions and consists mainly of carbon. This process is called pyrolysis (Lehmann, Gaunt, & Rondon, 2006). Applied to the soil, part of this biochar carbon remains stable over the centuries and can represent an atmospheric carbon sink as biomass is regrown (Minx et al., 2018). Application of biochar in soils has attracted a lot of attention as it can provide additional benefits such as increased soil productivity, lower soil emissions, lower leaching of nutrients, improve soil water retention among others (Tisserant & Cherubini, 2019) (Fuss et al., 2018). Biochar is also technologically easy to implement and is believed to be one of the less expensive NET currently available, allowing for earlier carbon dioxide removal (CDR) (Tisserant & Cherubini, 2019). Biochar could reduce greenhouse gas emission and removes 5.5–9.5 billion tonnes of carbon per year (GtC/yr) by 2100 (Lehmann, Gaunt, & Rondon, 2006) and also 1Gt C/yr by 2050 (Woolf, Amonette, Street-Perrott, Lehmann, & Joseph, 2010)

Life cycle assessment (LCA) is commonly used to perform an environmental analysis of production systems. LCA allows us to follow flows of energy, materials, and emissions from the different processes involved in the supply chain, therefore evaluating the environmental performance of the production system over its life cycle, allowing us to identify potential co-benefits or trade-offs. Several studies of biochar production systems are available with a research focus on greenhouse gas emissions, energy, and benefits of biochar and its application (Hammond, Shackley, Sohi, & Brownsort, 2011),(B. Dutta & Raghavan, 2014; Ibarrola, Shackley, & Hammond, 2012; Roberts, Gloy, Joseph, Scott, & Lehmann, 2010).

Norway is also one of the largest exporters of oil and natural gas in the world (Petroleum, 2019)hence the extraction of oil and gas emits a huge amount of Greenhouse gas (GHG) emissions. In 2019, 50.03 million tonnes of CO_2 equivalents were released in Norway, (Statistics, 2019) .Norway has a climate target reduction of at least 40% of greenhouse gases and to become a low emission nation by 2050 (Environment, 2018)

This master thesis aims to perform the environmental analysis and climate mitigation benefits of biochar production in Norway. Biochar will be assumed to be produced from forest residues. The biochar is more stable than the forest in storing carbon as forests are burned, destroyed, and decayed so forest residues can be utilized as feedstock for biochar production. Most of the forest residues in Norway are unused and the total volume is about 1.7M ton dry basis yr−1(Cavalett & Cherubini, 2018)

This study analyses the life cycle of biochar produced from forest residues using slow pyrolysis to know the impacts specifically global warming and the use of biochar as a soil amendment. In this work, we will compare the climate mitigation benefits of biochar produced at 350°C and 650°C. The Emissions may occur all along the supply chain, while pyrolysis conditions affect biochar yield and stability.

1.2 Research Questions

This research aims to understand the environmental impacts of biochar production;

- How biochar can have impacts, both positive and negative, on the environment? What has been done in terms of LCA studies?
- What are the environmental impacts associated with biochar production in Norway?
- How does biochar produced at 350°C and 650°C compare between each other regarding climate mitigation potential, and other environmental impacts?

1.3 Limitation and challenges

The study was limited to the pyrolysis of biochar only. All the assigned tasks like LCA of biochar system, soil biochar benefits, flow sheet diagram, and possible environmental impacts and interpretation were done. This thesis couldn’t cover the task of applying the biochar in the soil of Norway because of the Corona pandemic, this work started late.

1.4 Structure of the study

There are 5 chapters in this thesis, the first chapter is an introduction with a motivation of research as to how the limiting of global warming is crucial for today, and how LCA and biochar can contribute to it, research questions, limitation, and challenges.

The second chapter is based on literature review like a definition of biochar, explanation of its co-products, pyrolysis method, different organization involvement in biochar research, effects of biochar on soil, the negative potential of biochar and Life cycle assessment details, review of LCA studies on biochar application to soils.

The third chapter includes the materials and methodology, where explanation of life cycle methodology like Goal and scope, System boundary, Inventory analysis.

The fourth chapter is result and discussion which explains the differences between two pyrolysis temperature for global warming potential and other impact categories.

The fifth chapter is the conclusion of the overall thesis as climate benefit is achieved more at pyrolysis temperature 650 °C.

2. Literature Review

2.1 Biochar

The thermochemical conversion of biomass in an oxygen-limited environment produces the carbon-rich solid material called biochar. (Z. Zhang, Zhu, Shen, & Liu, 2019) , which can be used to restore the soil, improve crop production (Jeffery et al., 2017), and helps in climate change mitigation technology(Lehmann, Kuzyakov, Pan, & Ok, 2015). It can be used as adsorbents, catalysts, anaerobic digestion, composting, and electrochemical energy storage materials due to its unique and versatile properties(Z. Zhang et al., 2019).

Being a porous material helps to retain water and nutrients in the soils (Lehmann et al., 2003) and have the potential to immobilize heavy metals, pesticides, herbicides, hormones (Y. Ding et al., 2016). Biochar has more ability to retain the cations better than all other soil organic matter with adsorbing properties leading it to sink the carbon and to reduce environmental pollution by fertilizer(Lehmann, 2007). The pH of biochar is generally alkaline from 7.1 to 10.5 depending on feedstock types. (Inyang, Gao, Pullammanappallil, Ding, & Zimmerman, 2010)

The biochar carbon stability test method estimates the fraction of biochar carbon will persist for more than 100 to 1000 years(Budai et al., 2013). The highly stable biochar has an average lifetime of more than 1000 years at 10 degrees Celsius. (Roberts et al., 2010). The factors like time of pyrolysis, the carbon content in biochar, pyrolysis temperature, soil nitrogen content have direct effects on the stability of biochar.

Biochar decomposition rate decreases with a) pyrolysis time, b) with increasing temperature up to 600°C,c)with increasing soil Nitrogen content, d) with decreasing C: N ratio (Chao, Zhang, & Wang, 2018). Higher pyrolysis temperature lowers biochar’s yield but increases its carbon content (Crombie & Mašek, 2015).

2.2 Sources of biochar

Mostly the organic materials as corn and wheat Stover, forestry by-products, urban yard wastes, industrial by-products, animal manure, and sewage sludge (Jindo et al., 2016) can be used as biomass to produce the biochar. Biomass rich in lignin can produce more biochar at higher carbon content (Demirbaş, 2001). For example, woody biomass contains around 20%–50% lignin whereas organic waste as manure, sewage or food waste is rich in nutrients as nitrogen (N), phosphorus (P), and potassium (K) but contain less carbon and have higher salt content which may be beneficial or harmful to soil or plant depending on the situation (S. Li, Harris, Anandhi, & Chen, 2019), for example, excess salinity renders less water available to plant.

The biochar derived from woods promote the soil microbial growth after 60 days of biochar amendment on soil whereas as from manure or crop residue feedstocks its shows earlier (Gul, Whalen, Thomas, Sachdeva, & Deng, 2015)

The biochar from sewage sludge may contain heavy metals, organic pollutants, and other toxic substances that may contaminate the soil (Lehmann et al., 2006). Furthermore, the preferred use of feedstock is linked to both quality and availability, since the source of the biomass has a significant impact on the energy and environmental outcome (Cherubini et al., 2009)

2.3 Pyrolysis, biochar production, and by-products

Biochar is produced during a process called pyrolysis. It consists of the thermal decomposition of biomass under the absence of oxygen and producing three products: the solid part is referred to as biochar, a condensable fraction referred to as bio-oil, and some incondensable gases (Schmidt et al., 2018).

According to (Sanna, Li, Linforth, Smart, & Andresen, 2011), the bio-oil is made up of over a hundred oxygenated condensable hydrocarbons, including hydraulic acid, methanol, aldehydes, ketones, oligomeric sugar, and water-insoluble compounds. It can be used for fossil fuel substitution, and heat and power generation (Bridgwater, 2012) but have a high concentration of oxygen (Mohan, Pittman, & Steele, 2006) and requires refining and upgrading, which may increase the costs and decreases the energy efficiency of the process (Bridgwater, 2012) (Matovic, 2011).

The remaining non-condensable gas consists of CO_2, CO, CH_4, H_2, and C_2 hydrocarbons and are highly inflammable(Sanna et al., 2011). This gas can be used to heat the pyrolysis and helps in drying feedstock or biochar(Becidan, Skreiberg, & Hustad, 2007). The choice of products depends on the pyrolysis method as slow pyrolysis yields more biochar, fast pyrolysis yields more bio-oil and gasification yields for pyrolytic gases which is tabulated below.

TABLE 1: DIFFERENT MODES OF PYROLYSIS FOR THE PRODUCT YIELDS (Bridgwater, 2012; Demirbaş, 2001; Jaya Shankar Tumuluru, 2011; Sharma, Pareek, & Zhang, 2015; Sikarwar et al., 2016; Tisserant & Cherubini, 2019)

Process	Temperature (°C)	vapor Residence time	Char %	Liquid %	Gas%
Slow pyrolysis	250-700	5-30 min	45-20	40-50	10-25
Intermediate pyrolysis	~500	10-30 sec	25	50	25
Fast pyrolysis	550-1000	~1 sec		50-75	5-35
Gasification	~750-900	10-20 sec	~5	~10	~85
Torrefecation	~290°C	-	80	0-5	20

Most of the researches are focused in the pyrolysis as Pyrolysis is considered a simple, versatile, and cost-effective technology (Laird, Brown, Amonette, & Lehmann, 2009).

