TECHNISCHE UNIVERSITÄT DRESDEN
Institut für Abfall- und Kreislaufwirtschaft
UNIVERSITAT POLITÈCNICA DE VALÈNCIA
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Master's Thesis

Life cycle assessment of wheat straw and corn stover biomass for the production of biochar applied in Saxony's agriculture

Author:	Laura Sofia Veracoechea D'Urso
Matriculation number:	5118657
E-Mail:	lave213e@tu-dresden.de; lauvedur@etsid.upv.es
Degree program:	Master in Energy Technologies for Sustainable Development
Supervisor:	M. Sc. Freya Sternkopf (TU Dresden, IAK Pirna)
Supervisor:	Dir. Tomás Gómez Navarro (UPV, IIE Valencia)

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GHG	Greenhouse gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
nFK	Usable field capacity
NET	Negative Emission Technology
EU	European Union
ETS	Emissions Trading Scheme
NBÖS	National Bioeconomy Strategy
BMEL	Federal Ministry of Food and Agriculture
ha	Hectare
CH_4	Methane
N_2O	Nitrous oxide
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
kWh	Kilowatt hours
MW	Megawatt
kg	Kilogram
t	Tonne
e.g.	For example
i.e.	That is
et al.	Et alia (and others)
FAO	Food and Agriculture Organization of the United Nations
p.	Page
m^3	Cubic meters
MWP	Microwave pyrolysis
H	Hydrogen
C	Carbon

O	Oxygen
S	Sulphur
N	Nitrogen
mL	Mililiters
min	Minutes
h	Hours
s	Seconds
m^2	Square meters
Wt.	Weight
Vol.	Volume
H_2	Hydrogen
CO	Carbon monoxide
C_2H_4	Ethylene
C_2H_6	Ethane
C_3H_6	Propene
cm^3	Cubic centimeters
°C	Celsius
BC	Biochar
N_2	Nitrogen gas
JAAP	Journal of Analytical and Applied Pyrolysis
CS	Corn stover
He	Helium
WS	Wheat straw
H_2O	Water
l	Liters
tkm	Tonne-kilometre
km	Kilometres
Hg	Mercury
Cd	Cadmium
C-sink	Carbon sink
EBC	European Biochar Certificate

ABSTRACT

Biochar is a porous carbon-rich material which is produced by the pyrolysis of biomass along with bio-oil and syngas. Applied, e.g., in agricultural soils acts a Negative Emission Technology (NET) creating a long-term carbon sink in which carbon absorbed by plants is retained and stored achieving a long-term carbon sequestration by containing CO_2 from the atmosphere. Moreover, it also promotes humus formation by adding nutrients to the soil, increases soil yields, expands the water capacity of soils and improves the resistance of soil to droughts among other factors.

Climate change is damaging soils in Germany. In particular, east Germany is affected by summer droughts that reduce water availability, diminish plants photosynthetic output and consequently, plant growth declines. Thus, e.g., applying biochar into the soil of the most affected areas of Germany, such as Saxony region, can contribute to the climate change mitigation and prevent soil damages that affects agriculture.

The aim of this study is to carry out an environmental assessment of the production of corn stover and wheat straw biochar through Life Cycle Assessment models following the ISO standards, ISO 14040 and 14044, and then compare the results obtained in both cases to verify the difference they have regarding impact assessment.

Crop production is the stage in the life cycle of biochar that constitutes the main environmental damage. Water emissions and raw materials are the main cause of environmental impacts in the ecosystem quality and human health due to the agricultural production and use of grain, seeds and nitrogen fertilisers in the step of harvest of both studied biomasses. Moreover, the results show that the life cycle of WS biochar constitutes a slightly superior environmental damage. However, in either case, biochar diminishes similarly the negatives impacts produced by crop production.

1. Introduction

1.1. Motivation and background

The irreversible impacts of climate change have led to decision-making and the creation of action plans by the different countries of the world [*6*]. Germany is experiencing particularly an increase in heavy rains, floods, droughts and number of hot days which is affecting the environment [*2*].

Saxony region is especially vulnerable to temperature increment as through the years there has been an augment of drought periods in which soil humidity decreases significantly, turning into drier soils that disfavour agriculture [*2*].

Thus, measures should be implemented in order to adapt the soil to climate change. Moreover, the necessity of reducing the negative impacts as well as the need of adaptation, requires the implementation of other actions that prevent the increase of global warming and climate change by containing and diminishing greenhouse gases emissions (GHG) which are the main cause of these global issues [6][67].

Biochar has been found to be a solution to minimize impacts on soil and retain the carbon dioxide emissions (CO_2) that plants absorb from the atmosphere. This product is a carbonaceous material which is created by the pyrolysis of biomass and benefits the soil by augmenting the nutrients content and consequently, promoting humus formation which it is essential for the growth of the plants [4][5].

Therefore, the motivation of this study is to analyse two different possible biomasses for the production of biochar in order to compare their results on environmental impacts by executing a Life Cycle Assessment (LCA) and conclude which of these two biomasses are more convenient to obtain biochar. In this manner, there is a contribution to the research of biochar production which provides more information to other researchers regarding which type of biochar has less repercussion to the environment throughout its life cycle.

1.1.1. Climate change

Planet Earth is suffering from climate change caused not from natural causes, but due to greenhouse gases (GHGs) emissions produced by human activity [67]. Industrialization, globalization and consumption, as many other factors, have contributed in the increment of human activity such as production, energy supply, forestry, agriculture, transport, etc. as there is a greater necessity to fulfil people's needs [66].

Resulting from these activities, GHG such as carbon dioxide (CO_2) are emitted to the atmosphere absorbing the infrared radiation reflected from Earth trapping heat and therefore, producing an increase in the planet's temperature which is also known as global warming [67].

Therefore, as it is illustrated in Figure 1, there is an increasing tendency of CO_2 emissions which represents a threat to the world as these changes in the atmosphere could have prejudicial consequences for humans and the environment.

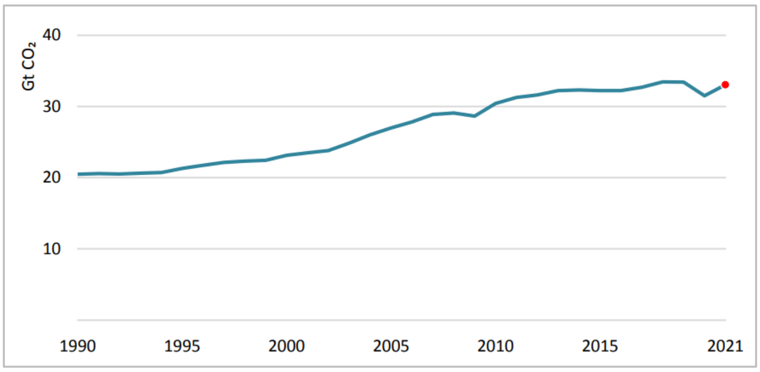


Figure 1. Global energy related CO2 emissions. [1]

Germany has not been an exception in respect of global warming and climate change. As in the rest of the world, Germany suffered a rise of 1.5°C in the average air temperature between 1881 and 2018 which is 0.5°C higher than global temperature deviation during the same period as it is represented in Figure 2 [2]. Furthermore, another rise of 0.5°C is expected in the near future, approximately up until 2050 [3].

