Kaunas University of Technology

Institute of Environmental Engineering

Faculty of Mechanical Engineering and Design

Assessment of the Environmental Footprint of Biochar Production and Use

Master‘s Final Degree Project

Patricija Mečkovska
Project author

Assoc. prof. dr. Daina Kliaugaitė
Supervisor

Kaunas, 2023

Kaunas University of Technology

Institute of Environmental Engineering

Faculty of Mechanical Engineering and Design

Assessment of the Environmental Footprint of Biochar Production and Use

Master‘s Final Degree Project

Sustainable Management and Production (6213EX001)

Patricija Mečkovska
Project author

Assoc. prof. dr. Daina Kliaugaitė
Supervisor

Prof. dr. Jolita Kruopienė
Reviewer

Kaunas, 2023

Mečkovska, Patricija. Assessment of the Environmental Footprint of Biochar Production and Use. Master's Final Degree Project / supervisor assoc. prof. dr. Daina Kliaugaitė; Institute of Environmental Engineering; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Environmental Engineering (E03) – main study field, Production and Manufacturing Engineering (E10), Business (L01), Engineering Sciences.

Keywords: Biocharcoal, environmental footprint, life cycle assessment, carbon storage.

Kaunas, 2023. Number of pages 44.

Summary

In the face of the problem of climate warming, the need to seek sustainable methods and decarbonization technologies to reduce the damage of climate change to the environment increases. Biochar or bioenergy carbon capture and storage (BECCS) technology attracts considerable attention as a means of CO_2 storage and climate change mitigation. Biochar produced through biomass pyrolysis, which is a solid carbon material similar to charcoal, not only provides a long-term storage solution for carbon but also improves soil properties.

This research is concentrated on a comprehensive assessment of the environmental footprint and carbon storage potential of biochar production, and use, specifically comparing two different biomass sources. The cradle-to-grave analysis of life cycle emissions of biochar using Life Cycle Assessment (LCA) methodology for a functional unit of 130 kg biochar from cleft timber/sewage sludge, is performed. To produce 130 kg of biochar, 1 t of cleft timber/ 5 t of sewage sludge are used by performing pyrolysis. Four cycle phases were considered: biomass production, transport, production, and use. The SimaPro 9.1 software, Ecoinvent v.3.6 database5, PURO2 guidelines, and data from a biochar production facility based in Lithuania have been used to perform that analysis. Furthermore, the evaluation of life cycle greenhouse gas emissions was carried out by applying the IPCC GWP100a v1.03 method and assessment of impact categories by ReCiPe 2016 method.

Results present that life cycle stage biochar production in the case study is the biggest contributor to climate change, resulting in 146 kg of CO_2 eq (IPCC GWP100a v1.03 method). The same pattern is spotted in the life cycle assessment of biochar from sewage sludge, with results of 322.3 kg CO_2 eq. On the other hand, the phase biochar use, where final product biochar is used in the soil because of its gradual release of carbon resulting in progressive enrichment of the soil, generated 6.6 kg CO_2 eq in both cases. Overall, it was also indicated that the amount of carbon sequestered over a 100-year time horizon by the amount of biochar manufactured from cleft timber is equal to 425.3 kg CO_2 eq and by the biochar from sewage sludge is – 255.3 kg CO_2 eq.

Although greenhouse gas emissions are highest during biochar production in both cases, the study concludes that biochar's application in soil from cleft timber has a positive effect on the environment due to carbon storage, yet biochar from sewage sludge resulted in a negative net amount of CO_2 sequestered, meaning unsuccessful climate mitigation. Therefore, the study suggests that the biochar from cleft timber can be a viable net-negative technology for climate change mitigation, and pyrolysis of sewage sludge is a good way to manage waste before further analysis on the characteristic of biochar from sewage sludge is conducted.

Mečkovska, Patricija. Bioanglies gamybos ir panaudojimo aplinkosauginio pėdsako vertinimas. Magistro baigiamasis projektas Vadovė doc. dr. Daina Kliaugaitė; Kauno technologijos universitetas, Aplinkos inžinerijos institutas; Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Aplinkos inžinerija (E03) – pagrindinė, Gamybos inžinerija (E10), Verslas (L01), Inžinerijos mokslai.

Reikšminiai žodžiai: Bioanglis, poveikis aplinkai, gyvavimo ciklo įvertinimas, anglies sulaikymas.

Kaunas, 2023. 44 p.

Santrauka

Susiduriant su klimato šiltėjimo problema išauga poreikis ieškoti tvarių būdų, dekarbonizacijos technologijų, kaip sumažinti klimato kaitos žalą aplinkai. Bioanglies arba biogeninės anglies deginimo technologija (dar vadinama bioenergijos gamybos surenkant ir saugant anglies dioksidą technologija (angl. „Bio-Energy Carbon Capture and Storage“), sulaukia nemažai dėmesio, kaip galima CO_2 saugojimo ir klimato kaitos švelninimo priemonė. Biomasės pirolizės būdu pagaminta bioanglis – stabilaus kieto pavidalo anglis, panaši į medžio anglis – yra ne tik būdas ilgą laiką saugoti anglį, bet ir pagerinti dirvožemio savybes.

Šio tyrimo tikslas yra atlikti išsamų bioanglies gamybos ir naudojimo poveikio aplinkai ir anglies saugojimo potencialo įvertinimą, lyginant du skirtingus biogeninės anglies gamybos šaltinius: malkinę medieną ir nuotekų dumblą. Darbe atliekamas bioanglies emisijų nuo žaliavų iki galutinio naudojimo būvio ciklo vertinimas (BCV). Funkciniu vienetu pasirinktas 130 kg bioanglies kiekis. Tokio kiekio bioanglies gamybai reikalinga 1 t malkinės medienos ir 5 t nuotekų dumblo. Buvo vertinami keturi būvio ciklo etapai: biomasės gamyba, transportavimas, gamyba ir naudojimas. BCV atlikti buvo naudojama SimaPro 9.1 programinė įranga, Ecoinvent v.3.6 duomenų bazė, PURO2 gairės ir Lietuvoje esančios bioanglies gamybos įmonės duomenys. Šiltnamio efektą sukeliančių dujų emisijų vertinimas atliktas taikant IPCC GWP100a v1.03 metodą, o kitų poveikio aplinkai kategorijų vertinimas atliekamas ReCiPe 2016 metodu.

Rezultatai rodo, kad bioanglies gamybos etapas yra didžiausias klimato kaitos veiksnys, dėl kurio susidaro 146 kg CO_2 ekv. Tokia tendencija pastebima ir bioanglies iš nuotekų dumblo būvio ciklo vertinime, gamybos etape susidaro 322,3 kg CO_2 ekv. Kita vertus, naudojimo etape, kai galutinis produktas bioanglis yra naudojama dirvožemyje dėl laipsniško anglies išsiskyrimo ir laipsniško dirvožemio gerinimo, abiem atvejais susidarė 6,6 kg CO_2 ekv. Viso būvio ciklo vertinimo balanso skaičiavimai parodė, kad per 100 metų laikotarpį iš malkinės medienos pagaminta bioanglis turi potencialą surišti 425,3 kg CO_2 ekv., o bioanglis iš nuotekų dumblo anglies saugojimo savybėmis nepasižymi – 255,33 kg. CO_2 ekv.

Nors abiem atvejais šiltnamio efektą sukeliančių dujų išmetimas yra didžiausias bioanglies gamybos etape, tyrime daroma išvada, kad bioanglies panaudojimas dirvožemyje iš malkinės medienos turi teigiamą poveikį aplinkai dėl anglies saugojimo potencialo, tačiau bioanglis iš nuotekų dumblo gali būti naudojama kaip vienas iš būdų dumblo atliekų tvarkymui, bet ne CO_2 saugojimui.

Table of Contents

List of figures

List of tables

Introduction

In this day and age, the world faces a great number of pressing environmental issues, from climate change and waste management to soil degradation, and deforestation, resulting from the growing global population associated with demand for resources. The necessity to deal with these challenges has become a primary concern for governments, companies, and the current generation overall. European Green Deal and The United Nations Sustainable Development Goals (SDGs) are only two initiatives from many that contribute to the bold steps in the direction of a climate-neutral and sustainable economy.

The need of tackling worldwide phenomena such as climate change has been acknowledged in the majority of existing legislations and international treaties, which provide methods and goals for reducing its consequences. The Paris Agreement, which was ratified by almost all countries, establishes a worldwide target of 1.5 degrees Celsius for the increase in average global temperatures over pre-industrial levels. Therefore, the heightened greenhouse effect caused by human activities and the pressure of governments promote the need for a shift to sustainable alternatives, especially carbon net-negative technologies.

One of the alternatives could be biochar, which is a very stable, solid form of carbon that can persist in soil for thousands of years, making it an ideal technology for carbon removal. Biochar or bioenergy carbon capture and storage (BECCS) technology attracts considerable attention as a means of CO_2 storage and climate change mitigation. Biochar is a type of black carbon that is produced from organic waste by thermal decomposition known as pyrolysis. It has been perceived as a promising tool for carbon storage, waste management, and soil quality improvement. Nonetheless, there is still much controversy about the impact that the production and use stages of biochar have on the environment. It has not been thoroughly investigated how specifically biochar fits in as a net-negative technology. Additionally, biochar has not been fully incorporated into current frameworks despite the availability of regulations and standards governing best practices to combat climate change.

This paper examines the literature that is currently available on biochar as well as research on the environmental implications that are generated by its production and usage. Moreover, substantial and authentic data regarding biochar production was obtained from the company working in this particular industry. On the basis of that review and gathered data, the environmental footprint of biochar production, and use is investigated through a Life Cycle Assessment (LCA) approach. The impact on the environment is assessed not only in terms of CO_2 emissions but also considers other categories, including the exploration of alternative raw materials derived from existing waste, specifically sewage sludge in the case of Lithuania. The findings of this research provide important light on the viability of biochar.

Project Object biochar system

Project Aim is to conduct a comprehensive assessment of the environmental footprint and carbon storage potential of biochar production, and use, in order to contribute to a carbon-neutral future

Project Objectives

- Examine scientific literature on biochar and perform review of currently available researches about Life Cycle Assessment of the topic of interest.
- Derive and analyze data regarding processes involved in being studied biochar system.
- Based on the obtained inventory data assess the environmental footprint of biochar production and use, and the ability to sequester carbon, specifically comparing two different biomass sources: cleft timber and sewage sludge.
- Interpret and analyze the outcomes, highlighting areas of concern.

1. Literature Review

1.1. Environmental Impacts of the Charcoal on the Environment

Long-term changes in temperature and weather patterns and sea levels are characteristics of the worldwide phenomena known as climate change. It is largely brought on by the increase of greenhouse gases (GHGs) and carbon dioxide (CO_2), from human activities including the burning of fossil fuels and industrial processes, in the Earth's atmosphere. The impact of climate change is widespread and provides difficulties for individuals, the economy, and ecosystems. Deforestation, loss of biodiversity, and coastal erosion are only a few consequences of rising global temperatures. These play havoc with agricultural yield, food security, and water supplies.

The Paris Agreement, which was ratified by 195 countries, strives to keep global warming well beneath 2 degrees Celsius over pre-industrialization levels and endeavour initiatives to keep the temperature rise to 1.5 degrees Celsius. Moreover, treaty as the United Nations Framework on Climate Change (UNFCCC) has also identified the need to reduce emissions [9]. However, the world is in the direction of a temperature increase of more than 3 degrees Celsius by 2100, according to scientific data. Thus, current policies with pledges are unlikely to meet these targets mentioned above.

To combat the issue of climate change, the reduction of the net output carbon dioxide (CO_2) into the atmosphere, is essential. Decarbonization is the process of lowering and eventually eliminating greenhouse gas (GHG) emissions, notably carbon dioxide (CO_2) emissions, from human activities. This transition includes a move towards carbon net-negative technologies. Accelerating the use of such a technology is necessary to mitigate the adverse impacts of climate change. By reducing CO_2 emissions, it is possible to limit global temperature rise, preserve ecosystems and promote sustainable development.

The application of biochar, charcoal produced from biomass, is one of the promising technologies to tackle climate change and work in the direction of a sustainable future. A study conducted in 2010 found that depending on the adoption rate, the production of biochar has the potential to sequester between 90 and 300 million metric tons of carbon dioxide by 2050 [7]. Global greenhouse gas emissions could be reduced by up to 12% by producing biochar instead of traditional coal [10]. Therefore, charcoal can be replaced by biochar, which works as a carbon storage tool when applied to the soil, as a way to limit global temperature rise. Additionally, according to a 2020 study, applying biochar on damaged soils increases crop productivity and soil fertility [1].

Overall, combating climate change and achieving decarbonization are crucial requirements for the sustainability of our world. The concerning forecasts of a rise in global temperatures and the impacts of climate change on ecosystems and human well-being are what drive action. The thorough decarbonization policies and the use of technologies like biochar for carbon capture, and storage, are the opportunities to reach a greener resilient future.

1.2. Biochar

Biochar is a type of black carbon that is produced by the thermal decomposition of biomass in an oxygen-free or low-oxygen environment [3]. This process is known as pyrolysis. Nonetheless, some technological innovations have been made recently that can produce biochar. Novel technologies are established on pyrolysis, gasification, and hydrothermal carbonization [3].