Pyrolysis gasification produced more pyrolysis gas which can be combusted on-site to meet the heat and electricity demand (Laird et al., 2009).

Torrefaction, a pre-treatment technology helps in grindability of feedstock. An increase of torrefaction temperature leads to a decrease in solid bio-char yield and increases liquid and non-condensable gases (Deng, Wang, Kuang, Zhang, & Luo, 2009).

Fast pyrolysis yields the highest amount of bio-oil which can be a good source of energy and the moisture of biomass must be below 10-15% and particle size should not exceed 2 mm (Sohi, Krull, Lopez-Capel, & Bol, 2010).

Slow pyrolysis reactors have been used to produce charcoal from woody biomass for thousands of years. The small-scale pyrolysis stove has replaced the traditional earth-mound, brick, and metal kilns used in developing countries to decrease the fuel consumption and deforestation, increase soil fertility and improved respiratory health. (Whitman, Nicholson, Torres, & Lehmann, 2011)

In this thesis, **slow pyrolysis** was preferred as it produces a high amount of biochar with good quality (Song & Guo, 2012). Here, process heat is supplied by combustion of the produced gas or partial combustion of biomass feedstock(Laird et al., 2009).The yield of pyrolysis dependent on feedstock type, heating rate, pyrolysis temperate, highest treatment temperature (HTT), vapor residence (Ronsse, van Hecke, Dickinson, & Prins, 2013). Slow pyrolysis of biochar have higher efficiency(33%) for carbon abatement ,if biochar is applied in soil(Hammond et al., 2011).

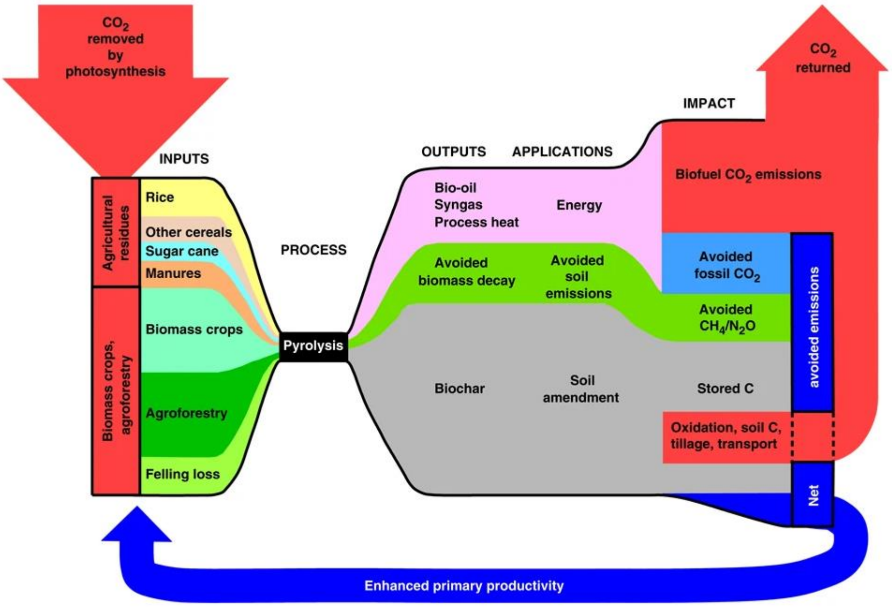

FIGURE 1: SUSTAINABLE CONCEPT OF BIOCHAR PRODUCTION(WOOLF ET AL., 2010)

Figure 1 explains the pyrolysis process with the input of several feedstocks as such as agricultural residues, biomass crops and agroforestry products tend to yield the biochar, bio-oil and syngas. Biochar is a recalcitrant form of carbon and act as soil amendment which can enhance the soil fertility, crop yield and store carbon. biooil and gas combusted to yield energy and co2. They emit avoided fossil emission which on burning will release carbon dioxide. Biochar amendment on infertile soil reduces the co2 by plant photosynthesis. There is a net avoided emission can be seen from all the pyrolysis yield

There are currently some organizations, working on the researches of biochar in Norway. From Table 2, Most of the research have focus on the biochar production and its use in fuel production, soil amendment targeting agriculture and industrial purpose. NTNU is doing lots of researches regarding the life cycle assessment of biochar. The main motives of these organization are to reduce the climate change through their innovative ideas, research and technology. Biochar is a multi-faceted strategy to mitigate climate change and effective negative emission technology(IPCC, 2018).

TABLE 2: SOME ORGANIZATION WORKING ON BIOCHAR IN NORWAY (NORDIC BIOCHAR NETWORK)

Name	**Region**	**Summary**
University I Agder Department of Engineering Sciences	Grimstad, Norway	Use biomass and biochar in industrial purpose
Standard Bio AS	Bo, Telemark, Norway	Used feedstock as woodchips, bio residues, sludge at max temperature 700 C and produce 250kg/hr biochar Produced nutrient-enriched biochar
Skjærgaarden Gartneri	Åsgårdstrand, Norway	aims to improve the soil Plant emissions measured: Per kg char: 3kg CO2, 169g CO, 172g PIC, 0.29g TSP, 2.68 NMVOC, 0.00 NOx Heat capacity: 400 kW

WAI Environmental Solutions AS	Horten, Norway	focuses on technology and knowledge transfer between Norway/Europe and China. Feedstocks as organic waste, sewage sludge, chemical sludge, drill cuttings, and contaminated sludge. Annual plant uptime: 7500 hrs/yr. Type of reactor: continuous
Norwegian Institute of Bioeconomy Research (NIBIO)	ås, Norway	researches in biochar for agricultural applications.
SINTEF Energy Research	Trondheim, Norway	production of biochar and its application in the metallurgical industry, as a fuel or soil amendment
Norwegian University of Science and Technology, Department of Energy and Process Engineering	Trondheim, Norway	researches in the field of biochar production and characterization as well as on life cycle assessment and climate impacts of biochar utilization

2.4 Effects of biochar in soils

As (Lehmann, 2007) expressed, “some biochar may decompose relatively rapidly in soils, while others persist for millennia” and “quantification of long-term stability requires long-, term observations, exceeding the periods feasible in a traditional experiment”.

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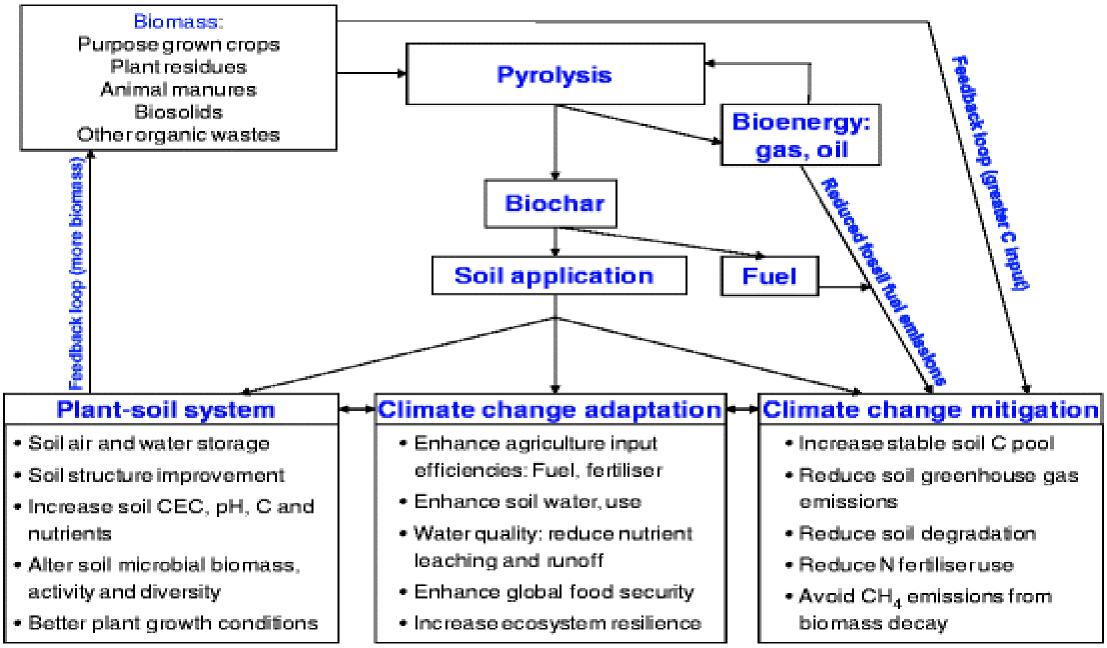


Figure 2:Potential co-benefit from Biochar Production and Application to soil (Downie, Munroe, Cowie, Van Zwieten, & Lau, 2012)

Figure 2 shows the benefits of biochar's in terms of plant-soil system, climate change adaptation, and mitigation' along with advantages of the production of useful co-products to recover the energy and aids in biomass production. Biochar reduces the soil GHGs, reduces methane emission acting as effective method to sequester the carbon.