Additionally, precipitations during winter are expected to be rise in a 10 % by 2050 in reference with the current values of precipitations which have already increase around 11 % since 1881 [3]. However, in Saxony region during winter, conditions have become slightly drier [2].

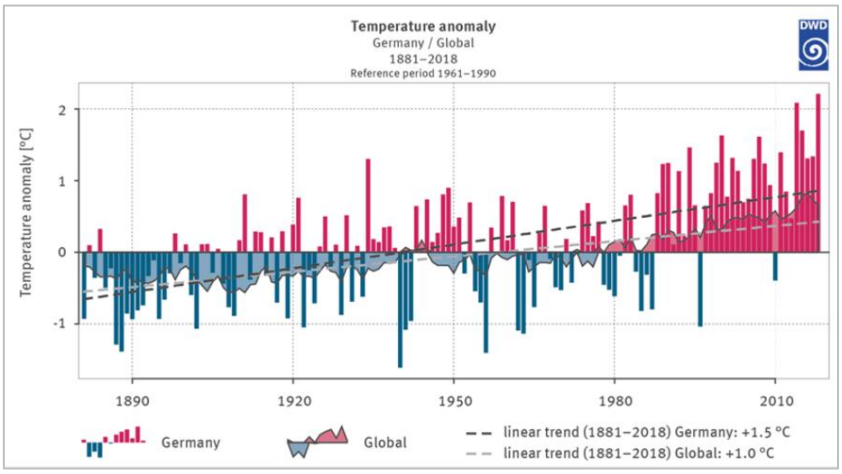


Figure 2. Temperature's deviation in Germany and globally from 1881 to 2018. [2]

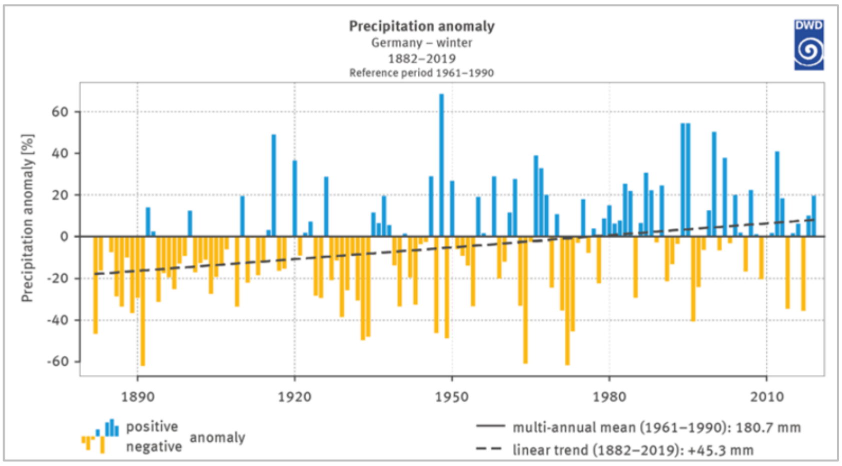


Figure 3. Percentage of precipitation's deviation in Germany during winter from 1882 to 2019. [2]

Other consequences of climate change in Germany are rising of sea levels, summer droughts, floodings and increasing number of hot days (Figure 4). Specially in east Germany, where Saxony region is located, limited availability of water and summer droughts are a threat as this will have an impact in agriculture and forestry, in addition to being a risk for human health due to high temperatures and heat stress [2].

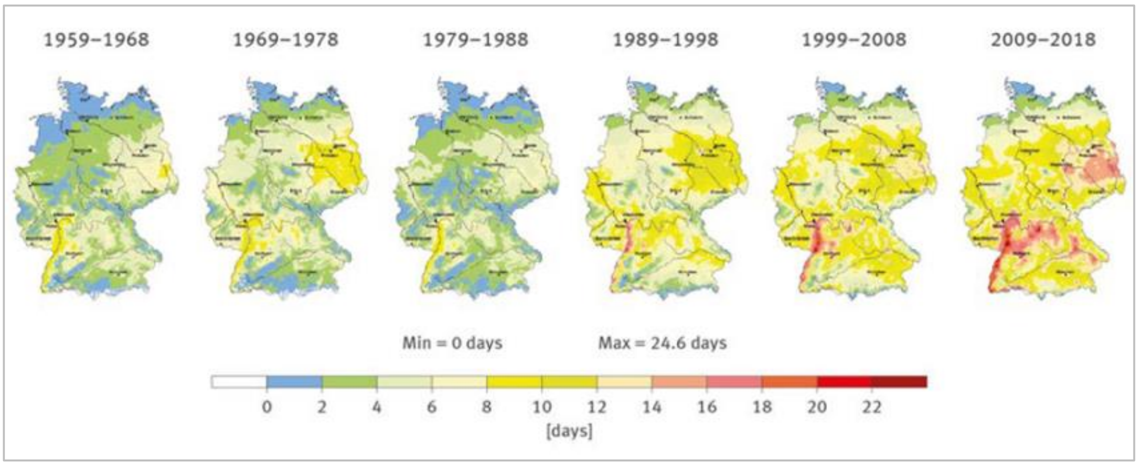


Figure 4. Average annual number of hot days in different periods. [2]

For example, in the years 2006 and 2015, approximately 6,000 heat-related mortalities were recorded. Additionally, regarding the risks in agriculture, groundwater levels drop significantly during summer which reduces water availability. For this reason, agricultural techniques need to achieve the boost of water and soil's humus supply in order to be prepared and endure summer drought periods as it can affect the photosynthesising activity of the plants or even kill them [2].

A drop beneath 30 % to 40 % nFK in soil humidity, which is indicates the degree of water supply available to plants and it is measured in percent of usable field capacity (% nFK), reduces plant's photosynthetic output causing decline in its growth [2].

Likewise, as it is represented in Figure 5 and Figure 6, dry soil is increasing particularly in Eastern Germany and the Rhine-Main area which can considerably affect agriculture. That is why, a solution has to be implemented in order to prevent and reduce this risk by augmenting water and humus supply that contains nutrients which are essential for soil [4].