Production involves any biomass feedstock. For example, two types of biochar can be highlighted, plant-derived biochar (PDB) and animal-derived biochar (ADB) [4]. The feedstock and processing conditions, that are used, highly influence important chemical and physical qualities of the resulting biochar [5]. Moreover, these properties have an impact on how biochar interacts with its surroundings

[5]. As a result, several legal guidelines, certificates, or standards exist to guarantee the quality of each practice of biochar [2].

Product as biochar has diverse environmental application areas: adsorption (water and air pollutants), soil improvement, catalysis, and waste management [6]. In addition, it can be used as a food additive and activated carbon [3]. However, production including only one product as biochar is assumed to be expensive, thus, supplementary by-products as liquids are demanded. [3].

1.3. Feedstock Sources of Biochar

Feedstock source is one of the main factors in the production of biochar, which has an influence on the physical and chemical properties of the product. Agricultural waste, compost, kitchen waste, crops, forestry and bioenergy residues, manure/animal waste, and sewage sludge are common types of biomasses that are used as feedstock [8]. Biomass can be divided into more general two groups woody and non-woody [11].

Woody biomass is preferred due to low moisture and ash levels, which reduce the needed heat energy and time for production, as well as that, low ash content in the resulting biochar increases the retention of herbicides [11]. Non-woody biomass resulting in lower biochar yield is preferred for the utilization of agricultural and organic waste [11]. What is more, all types of biomasses have various thermal degradation ranging from 180 °C to 500 °C due to variations in their chemical composition [12].

An increased amount of organic component in the feedstock as lignin, which high levels are found in rice and coconut husk, is linked to the growth of biochar production, and ash levels of it [11]. Sewage sludge and manure/animal waste are not suitable feedstocks when production is aimed for output as a solid fuel [12]. However, biochar from animal waste can be used as a soil amendment on account of pore volume resulting from higher thermal degradation [13]. A study by Yang, O. et al. (2021) presented that biochar from rice straw had the highest potential for sequestering carbon due to its higher carbon content and lower ash level.

In general, the choice of feedstock source has a great influence on the characteristics and potential applications of biochar. The most widely used feedstock sources are agricultural and forestry residues due to their properties, although other resources have potential as well. More study is required to completely comprehend the ideal feedstock and production technique for biochar in different applications.

1.4. Biochar Production

Production of biochar can be accomplished through several thermochemical conversion processes, including slow pyrolysis, fast pyrolysis, gasification, hydrothermal carbonization, and torrefaction [15]. Each method’s properties have a vital impact on biochar yield percentage [16]. The amount of biochar produced from a biomass feedstock is referred to as biochar yield, which can affect the economic viability of the process and potential environmental advantages [17].

As lignin, cellulose, and hemicellulose, which comprise a significant portion of the feedstock for biomass, have different pyrolysis temperatures, the production process of biochar becomes a complex procedure [17]. Before any thermochemical conversion process is started, pre-treatment of feedstock sources can be done to impact biochar characteristics. Pre-treatment solutions include immersion of biomass into fluids, steaming, and baking [15].

1.4.1. Slow Pyrolysis

Slow pyrolysis involves heating the feedstock source in an oxygen-free environment at temperatures ranging between 300 °C and 500 °C for a prolonged time [12]. During the process, biomass is decomposed into target product biochar and possible by-products such as bio-oil, and combustible gas [17]. High pyrolysis temperature, lower heating rate, and longer resistance time are key parameters of slow pyrolysis, which influence better quality biochar with high yield [17].

According to Cantrell, K.B. et all (2012) biochar yield during slow pyrolysis stands at 35%, bio-oil yield at 30%, and combustible gas at 35%. Moreover, target product biochar comes out typically low in ash content, and high in carbon content and surface area [17]. Tomczyk, A. et al. (2020) indicates that the high carbon content of biochar has the potential for carbon storage for climate change mitigation.

Low ash content makes biochar an excellent soil amendment without affecting soil pH [19]. High surface area increases the capability of biochar to remove pollutants from the environment and creates a habitat for microorganisms while used for soil [6]. Apart from biochar, if by-product bio-oil is collected from released pyrolysis vapors, value-added bioproducts can be extruded from contained chemicals in it [17].

1.4.2. Fast Pyrolysis

Fast pyrolysis in comparison with slow, involves temperatures from 350 °C to 700 °C and high heating rates [12]. In a fast process, the target product is bio-oil and the by-product is biochar or combustible gas [17]. Based on Cantrell, K.B. (2012), during fast pyrolysis biochar yield is equal to 12%, bio-oil yield 75%, and combustible gas 13%.

Produced biochar is best when used in agricultural applications due to its high porosity and surface area [6]. Target product bio-oil contains high oxygen and acidity levels, making it difficult to use it as a fuel [17]. However, extended researches focus on improving bio-oil upgrading technologies. Overall, fast pyrolysis is faster and less energy consuming than slow pyrolysis. Yet, the addition of catalysts to the process is needed to acquire the best results for biochar's yield or bio-oil characteristics.

1.4.3. Gasification

Gasification is a process of heating biomass at temperatures between 700 °C and 1000 °C while supplying it with a limited amount of oxygen or air [20]. The most common gasification agent is air. The process of gasification involves sub-operations such as drying/evaporation of moisture in biomass without energy recovery and oxidation/combustion of gasification agents [15].

The target product of gasification is syngas, the by-product is biochar, which happens to be unacceptable if oxygen is used as a gasification agent causing a decrease in biochar yield and an increase in ash level [21]. According to Klinghoffer, N.B. et al. (2015), for the gasification process biochar yield is 10%, bio-oil yield 5%, and syngas 85%. The syngas mainly contains carbon monoxide, carbon dioxide, hydrogen, methane, and smaller quantities of other gases [21].

1.4.4. Hydrothermal Carbonization

A hydrothermal carbonization is a viable approach for creating biochar using heat and water to transform biomass feedstock with high moisture into a solid, carbon-rich substance [16]. As the process is done at temperatures between 180 °C and 250 °C, it is seen to be a promising sustainable replacement for traditional biochar manufacturing techniques [15]. The final product of the process is called hydrochar of solid and liquid consistency [16].

Based on the Funke, A. & Ziegler, F. (2010) study, biochar yield in hydrothermal carbonization ranges from 50% to 80%, bio-oil yield is 5–20%, and syngas is 2–5%. HTC-produced biochar is thought to be very promising for water treatment from pollutants. Moreover, hydrochar comes out with high carbon content and improved combustion properties making it a great product for renewable energy [16].

1.4.5. Torrefaction

Torrefaction is a thermal conversion process, which involves heating biomass feedstock in the absence of oxygen in temperatures between 200 °C and 300 °C [24]. It typically involves low heating rates, a short holding period, an environment of inert gas, and atmospheric pressure [25]. The target product of torrefaction is biochar and by-products can be permanent gases, condensable solutions, or organic compounds [25].

The resulting biochar's energy density can be raised to be nearly as high as traditional coal's, which is utilized for generating electricity and heat [21]. Two types of torrefactions exist, dry and wet. Recently, the vast majority of studies are focused on dry torrefaction and its positive influence on the heating value of biochar. However, still, a number of obstacles are faced in the implementation of torrefaction technology for biochar production.

First of all, the level of moisture in the feedstock sources is mostly too high for the process, which results in the need for a drying operation that is not efficient in an economical matter [25]. Secondly, high ash levels in resulting biochar are linked to the presence of contaminants [25]. On the other hand, wet torrefaction is thought to be even more promising than dry because of its ability to work with a range of moist biomass resources [25]. According to Bach, Q. & Skreiberg, Ø. (2016), the yield of biochar adopting torrefaction is about 80% and permanent gases stand for 20%.

1.4.6. Portable Systems

Portable systems or mobile systems are solutions to the production of biochar on a small scale, in order to reduce costs of transportation and emissions of it [26]. These systems can be based on all production methods presented above. Mostly used and evaluated systems are Biochar Solutions Incorporated (BSI), Kiln, and Air-curtain Burner [26].

1.5. Biochar Application for Sustainable Environmental Management

According to numerous studies, biochar could be effectively used for two interrelated environmental goals, namely sustainable agriculture and pollutants remediation. Moreover, biochar could significantly aid in reducing the effects of climate change by sequestering carbon and decreasing greenhouse gas emissions.

1.5.1. Carbon Storage

The process of removing CO_2 from the atmosphere and permanently storing biogenic carbon is referred to as carbon storage. Biochar is one of the methods for achieving that goal, as it is capable to store carbon in the soil for a long period. The reason for such a biochar ability is its high carbon content and resistance to decomposition.

For example, biochar made from hardwood can last in the soil for up to 1000 years [34]. According to a study by Lehmann, J. et al. (2015), biochar made from forestry biomass had the greatest ability to store carbon, whereas made from agricultural residues had less potential. Based on another study written by Jeffrey, S. et al. (2015), applied biochar can increase the amount of soil organic carbon by 30%.

Besides from carbon storage, adding biochar to soil affects the mitigation of greenhouse gas emissions by shrinking gaseous emissions. It is claimed that some cycles of biochar emit less greenhouse gas than consume. What is more, biochar can decrease nitrous oxide emissions from soil, which take a role in the development of toxic pollutant as tropospheric ozone [28].

1.5.2. Waste Management

The use of biochar for waste management has been the subject of several studies recently. The potential of biochar usage for the treatment of sludge from a wastewater treatment plant was examined by Rangabhashivam, et al. (2022) and it was reported that biochar is able to lower the number of heavy metals and organic contaminants in the sludge. The same improvements were discovered when biochar was used to treat textile industry wastewater [30]. Moreover, according to Kumar, et al. (2021), biochar can improve the efficiency of the anaerobic digestion process, increasing biogas generation. Waste-derived biochar can be used as a soil amendment, but it does not increase soil fertility as much as it might if a different feedstock was employed.

1.5.3. Soil Amendment

Global agriculture is very concerned about soil deterioration, which includes lower fertility resulting from long-term soil cultivation. Many studies have established that biochar increases soil fertility by fostering positive effect on its capability to retain nutrients. Moreover, by improving soil porosity, biochar helps to improve water infiltration and retention [32].

Biochar is able to change the physical and chemical properties of soil. Therefore, it can increase soil pH level even by 1 unit, if hardwood biochar is used [32]. Overall, specific biochar properties, which depend on used feedstock and heating temperature, can induce plant growth.

On the other hand, biochar can threaten plant growth by setting off microbial activities [32]. Nutrition imbalance is caused by a high carbon-to-nitrogen ratio [32]. Additionally, toxic substances can be released from biochar.

1.5.4. Remediation of Water and Soil

Firstly, biochar can be used to get rid of contaminants from water. In several studies, it was reported about the efficient removal of heavy metals as lead, zinc, and copper, from contaminated water. In a study by Kumar, et al. (2021), lead and cadmium were taken out of aqueous solutions using biochar made from peanut shells, with an efficiency of 99.5%. The same results were reported in the study by Cai, et al. (2021). Features of biochar as porous structure and specific area are key elements to efficient adsorption.

Secondly, biochar can be employed as soil amendment remediating soil, which is contaminated with heavy metals and hazardous compounds. Inorganic contaminants such as heavy metals cannot be broken down by microorganisms, therefore contaminated soil can have tremendous negative effects on the ecosystem and human health. What concerns organic contaminants, it is not commonly reported that biochar can be used to remediate these types of pollutants [21]. However, according to the Yaashikaa, P.R. et al. (2020) study, biochar with increased concentration, successfully performed adsorption of organic pollutants.

1.5.5. Other Applications

The most promising biochar applications were discussed above, yet they can be used in various other ways. For example, biochar can be added to livestock feed to improve animal health. On top of that, it can be added to the animal manure compost to reduce odor by absorbing volatile organic compounds (VOCs) and ammonia. Furthermore, in the future biochar can play a big role as a resource in the production of renewable energy to achieve energy security in the world.

1.6. Research Studies on Life Cycle Assessment of Biochar Production and Use

Environmental footprint is assessed via the scientific method of Life Cycle Assessment (LCA). This methodology is a great instrument for identifying ecological stress points and evaluating the sustainability of different alternatives/options by assessing products or processes throughout their entire life cycle. The four stages of life cycle analysis are establishing a scope and objectives, doing an inventory analysis, evaluating the results, and drawing conclusions.

The aim and scope definition stage comprises establishing the purpose of the study, the boundaries of the system under investigation, and the functional unit of the analysis. Quantifying the system’s inputs and outputs, including raw materials, energy use, emissions, and waste, is a part of the inventory analysis stage. At the impact assessment step, the potential environmental effects of the system are assessed by a number of impact categories. The findings of this stage are examined in the interpretation stage in order to make judgments regarding the system's environmental performance.

LCA has been applied in a variety of contexts, such as business sustainability reporting, environmental legislation, and product design. This method has the advantage of taking into account numerous environmental impacts rather than concentrating on a single one. As a result, a more comprehensive understanding of how well a process or product performs in terms of the environment is enabled.

Nonetheless, LCA does have certain restrictions. In fact, one drawback is that the methodology is data-intensive and needs a lot of resources to perform a comprehensive analysis. Another drawback is that it simply assesses environmental effects without accounting for social or economic considerations. Overall, regardless of the drawbacks mentioned above, LCA is a crucial technique for measuring the ecological impact of products and processes. It is anticipated to be used much more frequently in the future as sustainability is prioritized by businesses and governments.

Most relevant scientific articles, mentioning LCA methods or biochar production, and use, are presented in Table 1, including information regarding the year of publication, authors, publication source, study objective, aim, system boundaries, environmental impacts, and main results. Chosen scientific articles presented a common impact category assessed, global warming potential (GWP). Most studies place attention on the environmental impacts and economic viability of production.