Some more aspects of biochar are discussed below:

2.4.1 Agricultural yield and soil fertility

Biochar can have tremendous effect on growth and crop yield by liming and fertilizing in low nutrients and acidic soil of tropics, but it as low to no effects in temperate soil as they are already rich in fertility and have neutral pH(Jeffery et al., 2017). The short term application of biochar does not increase the crop yield but if applied with a combination of inorganic fertilizers than it can increase the crop yield by 11-19% i.e. biochar can act as fertilizers and liming agents(Ye et al., 2020).

Biochar amendment in soil improves the overall activities of microbes and helps in the utilization of carbon and can suppress plant diseases (Jaiswal et al., 2017).

Humic substances have a great role in soil fertility and carbon sequestration,(Spaccini, Piccolo, Conte, Haberhauer, & Gerzabek, 2002) and it can be increased by the application of biochar with compost. (J. Zhang, Lü, Shao, & He, 2014).

2.4.2 Soil water retention

An arid/semi-arid zones with low organic carbon soil shows an improvement of water retention capacity on the amendment of biochar as it influences the soil properties by increasing the soil porosity, aggregate stability, water holding, capacity, and saturated hydraulic conductivity (Omondi, 2016).

Biochar increases water availability to plant by 14 to 45% depending on soil texture (Razzaghi, Obour, & Arthur, 2019).

2.4.3 Soil contaminants

Soil rich in organic carbon; biochar amendment reduces the accumulation of Cd, Pb, Cu, Zn (heavy metals) in plant tissues specially manure derived biochar than feedstock (Chen et al., 2018).

Biochar can be a sink or source of organic and inorganic contaminates with low bioavailability of these contaminates to soil and plant. (Hilber et al., 2017).

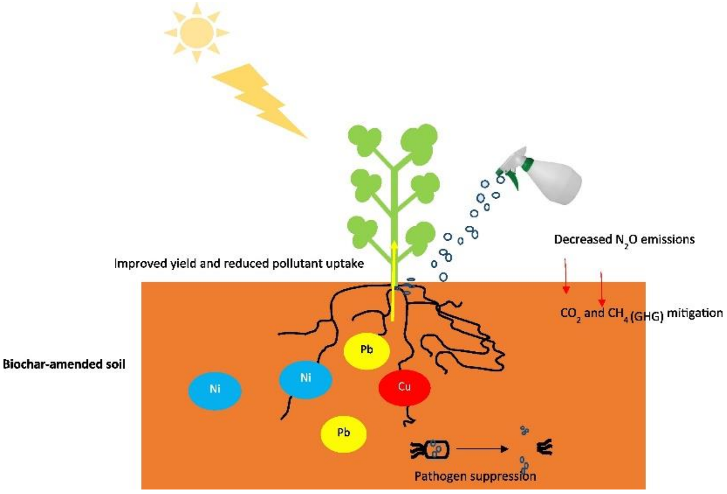


FIGURE 3: POTENTIAL POSITIVE EFFECT OF BIOCHAR AMENDMENT IN SOIL(KAVITHA ET AL., 2018)

Figure 3, shows the mitigation of Carbon dioxide methane, decreased nitrogen emission when biochar is applied in soil. it also increases the crop yields and reduced the heavy metal uptakes.

2.4.4 Biochar and soil emissions

Use of fertilizer are responsible for emissions of N_2O and NH_3 from soils. Biochar can reduce soil N_2O emissions but can have mixed effect on soil NH_3 volatilization. Biochar amendment on crop can decrease 3 to 14% of reactive Nitrogen loss globally (Q. Liu et al., 2019).

Biochar amendment altered the soil methane emissions depending on the biochar characteristics, soil types, feedstock, pH, pyrolysis temperature for instance, 12 to 84% reduction of methane depending on soil types (Ji et al., 2018).

Biochar can stabilize soil organic carbon, potentially increasing non-biochar soil carbon in soil (F. Ding et al., 2018).

Biochar has been shown to reduce soil emissions of nitrous oxide and methane which are two important GHGs (Cayuela et al., 2014; A. Zhang et al., 2010)

2.4.5 Biochar and soil albedo

Biochar reduces the albedo, by absorbing more short wave radiation from the sun at the surface, this has a warming effect counter balancing to some extent the effect of biochar’s carbon sequestration as climate mitigation method(Genesio et al., 2012). The overall climate mitigation benefit of biochar system have reduced by 13-22% due to change in albedo. (Meyer, Bright, Fischer, Schulz, & Glaser, 2012)

Biochar have some detrimental effects in soils like retention of nutrients, immobilization of pesticides, herbicides, decrease microbial growth and source of contaminates to soil but these things may be beneficial in some other types of soil. Some examples of potential negative effects are provided in table 3

TABLE 3: POTENTIAL NEGATIVE EFFECT OF BIOCHAR

Mode	Effects of biochar	Reference
Soil, microorganism, and plants	• limiting of P alter the growth of plants ▪ oxidation of biochar can create negatively charged surfaces causing higher CEC and nutrient retention depending on situation ▪ decreased the population of beneficial bacterivorous, fungivores, herbivorous nematodes ▪ biochar of sewage sludge may contain heavy metals, organic pollutants, and other toxic substances contaminate the soil	(Jeffery et al., 2017) (Liang et al., 2006) (T. Liu et al., 2020) (Lehmann et al., 2006)
Pesticides, herbicides	▪ Immobilize pesticides and herbicides increased soilborne pathogens, increase weed competition	(Nag et al., 2011) (Kavitha et al., 2018)
Germination of seedlings	▪ Volatile organic carbon and free radical of biochar may impair germination,	(Spokas et al., 2011) (Liao, Pan, Li, Zhang, & Xing, 2014)
Environment	▪ Source of contamination by bringing polyaromatic hydrocarbons (PAHs), dioxins, VOCs, and heavy metals depending on its feedstock and production conditions ▪ Decrease the albedo, darker soil absorbs more solar energy, aggravate climate change	(T. Dutta et al., 2017) (Hilber et al., 2017) (Qiu et al., 2015)

Environment emission	▪ biochar can increase soil dust emissions of particles <10 µm (PM_{10}) possess elevated levels of toxic chemicals ▪ Increase the emission of black carbon and aerosols ▪ the continues removal of crops residues to produce biochar may affect the carbon sequestration, conservation of soil and water, microbial activity, and agricultural productivity	(Gelardi, Li, & Parikh, 2019) (Ravi et al., 2016) (C. Li, Bair, & Parikh, 2018)
human	▪ increase in PM_{10} from biochar-amended soils may affect the human health	(Ravi et al., 2016) (C. Li et al., 2018)

2.5 Life-cycle assessment

Life cycle Assessment is a methodological tool to calculate the overall environmental impacts of products in its full life cycle from extraction of resources to production, use, recycling, and/or ultimate disposal (ISO, 2006a). In the life cycle chain, the inputs are energy and raw materials with outputs of useful products, final products, and by-products as well as emissions to air soil and water (Cherubini, 2010). Climate change, stratospheric ozone depletion, eutrophication, acidification, toxicological stress on human health and ecosystems, depletion of resources, water use, land use, and noise are some impacts contributed by the product in each life stages (Rebitzer et al., 2004). An important achievement during the 1990s was the publication of LCA standards in the ISO 14040 series: ISO 14040, 1997 (LCA – principles and framework); ISO 14041, 1998 (LCA – goal and scope definition, and inventory analysis); ISO 14042, 2000 (LCA – life cycle impact assessment); and ISO 14043, 2000 (LCA – life cycle interpretation). The updated ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b) replaced the previous standards and are regarded as the indispensable framework for LCA

The use of International Standard organizations (ISO)14040 series LCA consisting of four steps as goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a). LCA is an innovative method which can accurately determine and address the impacts of the whole process or production cycle on the environment (Parra-Saldivar, Bilal, & Iqbal, 2020)

2.5.1 Use of LCA

The international standard ISO 14040 lists the following applications for LCA:

- identification of opportunities to improve the environmental performance of products at various points in their life cycle;
- information to decision-makers in industry, government or non-government organizations (e.g. for strategic planning, priority setting, product or process design or redesign);
- selection of relevant indicators of environmental performance, including measurement techniques; and marketing (e.g. implementing an eco-labeling scheme, making an environmental claim, or producing an environmental declaration).

2.5.2 Structure of LCA methodology

LCA methodology is divided into four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation.

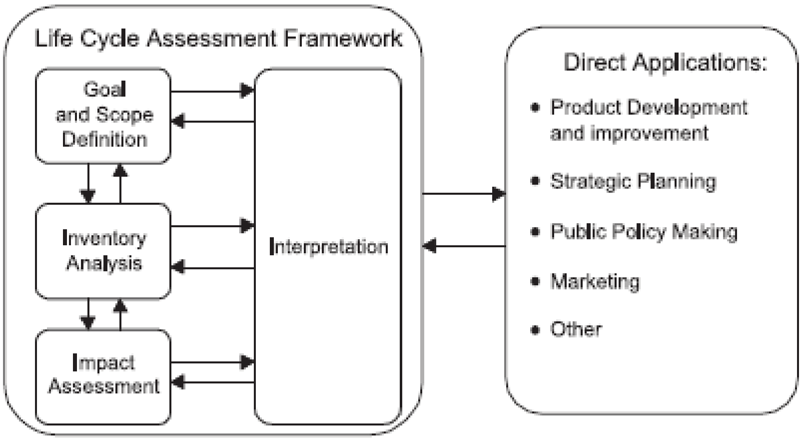


FIGURE 4: PHASES OF LCA (ISO, 2006A)

2.6 Review of LCA studies of biochar

Table 4 showed some results of the LCA of biochar with more focus on Climate change mitigation. Most of the results have negative values of GHG which means the net avoided emission of Greenhouse gas and positive values means net emissions of GHGs. Some research also considers the positive impacts of biochar’s in soil and crop yield or how increasing pyrolysis temperature increases the stability of biochar in soil. Regarding economic losses, transportation is one of the burdens among some paper. Also, the plantation, feedstock collection, transportation, pyrolysis processes play an important role in the emission of GHG emission. The energy recovery is higher in higher temperature but yields less char and have decreased environment performance. Similar things are focused in this thesis with the comparison between two pyrolysis temperature as 350°C and 650°C to evaluate the climate change potential and environment performance. Some differences in pyrolysis temperature as low pyrolysis accumulate more tars and organic compounds with more phytotoxins (Gell, van Groenigen, & Cayuela, 2011).The increasing pyrolysis temperature yields more stable biochar in all feedstock types. The wood feedstock can produce more stable biochar hence helps in carbon sequestration whereas biochar’s from animal manure are mostly rich in nutrients, which can be best for agriculture. (Conz, Abbruzzini, Andrade, Milori, & Cerri, 2017).