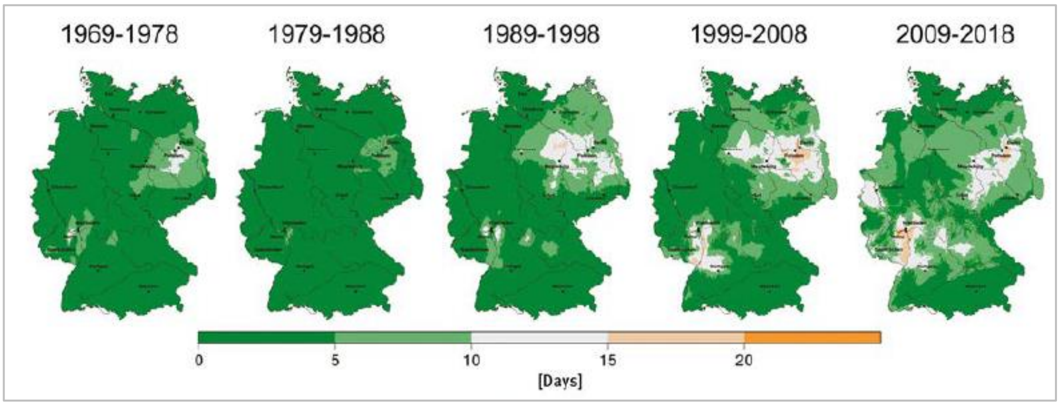


Figure 5. Average annual number of days with soil humidity of less than 30 % nFK for winter wheat on heavy soil. [2]

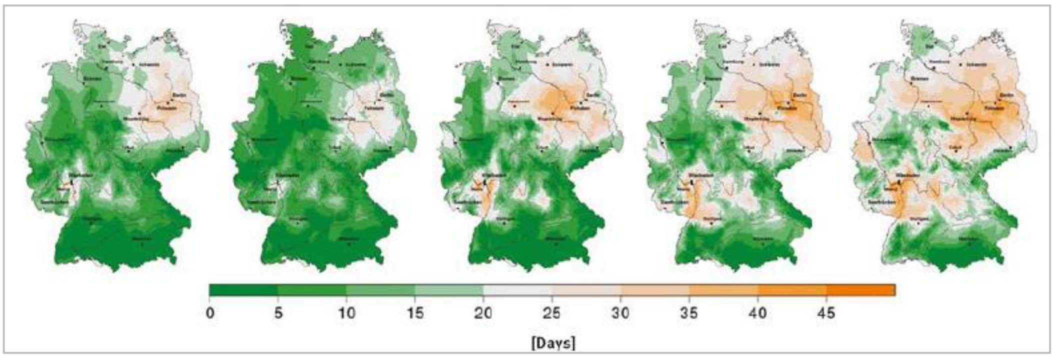


Figure 6. Average annual number of days with soil humidity of less than 30 % nFK for winter wheat on light soil. [2]

Biochar is a carbonaceous material which is produced by the pyrolysis of biomass that could be a solution for these agricultural problems as it supports the expansion of soil organic matter (humus) and acts a Negative Emission Technology (NET) as it retains the CO_2 that plants absorb from the atmosphere and therefore, preventing the boost of global warming and climate change [5].

1.1.2. Climate Action Plan 2050

Viewing the consequences of climate change in the world, in 2020, the European Commission decided to establish *The 2030 Climate Target Plan* [6] which goal is to reduce by at least 55% greenhouse gases emissions by 2030 that also sets a path to achieve climate neutrality by 2050 [7].

The long-term strategy that aims an economy with net-zero greenhouse gases emissions by 2050 is also a derivative of the Paris Agreement [8] which sets a limitation of global warming below 2°C and aims to limit the increase to 1.5°C in order to avoid dangerous climate change.

By this means, EU Member States are required to implement national action plans in order to accomplish the objectives of this legal international agreement and strategies [7].

Therefore, the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety of Germany published in November 2016 the *Climate Action Plan 2050* in which Germany's strategies and actions to achieve climate targets, which are in line with the Paris Agreement, are defined in order to become a climate neutral country [9].

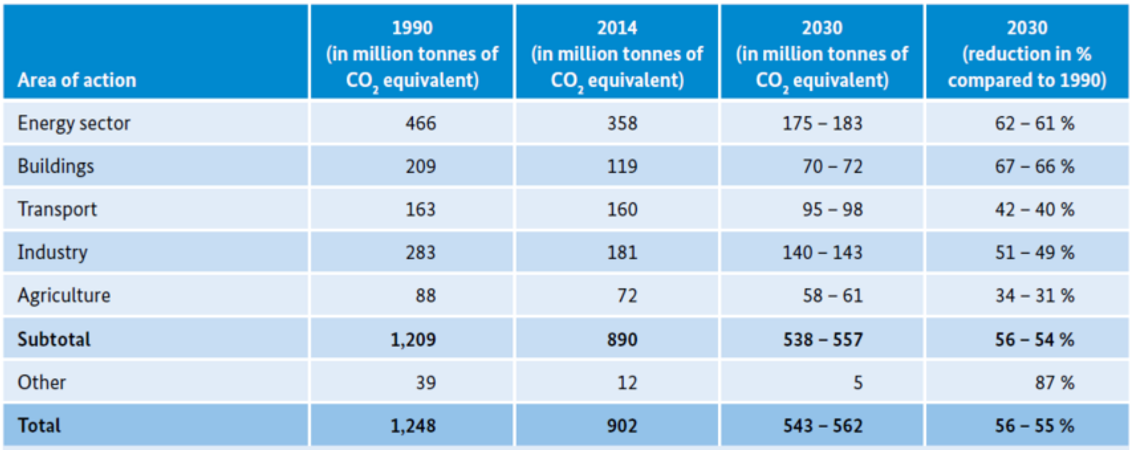
The aim of the German *Climate Action Plan 2050* is to achieve the reduction of greenhouse gases emissions around 80 to 95 percent by 2050 in respect of the year 1990 [9]. This long-term target was already proposed by the German government in 2010 before the Paris Agreement and, in this manner, previously contributing to accomplish the subsequent commitment made in Paris in 2015.

Likewise, in order to achieve this goal, the strategy of this action plan is to modernise German economy and give guidelines to the different areas of action; these being energy, buildings, transport, industry, agriculture and forestry. Consequently, the German government will focus on promoting and investing in new technologies that increase the energy efficiency and the use of renewable energies [*9*].

Moreover, due to the higher greenhouse gases emissions per capita that Germany has in respect of the EU and global average, the German government is determined to make the European

Emissions Trading Scheme (ETS) more effective as utilizing this instrument can produce centralised price incentives to reduce CO_2 emissions through CO_2 prices [*9*].

Although all the aspects of the areas of action are significant, to achieve the long-term climate target for 2050, the German *Climate Action Plan 2050* considers necessary to prevent most emissions in the energy sector and the energy-related domains of the rest of areas of actions (Figure 7).



