Carbofex

LCA Report – Carbofex's biochar product

Life Cycle Assessment according to ISO 14040 and Puro.Earth Biochar Methodology

20.3.2023

Summary

Potential greenhouse gas emissions of biochar were studied in a life cycle assessment presented in this report. The commissioner of the study was Carbofex. The study was conducted by Ecobio Oy.

The purpose of this study is to calculate the greenhouse gas emissions of biochar produced in Finland and assess the greenhouse gas compensation potential. The system boundary is set cradle-to-grave and includes emissions from production and supply of the biomass, from biomass conversion to biochar, and from biochar distribution and use. The amount of carbon dioxide removal certificated (CORCs) resulting from the biochar production activity over a given reporting period for a given amount of biochar produced is not calculated.

Data for the study was collected from Carbofex, databases available at Ecobio, and from the literature. This study is conducted following the LCA methodology described in standards ISO 14040 and 14044, as well as in Puro.Earth's Standard Biochar methodology, which gives requirements and guidelines for the quantification of the carbon footprint of products. It also provides procedures to verify the compliance of CO_2 removal activity with the removal method. It specifies the system boundaries, detailed calculation formulas and the proof needed for the issuance of CORCs regarding the LCA.

Based on the LCA, the biggest emitter during the life cycle is the harvesting process of the energy wood (66,28 kgCO2eq). Other significant emissions source is the biochar distribution (60,37 kgCO2eq), of which 43,15 kgCO2eq is caused by sea transportation. The most significant climate change impacts during the production process of biochar are caused by internal transportation (14,38 kgCO2eq) and capital goods (11,13 kgCO2eq). This is a concern in relation to the uncertainty associated with the calculation of capital goods. The major contributor in energy usage on site is caused by the light fuel oil (7,42 kgCO2eq) and the emissions to air from preheating the reactor (46,05 kg CO2eq). The most electricity intensive unit process is the feedstock drying (4,77 kgCO2eq) and biochar production process (3,96 kgCO2eq). Replacements and repairs (0,147 kgCO2eq), manufacturing process of packaging material (4,75 kgCO2eq) and end-of-life treatment of packaging material (1,04 kgCO2eq) have minimal effects during manufacturing process. The biochar mixing and spreading in use phase (0,323 kgCO2eq) also has a small contribution to the results. The total emissions produced are 240,91 kgCO2 per tonne of biochar produced.

Table of Contents

Abbreviations

CORC	Carbon dioxide removal certificates
eq	equivalent
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULUC	land use and land use change
LHV	Lower heating value
PM	Particulate matter
RER	Europe
SE	Sweden
tkm	ton kilometre, transport unit (1 ton x 1 km)

1. Introduction

Potential environmental impacts of biochar were studied in the life cycle assessment (LCA) presented in this report. The system boundary is set cradle-to-grave and include emissions from production and supply of the biomass, from biomass conversion to biochar, and from biochar distribution and use. This LCA study is conducted to update carbon credit generation calculation associated with its biochar product manufactured in Carbofex's production facility in Tampere. To be eligible for Puro.Earth's marketplace producer must proof the carbon dioxide removal achieved by the production of biochar with LCA in Production Facility Audit.

2. Goal and scope definition

2.1. Commissioner, conductor, and date of the study

The commissioner of the study was Carbofex. The study was conducted by Ecobio Oy.

This LCA study follows the methodology described in ISO 14040 and ISO 14044 standards where applicable. Puro.Earth's Marketplace 2019 Rules and Puro Standard Biochar Edition 2022 methodology is also applied as it provides procedures to verify the compliance of CO_2 removal activity with the removal method. It specifies the system boundaries, detailed calculation formulas and the proof needed for the issuance of CORCs regarding the LCA.

The life cycle assessment was completed on 20 March 2023.

Persons involved in the project:

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2.2. Goal of the study

The goal of the study is to:

- gain information on how the environmental impacts of the biochar and its co-products are distributed throughout the life cycle, and
- provide material for the customer inquiries related to the environmental performance of the biochar and its co-products.
- serve as background for the audit process to Puro.Earth CO_2 removal marketplace. To be eligible for Puro.Earth's carbon dioxide removal certificates (CORCs) the producer must proof the CO_2 removal achieved by the production of biochar with LCA.

2.3. Reasons for carrying out the study

The reason for carrying out the study is to be able to respond to the customer inquiries about the environmental performance of biochar and to acquire information on LCA results for Puro CO2 Removal marketplace. By conducting the study, Carbofex prepares for the continuously growing demand for environmental information required by the customers and other key stakeholders.

2.4. Intended audience

The results of the study are primarily presented internally at Carbofex. The results of the study are not intended for comparative assertions to be disclosed to the public.

2.5. Scope of the study

2.5.1. The product

The scope of this study was to develop a cradle-to-grave life cycle assessment for biochar processing including a life cycle impact assessment (LCIA) to evaluate the environmental impacts from raw material supply to the thermochemical conversion of biomass into biochar (product manufacturing). Biochar and its co-products are produced by Carbofex Oy. Energy and co-products produced by the system include pyrolysis oil and district heat.

Biochar is produced from wood biomass, such as slash and thinning, through pyrolysis process. The woody biomass is dried and chipped prior to the pyrolysis process. Pyrolysis produces an extremely stable solid form of carbon that can withstand in soil for thousands of years, making it an ideal approach for carbon removal. The Carbofex pyrolysis process heats the wood biomass to approximately 600 °C. The outputs from the pyrolysis process include biochar, pyrolysis oil, pyrolysis gas, and flue gas. The pyrolysis gas is reused in the process of firing the pyrolysis process. Light fuel oil is used in heating the pyrolysis process. The high firing temperature of the pyrolysis gas results to very accurate carbonization and low emission in the flue gas.