Table 1. Articles selected for the literature review on LCA of biochar production and use

Author, Year, Publication source	**Aim**	**Functional unit**	**System boundary**	**Environmental/Health impacts**	**Main Results**
Puettmann et al. (2020) Journal of Clear Production, Volume 250	To compare the environmental impacts of producing biochar from forest residue using three portable systems while taking various production sites, feedstock quality, and power sources into account.	1000 kg of marketable biochar for production systems; % of fixed carbon in the biochar-for comparison of feedstock; 1000 kg of forest residue for comparison with pile burning.	Cradle to gate: from harvesting feedstock source to marketable biochar.	Global warming potential (GWP)	In comparison to pile burning, the generation of biochar from forest residues reduced GHG emissions by 0.33-1.83 t of CO_2 eq./dry t of forest residue. Following, from three suggested portable systems, BSI system did not present significant potential to reduce GHG emissions. What is more, GHG reduction in biochar production is larger at the near-forest location. However, if facility is located in-town, grid power availability becomes an advantage. Lastly, it was reported that feedstock source has a major effect on the quality of biochar.
Sahoo et al. (2021) Int J Life Cycle Assess 26, 189-213	To assess the environmental effects and economic viability of producing biochar from forest residues using portable systems.	1 t of biochar sold to a consumer with biochar applied in the field; % of fixed carbon in the biochar-for comparison of feedstock; 1000kg of forest residue-for comparison with pile burning.	Cradle to grave: from harvesting forest residues to applying to the soil.	GWP	The GW impact of producing biochar using gasifier-based generator was significantly reduced by 64-70% compared to using a diesel generator. When clean forest residues were used, less GW impact happened than using chipped residues. In the final product carbon content stored in the biochar when applied to the field had a considerable GHG mitigation effect than the GHG emissions generated during production, resulting in a negative GHG impact.

Author, Year, Publication source	Aim	Functional unit	System boundary	Environmental/Health impacts	Main Results
Gievers et al. (2020) Multidisciplinary Journal for Waste Resources & Residues	To compare the environmental impacts of sewage sludge pyrolysis with incineration, and determine the most suitable application of target product biochar.	Treatment of 1 kg sewage sludge after anaerobic digestion with a solids content of 5%.	Gate to grave: from pre-treatment of sewage sludge to four different applications.	GWP, ODP, IR, FE, FET, ME, MET, TA, TET, FD, HT	Using biochar as a fossil fuel for sewage sludge treatment can reduce the impact on climate change. Overall, biochar leads to lower emissions compared to the traditional incineration of sewage sludge. The assessment indicated that biochar performed better than the benchmark as incineration for critical categories. However, GWP, FD,TD and ODP were worse. Moreover, GHG savings differ depending on how biochar is used. For example, biochar applied directly to the soil was less efficient than if additional utilization steps would be added.
Mohammadi et al. (2016) Journal of Cleaner Production, Volume 116, Pages 61-70	To compare open burning of rice residues with conversion to biochar.	Production of 1 kg of milled rice.	Cradle to gate: from farming rice to milling.	GWP, CF	Reduction of 38-49% of the CF was reported in the fields, where biochar from pyrolysis process was applied. These results were spotted after eight years of using. In addition, biochar could aid in reducing field CH4 emissions.
Hamedani et al. (2019) Energies 12 (11)	To compare positive and negative environmental impacts of biochar production and use for soil amendment in drought- sensitive soils.	1 t of produced biochar	Cradle to gate	OD, RO, FETP, TETP, LU, FA, FE, GWP, FDP, MDP, RAD, RI, H-Human, T-cancer, H-Human, T-non-cancer	Based on chosen impact categories feedstock from willow outperformed from manure one. Pig manure requires pre-treatment before pyrolysis process, resulting in not that sustainable way for producing biochar.

Author, Year, Publication source	Aim	Functional unit	System boundary	Environmental/Health impacts	Main Results
Yang et al., (2021) Applied Energy, Volume 282, Part B	To assess the incorporation of biochar into agriculture throughout the nation and its possible advantages.	1 t of crop residues	Cradle to grave: from acquiring crop residues to application to the field	ADP, AP, EP, ODP, POCP, TETP, FAETP, MAETP	Producing biochar from 1t of agricultural wastes may sequester more than 920 kg CO_2 eq. The ability to sequester carbon differed through the country of China and its characteristics were key factors affecting it. Additionally, the degradation of marine aquatic species, and acidification of the soil and water surfaces, might be mitigated by biochar as well.

Difference between the scope and system boundaries of research papers creates an obstacle to holistic comparison. Nevertheless, two very similar studies were found. According to Puettmann et al. (2020) and Sahoo et al. (2021), biochar produced from forest residues reduces GHG emissions. Better results were seen in the scenario, where the process is done near-forest as transportation is not needed. Additionally, Sahoo et al. (2021) indicated that production established in town can have a possible advantage due to the use of grid power and by this mean lowering GHG emissions by 56% than using diesel generators. It is important to highlight that results were based on small-scale production using portable systems.

In Gievers et al. (2021) study, biochar from sewage sludge was analyzed. In the results, authors indicated that GHG emissions varied between different applications of biochar and that further analysis is needed for more precise knowledge. However, it was stated that the production of biochar from sewage sludge is certainly a better option for lowering carbon emissions than the incineration of sewage sludge. Moreover, during incineration of sewage sludge, most beneficial nutrients are released as gases, in contrast, pyrolysis of sewage sludge retains them.

The most detailed approach was presented by Hamedani et al. (2019) using a wide range of impact categories to evaluate two types of feedstocks. Animal-derived feedstock for biochar production required a more complex pre-treatment process resulting in higher emissions than willow feedstock. Moreover, biochar from animal manure contains fewer nutrients and contains lower proportions of stable carbon, which is an important index for the level of ability to sequester carbon.

Largely scientific papers on biochar cover the techniques of biochar production, its characterization, effects on agricultural productivity, crop yield, and soil fertility. What is more, potential reductions of GHG emissions are discussed, however, on small-scale production. The focus on previously listed aspects of interest might be higher as biochar is a relatively new topic, and researchers are primarily concentrated on understanding its production options, characteristics, and potential applications rather than performing broad LCAs. However, as the field of research evolves with new insights, the focus of scientific papers starts to vary. Shifting levels of attention receive other aspects related to the biochar for example its potential to sequester carbon dioxide when applied to the soil, its way to manage waste, and its effects on ecosystem functioning.

1.7. Summary and Conclusion of Literature Analysis

The vast majority of studies focus on the assessment of biochar production and ignore possible trade-offs of its application. Little attention has been paid to the overall environmental footprint of biochar production and use. For example, forestry residue is reported to be the most efficient feedstock for biochar production as a soil amendment, if the best results for soil are wanted. Thus, it is important to analyze if it will not result in increased deforestation or other environmental problems. What is more, cultivating crops for the production of biochar has raised questions about the trade-off involving the area required to cultivate these crops, as this land may be destined for conservation or food crops. Following, biochar from sewage can be a great way to treat wastewater, but on the other hand it can contaminate the waters in which it is used for cleaning. Although biochar is used for many different things, its effects on the environment must be adequately considered to prevent negative impacts. Based on the conclusion made from the literature review, the current study work is focused on advancing the field of study that focused on LCA of biochar produced through slow pyrolysis by addressing the following research questions:

What impacts do biochar production, from forestry and sewage sludge, have on the environment?

What impacts do biochar applications, such as soil amendment and fertilizer, have on the environment?

What are possible trade-offs between the potential benefits?

2. Methods

2.1. The Methodology Roadmap

The employed methodology follows subsequent phases presented below in Fig. 1.

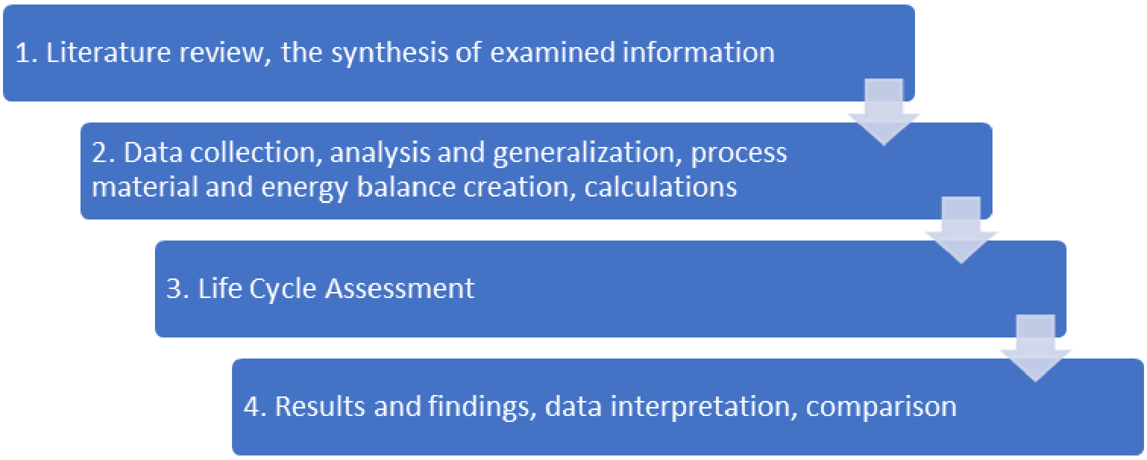


Fig. 1. The methodology roadmap

The methodology of this paper entails a few steps. First, a thorough examination of literature and existing research that has been written on biochar. The literature review provides background information and context for the study on a chosen topic. Second, a gathering of information and data selection on the inputs and outputs of the synthesis of biochar, such as biomass, transportation, and other elements. Analysis and selection of acquired data on biochar production, and characteristics, from a company producing biochar in Lithuania. Third, the application of the scientific method Life Cycle Assessment (LCA) and PURO2 formula guidelines to reach the goal of this study, such as assessment of the environmental footprint of biochar production and use. The whole research is executed in accordance with ISO 14040:2006 and ISO 14044:2006 standards. In performing LCA particular sequence of steps is involved. LCA methodology phases are presented below in Fig. 2..

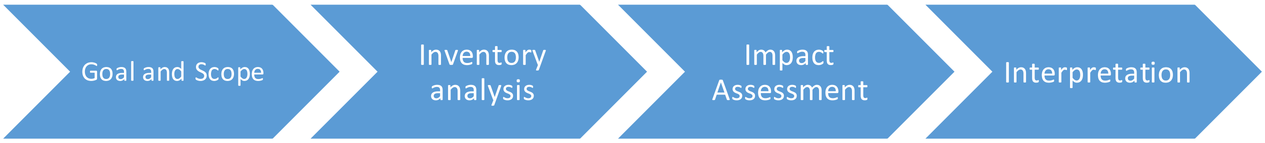


Fig. 2. LCA methodology phases

2.2. The Description of the Case Study Process

Prior to the establishment of the study's aim and depth, a description of detailed processes is needed. The process that is described below is obtained from conducting interviews with a biochar production company based in Lithuania. These in-depth discussions helped to form the basis for the outlined process and ensured its accuracy and reliability. This research not only outlines a theoretical framework but also combines practical information from industry experts. The process described below contains key insights provided by the Lithuanian biochar producing company.

Production of biochar starts with the supply of primary raw material as timber from the retrieving location, which is assumed to be roughly 30 km distant (fig. 4.). Clefted timber is transported and stacked next to the conveyor belt of power 1.5 kW. Biomass is manually loaded on the industrial conveyor, which transports it to the retort adjacent to it.

The capacity of the reactor is 1 t of wood feedstock. The filled retort is lifted by the crane of force 7.5 kW powered by electricity and moved to the oven for drying, where it is left for approximately 4 hours at starting temperature of 100 °C to 200 °C. Following, the retort is taken out of the drying oven section by crane to be moved to the pyrolysis side.

An EKOLON 5.2 unit with a thermal output of 1500 kW is used in the pyrolysis process to create biochar. The temperature of the process is around 1000 °C with a duration of 4 hours. During wood's thermal disintegration by-products can be created. However, the current study does not include one. Only small amounts of vapor and liquid that escaped from the retort during heating are combined and burned.

The heat from the incineration is used to heat retort, making the process self-sufficient. Production is aimed to keep running smoothly 24/7 to reduce the use of additional fuel for the oven system when it cools down. Part of the energy from incineration is transferred to the drying section, where an excess of it is released via the chimney.

After heating biomass in the low-oxygen atmosphere for 4 hours, biochar is created. The retort is pulled out of the oven and moved to the platform where it is filled with 0,5 m^3 of water in order for biochar could cool off. When biochar is soothed, the retort can be emptied and moved back to the beginning of the manufacturing operation.

Eventually, the final product is acquired, yet if the biochar is used as a soil amendment, it should undergo one more procedure. To get finer fractions of coal, it is passed to the shredder. Shredded biochar is placed in the bags and shipped to the customers, where it decomposes for approximately 100 years.

Based on the information presented above and retrieved from scientific literature, two schemes were created. One is presenting process material and energy balance (Fig.3), and the second is a scheme of the biochar life cycle.