Area of action	1990 (in million tonnes of CO_2 equivalent)	2014 (in million tonnes of CO_2 equivalent)	2030 (in million tonnes of CO_2 equivalent)	2030 (reduction in % compared to 1990)
Energy sector	466	358	175 – 183	62 – 61 %
Buildings	209	119	70 – 72	67 – 66 %
Transport	163	160	95 – 98	42 – 40 %
Industry	283	181	140 – 143	51 – 49 %
Agriculture	88	72	58 – 61	34 – 31 %
Subtotal	**1,209**	**890**	**538 – 557**	**56 – 54 %**
Other	39	12	5	87 %
Total	**1,248**	**902**	**543 – 562**	**56 – 55 %**

Figure 7. Emissions reduction target for the different areas of action. [9]

1.1.2.1. Climate action in the energy sector

The energy sector represented the 40 % of Germany's greenhouse gas emissions in 2014, being the most pollutant sector. For that reason, a modernisation of the energy sector by using green energies with net zero CO_2 emissions, such as renewable energy technologies, is needed for the future of energy systems in Germany [*9*].

Thus, the greatest investments for the German energy transition will be done for energy projects that aim to increase the use of renewable energy sources, improve the energy efficiency and adapt the grid infrastructure to the modern energy systems. Additionally, as the emissions are directly related to the energy consumption, the German government also seeks for a depletion of the energy demand [*9*].

Consequently, in order to decrease the energy demand, the efficiency of energy systems in buildings, transport and industry will be increased and the energy demand of the new projects will be supplied by renewables. Although, the German government supports the augment of the latter, it also states that renewable energy should be develop in such a way that resources are preserved and there is not negative impact on nature [*9*].

Biomass derive from residues and waste products will take an important role in the future to generate bioenergy for energy provision, for example, as a thermal energy source in the different sectors [*9*].

In addition, electricity must be affordable for German consumers providing it with smart grids that connect consumers with the electricity generation plants balancing supply and energy demand. Moreover, future energy systems will combine renewables with combined heat and power generation systems following a regional and industrial policy strategy [*9*].

To sum up, with these strategies, the German government aims to diminish GHG emissions between 175 and 183 million tonnes of CO_2 equivalent by 2030 and, also achieve further emissions decline by 2050 [9].

1.1.2.2. Climate action in agriculture

Although the reduction to net zero emissions in agriculture is practically impossible due to the biological processes produced during crop cultivation and livestock farming, the German government will implement measures to diminish the emissions and contribute to the climate change mitigation [*9*].

In 2014 the agriculture sector constituted an 8% of the GHG emissions in Germany which corresponded to 72 million tonnes of CO_2e. This sector was the second least pollutant with respect to the rest of action areas selected in the German *Climate Action Plan 2050.* Nevertheless, the German government considers also necessary to implement measures that reduce the greatest number of emissions as possible [9].

For this reason, the German government published the *National Bioeconomy Strategy (NBÖS)* which promotes the combination of economy and ecology for a sustainable use of resources and production [10]. This implies diminishing the use of fossil fuels in agricultural machinery and vehicles, establishing a circular economy which reuses agricultural waste to produce bioenergy for multiple sectors or even as an organic fertilizer to improve the soil fertility, limiting the number of livestock units per hectare to minimize methane emissions, reducing the utilization of nitrogen in fertilizers to prevent nitrous oxide emissions and avoiding food waste [10].

Likewise, the German government’s strategy is to achieve a bio-based economy founded on natural material cycles in which 20 percent of the land used for agriculture is based on organic farming and focuses on the utilization of organic fertilizers and the use of agricultural waste for sustainable purposes. Consequently, helping to reach the goal to reduce agriculture GHG emissions around 60 million tonnes of CO_2e by 2030 [*10*].

1.1.2.3. Climate action in forestry

Forests act as a sink sequestering carbon dioxide and they produce biogenic solid fuels which generate electricity and heat that can be used to supply energy for other sectors. In 2014, German forests sequestered about 58 million tonnes of CO_2e and biogenic solid fuels energy generation prevented approximately 31 million tonnes of CO_2 emissions [*9*].

That is why, the German government is aiming to increase the amount of forested land in Germany as forestry will contribute to climate change mitigation. Additionally, Germany is also focusing on using waste wood as an energy source that must have a legal regulation so that the sustainable function of forestry compromised [*9*].

The Federal Ministry of Food and Agriculture (BMEL) will implement measures to obtain a sustainable contribution of wood which will be proved previously and subsequently with an environmental impact assessment to ensure achieving the climate change targets [*9*].

Moreover, as forestland and permanent grassland should not be decreased, the development of infrastructure in land will be lessened to 30 hectares per day according to the *German Sustainable Development Strategy* [11].

1.1.3. Agriculture in Germany

As it is stated by the German Environment Agency in the publication of the *Environment and agriculture 2018* according to the data obtained from the Federal Statistical Office of Germany, in 2016 more than half of Germany's land was used for agricultural purposes (Figure 8) that are distinguished between farmland for crop cultivation and permanent grassland. Likewise, this agricultural area is placed mainly in Bavaria and Lower Saxony [*12*].

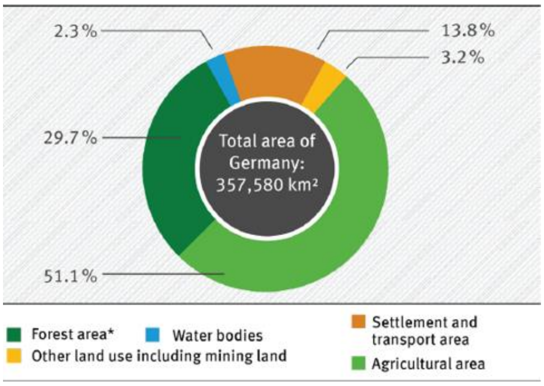


Figure 8. Land use in Germany (2016). [12]

This means that agriculture plays an important role in German economy and for that, it also contributes to the increase of greenhouse gases emissions (Figure 9). Additionally, as most of the agricultural cultivation techniques are still based on an intensive livestock farming, the agricultural areas produce significant environmental impacts [*12*].