2.5.2. Declared Unit / Functional unit

The main function of the whole system is the production of biochar for soil amendment, and the functional unit of the study is therefore 1 t of dry biochar stored in soil for 100 years.

2.5.3. Product system to be studied and its boundary

The product system to be studied consist of biochar. The system boundary of the life cycle assessment was set to cradle-to-grave, or, more specifically, the system is studied from raw material supply to biochar soil amendment. The life cycle stages include emissions from production and supply of the biomass, from biomass conversion to biochar, and from biochar distribution and use. The materials and manufacturing of the pyrolysis and other machinery are included in the life cycle assessment. Figure 1 illustrates the system boundaries and the life cycle phases included in the life cycle model. The specific unit processes are described in section 3.4.

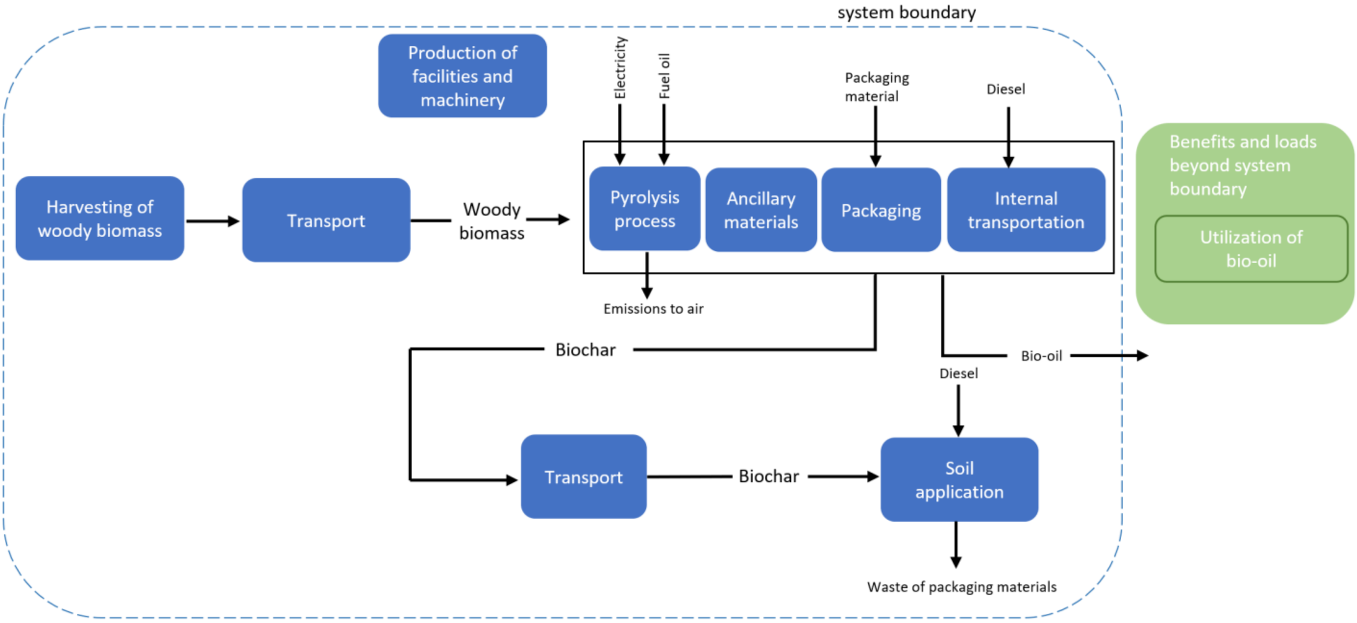

Figure 1. Flow diagram describing the system boundaries.

2.5.4. Allocations

Allocation is used in LCA, if the impacts of certain processes need to be divided to several processes or products, e.g., the environmental impacts from a production line can be allocated to several different products. ISO 14044 recommends that the inputs and outputs of the system should be allocated between the different products by reflecting the underlying physical relationships between the products, where allocation cannot be avoided (4.3.4.2).

There are grounds for allocation concerning biochar production. Biochar is always product of a multi-output product. These include syngas and pyrolysis oil in addition to biochar. The energy content allocation between the biochar and the co-product (pyrolysis oil) is applied. The approach was selected since the preferred allocation approach based on Puro Biochar Standard methodology is energy allocation, if the pyrolysis co-products represent high-value products or a large share of the initial biomass energy content. Lower heating value (LHV) of bio-oil is 5,5 kWh/l and of biochar is 9,3 MWH/t and these are provided by the commissioner. Co-product allocation is applied for the raw material supply, transportation of raw materials and manufacturing phase. The impacts of packaging materials, transportation to customer and use phase are 100 % allocated to biochar.

Table 1. Data used for determining energy allocation values for biochar and bio-oil

Product	Product output	LHV	Energy content [MWh]	Allocation value
Biochar	52 t	9,3 MWh/t	483,6	483,6/ 569,48 = 0,8492
Bio-oil	15 615 l	5,5 kWh/l	85,88	85,88 / 569,48 = 0,1502
Total			569,48	

2.5.5. Classification of data

The data categories used in life cycle assessment depends on the goal of the study. The most important headings under which the data are classified are:

- energy inputs, raw material inputs, ancillary inputs, other physical inputs,
- products, co-products and waste,
- emissions to air, water and soil, and
- other environmental aspects (EN ISO 14044, 4.3.2.3).