TABLE 4: LCA STUDIES OF BIOCHAR

Topic	Remark
Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential (Roberts et al., 2010)	▪ Net GHG emissions of corn Stover and yard waste biochar's were negative as -864 and -885 kg Co2 eq/ tonne dry feedstock, ▪ 62-66% reduction due to carbon sequestration by biochar whereas switchgrass act as net GHG emitter +36 kg Co2 eq if GHG emissions associated with indirect land-use change are modelled ▪ Transportation acts as hurdles for economic profitability
Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK (Hammond et al., 2011)	▪ Carbon abatement of 0.7–1.3 t CO2 equivalent/oven dry tonne of feedstock ▪ 43% of the carbon in the biochar remains stable
Pyrolysis biochar systems for recovering biodegradable materials: A life cycle carbon assessment (Ibarrola et al., 2012)	• Poultry Litter: high degradability rate of biochar, more Nitrogen, more char, less liquid, high in organic matter, good for agriculture • Pine residues: inhibit microbial growth, good for carbon sequestration
Life cycle perspective of bio-oil and biochar production from hardwood biomass; what is the optimum mix and what to do with it? (Lu & El Hanandeh, 2019)	• Environmental performance decreases with increasing pyrolysis temperature due to reduced biochar yield and increasing energy consumption for pyrolysis ▪ Life cycle cost reduced with increasing temperatures as bio-oil have more economic value than biochar ▪ GHG offset of 1050and 1680 kg CO2 per tonne feedstock were observed at 300 to 500 ▪ More energy is recovered at 600 than 300 C

Life cycle environmental impact assessment of biochar-based bioenergy production and utilization (Homagain, Shahi, Luckai, & Sharma, 2015)	▪ Reduces the GHG emission by 68.19 kg co2 per tonne of biochar, improves ecosystem quality, reduce climate change and human toxicity ▪ about 75 % of the total GHG emissions was from biomass collection, transportation, and pyrolysis processes
Environmental hotspots in the life cycle of a biochar soil system (Muñoz, Curaqueo, Cea, Vera, & Navia, 2017)	▪ Biochar amendment on soil reduces GHG up to 2.67-2.74 t CO2 eq/t of wood residues at 300 and 500 ▪ Transportation contributes environmental loads whereas Carbon storage, natural gas avoided, and urea avoided creates environmental benefits
A life cycle assessment of the environmental and economic balance of biochar systems in Quebec (B. Dutta & Raghavan, 2014)	▪ Corn fodder show better on emission than forest residues ▪ Increasing pyrolysis temperature is suited for carbon sequestration ▪ 38.6% and 44.3% of electricity and heat generation is higher in corn fodder than forest residues
Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm.(Azzi, Karltun, & Sundberg, 2019)	▪ Mitigation of 10 -20 % can be seen in biochar with animal husbandry than direct soil incorporation ▪ Reduces GHG intensity of 0.25 -1 tCo2 eq/t feedstock
LCA and environmental valuation of biochar production two cases studies in Belgium (Rajabi Hamedani et al., 2019)	▪ Willow shows better results than pig manure in all environmental impact categories and monetary values also. ▪ (−2063 vs. −472 kg CO2 eq /t GHG from willow and pig manure

Life cycle assessment of biochar produced from forest residues using a portable system (Puettmann, Sahoo, Wilson, & Oneil, 2020)	▪ (-0.10–1.63 tonne CO_2eq./tonne of residues) of GWP produced from forest residues ▪ can reduce environmental impacts (2–40 times lower net CO_2eq. emissions) compared to slash burning.

3. Material and Methods

The keyword like biochar, LCA, pyrolysis temperature, Biochar carbon sequestration, forest residues in Norway was used to perform the broad search of the literature within google scholar, Elsevier, ResearchGate, Web of Science, Wilney Online library e.tc. The focus was made in all sorts of relevant articles from 2000 to 2020. LCA standard was followed for the evaluation of the pyrolysis process for biochar production at Two scenarios 350°C and 650°C. This includes review of LCA of biochar, table 4 along with the explanation of structure of LCA methodology as Goal and Scope, Inventory Analysis, Impact Assessment as in Figure 3.

3.1 Goal and Scope

The goal of this thesis is to analyze the environmental impacts to produce 1kg of biochar from the forest residues through the slow pyrolysis. The use of SimaPro, Ecoinvent database helps in result processing. Heat and biochar are the output of the system. Excess heat from the combustion of bio-oil and gas is assumed to displace district heating produced from natural gas. This study applied an LCA approach to compare the GHG emission from biochar production at pyrolysis temperatures 350°C and 650°C. The temperature has a huge impact on the amount and quality of final pyrolysis products (Crespo, Naranjo, Quitana, Sanchez, & Sanchez, 2017). The use of lower and higher temperature helped to know the variation in pyrolysis results. The **functional unit** of biochar LCA is a production of 1kg of biochar.

3.2 System boundary

for the LCA of biochar begins with the pyrolysis of feedstocks and end up in its results. Current work was to develop inventories for pyrolysis at 350°C and 650 °C, as shown in the white square in figure 4. Modelling of the feedstock provision for the pyrolysis (forest residues) was taken from previous work by (Cavalett & Cherubini, 2018) And are represented by the silviculture and forestry inputs in figure 5. The LCA ends with the handling of the two products of pyrolysis: (1) biochar which is assumed to be spread on field, but was not modelled in the current work and (2) excess heat from combustion of bio-oil and gas that is assumed to displace need for district heating produced from natural gas in Norway.

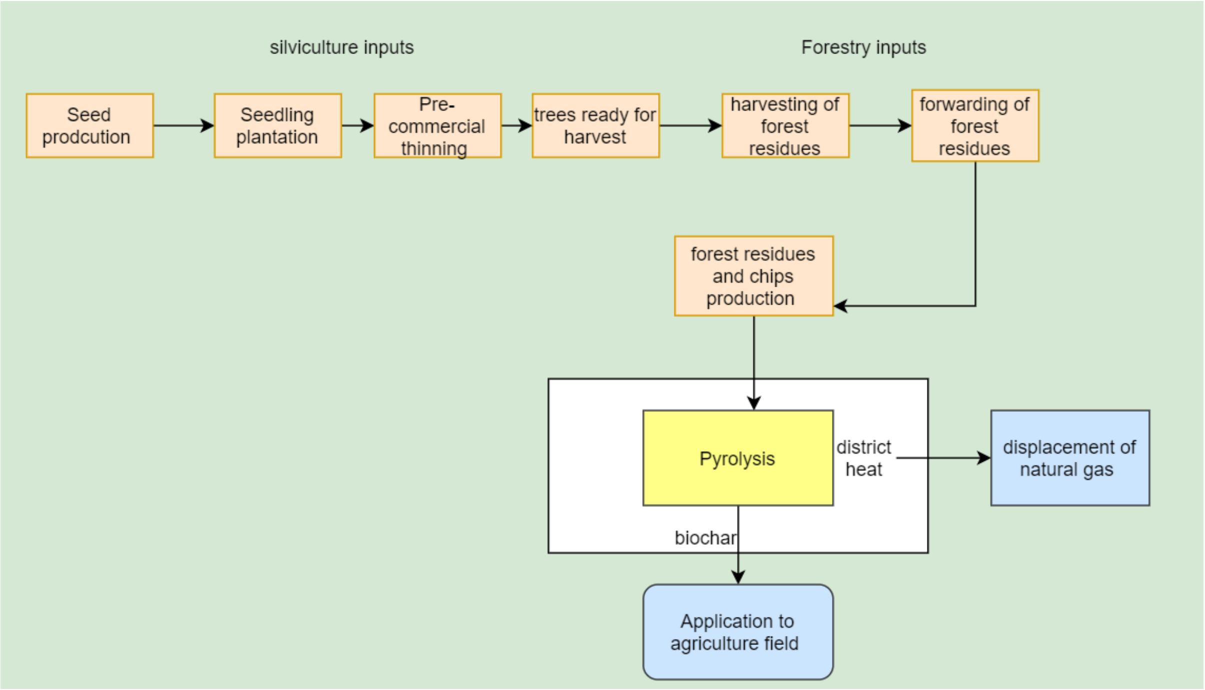


FIGURE 5: SYSTEM BOUNDARY FOR LIFE CYCLE ASSESSMENT (LCA) OF BIOCHAR PRODUCTION (CAVALETT & CHERUBINI, 2018)

3.3 Mass, carbon and energy balance

Mass, carbon, and energy balance data for the pyrolysis and biochar production was taken from(Crombie & Mašek, 2015), based on their results on yield and energy content for wooden pellet at 350°C and 650°C. Based on their biochar yields, 2.23 kg and 3.03 kg of feedstock are used to produce 1 kg of biochar at a temperature of 350°C and 650°C respectively Table 5 explained the percentage of results from the pyrolysis process to calculate per kg of biochar for this thesis.