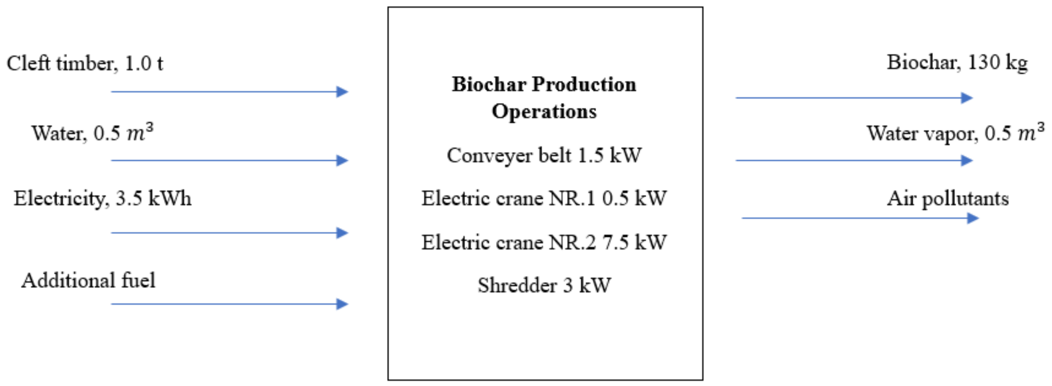


Fig. 3. Biochar production process material and energy balance

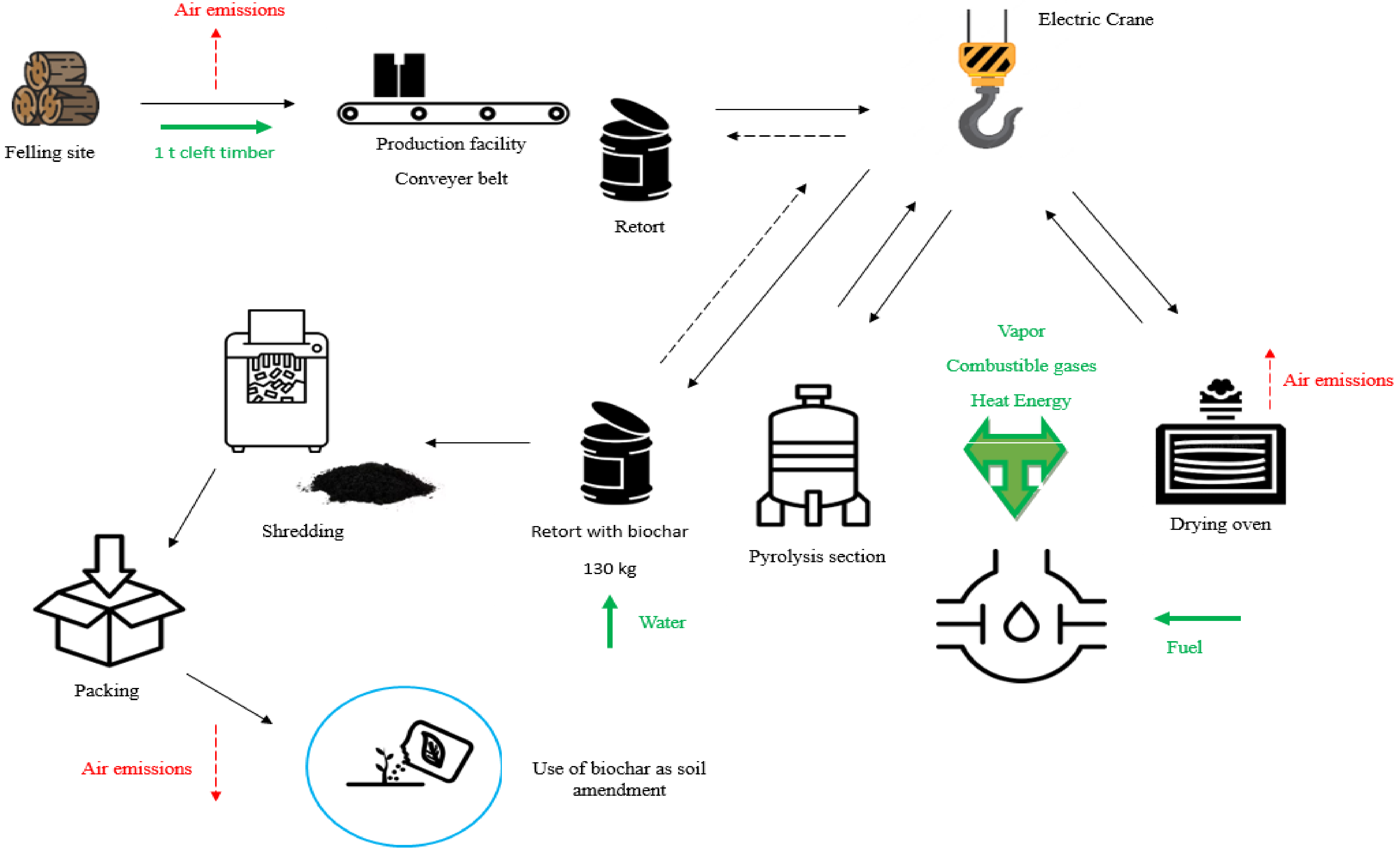


Fig. 4. Biochar life cycle scheme

2.3. Process Description of the Biochar from Sewage Sludge

In this research, an alternative scenario was considered that involves sewage sludge as feedstock for biochar production via pyrolysis. The life cycle scheme of biochar from sewage sludge is similar to the one presented in Fig. 4. However, a few stages should be clarified.

First of all, material such as sewage sludge is acquired from a wastewater treatment plant after anaerobic digestion. The distance between two objects is assumed to be 30 km. Delivered biomass undergoes dewatering to reduce volumes and for the further best treatment in economical means. Subsequent processes involve pyrolysis and are exactly the same as for biochar from woody biomass. In the end, shredded biochar is transported to the customers, where it is used as a soil amendment or fertilizer.

2.4. Life Cycle Assessment

To assess the environmental impact of a chosen product throughout its entire life cycle SimaPro 9.1 was used. The software's user-friendly interface and comprehensive database of environmental impact data allow quick and easily assessing of the environmental impact of a product. SimaPro 9.1 supports a variety of impact assessment techniques, including ReCiPe, which was chosen for this study. With the aid of these techniques, the effects of many factors on the environment can be evaluated, such as climate change, human toxicity, and water use.

2.4.1. Goal and Scope

The goal and scope of this research are to assess the cradle-to-grave life cycle carbon emissions of the biochar production process, which is described above in the previous segment.

2.4.2. System Boundary

The system boundary for the life cycle assessment of a biochar is defined as from cradle-to-grave.

Four stages are included:

- Biomass (module A1);
- Transportation of raw materials to the production facility (module A2);
- Production of biochar by fast pyrolysis (module A3);
- Use of biochar as a soil amendment for 100 years (module B1).

The scheme of the system boundary is presented below in Fig. 5..

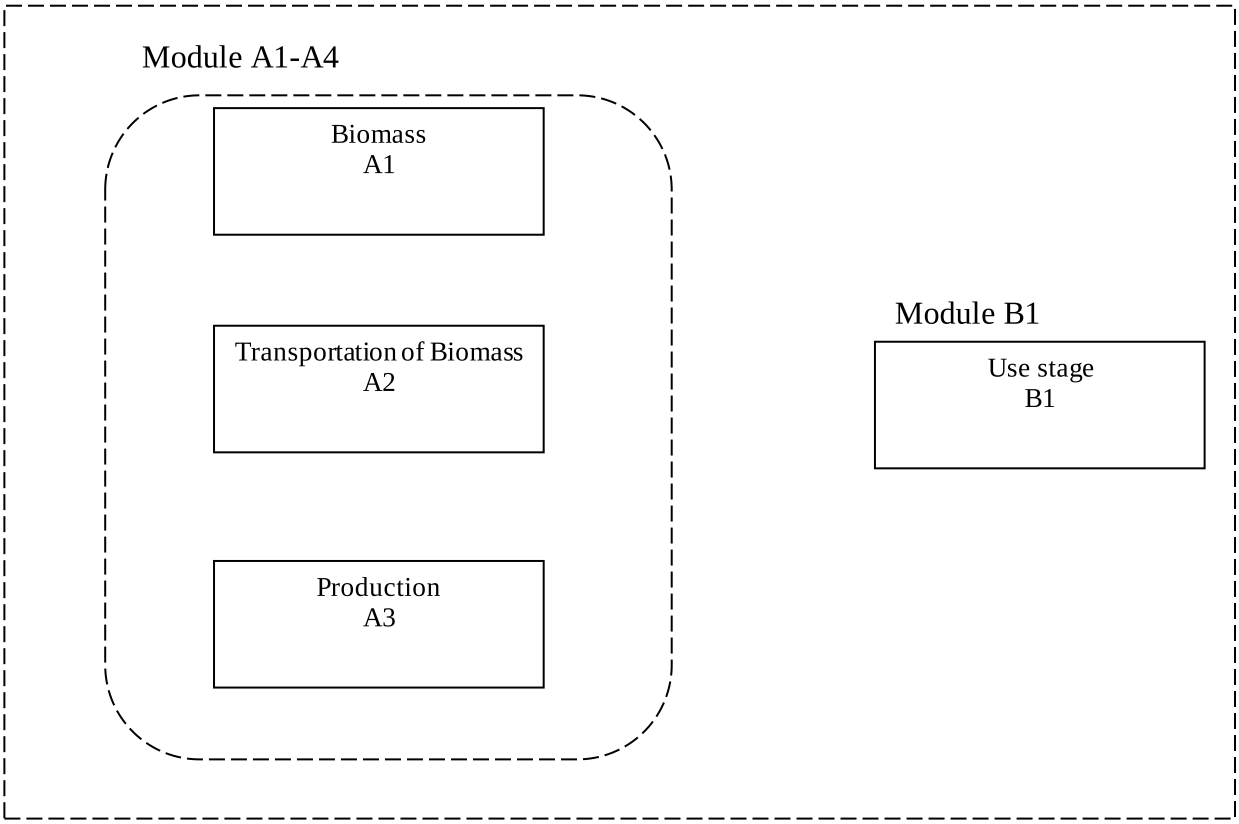


Fig. 5. System Boundary for Biochar

2.4.3. Functional Unit

The functional unit of this study is 130 kg of biochar within a 100-year time horizon. It applies to both case study and biochar from sewage sludge, allowing comparison.

Table 2. Characteristics of biochar from cleft timber retrieved from the Lithuanian Energy Institute

Content of	**Amount**
Moisture	2.5 %
Ash	1.8 %
Fixed carbon	91.4 %
Volatile carbon	6.8 %

Table 3. Characteristics of biochar from sewage sludge [42,43]

Content of	**Amount**
Moisture	4.9 %
Ash	61.3 %
Fixed carbon	19.4 %
Volatile carbon	14.4 %

2.5. Life Cycle Inventory

The life cycle inventory (LCI) stage is crucial to the Life cycle assessment (LCA) as it lays the groundwork for other stages, such as impact assessment and interpretation. LCI step involves the creation of a thorough inventory of all the inputs and outputs connected to the biochar system, including raw materials, energy, and emissions. That requires gathering and analyzing data, which can be accomplished using surveys, literature reviews, and other sources of knowledge.

It is important to highlight that data regarding the case study was acquired from a company producing biochar in Lithuania. All in all, the LCI stage is concerned with quantifying the system's inputs and outputs, from biomass extraction to end-of-life. Following, environmental indicators are calculated using the LCI data.

2.5.1. Case Study Inventory

Module A1

For this section Ecoinvent database version 3.6 Cleft Timber, measured as dry mass "Europe without Switzerland" market for APOS, U was used in the process. This data set shows the production and gathering of 1 m^3 of woody feedstock from sustainable forest management in Europe. All starts with preparing the site, planting, caring for young growth, clearing, thinning, and harvesting, as well as turning wood into chips, bundles, and logs. The process is over when the piles are on the forest road and left to dry before they can be moved.

1 t of wood feedstock was taken into account to produce 130 kg of biochar via pyrolysis.

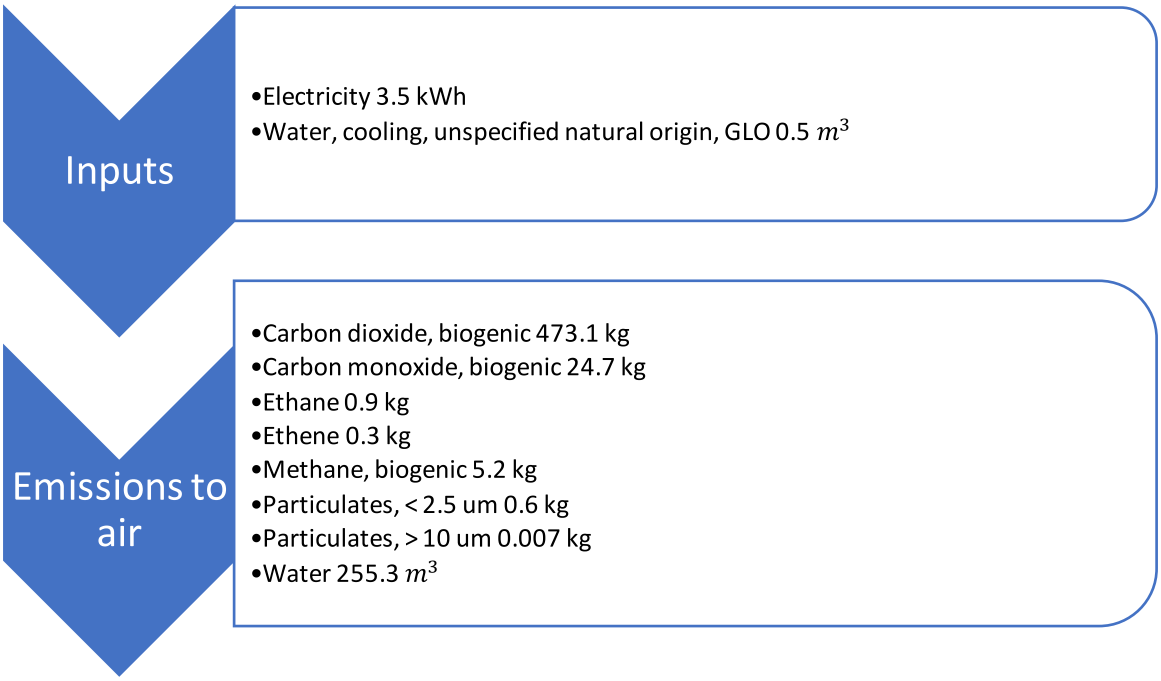
Module A2

Module A2 includes the transportation of biomass from the collection site to the production facility. Ecoinvent database version 3.6 Transport, freight, lorry > 32 metric ton, EURO5 {RER} transport, freight, lorry > 32 metric ton, EURO5 APOS, U was used. 30 km distance was taken to account for 1 t of biomass.