The data used in this LCA cover the three first mentioned sections.

2.5.6. Environmental impact categories

This study assessed one environmental impact category parameter: global warming potential (GWP). The GWP results are expressed as kg CO_2 eq. Biogenic and fossil CO_2 emissions are treated equally in the model.

2.5.7. Selection criteria of inputs and outputs

For the biochar production, all reported and known inputs and outputs were taken into account. No losses of materials were considered in the inventory data, as the raw material and energy inputs are accounted for either in the end products or used within the production process.

2.5.8. Data quality requirements

The quality requirements for the LCA were set according to the EN ISO 14044 standard (4.2.3.6). The used data is as up-to-date as possible and at most five years old for producer-specific data and at most ten years old for generic data.

The datasets described in this LCA report, and the datasets inserted into the biochar model in SimaPro are based on data for 45 time period of data with 8 days of downtime and 37 days of a production and 1 ton as functional unit. The choice of data presentation ensures consistency and comparability of the data with the biochar production.

Geographically, the production of the biochar concerns conditions in Finland. The data corresponds to modern western technology and the physical properties of the product.

Specific data collected in demo scale plant from Carbofex were used for the production processes. For upstream and downstream processed generic data was used. Generic data is from 2022 (Ecoinvent 3.8).

The accuracy of the data was assessed when creating the life cycle model. Clear deviations and suspicious values were checked. When entering the values into the model, they were critically examined, and possible misspellings were detected and corrected.

In the information categories, all the gathered data were used without excluding categories in advance but following the boundaries of the system set earlier. The data used are primarily gathered from the actual unit processes. They are produced specifically for the model complying with the general principles of the life cycle assessment standard, and also in the way that the assessment can be re-conducted by an external party. No statistical limits are set to the uncertainty of the source information.

Used datasets are described more in detail in section 3.5.

2.5.9. Restrictions

Restrictions and/or limitations, which can influence the extent of the LCA, the interpretation and application of the results, are described in this chapter.

For the transportation distance of the energy wood, information was used as provided by the commissioner. Nevertheless, it was assumed that given distance is sufficient for a representative impact assessment. Transportation processes for other inputs like plastic bags and light fuel oil were not considered due to neglected impact on the end results.

The dataset of energy wood does not fully correspond to the actual input wood raw material used in the biochar production. The raw material for biochar production varies over time. Typically, the by-products of forest industry are used, such as slash, logging residue, and thinning. The energy wood dataset could be developed so that the various forest industry by-products are considered, and the impacts are allocated for the saw log and the energy wood in a different manner. In the current model, the energy wood dataset is based on the hard- or softwood forestry, as are the saw log datasets, and thus, the inputs in the energy wood and saw log datasets are the same for the most part. The differences between the energy wood and the saw log datasets of birch per kg of material are in the allocated amounts of skidding and forwarding. The energy wood dataset includes about half of the forwarding inputs of the saw log dataset, but no skidding compared to saw log dataset.

According to Puro Standard Biochar methodology, the CORC value is based on the product's biogenic carbon storage and fossil emissions. Biogenic or LULUC CO2eq emissions are not considered in the CORC calculation, and thus, are not included in the study. The life cycle model includes only the greenhouse gas emissions as air emissions and excludes other types of air emissions. Therefore, the following air emissions are excluded from the study as they do not cause any climate change impacts. There are air emissions produced from the pyrolysis process in the form of nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), particulate matter (PM) and total volatile organic compounds (TVOC) emissions. The concentrations measured in the flue gas measurement are reported as concentrations in dry gases under NTP conditions. The amount of NO_x is approximately 65 mg/m^3n, PM 2,0 mg/m^3, sulfur dioxide lower than 3 mg/m^3 and TVOC 2,0 ppm.

The impact assessment results are relative expressions and do not predict impacts on category endpoints, the exceeding thresholds, safety margins or risks (ISO 14044, 5.2 e8).

2.5.10. Critical review

A critical review as described in the life cycle assessment standards is a process to enhance the understanding of the study and its reliability. Comparative assertions based on a life cycle assessment require a critical review, especially if the results are intended to be communicated to external parties or public statements are to be made.

No comparative assertions are to be made based on this life cycle assessment and no critical review was done on this study.

3. Life cycle inventory analysis (LCI)

The life cycle inventory analysis (LCI) includes the collection of the data necessary to meet the goals of an LCA study as well as analysis of the life cycle inventory. The life cycle model used for the inventory analysis was created with the SimaPro LCA software. The software is developed by Pré Consultants. The structure of the life cycle inventory analysis is presented in Figure 2.

As a result of the inventory analysis, a life cycle inventory is obtained, which is the material and energy balance for the studied product system. This is used as a base for the life cycle impact assessment (LCIA).

In this chapter, the essential method and data used for the life cycle inventory analysis is described.