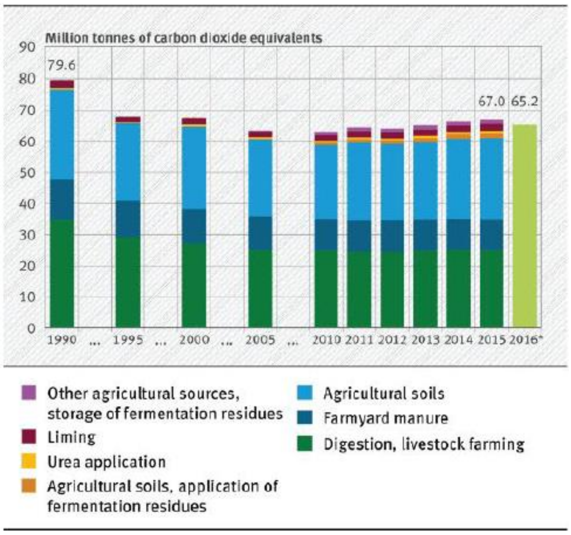


Figure 9. GHG emissions from agriculture (2016). [12]

Thus, the impacts of climate change in the soil, the limited degree of water supply for plants and the issues regarding agriculture such as the use of fossil fuels for machinery, the intensive livestock farming and the utilisation of not organic fertilizers bring the necessity to implement adaptation measures [9] that prevent the increase of those impacts on the environment and mitigate climate change.

The labour in German agricultural farms is done by non-family or family members. In respect of every amount of surface of agricultural area, family labour predominates over non-family labour. However, in eastern Germany where Saxony region is located, non-family employees stand out over relatives [*13*].

Nevertheless, manpower is declining as the employment of machinery is rising for its rapid facility of production. Already in 2007 farm labour decreased by 14 percent since 1990. Moreover, in exception of eastern Germany, the number of agricultural farms show a noticeable decreasing tendency as farm structure has changed and a smaller number of agricultural areas with higher surface (ha) are currently preferred (Figure 10). However, as in eastern Germany already had a predominance for large agricultural farms, this tendency remains not significant [*13*].

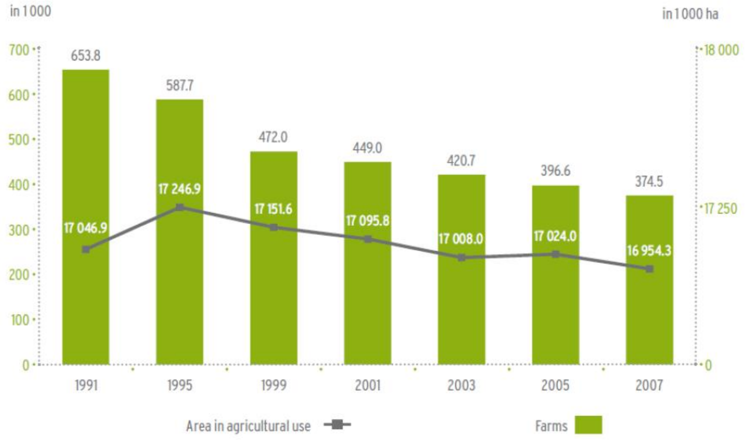


Figure 10. Number of farms and area in agricultural use. [13]

As it can be seen in Figure 11, Germany's most common type of farming is fodder production for livestock followed by crops/livestock fields which are mixed farms that combine cropping with grazing cattle. Moreover, as it is represented in Figure 12, most of the plant product yields are cereals which include wheat, grain maize and corn-cob mix among others [*13*].

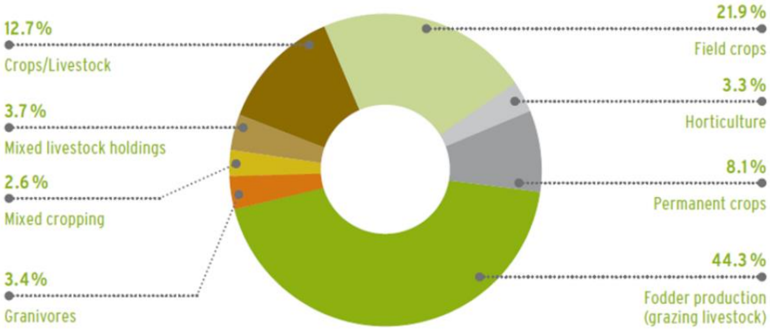
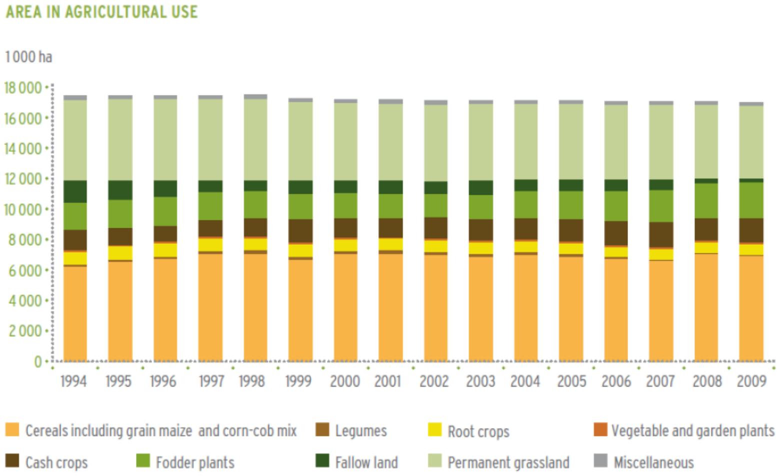


Figure 11. Germany's types of farming (2009). [13]



Miscellaneous: garden land, orchards, tree nurseries, vineyards
Cash crops: oil seeds, hops and other commercial plants, e.g. beets and grass to obtain seeds, medical plants and herbs

Figure 12. Area of different types of crops in agricultural use (2009). [13]

As for plant fertilizers and production products applied for cultivation, the German Federal Ministry of Food and Agriculture established the *Fertiliser Application Ordinance* which regulates and specifies the requirements for an appropriate fertilisation that ensures nutrients to crops and prevents risks to the environment [14], as well as, the *National Action Plan on the Sustainable Use of Plant Protection Products* which indicates procedures to reduce risks in plant protection, introduces new technologies in farming, defines quantity pesticides limits, etc. [15] Likewise, the German government's strategy is to increase organic farming that ensures an adequate use of these components.

In respect of water use, irrigation farming does not play a big role in German agriculture. However, this varies depending on the Federal States of Germany. Lower Saxony employs more than half of the water in Germany, but on the contrary Saxony water use is less significant (Figure 13) [*13*].