Module A3

Section A3 is about the production of biochar that includes the pre-treatment of biomass and its transformation to the final product. Material and energy inputs for operating the reactor, and outputs from the reactor's chimney, were considered. The pyrolysis method used for this research yields no co-products, such as heat, bio-oil, or power.

A small portion of the heat produced by the combustion of the pyrolysis gases is required to maintain the reaction and dry the wood feedstock. However, the mentioned process is internal and does not need to be included in the life cycle assessment because it has no impact on it. On the other hand, if there were any surplus (heat, electricity, or bio-oil) energy that is not utilized during the pyrolysis process, problems with multi-functionality in life cycle analysis would occur.



- Electricity 3.5 kWh
- Water, cooling, unspecified natural origin, GLO 0.5 m^3

- Carbon dioxide, biogenic 473.1 kg
- Carbon monoxide, biogenic 24.7 kg
- Ethane 0.9 kg
- Ethene 0.3 kg
- Methane, biogenic 5.2 kg
- Particulates, < 2.5 um 0.6 kg
- Particulates, > 10 um 0.007 kg
- Water 255.3 m^3

Fig. 6. LCI of production, case study

In Fig. 6. the Life Cycle Inventory of production biochar from cleft timber is presented. Inputs include electricity used for thermal decomposition and water for cooling biochar after pyrolysis. Emissions to air are included carbon dioxide (biogenic), carbon monoxide (biogenic), ethane, ethene, methane (biogenic), particulates, and water.

Module B1

The last module is meant for the use phase. The final product biochar is sold as a soil amendment with a time horizon of 100 years. This stage includes greenhouse gas emissions associated with the movement and processing of biochar up until the point at which it is incorporated into a mineral matrix from which it cannot be removed. Therefore, the emissions related to its eventual disposal or decomposition should not be taken into account.

Inputs applied from Ecoinvent database version 3.6:

- Textile, non-woven polypropylene {GLO}| market for textile, non-woven polypropylene | APOS, U – 0.5 kg;
- Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified APOS, U – 39 tkm.

2.5.2. Inventory of Biochar from Sewage Sludge

Module C1

For this section 5 t of digested sewage sludge was taken into account to produce 130 kg of biochar via pyrolysis. Biomass waste-derived.

Module C2

Module C2 includes the transportation of feedstock from the wastewater treatment plant to the production facility. Ecoinvent database version 3.6 Transport, freight, lorry > 32 metric ton, EURO5 {RER} transport, freight, lorry > 32 metric ton, EURO5 APOS, U was used. 30 km distance was taken to account.

Module C3

Section C2 covers the manufacture of biochar, which involves pre-treating biomass and transforming it into the finished product. The reactor's energy and material inputs as well as its chimney's emissions were taken into account. The pyrolysis technique utilized in this study produces no byproducts.

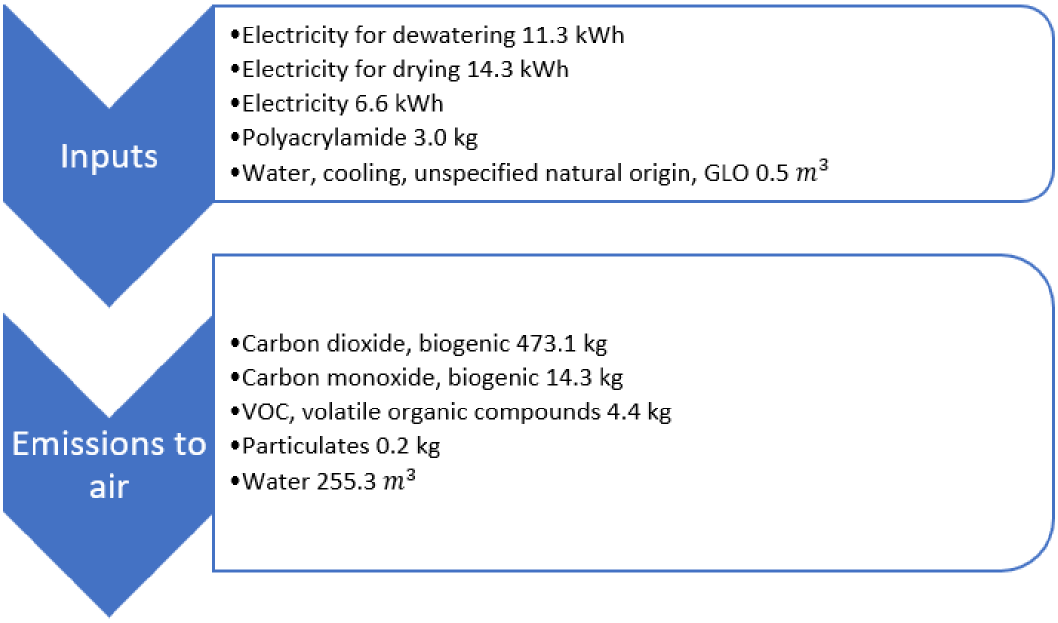


Fig. 7. LCI of biochar production from sewage sludge

In Fig. 7. the Life Cycle Inventory of biochar from sewage sludge is presented. Inputs include electricity for dewatering, drying, and thermal decomposition, polyacrylamide used in dewatering to enhance the efficiency of the process, and water used for cooling biochar after pyrolysis. Emissions to air are included as carbon dioxide, carbon monoxide, VOC, particulates, and water. Inputs and Emissions to air were calculated and assumed based on scientific literature regarding biochar production from sewage sludge [42,43].

Module D1

Transportation of the final product from the production facility to the customers is covered in Module D1 Use. Inputs were applied from Ecoinvent database version 3.6:

- Textile, non-woven polypropylene {GLO}| market for textile, non-woven polypropylene | APOS, U – 0.5 kg;
- Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified APOS, U – 39 tkm.

It is assumed that module D1 Use and B1 Use from the baseline scenario, remain the same. However, further detailed research on this matter is required and recommended.

2.6. Life Cycle Impact Assessment

Software SimaPro 9.1 and the Ecoinvent 3.6 database are used to model the life cycle. Essential data for energy, transportation, and any other additional materials is utilized from the Ecoinvent in order to guarantee that the research results are comparable. Not available data is gathered through scientific literature.

For evaluating the inventory's ecological footprint, the software SimaPro offers a number of tools. To categorize and classify the results into several environmental categories in this LCA, the ReCiPe midpoint assessment approach and IPCC GWP 100a are used. The ReCiPe 2016 methodology is used to reduce the extensive data from life cycle inventories to a manageable set of indicator scores. A category's indicator score reflects how severe an influence on the environment is. The IPCC GWP100a v1.03 (2013) approach lists the IPCC's climate change contributing variables over a 100-year period.

2.6.1. Choice of Environmental Impact Categories

Since the chosen impact assessment method as ReCiPe 2016 includes a great deal of impact categories, only pertinent to this thesis were picked for future evaluation.

Table 4. Chosen Impact Categories [43]

Impact category	Unit	Description	Motivation
Climate Change	Kg CO_2 eq.	The climate change category assesses a possible influence on the planet's climate system. How much a procedure or product might contribute to global warming and how it might affect the environment and people's health.	To evaluate a possible effect of a product or process on the Earth's climate system, which is a major environmental concern.
Stratospheric Ozone Depletion	Kg CFC11 eq.	The stratospheric Ozone Depletion category assesses a possible influence on the ozone layer thinning.	To evaluate a possible effect of a product or process on the Ozone layer depletion.
Ionizing radiation	kBq Co-60 eq.	The ionizing radiation category assesses a possible display to ionizing radiation.	To evaluate a possible impact of radiation linked to the product or process. Feedstock and feedstock combustion may be sources of ionizing radiation.
Fine Particulate Matter Formation	Kg $PM_{2.5}$ eq.	This category evaluates what impact can have on the formation of fine particulate matter on human health and the environment.	To evaluate the possible impact of a product or process on air quality or human health.

Impact category	Unit	Description	Motivation
Freshwater Eutrophication	Kg P eq.	Freshwater Eutrophication assesses the possible impact of excess nutrients on the balance of freshwater.	To evaluate a possible impact of a product, applied as a soil amendment, on nutrient balance in soil that can lead to disbalance of freshwater.
Freshwater Ecotoxicity	Kg 1.4-DCB	Freshwater Ecotoxicity evaluates the possible impact of a product or process on the toxicity of freshwater.	To evaluate the possible impact of processes, where chemicals are used, on the toxicity of aquatic ecosystems.
Terrestrial Acidification	Kg SO_2 eq.	Terrestrial Acidification evaluates the possible impact of released acidic substances on the terrestrial ecosystem.	To evaluate a possible impact of a product, applied as a soil amendment, on the pH of the soil.
Terrestrial Ecotoxicity	Kg 1.4-DCB	Terrestrial Ecotoxicity assesses the potential impact of released pollutants on the living organisms in terrestrial ecosystems.	To evaluate a possible impact of a product, applied as a soil amendment, on the toxicity of the soil and health of living organisms.
Fossil depletion	Kg oil eq.	Fossil resource scarcity evaluates an impact on the depletion of non-renewable resources.	To evaluate the possible impact of processes on fossil resource scarcity.
Human toxicity	Kg 1.4-DCB	Human toxicity evaluates a possible impact on human health.	To evaluate the possible impact of a product or process on human health.

Damage to ecosystem, human heath, and resources are the three basic areas into which chosen impact categories are divided in normalization. These groups represent several facets of a system's potential environmental effects. The general scope of each category is broken down as follows.

- Damage to ecosystem: This category focuses on how a system affects the environment and the ecology. It comprises elements like climate change, ozone depletion, eutrophication, acidification, ecotoxicity.
- Damage to human Health: This category focuses on potential effects on human health brought on by a system. Air pollution, toxic discharges, exposure to dangerous substances, occupational health risks are example of the elements that are included.
- Damage to resources: This category takes into account how a system depletes natural resources. It takes into account mineral resource depletion.

2.7. PURO² Guidelines for CORCs Calculations

The formula to determine the amount of net CO_2 eq eliminated over a 100-year period by the biochar production activity was retrieved from PURO² [41].

1. $CORC_s = E_{stored} - E_{biomass} - E_{production} - E_{use};$

Estored (tonnes CO_2 eq) – amount of CO_2 sequestered over a 100-year period by the quantity of produced biochar [41].

The formula for computing Estored [41]:

2. $E_{stored} = Q_{biochar} \times C_{org} \times F_p^{TH,Ts} \times \frac{44}{12};$

$Q_{biochar}$(tonnes) – the amount of biochar produced [41];

C_{org} – the organic carbon content of the biochar produced [41];

$F_p^{TH,Ts}$(%) – the biochar carbon stability [41].

$E_{biomass}$ (tonnes CO_2 eq) – greenhouse gas emissions across the course of biomass production and delivery to the manufactory [41].

$E_{production}$ (tonnes CO_2 eq) – total greenhouse gas emissions that result from the production facility's conversion of biomass into biochar [41].

E_{use} (tonnes CO_2 eq) – greenhouse gas emissions from distribution of the final product, up to the moment of use [41].

3. Results and Discussion

3.1. Life Cycle Assessment of Biochar Life Cycle, Case Study

In the table below, LCIA results of the GWP category for all biochar life cycle phases are presented. The method applied is IPCC GWP 100a. The biggest contributors are the production (A3 Module) and biomass gathering (A1 Module) stages. A similar influence of these modules is spotted on other selected impact categories from ReCiPe 2016 method.

Table 5. Impact results for biochar from cleft timber, GWP category

Impact category	**Module**	**Value, kg CO_2 eq**
GWP	A1	34
GWP	A2	2.7
GWP	A3	146
GWP	B1	6.6

Lower values represented by Modules A2 and B1 are the result of applied relatively short transportation distances from the biomass gathering point to the production facility, and from the production facility to the customers. Module B1 value is higher than A2 due to included input used for packages of final product transportation.