TABLE 5: PYROLYSIS TEMPERATURE AND THEIR RESULTS

Pyrolysis temperature	**Biochar %**	**Bio-oil %**	**Gas %**	**Reference**
350°C	44.8	34.8	20.8	(Crombie & Mašek, 2015)
650°C	33.3	43.85	22.85	

This helped to calculate the carbon input for this work as 53.7% of carbon is contained in dry wooden pellet, hence the carbon balance was done with the reference of Crombie paper, using the carbon content in the different products of the pyrolysis. The conversion of carbon to carbon dioxide can be achieved by the multiplication of carbon with 44/12. Carbon in biochar is assumed to represent a fossil carbon storage and is therefore accounted as negative. Carbon contained in the bio-oil and gas from pyrolysis is assumed to be released as biogenic carbon as it is burned for energy recovery. Biochar's stability over 100 years was assumed following the current proposed guidelines for biochar stability by the IPCC. Their recommended values are to account that 65% and 89% of the carbon in biochar produced at temperature below 350°C and above 650°C respectively will remain in soils after 100 years (IPCC, 2019)

TABLE 6: PYROLYSIS TEMPERATURE WITH STORED AND BIOGENIC CARBON DIOXIDE

Pyrolysis temperature	Stored CO2 in biochar (kg CO2 eq)	Biogenic CO2 emitted (kgCO2 eq)	Biochar carbon stable over 100 years in soil (kg CO2 eq)
350°C	-2.27	1.64	-1.48
650°C	-2.56	2.78	-2.28

The energy balance was done using the higher heating value of 17.6 MJ/kg for the wooden feedstocks and other HHV values of pyrolysis results from Crombie, 2015. It was assumed that 8% of the feedstock higher heating value (HHV) was required to maintain the pyrolysis reaction(Crombie & Mašek, 2014). This energy was subtracted from the heat that could be recovered from burning the bio-oil and gas produced during the pyrolysis. The excess heat (HHV contained in the co-products minus pyrolysis energy needs) are assumed to produce district heating at an efficiency of 80%.

TABLE 7: PYROLYSIS TEMPERATURE AND ENERGY

Pyrolysis temperature	Heat required to run pyrolysis (MJ)	Recoverable heat from the co-products combustion (MJ)	Recover heat with assumed 80% efficiency (MJ)
350°C	3.13	3.23	2.584
650°C	4.26	8.2	6.56

3.4 Inventory

Data were collected from through the scientific literature mainly of Crombie,2015 for the balancing of mass, carbon, and energy as explained in the above paragraph. The Inventories related to feedstock production, harvesting, and chipping and collection were taken from the Cavalett (Cavalett & Cherubini, 2018). The production of wood residues includes activities like plantation, several intercultural operations, harvesting, chipping, and drying which need lots of inputs like seeds, fertilizers, machinery operations, dryer and transportation, fuel etc., these processes may emit more and may have effects on several impact categories.

Construction of the pyrolysis plant was modelled using the process Furnace Production, 1MW soft woodchips in Eco Invent. At 17.6 MJ of wood chips feedstock, 1MW correspond to about 204.55 kg/hour of feedstock, and a production of 91.65, and 67.50 kg biochar per hour at 350 deg C and 650 deg C respectively. 25 years of operation for the plant at 7500hr/year was assumed. This corresponds to furnace production of a 5.82E-08 and 7.90E-08 unit/kg biochar respectively for the two givens temperature.

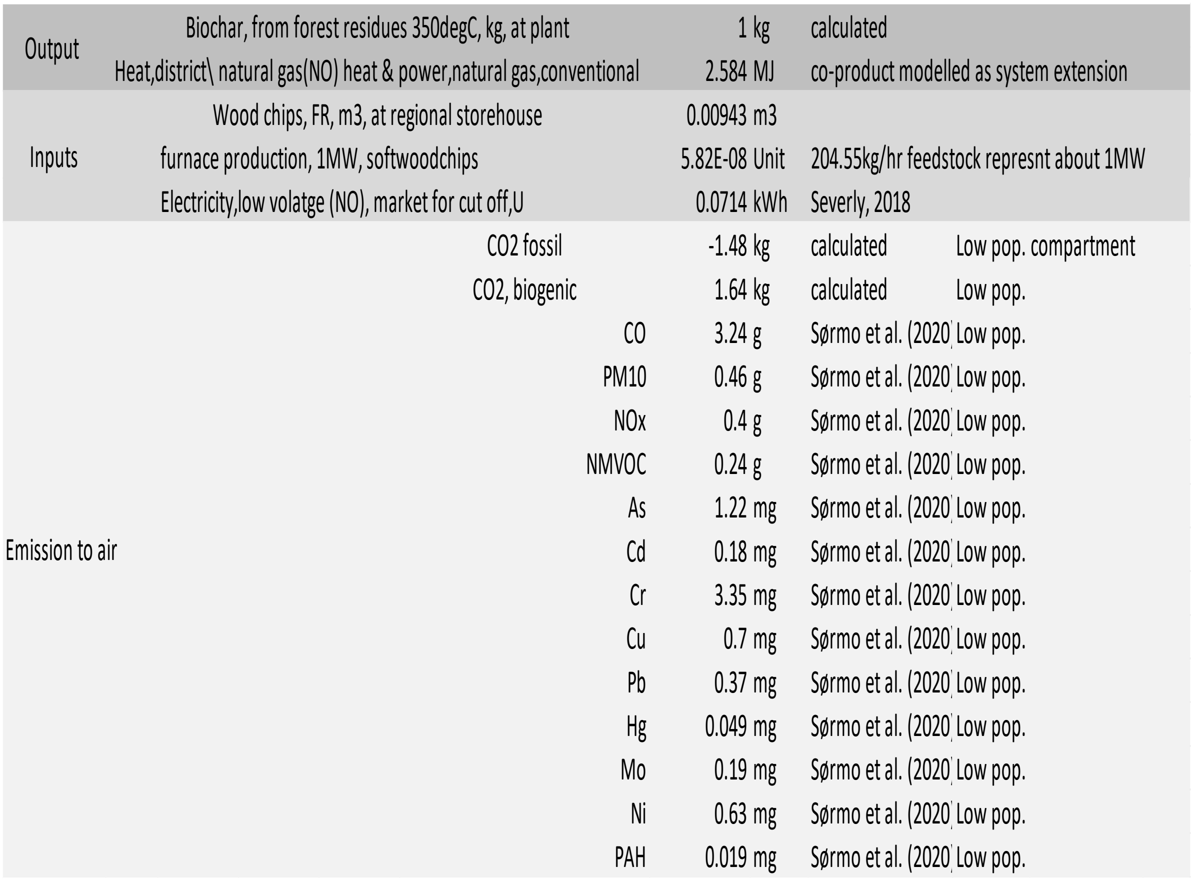
The transport distance was assumed to be 160 kilometres (0.160tkm) which are close to transport distance assumed for the Norwegian industry in LCAs as 120 kilometres (Michelsen, Solli, & Strømman, 2008).

In Ecoinvent, the feedstock must be in m^3, the wet density of wood is 236.6 kg/m^3, so for calculation of the woodchips at the regional storehouse, the feedstock is divided by the density, 0.00943 m^3 and 0.0128 m3 of woodchips at pyrolysis temperature 350 C and 650C.

Power consumption for the plant was taken from a pyrolysis pilot plant experiment by (Severy et al., 2018) were the average power consumption for the double auger reactor was used. An average of 4.5 kW of power was used to produce 63 kg/hr biochar, which corresponds to 0.0714 kWh/kg biochar and was assumed to be taken from the low voltage of the Norwegian market, Cut -off. Respectively 0.718 and 1.822 kWh of heat was assumed to be recovered, displacing Norwegian district heating from natural gas.

Regarding emissions during pyrolysis, emission factors for wood pyrolysis were taken from (Sørmo et al., 2020) for carbon monoxide (CO), methane (CH4), non-methane volatile or organic carbon (NMVOC), nitric oxides (NOx) and Particulate matters (< 10 um, PM10) and the emissions of metals like As, Cd, Cr, Cu, Pb, Hg, Mo, Ni and PAH values. As (Sørmo et al., 2020), run the pyrolysis at 600°C, their emissions factors should be in the range for our 650°C scenario. However, at 350°C, less feedstock is required to produce 1 kg biochar compared to at 650°C. That means that less heavy metals come into the reactor, and less bio-oil and gas is produced per kg of biochar produced. For these reasons we adjusted the emission factors from (Sørmo et al., 2020) for biochar production at 350. As a proxy, we adjust the emission factors based on the relative input of feedstock: we use 0.73 times less feedstock at 350°C compared 650°C, so the emission factors are corrected with the same factor.