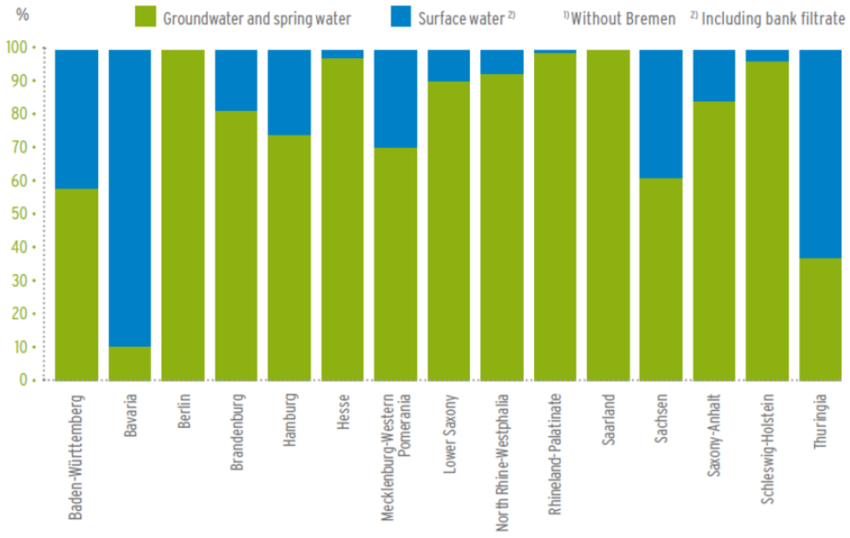


Figure 13. Water withdrawal for irrigation (2007). [13]

Although Germany is implementing measures to adapt to climate change, there is still room for improvement as agriculture is facing with difficulties. Certain crops such as maize increase erosion risk in the soil which contributes to the loss of nutrients and humus content degradation [*13*]. In the same way, the use of biomass derived from crops as a resource for renewable energy systems to produce biogas diminishes humus content of soil requiring a humus balance stabilization [*13*].

Additionally, areas where strong precipitation is more frequent, experience soil erosion which consequently induces to soil loss and therefore, there is a depletion of soil thickness, nutrients and humus in the upper soil [*13*].

Humus provides nutrients such as nitrogen that are essential for a healthy soil which is crucial for plant growth in agriculture [*4*]. Moreover, humus-enriched soil acts as a carbon sink, retaining the CO2 emissions absorbed by the plants from the atmosphere and consequently, protecting the ozone layer and reducing climate change [*5*]. Eastern Germany, the corresponding area to Saxony's region, presents the minor organic matter content in Germany and it is declining due to climate change (Figure 14) [*13*]. For that reason, it is important to apply measures to the soil in order to prevent these losses.

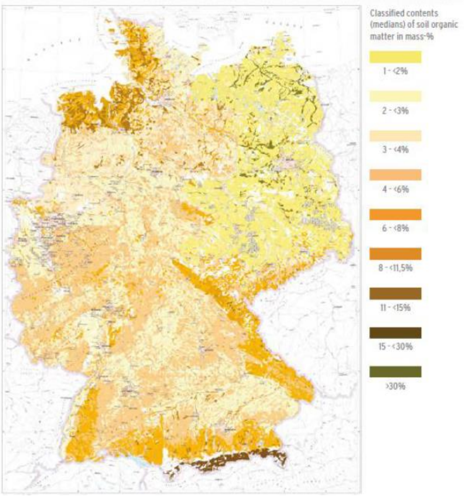


Figure 14. Content of organic matter in topsoil of Germany (2007). [13]

Agriculture is the third-largest producer of greenhouse gases in Germany, being methane (CH_4) and nitrous oxide (N_2O) the gases with major contribution resulting from this sector (Figure 15). Thus, the German government promotes the increase of organic farming as it diminishes GHG emissions and risks for the environment, maintaining healthy soils for agriculture [*13*].

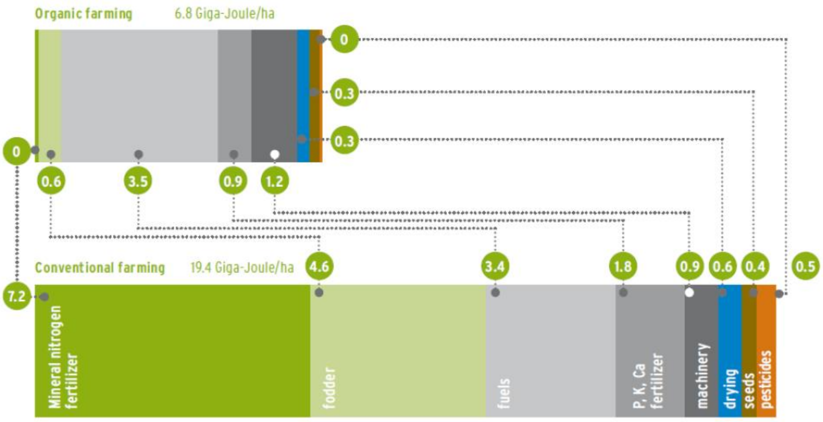


Figure 15. Energy use per hectare in conventional and organic farming. [13]

1.2. Biochar

1.2.1. Description

The European Biochar Certificate (2022, p.10) defines biochar as a "*porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation"* [*5*].

Biochar characteristics are essential in order to define the strategies to modify the biochar properties with the aim that an adequate performance is achieved for a certain application [34]. The type of feedstock and its composition of cellulose, hemicellulose and lignin are among the most influential factors that define biochar properties [34].

Biochar is composed of a high carbon content that can vary from 35% to 95% of dry matter depending on the introduced biomass in the pyrolysis process and the pyrolysis temperature [*5*][61]. In the matter of pyrolyzed straw, the carbon content is approximately between 40 and 50%. While pyrolyzed wood can contain about 70 to 90% of carbon [5].

Furthermore, the molar H:C ratio of biochar is an indicator of biochar's carbon structure [*5*] [*34*]. As the European Biochar Certificate states, this ratio must be less than 0,7 and it is one of the most significant characteristics of biochar as it contributes to the determination of the C-sink value[1] [5]. Moreover, it also defines the aromaticity and resistance of biochar to microbial and chemical degradation [34].

Likewise, the molar O:C ratio also presents a relevancy in the characterization of biochar [*5*]. It determines the stability of biochar and its value should be below 0,4 as the European Biochar Certificate indicates [34].

Due to the expansion of production and use of biochar, the EBC developed by the Ithaka Institute establishes guidelines that regulate biochar characteristics and properties guaranteeing a sustainable production, processing and sale of biochar. Thus, the aim of this standardization is to control biochar production and quality that prevents hazard to the health and the environment [63]. EBC guidelines have been effective since January 2012 and are the base of biochar certification throughout the world [5].

1.2.2. Obtaining process

"*Biochar is produced by biomass pyrolysis*" (European Biochar Certificate (EBC), 2022, p.10) [*5*]. Pyrolysis is a process in which the organic substances are degraded at temperatures ranging from 350°C to 1000°C in a low-oxygen environment [*5*]. Moreover, along with biochar, bio-oil and gas appear as value-added products of the pyrolysis process (Figure 16) [*30*].

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[1] The C-sink potential of biochar is defined as the amount of carbon it contains minus the carbon expenditure of its production [62].