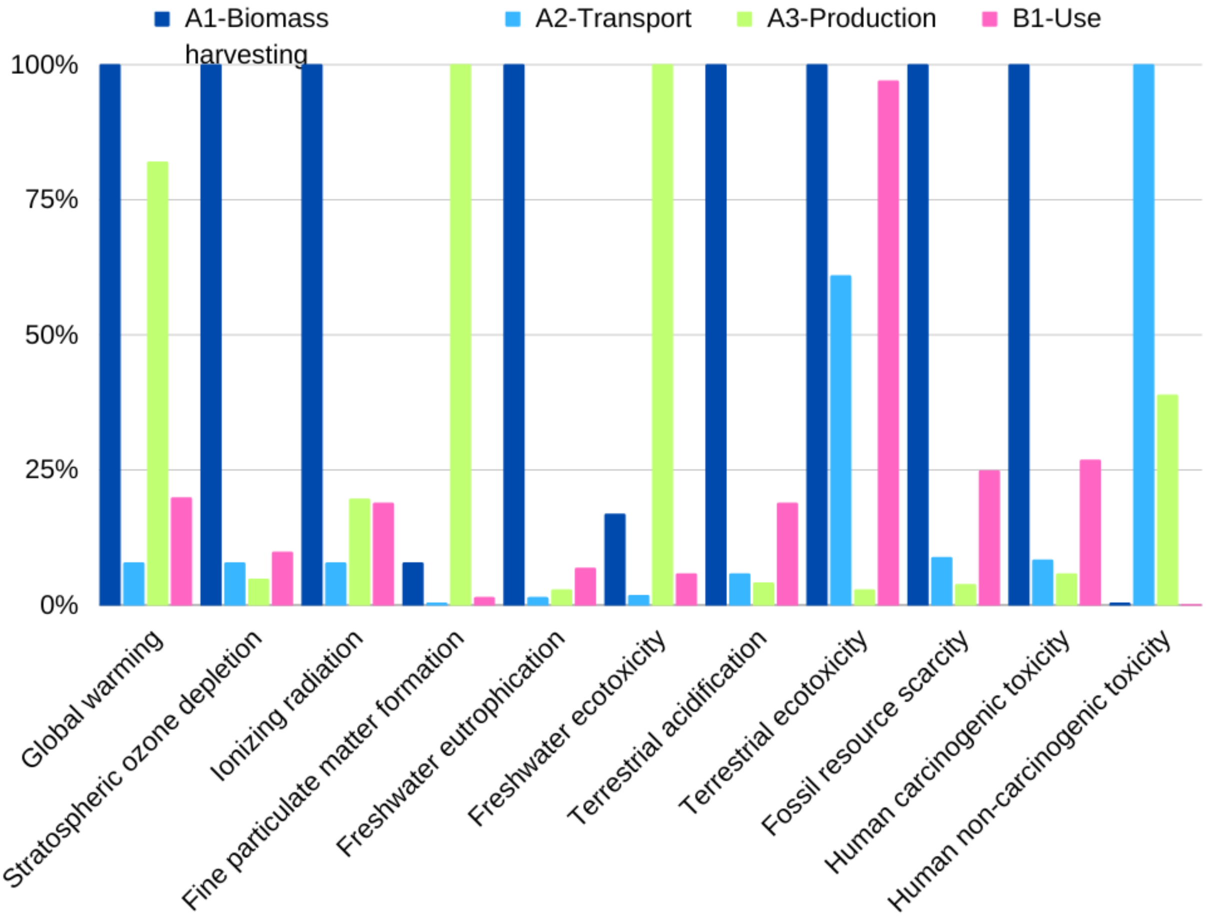


Fig. 8. Characterisation of impact results of the biochar life cycle from cleft timber, ReCiPe 2016 method, Modules A-B

Fig. 8 displays a breakdown of the relative contributions that each module makes to the specified impact categories. The dominant phase that causes environmental burdens in most impact categories is biomass gathering (Module A1) generally because of woody feedstock harvesting that leads to soil erosion and habitat destruction. Moreover, heavy machinery with a great amount of air pollutants is used in the harvesting procedure. The immense impact of production (Module A3) in comparison to the other phases is spotted in fine particulate matter formation and freshwater ecotoxicity categories.

The sum of carbon emissions for the biochar system is equal to 190.3 kg CO_2 eq. based on IPCC GWP 100a method. As according to the performed literature review, the main benefit to the environment of biochar is its ability to conserve carbon dioxide. Thus, the net amount of carbon conserved over 100-year horizon, was calculated. Estimations show that 236 kg CO_2 eq. can be conserved over 100 years for a functional unit outlined in the paper. Conducted calculations can be found in Annex 1.

Therefore, these results suggest that biochar produced from cleft timber by pyrolysis and used as a soil amendment, that decomposes over 100-year horizon, could be called a carbon net-negative product. In terms of biochar's ability to trap carbon, preliminary calculations, and findings are encouraging. Yet, it is important to highlight the information stated above, which describes that biomass gathering operations had the largest take in impact categories as terrestrial acidification, terrestrial ecotoxicity, fossil resource scarcity, and freshwater eutrophication, which seems to be a trade-off between potential benefit as carbon storage.

Table 6. presents results based on which characterization of impact results of the biochar life cycle from cleft timber was done. Results are retrieved by performing ReCiPe 2016 method.

Table 6. Impact results of biochar from cleft timber, ReCiPe method

Impact category	**Unit**	**A1** **Biomass harvesting**	**A2** **Transport**	**A3** **Production**	**B1** **Use**
Global warming	Kg CO_2 eq.	32.2	2.7	26.4	6.3
Stratospheric ozone depletion	Kg CFC11 eq.	3.7E-4	2.9E-5	1.8E-5	3.9E-5
Ionizing radiation	kBq Co-60 eq.	3.5	0.3	0.7	0.7
Fine particulate matter formation	Kg $PM_{2.5}$ eq.	4.6E-2	3.3E-3	5.9E-1	9.3E-3
Freshwater eutrophication	Kg P eq.	1.2E-4	1.9E-4	3.5E-4	7.9E-4
Freshwater ecotoxicity	Kg 1.4 – DCB	0.6	0.6E-1	4.7E-2	0.2

Impact category	**Unit**	**A1** **Biomass harvesting**	**A2** **Transport**	**A3** **Production**	**B1** **Use**
Terrestrial acidification	Kg SO_2 eq.	0.1	0.7E-2	0.5E-2	0.2E-1
Terrestrial ecotoxicity	Kg 1.4 – DCB	11.7E1	71.3	3.4	11.3E1
Fossil resource scarcity	Kg oil eq.	10.8	1	0.4	2.7
Human carcinogenic toxicity	Kg 1.4 – DCB	41.5	3.5	2.4	11.1
Human non-carcinogenic toxicity	Kg 1.4 – DCB	2.7E3	448	173	1.19E3

3.2. Life Cycle Assessment of Biochar from Sewage Sludge

The results for biochar from sewage sludge were acquired through the two above-mentioned methods – IPCC GWP 100a and ReCiPe 2016.

Table 7. Impact results for biochar from sewage sludge, GWP category

Impact category	**Module**	**Value, kg CO_2 eq**
GWP	C1	-
GWP	C2	2.7
GWP	C3	322.3
GWP	D1	6.6

In Table 7 difference between emissions from all biochar life cycle phases is visible. Production (Module C3) has the most significant impact as several procedures contributing to the emissions are involved in it. Partly attributed to the dewatering process where polyacrylamide is used to improve the separation of the solids from liquid. Moreover, the drying process of sewage sludge is known for high greenhouse gas emissions and VOC.

It is important to point out that it is assumed that heavy metals from sewage sludge do not evaporate during pyrolysis. More complex research with laboratory experiments is needed to track their behaviour. The majority of analyzed studies performed on LCA of biochar from sewage sludge consider no change in the proportions of metallic elements. The value of module C1 biomass is not indicated because digested sewage sludge comes as waste.

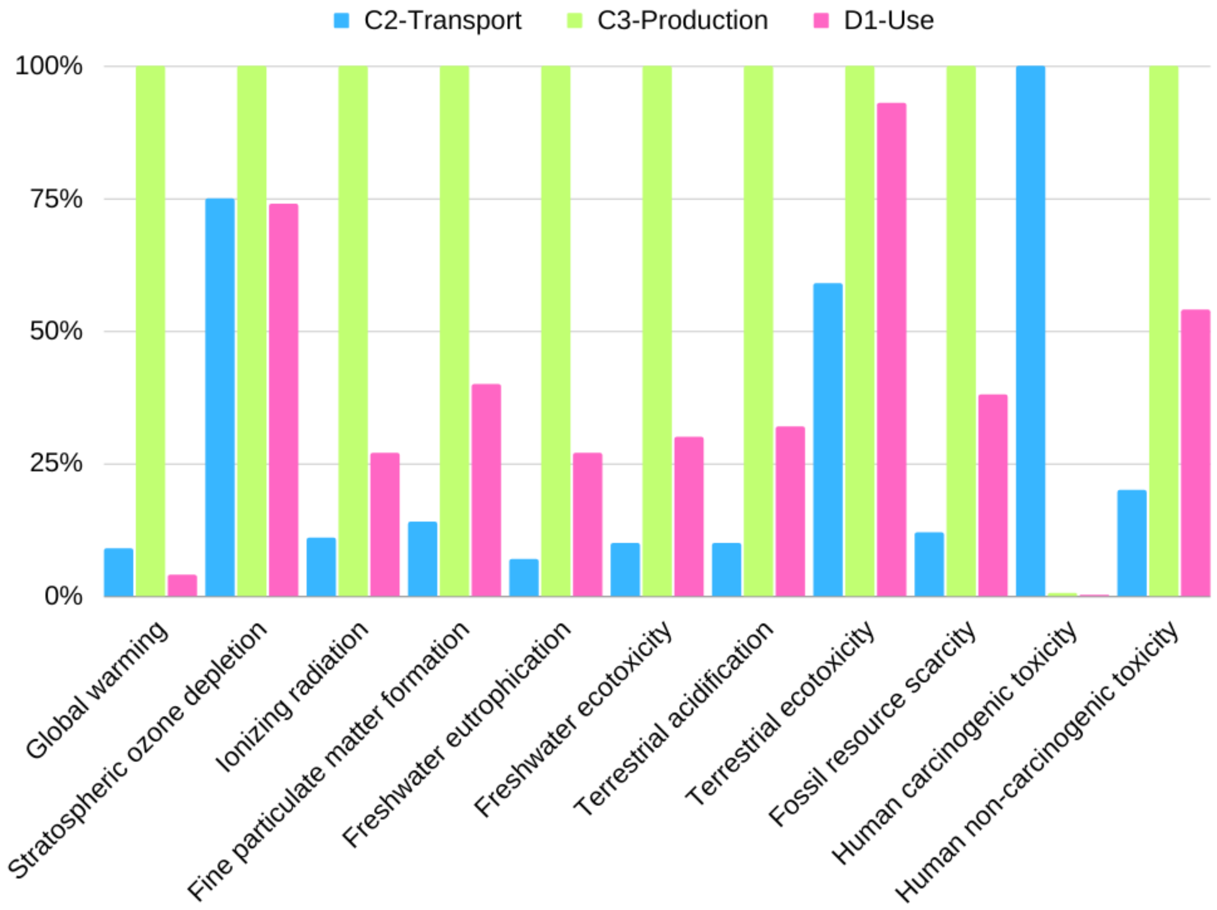


Fig. 9. Characterisation of impact results of the biochar life cycle from sewage sludge, ReCiPe 2016 method, Modules C-D

In Fig. 9, the characterization of impact results, based on the ReCiPe method, is presented. Module C3 takes the biggest stake in ten out of eleven impact categories. Production of biochar from sewage sludge requires more energy than from other biomasses.

What is more, biochar from sewage sludge raises concerns about whether particular contaminants are eliminated during pyrolysis. However, high amounts of phosphor in it have the potential to create valuable fertilizer. According to the European Biochar Industry Consortium, biochar from SS used as soil fertilizer might reduce the environmental impact caused by conventional fertilizers that are from non-renewable resources.

The total carbon release for the alternative scenario is equal to 331.6 kg CO_2 eq. based on IPCC GWP 100a method. With this number, the sum of net carbon sequestered over 100-year horizon by biochar production operations was calculated. Evaluation reveals negative output – 255.3 kg CO_2 eq. Minus value means elevation of CO_2 levels and unsuccessful mitigation of climate change.

As reported by Gbouri, et al., 2022, such results are only harsh estimations as biochar's ability to sequester carbon highly depends on its characteristics, which change from each batch of used sewage sludge. Thus, ongoing investigations are focused on creating perfect conditions for desirable biochar characteristics. However, based on this research it can be stated that biochar from sewage sludge could be a great way to manage waste as sewage sludge, as the amount of it was decreased by 97.4%.

Table 8. presents results, based on which characterization of impact results of biochar life cycle from sewage sludge, was done. Results are retrieved by performing ReCiPe 2016 method.