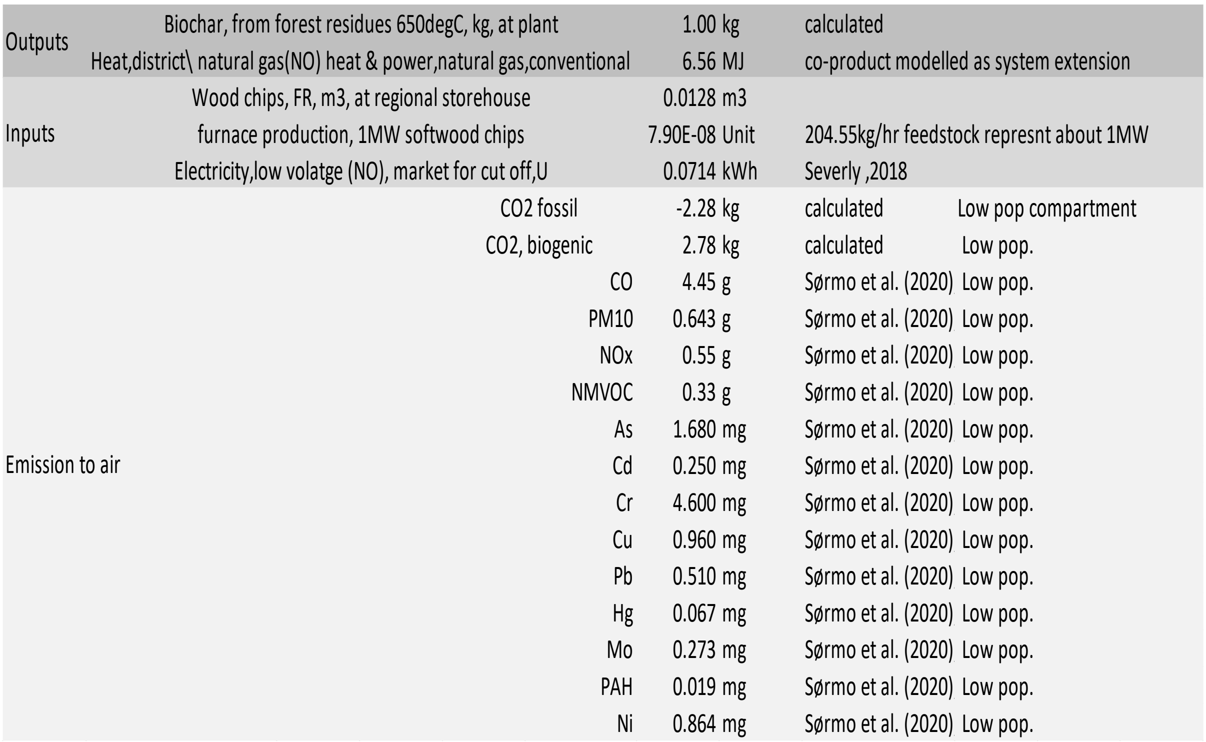
TABLE 8: INVENTORY DATA FOR 1 KG OF BIOCHAR PRODUCTION AT PYROLYSIS TEMP 350°C



Output	Biochar, from forest residues 350degC, kg, at plant	1 kg	calculated	
	Heat,district\ natural gas(NO) heat & power,natural gas,conventional	2.584 MJ	co-product modelled as system extension	
Inputs	Wood chips, FR, m3, at regional storehouse	0.00943 m3		
	furnace production, 1MW, softwoodchips	5.82E-08 Unit	204.55kg/hr feedstock represnt about 1MW	
	Electricity,low volatge (NO), market for cut off,U	0.0714 kWh	Severly, 2018	
Emission to air	CO2 fossil	-1.48 kg	calculated	Low pop. compartment
	CO2, biogenic	1.64 kg	calculated	Low pop.
	CO	3.24 g	Sørmo et al. (2020	Low pop.
	PM10	0.46 g	Sørmo et al. (2020	Low pop.
	NOx	0.4 g	Sørmo et al. (2020	Low pop.
	NMVOC	0.24 g	Sørmo et al. (2020	Low pop.
	As	1.22 mg	Sørmo et al. (2020	Low pop.
	Cd	0.18 mg	Sørmo et al. (2020	Low pop.
	Cr	3.35 mg	Sørmo et al. (2020	Low pop.
	Cu	0.7 mg	Sørmo et al. (2020	Low pop.
	Pb	0.37 mg	Sørmo et al. (2020	Low pop.
	Hg	0.049 mg	Sørmo et al. (2020	Low pop.
	Mo	0.19 mg	Sørmo et al. (2020	Low pop.
	Ni	0.63 mg	Sørmo et al. (2020	Low pop.
	PAH	0.019 mg	Sørmo et al. (2020	Low pop.

In table 8, there are inputs like wood chips, furnace production, and electricity with the emission of biogenic and fossil carbon dioxide, several gases, metals and PAH to produce the 1 kg of biochar and 2.584 MJ of heat from coproduct.

TABLE 9: INVENTORY DATA FOR 1 KG OF BIOCHAR PRODUCTION AT PYROLYSIS TEMP 650°C



Outputs	Biochar, from forest residues 650degC, kg, at plant	1.00 kg	calculated	
	Heat,district\ natural gas(NO) heat & power,natural gas,conventional	6.56 MJ	co-product modelled as system extension	
Inputs	Wood chips, FR, m3, at regional storehouse	0.0128 m3		
	furnace production, 1MW softwood chips	7.90E-08 Unit	204.55kg/hr feedstock represnt about 1MW	
	Electricity,low volatge (NO), market for cut off,U	0.0714 kWh	Severly ,2018	
Emission to air	CO2 fossil	-2.28 kg	calculated	Low pop compartment
	CO2, biogenic	2.78 kg	calculated	Low pop.
	CO	4.45 g	Sørmo et al. (2020)	Low pop.
	PM10	0.643 g	Sørmo et al. (2020)	Low pop.
	NOx	0.55 g	Sørmo et al. (2020)	Low pop.
	NMVOC	0.33 g	Sørmo et al. (2020)	Low pop.
	As	1.680 mg	Sørmo et al. (2020)	Low pop.
	Cd	0.250 mg	Sørmo et al. (2020)	Low pop.
	Cr	4.600 mg	Sørmo et al. (2020)	Low pop.
	Cu	0.960 mg	Sørmo et al. (2020)	Low pop.
	Pb	0.510 mg	Sørmo et al. (2020)	Low pop.
	Hg	0.067 mg	Sørmo et al. (2020)	Low pop.
	Mo	0.273 mg	Sørmo et al. (2020)	Low pop.
	PAH	0.019 mg	Sørmo et al. (2020)	Low pop.
	Ni	0.864 mg	Sørmo et al. (2020)	Low pop.

In table 9, there are inputs like wood chips, furnace production, and electricity with the emission of biogenic and fossil carbon dioxide, several gases, metals and PAH to produce the 1 kg of biochar and 6.56 MJ of heat form coproduct.

3.5 Impact assessment

The impact assessment was performed using the SimpaPro software and following the methodology of ReCiPe 2016 Midpoint (H) V1.03/World (2010) H midpoint. The impact categories were analysed between the two-pyrolysis temperature where more focused was given to global warming (kg Co_2 eq). These results were characterized and interpreted in terms of define impact categories.

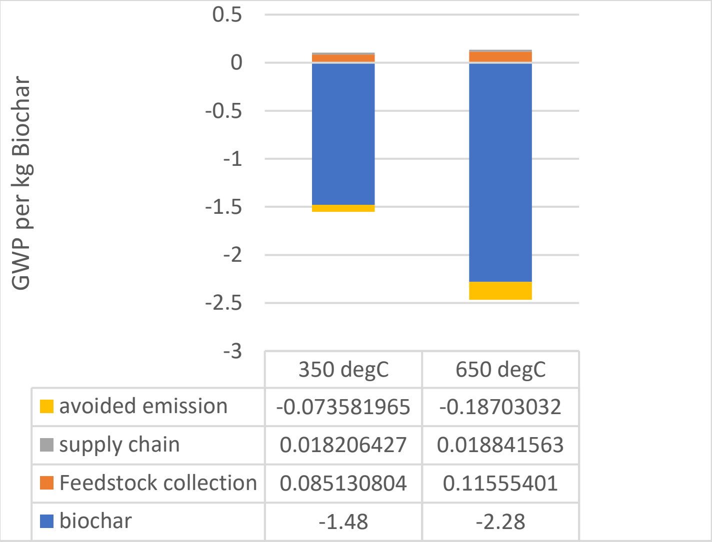
4. Results and discussion

Here we show the obtained results with the discussion based on Global warming potential and other impact categories and potential of Norway to sequester carbon dioxide.

4.1 Global warming potential

Here, Figure 6 presents the contribution of the different life-cycle stages of biochar production for climate change impact category.