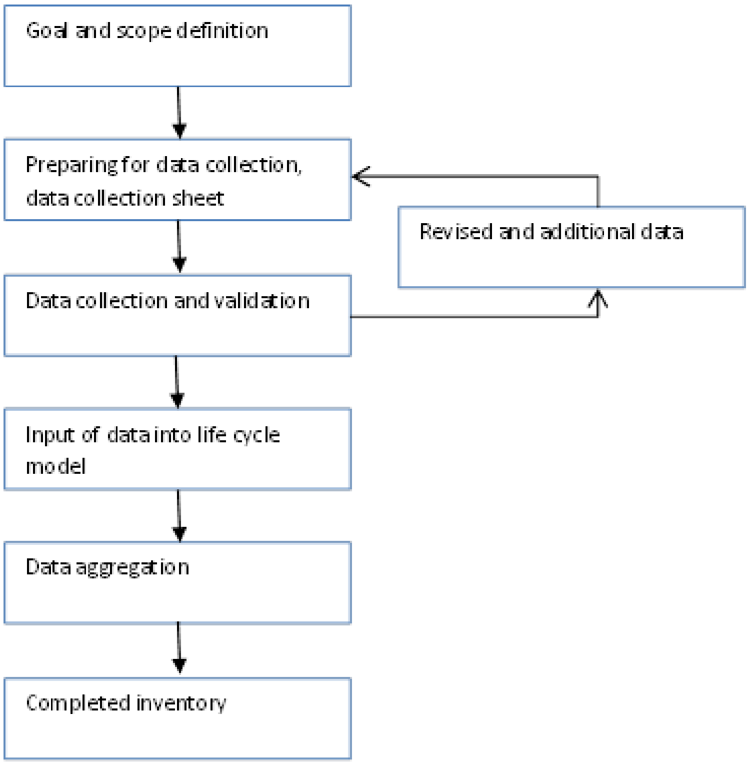

Figure 2. The structure of life cycle inventory analysis (LCI).

3.1. Data collection methods

The input data for the study was collected in several stages. The aim was to collect as comprehensive information as possible on the materials and masses used in order to obtain data also from the materials which could cause potential environmental impacts already at small amounts. The accuracy and the age of the data were underlined when collecting information, focusing on the data being as up-to-date as possible.

Information on the raw materials and the manufacturing process was collected from the manufacturer. Data describing materials were collected from the manufacturer, the suppliers and Ecobio's database.

Based on the inventory table, life cycle model of the product was created with SimaPro. The life cycle models are described in section 3.5.

3.2. Missing data

The input data used in the study should correspond to the actual practice of the studied product system as far as possible. In an ideal situation, each unit process can be described with data based on measurements or annual material and energy balances. In an ideal situation, the supplier should also be able to provide the life cycle inventory data for their share of the life cycle (e.g., from raw material supply to the factory gate). Relatively few material suppliers can provide this life cycle inventory data, hence the input data must be collected from alternative sources.

In this study the following principles have been followed when collecting and treating missing data:

- collecting LCI-data from the manufacturer
- collecting LCI-data from the supplier
- collecting LCI-data from Ecobio's database
- collecting LCI-data from an industry organization
- collecting LCI-data from the literature
- collecting data from other commercially available databases (*only if the missing data is assumed to have a major impact on the overall impact assessment*)
- theoretical calculation of LCI-data on a rough level (*only if the missing data is assumed to have a major impact on the overall impact assessment*)
- replacement of the data with data for a similar material
- pointing out and documenting that the data is missing

In this LCA, no data was collected from other sources than the manufacturer, supplier or Ecobio's databases (Ecoinvent 3.8).

3.3. Units in the life cycle model

SI units are applied in the life cycle model; raw materials, emissions, and waste as mass (kg or t); energy as watt-hours (kWh, MWh). Transportation is entered as ton kilometres (tkm).

3.4. Life cycle model

Data collection for the biochar system encompasses a cradle-to-grave system boundary. The model considers the co-products as well. No material losses were considered in the data collection, as it was estimated that materials are not lost during the life cycle, but the yield is 100 %.

All forest residues were considered waste and therefore forestry operations related to management and harvesting were excluded from this LCA. The wood biomass input is modelled based on the dataset of energy wood bundles from the Ecoinvent 3.8 database. The energy wood bundle dataset includes the inputs from nature (wood as energy content and as resource input, land occupation for forest and forest roads) and inputs from technosphere as materials, fuels, and energy (diesel consumption for forest road construction and planting, forwarding of stemwood and energy wood, gravel for forest road construction, harvesting by forestry harvester, and power sawing needed for site preparation, tending, pruning, and harvesting). The bundling of energy wood is removed from the dataset of energy wood, as the input biomass in Carbofex process is not bundled. In addition, the dataset for harvesting process included carbon dioxide sequestration, which signified carbon sink. That was changed to zero.

In this study, as average biochar yield of 25 % is assumed, excluding any moisture in both biomass and biochar. Consequently, 3981 kg of biomass is required to produce 1 t of biochar in dry basis. As a results, the total biochar produced is 52 t as dry weight and the raw material input is 207 t as dry weigh. The moisture content of raw material varies from 30 – 50 %, and thus, the average moisture content of 40 % is assumed. The total raw material input is 345 t including water. The biochar input is expressed as dry weight and the biochar have approximately 30 % moisture content when it is stored and transported in the bags. In addition to biochar, 15 615 liters of bio-oil is produced.

The transport mode and distance were known for all raw materials and were considered as such in the model. Road was used as transport type. For road transport diesel truck with EURO6 standard and more than 32 t capacity is used as a baseline for the modelling. No losses during the transport were expected. It is assumed that the average transportation distance of woody biomass to the production facility is 60 km by road. Water was included in the transported weight, as the wood was wet at the time of transportation. For transportation to customer, 225 km by road and 300 km by sea transportation is modelled. The transported weight includes the biochar with moisture and packaging materials. Transportations were entered as ton kilometres (tkm), which takes into account both the weight and the distance of the transported goods. The datasets are based on ecoinvent 3.8 database, which uses average European road transport load capacities for the modelling. Data from LIPASTO-database was applied for the calculation so that certain airborne emissions and diesel consumption were modified according to the full load capacity.