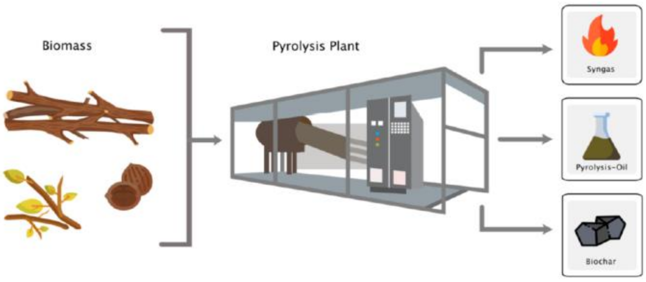

Figure 16. Inputs and outputs in the pyrolysis of biomass. [61]

Furthermore, as Li, Y., et al. (2022) states, there are six main types of pyrolysis technologies which correspond to fast pyrolysis, flash pyrolysis, slow pyrolysis, vacuum pyrolysis, hydro-pyrolysis and microwave pyrolysis (MWP) [*30*]. These technologies are distinguished by their procedural conditions: heating rate, pyrolysis temperature, residence time, reaction environments and heating methods [*30*].

Slow pyrolysis is the most applied technology for the production of biochar [*34*]. It is operated with a slow heating rate from 1 to 20°C/min and long residence times as well as having a pyrolysis temperature in the range of 300°C to 700°C [*34*][*30*].

However, MWP is a new technology that unlike conventional pyrolysis, the thermal energy is supplied to the feedstock biomass through microwaves that penetrate this organic material causing a vibration of its molecules [*30*]. Nevertheless, MWP pyrolysis temperatures have a similar range to slow pyrolysis, e.g., Zhu, L., et al. (2015) analysed experimental results with different temperatures between 500°C and 700°C [*31*].

Fast and flash pyrolysis are inclined to produced liquid products (bio-oil) over biochar. Fast pyrolysis temperatures range from 500°C to 1200 °C and its residence time varies between 0,5 to 10 s. Similarly, flash pyrolysis temperatures can exceed 900°C and its residence time can be below 1 s [*30*].

Additionally, vacuum pyrolysis is characterised by using a reactor that operates in a sub-atmospheric pressure system which produces the thermal degradation of biomass in the absence of oxygen [*30*]. On the contrary, hydro-pyrolysis works with high-pressure hydrogen atmospheric conditions in the reactor [*30*].

1.2.3. Application and benefits

The efficiency of biochar for distinct applications such as soil amendment, climate change mitigation, environmental remediation and industrial utilization, has managed to increase the interest of professionals in this product [*34*].

The application of biochar in the soil or its utilisation for other purposes creates a carbon sink (C-sink[2]) which absorbs and stores carbon. However, the overall balance of biochar production must be positive for the climate in order to generate a proper carbon sink. Therefore, biomass production must not decline existing carbon sinks, emissions from processing and transport must be deducted and depending on the implementation of biochar, the durability of the carbon sink can be different [64].

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[2] Carbon sink is defined as the reservoir that temporarily or permanently absorbs and stores carbon [64].

As previously mentioned, biochar can be added to agricultural or urban soils ensuring long-term carbon sequestration[3] through carbon sinks[2]. In this manner, biochar acts as a Negative Emission Technology (NET) which removes CO_2 from the atmosphere. Plants extract CO_2 emissions from the atmosphere while biochar allows to retain in the soil the carbon stored in the plants, in the long-term [64].

Furthermore, biochar can also be incorporated into building materials such as concrete and industrials materials such as plastics or other recyclabe materials. However, the latter application has to take into account the leght of life time of the material. The carbon sink created through this biochar implementation requires a statistical analysis of its service life and an effective monitoring [64].

Biochar can be beneficial for agricultural soils as it contributes to increase yields, promotes humus formation, expands the water capacity of soils and reduces GHG emissions. Thus, it helps with climate change mitigation and improves the resistance of soils to drought.

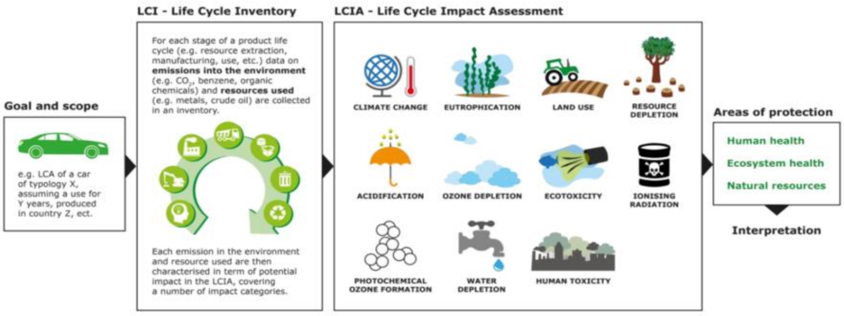
1.3. Life Cycle Assessment (LCA)

1.3.1. Description

The European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p. IV) [*38*] defines a Life Cycle Assessment (LCA) as a "structured, comprehensive and internationally standardised method" which is defined by the ISO 14040 [39] and 14044 [40] standards. LCA collects and evaluates all the inputs, outputs and environmental impacts throughout a product's full life cycle [41]. Therefore, it takes into account all the stages in a product's life (goods or services) "from the extraction of resources, through production, use and recycling, up to the disposal of remaining waste" as it is described by the European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p. IV) [*38*].

Moreover, LCA prevents creating new environmental problems while solving others which makes it a useful support tool that complements other methods improving efficiently the sustainability of production and consumption of goods and services [38].

Life Cycle Assessment (LCA) framework is based on 4 different phases which are defined in the next order: goal and scope, inventory analysis, impact assessment and interpretation [41].



e.g. LCA of a car of typology X, assuming a use for Y years, produced in country Z, ect.

For each stage of a product life cycle (e.g. resource extraction, manufacturing, use, etc.) data on **emissions into the environment** (e.g. CO_2, benzene, organic chemicals) and **resources used** (e.g. metals, crude oil) are collected in an inventory.

Each emission in the environment and resource used are then characterised in term of potential impact in the LCIA, covering a number of impact categories.

Figure 17. Life cycle assessment (LCA) methodology phases. [41]

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[3] Carbon sequestration is defined as the process of capturing and storing atmospheric carbon dioxide [64].

1.3.2. Goal and scope

Goal and scope definition corresponds with the first step in the LCA analysis in which the aims of the study are defined. Following ISO standards [39[40], this stage should explain the reasons for executing the analysis, the intended application of the results, the encountered limitations, the target audience of the results, etc. [42]

Additionally, the main methodological choices should also be defined and identified during this phase. Mainly, there should be an exact definition of the functional unit, the system boundaries, the allocation procedures, the main impact categories and the Life Cycle Impact Assessment (LCIA) models used for the analysis [41].