Table 8. Impact results of biochar from sewage sludge, ReCiPe method

Impact category	**Unit**	**C1 Biomass**	**C2 Transport**	**C3 Production**	**D1 Use**
Global warming	Kg CO_2 eq.	-	2.6	68.2	6.3
Stratospheric ozone depletion	Kg CFC11 eq.	-	2.9E-5	1.5E-4	3.9E-6
Ionizing radiation	kBq Co-60 eq.	-	0.3	2.2	0.7
Fine particulate matter formation	Kg $PM_{2.5}$ eq.	-	3.3E-3	19.7E-3	9.3E-3
Freshwater eutrophication	Kg P eq.	-	1.9E-4	2.7E-3	7.9E-4
Freshwater ecotoxicity	Kg 1.4 – DCB	-	6.2E-2	0.6	0.2
Terrestrial acidification	Kg SO_2 eq.	-	6.9E-3	5.9E-2	2.1E-2
Terrestrial ecotoxicity	Kg 1.4 – DCB	-	71.3	49.7	11.3E1
Fossil resource scarcity	Kg oil eq.	-	0.9	7.2	2.7
Human carcinogenic toxicity	Kg 1.4 – DCB	-	3.5	25.7	11.1
Human non-carcinogenic toxicity	Kg 1.4 – DCB	-	44.8E1	2.2E3	1.2E3

3.3. Normalization Results of Biochar Life Cycle from Cleft Timber and Sewage Sludge

Examining the relative importance of categories and assessing the viability of the results are the main goals of normalization. The same units are used to obtain normalized values, making comparison between then simpler.

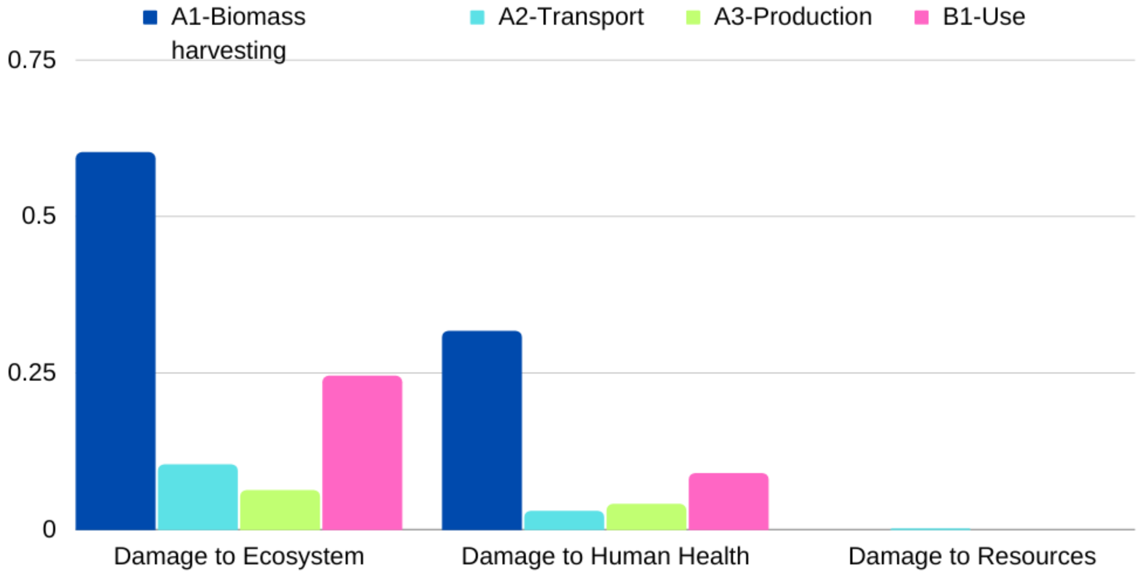


Fig.10. Normalization of impact results of the biochar life cycle from cleft timber, ReCiPe 2016 method, Modules A-B

The Fig.10 presents normalization of impact results of the biochar life cycle from cleft timber. Module A1 as biomass harvesting has the biggest take in all categories. The highest score is visible in the damage to ecosystems category, which is a result of harvesting cleft timber and how it affects the ecosystem. However, even though that biomass harvesting has the highest number in resources category, it is not that dramatical. Following, use phase has higher scores than two others as transport and production. Based on the results, it can be stated that production of biochar does not have big impact on ecosystem, human health and resources.

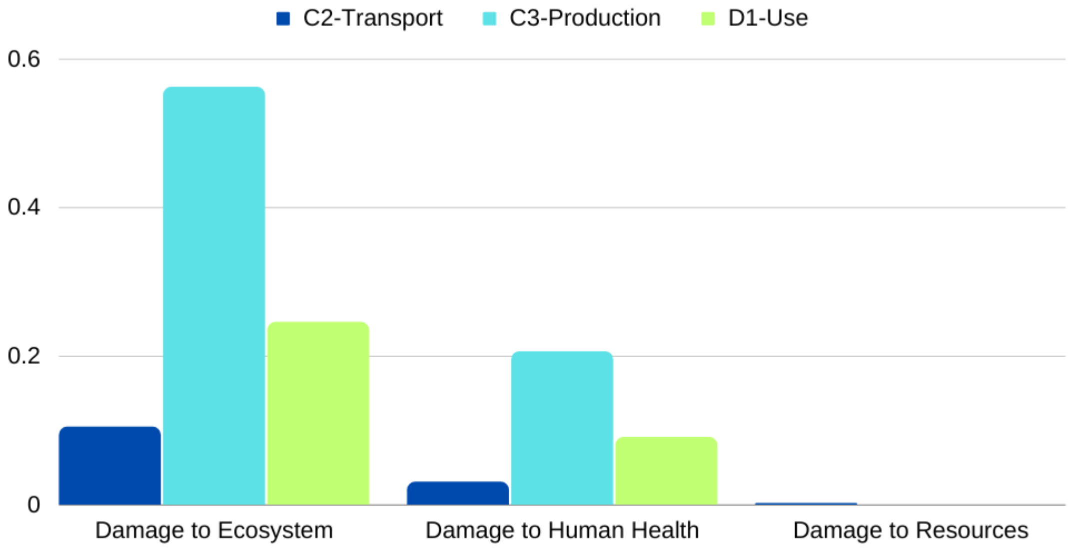


Fig.11. Normalization of impact results of the biochar life cycle from sewage sludge, ReCiPe 2016 method, Modules C-D

The normalization results of the biochar life cycle from sewage sludge are presented in Fig. 11. The production stage has the biggest scores in ecosystems and human health stages. The same results were spotted in characterization results regarding biochar from sewage sludge. Module biomass is not included as it is waste derived.

3.4. Comparative Analysis of Biochar from Cleft Timber and Sewage Sludge

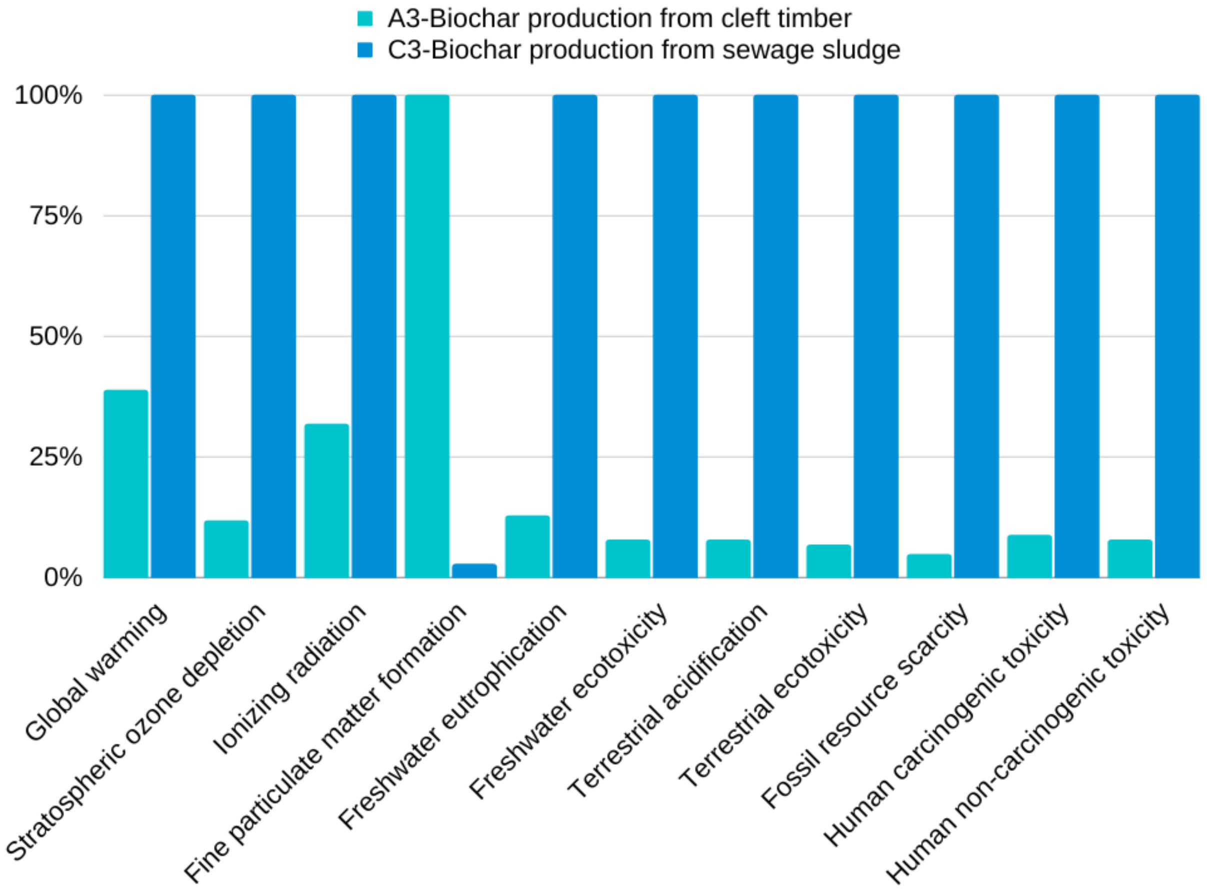


Fig. 12. Characterization of impact results of the biochar production process from two different biomasses, cleft timber, and sewage sludge

The results of the Life Cycle Assessment for the biochar production from cleft timber and sewage sludge are presented in Fig. 12. Comparing two production processes, a case study has lower CO_2 emissions to the environment than the biochar production from sewage sludge by 57%. Moreover, according to this study's calculations, only biochar from cleft timber has a positive outcome in net carbon storage over 100-year horizon. For biochar from sewage sludge, negative results indicate its failure to mitigate climate change. The study also demonstrates that, when compared to biochar production from cleft timber, biochar produced from sewage sludge has a higher impact in a number of areas. On the other hand, due to the possible effects of wood harvesting, biochar production from cleft timber has larger implications in the vast majority of categories as well.

Overall, the findings imply that the selection of the feedstock may have a substantial impact on the environmental effects of the production of biochar and that careful evaluation of the features of the feedstock and the production process is necessary to maximize the environmental advantages and minimize the drawbacks. What concerns this study's findings, biochar from cleft timber can be seen as carbon net-negative technology and pyrolysis of sewage sludge as a valid way to manage waste.

Conclusions

1. Reviewed literature on biochar presents it as a promising carbon storage tool, thereby reducing greenhouse gas emissions driving climate change. Its production helps to manage waste and generate renewable energy by using organic materials for feedstock. Moreover, biochar applied to the soil increases crop yields by improving soil quality. Nevertheless, available studies do not deliver evident outcomes regarding biochar's environmental footprint from production and use. Possible trade-offs between potential benefits are not discussed widely.
2. The biomass generation (module A3) and harvesting (module A1) phases of the case study are the cycle stages with the highest contributions to almost all effect categories. Transportation (module A2) and usage (module B1) are the cycle phases that contribute less to practically all effect categories. The stage of collecting biomass is responsible for 75% of all impacts in practically all categories. A little under 77% of the category for global warming potential is contributed by the production process.
3. In the life cycle assessment of biochar from sewage sludge, the cycle stage with the biggest contributions to practically all impact categories is the production phase (module C3). Usage (module D1) and transportation (module C2) are the cycle stages that have the lowest impact on almost all affect categories. As sewage sludge is waste, the biomass stage is not shown in any effect category. The production process contributes to almost 97% of the category of global warming potential.
4. The total of net carbon storage over 100-year horizon by biochar production operations from cleft timber is equal to 236 kg CO_2 eq, and from sewage sludge is – 255.3 kg CO_2 eq. Thus, only biochar from cleft timber could be called a net-negative product.
5. The analysis of the literature on biochar indicates that the environmental benefits of it, such as climate change mitigation, soil quality improvement, and water retention, can be outperformed when the most suitable characteristics of biochar and feedstock will be found.
6. The biochar from cleft timber is recommended to be used as a soil amendment for carbon storage. However, pyrolysis of sewage sludge is suggested as a good way to manage waste before further analysis of the characteristic of biochar from sewage sludge is made.