The production consumes energy in the form of electricity. The electricity is 100 % produced with renewable energy sources and more precisely by wind power. The climate change impact of the electricity production mix in manufacturing process is 29,9 g CO_2-eq/kWh. The value includes fossil, biogenic and land use related climate change impacts. The chipper consumes 1 127 kWh of electricity, the dryer consumes 9 828 kWh of electricity, and the pyrolysis process consumes 8 148 kWh of electricity.

932,41 kg of light fuel is consumed with density of 0,834 kg/dm3 as the production process requires a fossil start-up fuel. The fossil CO_2 emissions emitted by light fuel oil is calculated with information provided by Statistics Finland and it is assumed that light fuel oil contains average of 4,0 % biofuel share of the energy content. This is done as no suitable dataset was found to describe the thermal energy obtained from light fuel oil in pyrolysis reactor. The net calorific value (NCV) used is 43,1 GJ/unit. The CO_2 default emission factor according to NCV for light fuel oil is 70,2 t/TJ. Thus, the amount of produced fossil CO_2 emissions by light fuel oil is 2,82 t.

The capital goods must be considered in LCA. The capital goods are included in the LCA using a general conversion factor from Department for Environment, Food & Rural Affairs (DEFRA, 2011). This guideline is provided by Puro.Earth. No readymade guidelines are provided in the Puro.Earth Biochar Methodology. These factors are only valid for climate change impacts, but as they are approved by Puro.Earth, they are suitable from carbon sequestration's point of view as input information for the calculation. Furthermore, information was received from Puro.Earth that since the production facility is in a rental property, the property does not need to be considered in the LCA in terms of production assets. Therefore, the factor used only estimates of greenhouse gas emissions related to the production of machines and equipment per currency of investment. The emission factor representing the capital goods is 0,56 kg CO_2e per £. As the average currency exchange from £ to € was 1,1632 during the reference period, the emission factor used for calculation is 0,48 kg CO_2e per €. The investment of the manufacturing plant is 510 559 € and the lifecycle of the plant is 25 years. An average of 750 tons of biochar is produced in one year. This information was provided by the commissioner of the study. The climate change impact over the entire 25-year life cycle is 245,8 tCO_2e, 9,83 tCO_2e per year. The climate change impact per one year for biochar is 8,35 tCO_2e based on the allocation factors presented in 2.5.4. Thus, the climate change impact per one ton of biochar is 11,13 kgCO_2e and climate change impact is 0,579 tCO_2e when 52 ton of dry biochar is produced. Data used for determining impact of the capital goods are presented in Table 2.

For packaging materials, 2,7 kg of polypropylene is needed for production of one packaging bag and total of 521 of propylene bags are needed, since 270 kg of biochar is packed in one bag. It is assumed that 80 % are reused and 20 % of them are going to waste treatment after use stage. Thus, the inventory includes the manufacturing process of 20 % of the propylene bags and waste treatment of 20 % of the polypropylene bags after use stage. The inventory of packaging material only includes the manufacturing process of polypropylene granulates as no suitable dataset is found to manufacturing process of polypropylene bags. As a conservative approach the end-of-life treatment for 20 % packaging materials is assumed to be municipal incineration. For internal transportation 279 liters of diesel is used.

The scenario is created for biochar mixing and spreading. It is assumed that mixing biochar takes 0,3375 min per one ton of biochar. The fuel consumption of the excavator is assumed to be 14 l per hour, and as a result it takes 22,8 min to spread 67,6 tons of biochar, which consumes 5,32 liters of fuel. The used datasets are presented in Table 3.

Table 2. Data used for determining the GHG emissions of the capital goods.

	Input	Unit
Emission factor	0,56	kg CO2e per £
Currency exchange rate (£ -> €)	1,1632	£/€
Emission factor	0,48	kg CO2 per €
Investment of the production plant	510 559	€
Life cycle of the production plant	25	years
Climate change impact over the entire 25-year life cycle	245,80	tCO2e
Climate change impact per one year	9,83	tCO2e
Climate change impact per one year for biochar	8,35 *)	tCO2e
Climate change impact per one ton of biochar	11,13 **)	kgCO2eq
Climate change impact per 52 ton of biochar	0,579 ***)	tCO2e

*) The value is calculated as 9,83 tCO2e*0,8492 = 8,35 tCO2e
**) The value is calculated as 8,35 tCO2e/750 $ton_{biochar}$ = 11,13 kgCO2eq
***) The value is calculated as 0,01113 tCO2e * 52 ton = 0,579 tCO2e

Table 3. Datasets used in life cycle model of biochar production.

Input/Output	Dataset	Year (dataset)	Amount	Unit
Product output	Biochar	-	52	t
Co-product output	Bio-oil	-	15 615	l
Raw material supply				
Woody biomass	Bundle, energy wood, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | Cut-off, U	-	207	t