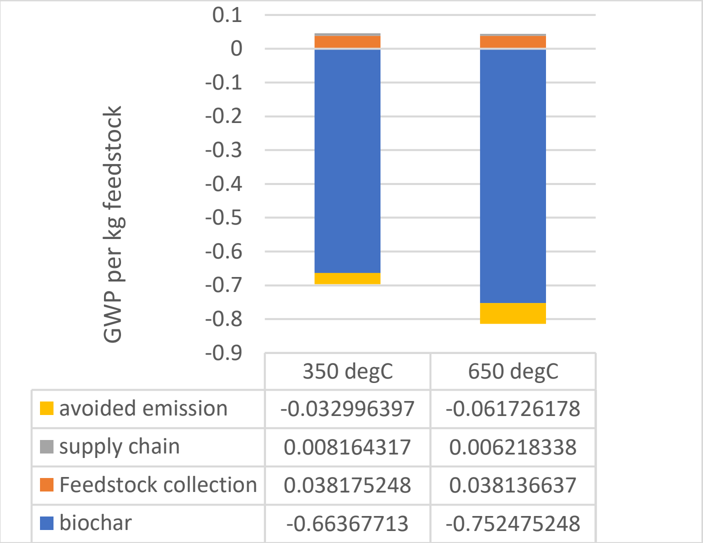
The supply chain corresponds to processes like a furnace production, feedstock transport, and electricity which have similar impacts on GWP for both temperatures and are very low. The biochar acting as carbon sequestration have negative impacts on GWP, there is almost double negative CO_2 equivalent at temperature 650°C. The per kg biochar produced from 650°C can reduce GHG emission more than 350°C (2.28 kg CO_2 eq vs 1.48 kg CO_2 eq) because the stable carbon content of 650°C is 24% higher than 350°C (IPCC, 2019). The avoided use of natural gas in district heating also leads to negative emission. At 650°C more natural gas use is avoided compared to at 350°C, because it produces more bio-oil and oil and gas, which means there is more energy output which can be used to substitute as heat or natural gas.



	350 degC	650 degC
🟨 avoided emission	-0.073581965	-0.18703032
⬜ supply chain	0.018206427	0.018841563
🟧 Feedstock collection	0.085130804	0.11555401
🟦 biochar	-1.48	-2.28

FIGURE 6: CONTRIBUTION OF DIFFERENT LIFE-CYCLE STAGES OF BIOCHAR PRODUCTION ON CLIMATE CHANGE PER KG BIOCHAR AT 350 °C AND 650 °C

Figure 7 compare the GWP based on per kg feedstock with different processes, avoided emission at pyrolysis 650°C has greater negative value in GWP contribution than at pyrolysis 350°C.The feedstock collection and supply chain being positive values contribute to GWP with the fewer differences from each other. The production of -0.66 and -0.76 kg CO_2 eq per kg feedstock is obtained from the pyrolysis process at 350°C and 650°C respectively which can be written as -650 and -760 kg CO_2 eq/ tonne dry feedstock. This can be compared with the experiment done by (Roberts et al., 2010) where net GHG emissions of corn stover and yard waste biochar were negative as -864 and -885 kg CO_2eq/ tonne dry feedstock. A similar type of results observed where the net GWP in biochar produced around 100–1630 kg CO_2eq /tonne of forest residues as the pyrolysis takes place around 680-750°C (Puettmann et al., 2020).



	350 degC	650 degC
🟨 avoided emission	-0.032996397	-0.061726178
⬜ supply chain	0.008164317	0.006218338
🟧 Feedstock collection	0.038175248	0.038136637
🟦 biochar	-0.66367713	-0.752475248

FIGURE 7: CONTRIBUTION OF DIFFERENT LIFE-CYCLE STAGES OF BIOCHAR PRODUCTION ON CLIMATE CHANGE PER KG FEEDSTOCK AT TEMP 350 °C AND 650°C

When the comparison is done between the per kg biochar and per kg feedstock (Figure 6 & Figure 7), there are fewer impacts from all the processes on GWP for per kg feedstock even in biochar production also. The contribution of biochar production for GWP has a difference of around 0.82 kg CO2eq and 1.53 kg CO2eq per kg feedstock at 350°C and 650°C. The biochar yield will decrease from 51.2% to 16% with the increasing pyrolysis production(Lu & El Hanandeh, 2019). At 350°C there is a high production of biochar and more energy contained in it whereas at 650°C there is less biochar and more energy contained in gas and liquid which can be used for heat generation. The choice of temperature can be dependent on the choices of outputs as biochar or heat. The higher temperature generates more energy and more stable carbon (Crombie & Mašek, 2015).

The net climate mitigation is calculated by the subtraction of carbon sequestration and emission i.e. (avoided emission + biochar production)- (feedstock collection+ supply chain). Hence the net climate mitigation for pyrolysis 350 °C and 650 °C is 0.644 kg CO_2eq per kg feedstock and 0.76 kg CO_2eq pe kg feedstock, respectively.

As Norway have wood residues of 1.7M tonnes dry basis per year (Cavalett & Cherubini, 2018), hence the potential of net climate mitigation for Norway at pyrolysis temperature 350 °C and 650 °C will be between 1.1 Mt CO_2 eq/yr and 1.3 Mtonnes CO_2 eq/yr. In 2019, 50 Mtonnes of CO_2 equivalents were released in Norway, (Statistics, 2019). Biochar in Norway could represent reduction in GHG emissions of between 2.2 and 2.6%. Also 4.4 Mtonnes of CO_2 equivalents were released by Agriculture in Norway (Statistics, 2019) that means a simple biochar production can make huge difference in reduction of GHG in soil or from agriculture in Norway, by offsetting between 25 and 30% of agricultural GHG emissions in Norway.

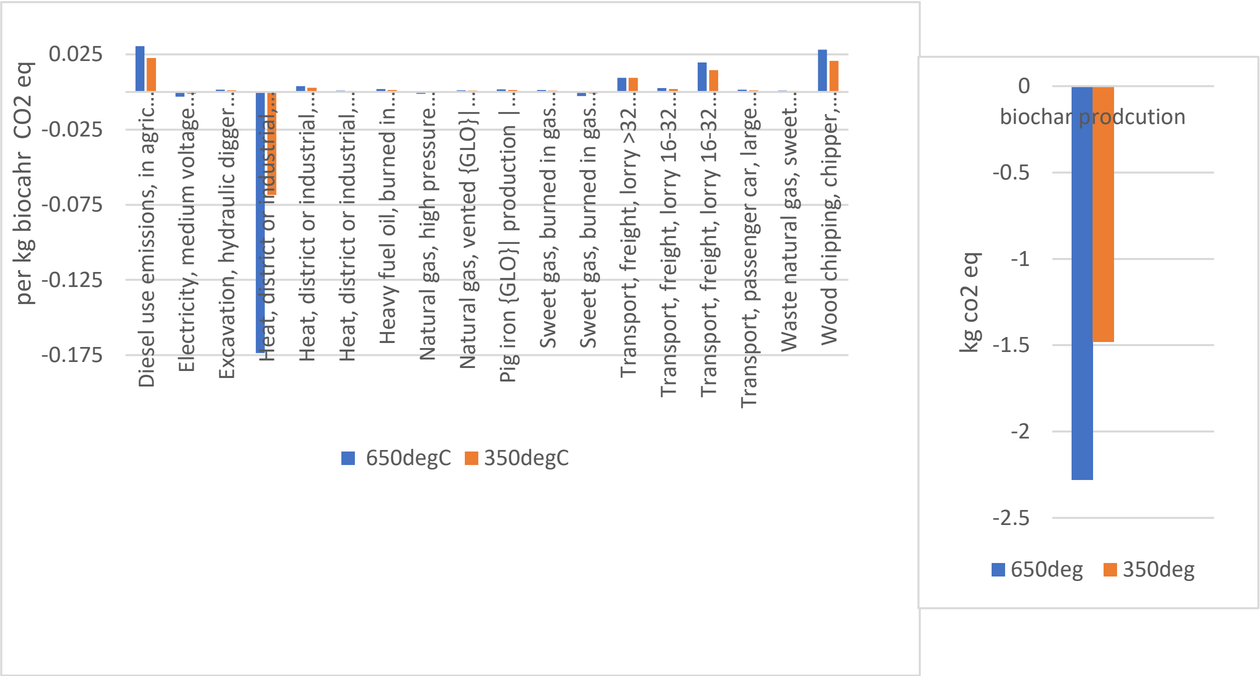


FIGURE 8: CONTRIBUTION OF PROCESSES FOR 1 KG BIOCHAR PRODUCTION AT PYROLYSIS TEMPERATURE 650°C AND 350°C

Figure 8, The graph showed the increasing GWP impacts by the several processes like diesel use emission in agriculture, transportation, wood chipping, heat use e.tc, higher at 650 than 350.per kg cO2. Impacts on climate change are higher at 650°C than 350°C. Regarding the avoided use of natural gas in district heating, an additional 0.1 kg CO2eq is saved between pyrolysis at 350°C and 650°C.shows the contribution of GWP impacts by the several processes like diesel use emission