List of References

1. HOSSAIN, M.Z., et al. Biochar and its importance on nutrient dynamics in soil and plant. Oxford: Elsevier Science, 2020, pp. 379-420.
2. CONTE, P., et al. Research and Application of Biochar in Europe, SSSA Special Publications, 2015.
3. HORNUNG, A., et al. Biochar – just a black matter is not enough. Biomass Conv. Bioref, 2021.
4. SCOTT, H.L., et al. Biochar: an improver of nutrient and soil water availability – what is the evidence?, CABI Reviews, 2014.
5. LEHMANN, J., & JOSEPH, S., Biochar for Environmental Management: Science, Technology and Implementation (2nd ed.). Routledge, 2015.
6. CHA, J.S, et al. Production and utilization of biochar: A review, Journal of Industrial and Engineering Chemistry, Oxford: Elsevier Science, 2016, Volume 40, pp. 1-15.
7. LEHMANN, J., et al. Biochar in climate change mitigation. Oxford: Elsevier Science, Ant. Geosci. 14, 2021, pp. 883-892.
8. SUN, Y., et al. Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties, Chemical Engineering Journal, 2014, Volume 240, pp. 574-578.
9. GLOBAL ENERGY REVIEW. CO2 Emissions in 2018. (2018) Retrieved from iea.org/reports/global-energy-review-co2-emissions-in-2018-2
10. IPCC. What are Carbon Dioxide Removal and Negative Emissions? (2018) Retrived from: ipcc.ch/sr15/?s=biochar
11. TOMCZYK, A., et al. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Biotechnol 19, Oxford: Elsevier Science, 2020, pp. 191–215.
12. TAG, A.T., et al. Effects of feedstock type and pyrolysis temperature on potential applications of biochar, Journal of Analytical and Applied Pyrolysis, Oxford: Elsevier Science, 2016, Volume 120, pp. 200-206.
13. SIKDER, S. & JOARDAR, J.C. Biochar production from poultry litter as management approach and effects on plant growth. Int J Recycl Org Waste Agricult 8, Oxford: Elsevier Science, 2019, pp. 47–58.
14. YANG, Q., et al. Country-level potential of carbon storage and environmental benefits by utilizing crop residues for biochar implementation, Applied Energy, 2021, Volume 282, Part B, 116275.
15. YAASHIKAA, P.R., et al. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy, Biotechnology Reports, 2020, Volume 28.
16. CHI, N.T.L., et al. A review on biochar production techniques and biochar based catalyst for biofuel production from algae, Fuel, Oxford: Elsevier Science 2021, Volume 287.
17. WANG, D., et al. Biochar production and applications in agro and forestry systems: A review, Science of The Total Environment, Oxford: Elsevier Science, 2020, Volume 723.,
18. CANTRELL, K.B., et al. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar, Bioresource Technology, Oxford: Elsevier Science , 2012, Volume 107, pp. 419-428.

19. SHAREEF, T.M.E. & ZHAO, B., Review Paper: The Fundamentals of Biochar as a Soil Amendment Tool and Management in Agriculture Scope: An Overview for Farmers and Gardeners, Journal of Agricultural Chemistry and Environment, 2017, Volume 6 No. 1.
20. YOU, S., et al. Towards practical application of gasification: a critical review from syngas and biochar perspectives, Critical Reviews in Environmental Science and Technology, 2018, Volume 48, pp. 1165-1213.
21. WANG, B., et al. Recent advances in engineered biochar productions and applications, Critical Reviews in Environmental Science and Technology, 2018, Volume 47, pp. 2158-2207.
22. YOU, S., et al. A critical review on sustainable biochar system through gasification: Energy and environmental applications, Bioresource Technology, 2017, Volume 246, pp. 242-253.
23. FUNKE, A. & ZIEGLER, F., Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering, Biofuels Bioproducts & Biorefining, 2010, Volume 4, Issue 2, pp. 160-177.
24. BACH, Q.W., et al. Predictions of biochar yield and elemental composition during torrefaction of forest residues, Bioresource Technology, 2016, Volume 215, pp. 239-246.
25. BACH, Q.W. & SKREIBERG, O., Upgrading biomass fuels via wet torrefaction: A review and comparison with dry torrefaction, Renewable and Sustainable Energy Reviews, 2016, Volume 54, pp. 665-677.
26. PUETTMANN, M., et al. Life cycle assessment of biochar produced from forest residues using portable systems, Journal of Cleaner Production, 2020, Volume 250.
27. JEFFERY, S., et al. Biochar application does not improve the soil hydrological function of a sandy soil, Geoderma, 2015, Volumes 251–252, pp. 47-54.
28. JEFFERY, S., et al. Biochar effects on crop yield, Biochar for Environmental Management, 2015, pp. 25.
29. RANGABHASGIYAM, S., et al. Sewage sludge-derived biochar for the adsorptive removal of wastewater pollutants: A critical review, Environmental Pollution, 2022, Volume 293.
30. SHUBHAM, S., et al. Recent advances in biochar technology for textile dyes wastewater remediation: A review, Environmental Research, 2022, Volume 209.
31. KUMAR, M., et al. A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge, Journal of Cleaner Production, 2021, Volume 305.
32. DING, Y., et al. Biochar to improve soil fertility. A review. Agron. Sustain. Dev. 36, 36, 2016.
33. CAI, Y.J., et al. Recommendations for stronger biochar research in soil biology and fertility. Biol Fertil Soils 57, 2021, pp. 333–336.
34. LI, Y., et al. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J Soils Sediments 18, 2018, pp. 546–563.
35. IPPOLITO, J.A., et al. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar 2, 2020, pp. 421–438.
36. QIU, M., et al. Biochar for the removal of contaminants from soil and water: a review. Biochar 4, 2022, 19.
37. GUO, X., et al. The role of biochar in organic waste composting and soil improvement: A review, Waste Management, Volume 102, 2020.
38. WU, Ch., et al. Immobilization of microbes on biochar for water and soil remediation: A review, Environmental Research, Volume 212, Part B, 2022.

39. BHATIA, S., et al. Trends in renewable energy production employing biomass-based biochar, Bioresource Technology, Volume 340, 2021.
40. WANG, D., et al. Biochar production and applications in agro and forestry systems: A review, Science of The Total Environment, Volume 723, 2020.
41. PURO.EARTH. Standard and Marketplace General Rules, Retrived from Puro.earth: https://puro.earth/documents/
42. MOHAMED, B.A., et al. Co-pyrolysis of sewage sludge and biomass for stabilizing heavy metals and reducing biochar toxicity: A review. Environ Chem Lett 21, 2023, pp. 1231–1250.
43. CAPODAGLIO, A.G. & CALLEGARI, A., Properties and beneficial uses of biochar from sewage sludge pyrolysis, Department of Civil Engineering & Architecture, 2017.

Appendices

Appendix 1. CORCs Calculations for Case Study

The formula for net CO_2 eq eliminated over 100-year period by the biochar production activity [41].

3. $CORC_s = E_{stored} - E_{biomass} - E_{production} - E_{use}$;

Ebiomass = (A1) raw material extraction + (A2) raw material logistics [41];

Eproduction = (A3) thermochemical conversion [41];

Euse = (A4) biochar logistics + (B1) biochar end uses [41].

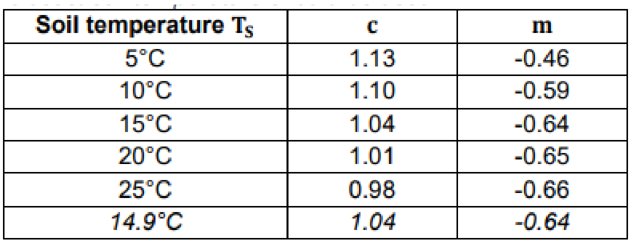
4. $E_{stored} = Q_{biochar} \times C_{org} \times F_p^{TH,Ts} \times \frac{44}{12}$;

   Qbiochar = (0.13 ton/100)*97.5% = 0.12675 ton ;
   - 130 kg (0,13 ton) – functional unit, biochar;
   - 97.5% - pure coal, as according to retrieved biochar (cleft timber) characteristics from the Lithuanian Energy Institute, humidity is 2.5%;

   Corg = 91.4% - data from laboratory test, provided by the company producing biochar in Lithuania.

5. $F_p = c + m \times H \div C_{org}$;

   Fp = 1.04+(-0.64*0.0604) =1.0013;
   - c=1.04 - based on PURO guidelines;
   - m=-0.64 - based on PURO guidelines;



Soil temperature T_S	c	m
5°C	1.13	-0.46
10°C	1.10	-0.59
15°C	1.04	-0.64
20°C	1.01	-0.65
25°C	0.98	-0.66
14.9°C	*1.04*	*-0.64*

Fig. 13. Biochar stability based on soil temperature [41]

6. $\frac{H}{C_{org}}\,(molar) = \frac{m_h(\%)}{m_c(\%)} \times \frac{M_C\ (g\,mol^{-1})}{M_H\,(g\,mol^{-1})} = \frac{m_h(\%)}{m_c\,(\%)} \times \frac{12}{1.0}$;

   H/Corg (molar) = (0.46% / 91.4% * 12 = 0.0604;
   - mH (%) = 0.46 – data from laboratory test, provided by the company producing biochar in Lithuania;
   - mC (%) = 91.4 – data from laboratory test, provided by the company producing biochar in Lithuania.

Estored = 0.12675 * 0.914 * 1.0013 * 44/12 = 0.4253 t CO_2 eq = 425.3 kg CO_2 eq;

CORCs = 425.3 – 36.7 – 146 – 6.6 = 236 kg CO_2 eq;

- 36.7 kg CO_2 eq – Ebiomass by IPCC GWP method;
- 146 kg CO_2 eq – Eproduction by IPCC GWP method;
- 6.6 kg CO_2 eq – Euse by IPCC GWP method.

Appendix 2. CORCs Calculations for Biochar from Sewage Sludge

The formula for net CO_2 eq eliminated over 100-year period by the biochar production activity [41]

7. $CORC_s = E_{stored} - E_{biomass} - E_{production} - E_{use}$;

Ebiomass = (A1) raw material extraction + (A2) raw material logistics [41];

Eproduction = (A3) thermochemical conversion [41];

Euse = (A4) biochar logistics + (B1) biochar end uses [41].

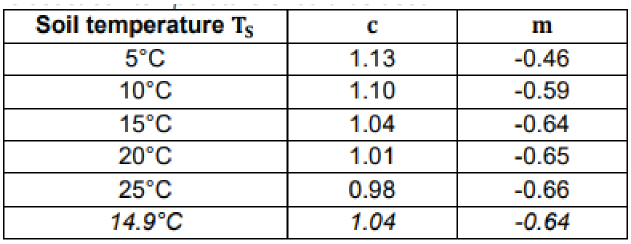
8. $E_{stored} = Q_{biochar} \times C_{org} \times F_p^{TH,Ts} \times \frac{44}{12}$;

   Qbiochar = (0.13 ton/100)*95.05% = 0.123565 ton;
   - 130 kg (0.13 ton) – functional unit, biochar;
   - 95.05% - pure coal, as according to retrieved biochar (cleft timber) characteristics from the Lithuanian Energy Institute, humidity is 4.95%;

   Corg = 19.35% - data from literature.

9. $F_p = c + m \times H \div C_{org}$;

   Fp = 1.04+(-0.64*0.266) =0.86976;
   - c=1.04 - based on PURO guidelines;
   - m=-0.64 - based on PURO guidelines;



Soil temperature T_S	c	m
5°C	1.13	-0.46
10°C	1.10	-0.59
15°C	1.04	-0.64
20°C	1.01	-0.65
25°C	0.98	-0.66
14.9°C	*1.04*	*-0.64*

Fig. 14. Biochar stability based on soil temperature [41].

10. $\frac{H}{C_{org}}\,(molar) = \frac{m_h(\%)}{m_c(\%)} \times \frac{M_C\ (g\,mol^{-1})}{M_H\,(g\,mol^{-1})} = \frac{m_h(\%)}{m_c\,(\%)} \times \frac{12}{1.0}$;

    H/Corg (molar) = (0.43% / 19.4% * 12 = 0.266;
    - mH (%) = 0.43% – data from literature;
    - mC (%) = 19.4% – data from literature.

Estored = 0,123565 * 0,1935 * 0,86976 * 44/12 = 0,07625 t CO_2 eq = 76,25 kg CO_2 eq.

CORCs = 76,25 – 2,7 –322,29 – 6,6 = -255,34 kg CO_2 eq;

- 2,7 kg CO_2 eq – Ebiomass by IPCC GWP method;
- 322,29 kg CO_2 eq – Eproduction by IPCC GWP method;
- 6,6 kg CO_2 eq – Euse by IPCC GWP method.

Appendix 3. Guidelines from PURO2

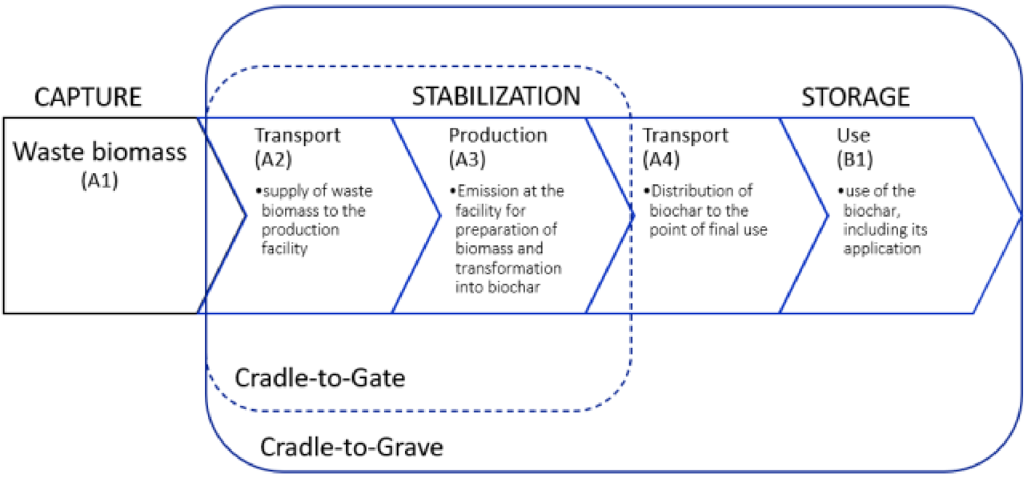


Fig. 15. System boundary for biochar from waste [41]

Based on this scheme presented above, impact of phase as biomass for LCA of biochar from sewage sludge was not calculated and included to the results.