Water	Water, unspecified natural origin, FI, biotic	-	138	t
Transportation of raw materials				
Raw material transportation	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U	2022	20 700	tkm
Biochar production process				
Chipper electricity consumption	Electricity, high voltage {FI}| electricity production, wind, >3MW turbine, onshore | Cut-off, U	2022	1 127	kWh
Dryer electricity consumption	Electricity, high voltage {FI}| electricity production, wind, >3MW turbine, onshore | Cut-off, U	2022	9 828	kWh
Production process electricity consumption	Electricity, high voltage {FI}| electricity production, wind, >3MW turbine, onshore | Cut-off, U	2022	8 148	kWh
Internal transportation	Diesel, burned in building machine {GLO}| processing | Cut-off, U *)	2022	9 578,29	MJ
Light fuel oil	Light fuel oil {Europe without Switzerland}| market for | Cut-off, U	2022	932,41	kg
Packaging materials	Polypropylene, granulate {GLO}| market for | Cut-off, U	2022	104,2	kg
Emissions to air from capital goods	Carbon dioxide **)	-	0,579	t
Emissions to air from pre-heating the reactor	Carbon dioxide, fossil	-	2,82	t
Lubricating oil	Lubricating oil {RER}| production | Cut-off, U	2022	1	kg
Steel parts	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, U	2022	1	kg
Silicon, graphite gaskets	Silicon, metallurgical grade {RoW}| production | Cut-off, U	2022	0,25	kg
	Graphite {RER}| production | Cut-off, U	2022	0,25	kg
Transportation to customer				
Biochar road transportation	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U ***)	2022	15 327,23	tkm
Biochar sea transportation	Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-off, U ****)	2022	20 436,30	tkm
Use phase				
Use of work machine	Diesel, burned in building machine {GLO}| processing | Cut-off, U *)	2022	182,64	MJ
End-of-life treatment of packaging materials				
Polypropylene bags	Municipal solid waste {FI}| treatment of, incineration | Cut-off, U	2022	104,2	kg

*The diesel process is created by including lower heating value (LHV), which is 42,7 MJ/kg of diesel and density, which is 0,804 kg/dm3.
** Value is already allocated to biochar by allocation factor 84,92 %
*** The value is calculated as (1,3*52+0,521) * 225 km = 15 327,231 tkm.
**** The value is calculated as (1,3*52+0,521) * 300 km = 20 436,30 tkm.

4. Life cycle impact assessment (LCIA)

The life cycle impact assessment (LCIA) is made based on the inventory analysis (LCI). The impact assessment is applied in order to evaluate the product system from an environment's perspective by using impact categories and impact category indicators, which are connected to the results of the inventory analysis (see section 3).

4.1. Methodology of LCIA and interpretation

Calculations for the impact assessment were conducted using the SimaPro software and the impact category parameters set by the EN 15804:2012 + A2:2019 standard. The LCIA method is described in the section 4.1.2. Interpretations, which are based on the LCIA methods, are made on the basis of the characterization phase according to the instructions of the life cycle assessment standard.

4.1.1. Structure, concept and nomenclature of the impact assessment

According to the SFS-EN ISO 14040 standard series, the LCIA includes both mandatory and voluntary parts. The mandatory parts of the LCIA are presented in Figure 3. Interpretation and conclusions of the impact assessment should be made on the basis of their actual result, which is the LCIA profile. The LCIA profile is also the outcome of the mandatory phase of the impact assessment. In the LCIA profile, the indicator result in each impact category should be expressed using specific quantitative impact category related indicators. This calculation of the impact categories' indicator results is called characterization.

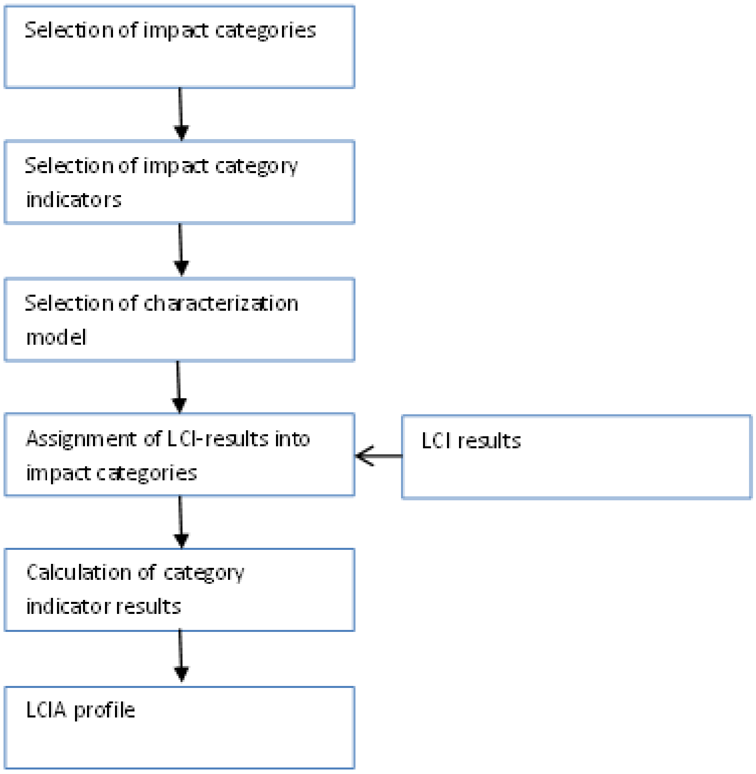

Figure 3. Mandatory parts of impact assessment (SFS-EN ISO 14040)-

Voluntary parts of the impact assessment include normalization, grouping and weighting. Voluntary parts of the impact assessment were not used in this life cycle assessment.

Normalization is proportioning of the LCIA results with respect to other relevant measures. For example, life cycle emissions of a specific product system could be compared in proportion to equivalent European emissions within the same time period.

Grouping means classification and ranking of the impact categories, for example with respect to their characteristics. Ranking is based on the value choices, and thus subjective.

Weighting is the most subjective part of the life cycle impact assessment, and its main function is to proportion every impact category with respect to each other. As an outcome, there is one index figure. For this measurement, many alternative methods have been developed, however, subjectivity is present in all of them. Back-grounds of the weighting methods should be well known when evaluating results related to them. Even at their best, weighting methods only give guidelines of proportional significance of the environmental impacts.