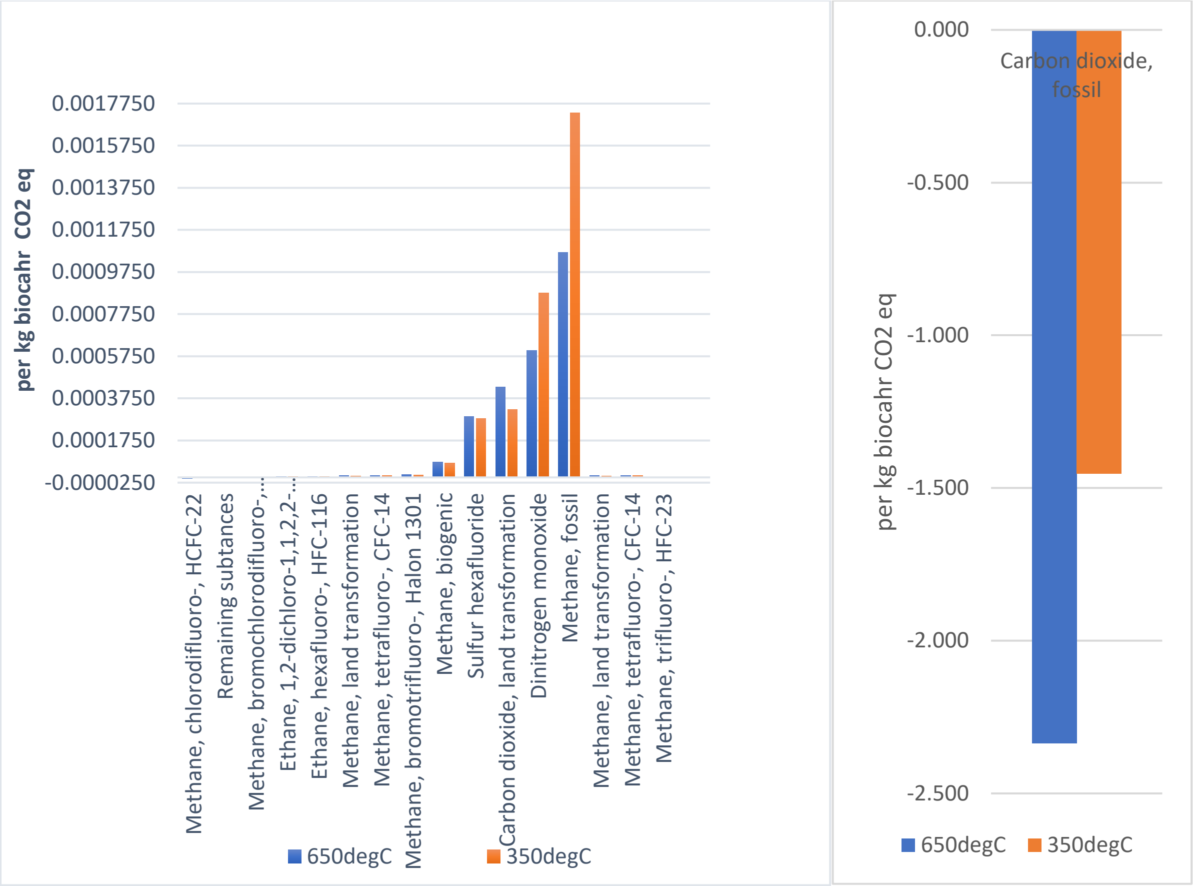


FIGURE 9:IMPACTS OF STRESSORS TO PRODUCE 1 KG BIOCHAR AT PYROLYSIS 650°C AND 350°C

Figure 9 explained the stressors that contributed to global warming in all the above processes. carbon dioxide fossil occupying a huge space on a graph(negative) with the potential of carbon sequestration, higher at 650°C. The substances like methane fossil, Dinitrogen monoxide influences the processes like feedstock collection, supply chain and avoided emissions mostly at 350°C followed by sulphur hexafluoride, biogenic methane similar on both temperatures but at a small unit of per kg biochar CO_2 eq. Similarly, the carbon dioxide land transformation at 650°C is more

4.2 Other impact categories

The characterization results of the life cycle impact assessment for the pyrolysis at 350°C and 650°C in terms of midpoint categories are shown in table 10.

Here the positive value means the burden to the environment whereas negative means environmental savings. Here global warming, fossil resource scarcity was reduced at 650°C compared to 350°C (-2.34 vs -1.46 kg CO_2 eq) and (-0.037 vs 0.0024 kg oil eq) respectively. More district heating can be displaced with pyrolysis at 650°C compared to 350°C, reducing and even offsetting the impacts in Fossil resource scarcity, due to avoided natural gas use. Because more energy can be recovered from the bio-oil and gas at 650°C than at 350°C. the more use of feedstock to produce one kg biochar at 650°C compared to 350°C, it requires more diesel use, transportation, wood chipping, land occupation, agricultural activities which emits more in all impact categories.

TABLE 10: IMPACT ASSESSMENT FOR DIFFERENT IMPACT CATEGORIES AT PYROLYSIS TEMP 350C AND 650

Impact category	Unit	350 °C	650 °C
Global warming	kg CO2 eq	-1.450245	-2.332407
Stratospheric ozone depletion	kg CFC11 eq	0.000000	0.000000
Ionizing radiation	kBq Co-60 eq	0.002855	0.003388
Ozone formation, Human health	kg NOx eq	0.000537	0.000641
Fine particulate matter formation	kg PM2.5 eq	0.000125	0.000151
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000572	0.000687
Terrestrial acidification	kg SO2 eq	0.000319	0.000386
Freshwater eutrophication	kg P eq	0.000010	0.000011
Marine eutrophication	kg N eq	0.000001	0.000001
Terrestrial ecotoxicity	kg 1,4-DCB	2.249146	2.953853
Freshwater ecotoxicity	kg 1,4-DCB	0.003058	0.003291
Marine ecotoxicity	kg 1,4-DCB	0.004646	0.004923
Human carcinogenic toxicity	kg 1,4-DCB	0.003060	0.003702
Human non-carcinogenic toxicity	kg 1,4-DCB	0.067288	0.081595
Land use	m2a crop eq	0.003036	0.003599
Mineral resource scarcity	kg Cu eq	0.000295	0.000354
Fossil resource scarcity	kg oil eq	0.002316	-0.036822
Water consumption	m3	0.002322	0.002191

For all other impact categories, pyrolysis at 350°C shows small differences than pyrolysis at 650°C in table 10 but **Terrestrial ecotoxicity** have difference of around 70%. The stressors for this impact are Copper followed by Nickel, mercury, Cadmium, lead and zinc respectively as shown in figure 8. Also the contribution for terrestrial ecotoxicity emission can come from fertilization and agricultural machinery for production of feedstock (Rajabi Hamedani et al., 2019). The differences of 0.70 kg 1,4-DCB is observed in terrestrial ecotoxicity at pyrolysis 350°C and 650°C. Heavy metals and other contaminants released from biochar production can affect the environment and living beings. (T. Dutta et al., 2017)

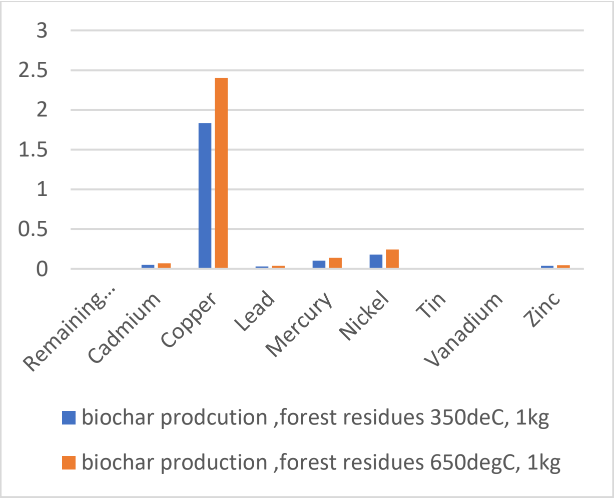


FIGURE 10 CONTRIBUTION OF SUBSTANCES IN TERRESTRIAL ECOTOXICITY FOR PRODUCTION OF 1KG BIOCHAR

In the inventory of pyrolysis we adjusted the emission factors measured by (Sørmo et al., 2020). It was assumed a linear relationship between the amount of feedstock used and the emissions. However, this may not be the case as pyrolysis product yields does not necessarily follow a linear relationship with pyrolysis temperature (Lu & El Hanandeh, 2019)The pyrolysis temperature is also an important determinant for the volatilization and fate of inorganic compounds in biomass (Leijenhorst, Wolters, Beld, & Prins, 2016), with lower pyrolysis temperature usually lowering heavy metals fate to oil and gas.

5. Conclusion

Due to higher biochar stability and more energy recovery at pyrolysis at 650°C compared to 350°C, more climate mitigation is achievable with pyrolysis at 650°C than 350°C. On the other hand, due to lower biochar yield at 650°C, more feedstock is required than at 350°C, which leads to decrease the environmental benefits in most of the impact categories. The higher pyrolysis temperature increased the stability of carbon yields and shifts the energy contribution to gas and liquid co products at 650°C. The stability of biochar at 650°C is higher than of 350°C (2.28 kg CO2 eq vs 1.48 kg CO2 eq) per kg of biochar. Overall, 1,5 times more climate mitigation benefit can be achieved by biochar produced at 650°C compared to biochar produced at 350°C. Most of the differences is observed in impact categories like Global warming, Terrestrial ecotoxicity, fossil resource scarcity. Terrestrial ecotoxicity seems higher than other impact categories in 650°C, which have more emission of heavy metals like copper, cadmium, lead, mercury.

Present work only considered the pyrolysis, in the future one could include in the model ; the transport of the biochar to the field and its incorporation to soils with the accounts of different aspects like effect of albedo, effect of soil carbon priming, reduction of soil methane, nitrate and fertilizer relationship.

6. References

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