4.1.2. Environmental impact categories

Climate change – total (*GWP-total, Global Warming Potential total*): informs the total potential effect of greenhouse gases, such as carbon dioxide (CO_2), to change the climate. Greenhouse gases block a part of the sun's infrared radiation to exit the atmosphere, causing the temperature at the earth's surface to rise. The effects of different greenhouse gases are converted into comparable form by proportioning them to carbon dioxide units.

GWP-total is the sum of global warming potential of fossil, biogenic and land use and land use change emissions. Unit: kg CO_2-eq.

Climate change – fossil (*GWP-fossil, Global Warming Potential fossil*): accounts the greenhouse gas emissions and removals originating the oxidisation, for example combustion or landfilling, of fossil fuels or materials containing fossil carbon. Unit: kg CO_2-eq.

Climate change – biogenic (*GWP-biogenic, Global Warming Potential biogenic*): accounts the greenhouse gas emissions and removals originating the oxidisation, for example combustion or landfilling, of biofuels or materials containing biogenic carbon. GWP-biogenic covers biogenic greenhouse gas emissions and removals from all sources except native forests. Unit: kg CO_2-eq.

Climate change – land use and land use change (*GWP-luluc, Global Warming* Potential land use and land use change): accounts for greenhouse gas emissions and removals of carbon stocks which includes also biogenic carbon content from native forests. Unit: kg CO_2-eq.

4.1.3. Used impact assessment methods

Environmental impact assessment factors set in the EN 15804 standard were applied in the assessment. Characterization factors according to EN 15804:2012+A2:2019 Annex C (EC-JRC) were used. The method uses the characterization factors as developed by the Intergovernmental Panel on Climate Change (IPCC) based on IPCC 2013, expressed as GWP for time horizon 100 years (GWP100). According to Puro Standard Biochar methodology, the CORC value is based on the product’s biogenic carbon storage and fossil emissions. Biogenic or LULUC CO2eq emissions are not considered in the CORC calculation, and thus, do not have any impact to the CORC-value.

4.2. Results of the life cycle impact assessment

The result consists of the LCIA profile. The LCIA profile was obtained at the characterization phase of the impact assessment. The results include all assessed life cycle phases. Table 4 presents the potential environmental impacts (GWP) of the life cycle of biochar using one ton of biochar as the functional unit and 84,92 % of the impacts are allocated to the biochar in raw material supply, and biochar production process.

Table 4. LCA results for 1 t of dry biochar.

Contribution levels			Per tonne of biochar produced and used								
Level 1	Level 2	Level 3	Climate change in kg CO2-eq	kg CO2 fossil	kg CH4 as CO2-eq	kg N2O as CO2-eq	kg other GHG as CO2-eq	kg CO2 biogenic captured	kg CO2 biogenic emitted	kg CO2 atmospheric captured	kg CO2 atmospheric emitted
$E_{biomass}$	Fertilizer production	-	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
$E_{biomass}$	Sowing, fertilizer spreading, harvesting	-	66,28	61,71	2,58	0,86	1,13	0,00	0,00	0,00	0,00
$E_{biomass}$	Soil emissions	-	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
$E_{biomass}$	Transport from field to plant	-	19,74	18,86	0,75	0,08	0,05	0,00	0,00	0,00	0,00
$E_{production}$	Pyrolysis equipment and operation	Capital goods	11,15	11,15	0,00	0,00	0,00	0,00	0,00	0,00	0,00
$E_{production}$	Pyrolysis equipment and operation	Replacements and repairs	0,147	0,131	0,0139	0,0011	0,0007	0,00	0,00	0,00	0,00
$E_{production}$	Emissions from pyrolysis	-	46,05	46,05	0,00	0,00	0,00	0,00	0,00	0,00	0,00
$E_{production}$	Energy usage on site	Feedstock drying	4,77	4,24	0,43	0,05	0,05	0,00	0,00	0,00	0,00
$E_{production}$	Energy usage on site	Chipper	0,55	0,49	0,05	0,01	0,01	0,00	0,00	0,00	0,00

$E_{production}$	Energy usage on site	Biochar pro-duction process	3,96	3,52	0,36	0,04	0,04	0,00	0,00	0,00	0,00
$E_{production}$	Energy usage on site	Light fuel oil for pre-heat-ing	7,42	6,56	0,78	0,06	0,02	0,00	0,00	0,00	0,00
$E_{production}$	Handling of biochar and bagging	Manufactu-ring of packaging materials	4,75	3,75	0,97	0,01	0,03	0,00	0,00	0,00	0,00
$E_{production}$	Internal transporta-tion	-	14,38	13,86	0,29	0,15	0,08	0,00	0,00	0,00	0,00
E_{use}	Transport to end-user	-	60,37	58,14	1,42	0,67	0,14	0,00	0,00	0,00	0,00
E_{use}	Biochar mixing and spreading	-	0,323	0,311	0,007	0,003	0,002	0,00	0,00	0,00	0,00
E_{use}	Handling of biochar and bagging	End-of-life treatment of packaging materials	1,04	1,01	0,0029	0,029	0,00032	0,00	0,00	0,00	0,00
Total	-	-	240,91	229,77	7,65	1,96	1,56	0,00	0,00	0,00	0,00

5. Interpretation

Results are reported according to the SFS-EN ISO 14044 -standard.

5.1. Identification of significant issues

Based on the LCA, the biggest emitter during the life cycle is the harvesting process of the energy wood (66,28 kgCO2eq). Other significant emissions source is the biochar distribution (60,37 kgCO2eq), of which 43,15 kgCO2eq is caused by sea transportation. The most significant climate change impacts during the production process of biochar are caused by internal transportation (14,38 kgCO2eq) and capital goods (11,13 kgCO2eq). This is a concern in relation to the uncertainty associated with the calculation of capital goods. The major contributor in energy usage on site is caused by the light fuel oil (7,42 kgCO2eq) and the emissions to air from preheating the reactor (46,05 kg CO2eq). The most electricity intensive unit process is the feedstock drying (4,77 kgCO2eq) and biochar production process (3,96 kgCO2eq). Replacements and repairs (0,147 kgCO2eq), manufacturing process of packaging material (4,75 kgCO2eq) and end-of-life treatment of packaging material (1,04 kgCO2eq) have minimal effects during manufacturing process. The biochar mixing and spreading in use phase (0,323 kgCO2eq) also has a small contribution to the results. The total emissions produced are 240,91 kgCO2 per tonne of biochar produced.

5.2. Completeness check

To assess the environmental impacts of the product stage, it is important to have accurate information on the material content and the manufacturing processes. The production of the studied product includes a limited number of raw materials, and their accurate consumption was known. The accurate electricity and fuel consumption of the manufacturing process was known.

5.3. Sensitivity analysis

Sensitivity analysis was conducted for this study regarding the selected co-product allocation method to better understand the impact that the choice has on the end results. Co-product allocation is described more broadly in section 2.5.4. Allocation factors were applied for the production of biochar to offset part of the environmental impacts to the bio-oil, which is a co-product from the production process of the biochar. In this sensitivity analysis the following approach is used, which is also described as an option in Puro.Earrth Biochar Methodology. In this sensitivity analysis, it is assumed that the pyrolysis co-products are not deemed as important product, and all the burdens are allocated to the biochar production (allocation factor 100 %) and any excess co-product is considered as burden free (allocation factor 0 %). Allocation factor 100 % is applied for the raw material supply, transportation of raw materials and manufacturing phase. The results are presented system boundary being cradle-to-gate where the biochar distribution, biochar use stage and packaging materials are not included, as the emissions are already allocated 100 % to biochar from life cycle stages listed below. In addition, the results are also presented with system boundary being cradle-to-grave. The results can be seen from Table 5.

Table 5. Results of the sensitivity analysis

	Change	Result with cradle-to-gate [kgCO2eq per tonne dry biochar]	Result with cradle-to-grave [kgCO2eq per tonne dry biochar]	Difference
Allocation factor	84,92 % -> 100% of emissions allocated to biochar	203,44	-	+ 14,27 %
		-	269,92	+ 10,75 %

As it can be seen in Table 5, as all the emissions are allocated to biochar, it brings up the environmental impacts of the biochar. Higher allocation value brings up the environmental impacts related to biochar by + 10,75 % as the system boundary is set cradle-to-grave. As the system boundary is set to cradle-to-gate, the results are increased by + 14,27 %.

5.4. Consistency check

Same sources of input data have been used to assure consistency in information describing the life cycle phases. For most of the input data, database (Ecoinvent 3.8) was used. The database information describes the production with average geographical data. If the production differs from the average, it can influence the results when assessing largest raw material amounts.

Same impact categories and impact assessment method has been utilized when assessing different life cycle phases to assure consistency in the impact assessment.

6. Conclusions and recommendations

Potential greenhouse gas emissions of biochar with co-products were studied in this LCA. The system boundary of the LCA was set to cradle-to-grave. Data for the life cycle assessment were collected regarding the material and energy inputs and outputs of the included life cycle stages: the raw material supply, transport to the production facility, the production process of biochar and the distribution to the point of final use. The conclusions of the impact assessment are made based on the results of the characterization phase.

Based on the LCA, the biggest emitter during the life cycle is the harvesting process of the energy wood (66,28 kgCO2eq). Other significant emissions source is the biochar distribution (60,37 kgCO2eq), of which 43,15 kgCO2eq is caused by sea transportation. The most significant climate change impacts during the production process of biochar are caused by internal transportation (14,38 kgCO2eq) and capital goods (11,13 kgCO2eq). This is a concern in relation to the uncertainty associated with the calculation of capital goods. The major contributor in energy usage on site is caused by the light fuel oil (7,42 kgCO2eq) and the emissions to air from preheating the reactor (46,05 kg CO2eq). The most electricity intensive unit process is the feedstock drying (4,77 kgCO2eq) and biochar production process (3,96 kgCO2eq). Replacements and repairs (0,147 kgCO2eq), manufacturing process of packaging material (4,75 kgCO2eq) and end-of-life treatment of packaging material (1,04 kgCO2eq) have minimal effects during manufacturing process. The biochar mixing and spreading in use phase (0,323 kgCO2eq) also has a small contribution to the results. The total emissions produced are 240,91 kgCO2 per tonne of biochar produced.

Including capital goods in the biochar LCA leads to higher fossil climate change impact results, but also to increased uncertainty, as the supply chain emission factor is based on rough estimation. Capital goods, such as buildings and machinery (infrastructure), are particularly difficult to determine and are therefore commonly based on inaccurate estimates even in international databases. Furthermore, the emission factor used is more than 10 years old and outdated from the LCA point of view. The uncertainty is further increased as the emission factor in euros depends on the exchange rate between the pound and the euro. Hence, it is considered that the inclusion of capital goods does not add quality to life cycle inventories of biochar product. Until good infrastructure life cycle inventories become available, and the uncertainty of impact modelling is reduced, it is suggested that capital goods are excluded from the obligatory scope of life cycle inventory initiatives. Thus, we consider that the added value to LCA by the inclusion of capital goods is low, since uncertainty remains high, while the efforts to collect them are significant, thus questioning its inclusion in LCA studies by default.

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