The functional unit (FU), as it is defined by the European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p.60), "quantifies the qualitative and quantitative aspects of the function(s) along the questions "what", "how much", "how well", and "for how long"" [*38*]. In this manner, environmental impacts relate to the function selected for the system and the comparison of two different systems is possible through this function [41]. Normally, functional units are categorized as energy-based (1 MJ, 1 kWh, 1 MW end products) or mass-based functional units (1 kg/ 1 ton feedstock or end product) [42].

The system boundaries determine which parts of the life cycle of a product and processes are included in the analysed system [*38*][*41*]. Therefore, they separate the studied system from the rest of the technosphere as well as setting a boundary between this system and the ecosphere [*38*]. In this manner, as it is stated by the European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p. 94), this boundary between the system and the technosphere/ecosphere is defined by the elementary flow which is described as "single substance or energy entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation" [*38*].

The standard ISO 14044:2006 [40], as it is indicated by the European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p. 21), describes allocation as "partitioning the input or output flows of a process or a product system between the product system under study and one or more product systems" [*38*]. Therefore, allocation works as a tool when there is a multi-functional process, i.e., when the process produces more than one product [*41*]. However, there could be no allocation which would imply that "the product takes the whole environmental burden in the production" as it is described by Yu, Z. et al. (2022) [*42*].

Life Cycle Assessment (LCA) models define the different stages of the analysed system in order to help assess their associated environmental impacts. There are three main types of LCA models: cradle-to-grave, cradle-to-gate and cradle-to-cradle [43].

Cradle-to-grave consists of a full life cycle assessment which begins with the extraction of raw materials and manufacture (cradle) and finishes in the disposal of waste (grave). However, in the case of cradle-to-gate analysis, the assessment focuses on a partial part of the product's life cycle from the raw materials extraction and manufacture (cradle) to the factory gate. Moreover, contrary to both of these models, cradle-to-cradle is based on a circular cycle in which the waste of the product is recycled to be reused in the process [43][44].

1.3.3. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) entails the collection of data and the different calculations executed for the quantification of inputs and outputs of the analysed system [*41*]. These inputs and outputs “concern energy, raw material and other physical inputs, products and co-products and waste, emissions to air/water/soil, other environmental aspects” (Sala, S. et al., 2017, p. 6) [*41*].

Furthermore, LCI is a step in LCA which involves the use of iterations. After data is collected in relation to the process and functional units, new requirements or limitations may need to be defined in order to meet the goal of the study [*41*].

1.3.4. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) associates the environmental aspects resulting from the LCI, raw materials and emissions, to the environmental impacts and indicators [*41*]. Firstly, emissions are classified in mid-point impact categories (Figure 19) such as climate change, eutrophication, acidification and so on. Secondly, these emissions are characterized to common units in order to allow comparison between categories (e.g., CO_2 and CH_4 emissions are expressed in CO_2e emissions by using their global warming potential) [*41*][*42*].

Moreover, these impact categories are related to three areas of protection (end-point categories): human health, ecosystem quality and resource depletion [*41*][*42*] (Figure 18). Both impact categories and areas of protection can be assessed through several methods [*41*], e.g., normalisation and weighting [43]. Therefore, the European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p. 113) states that “normalization and weighting are optional steps under ISO 14044:2006 to support the interpretation of the impact profile and are steps towards a fully aggregated result” [*38*].

In normalisation, indicator results from both mid-point categories and end-point damages are divided by a reference value which are typically the impact or damage results of the annual elementary flows of a certain country or region [*38*]. While the weighting method, the indicator results which are already normalised are multiplied by a weighting factor in order to reflect the relevance of the different impact categories or end-points among each other [*38*].

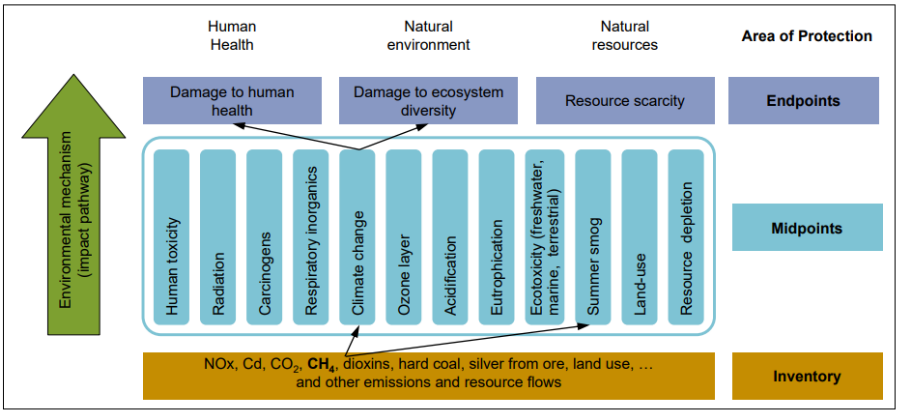


Figure 18. Life cycle assessment. Schematic steps from inventory to category endpoints. [38]

1.3.5. Interpretation

The interpretation step studies the results obtained from LCI and LCIA in accordance to the defined goal and scope. In this manner, results evaluation is done considering completeness, sensitivity and consistency checks in addition to the assessment of their uncertainty and accuracy [*41*].

As the European Commission, the Joint Research Centre and the Institute for Environment and Sustainability (2010, p. 289) describes completeness checks "are performed in order to determine the degree to which it is complete and whether the cut-off criteria have been met". Therefore, missing factors and relevant elementary flows need to be checked so that this additional or improve that can satisfy the goal and scope of the LCA [*38*].

The sensitivity analysis assesses the reliability of the final results due to the uncertainties among the inventory data, impact assessment data and methodological assumptions and, if it is needed change these introducing the sensitivity check along the LCA phases [*38*].

The consistency check proves if the different assumptions, methods and data have been consistent through the LCA [*38*]. In this type of analysis, inventory data and impact assessment issues in respect to their consistency are studied. Inventory data could present consistency issues regarding its time-related, geographical and technological representation as well as the adequation of its chosen units and the precision of this data [*38*]. Likewise, impact assessment could also introduce consistency issues in respect to the application of the LCIA elements such as normalisation and weighting factors [*38*].

2. Selected biomass

Harvest residues such as stalks, straw, etc. are admissible for the production of biochar [53]. Likewise, this type of biomasses meet all the EBC certification classes as the European Biochar Certificate (EBC) indicates in the *Positive list of permissible biomasses for the production of biochar* [53]. Therefore, biochar produced through these types of biomasses is permissible for different purposes following the distinct regulations respective for each sector [*5*].

Thus, as it is defined for EBC-Agro certifications, biochars which derive from the pyrolysis of harvest residues comply with the requirements of fertiliser regulations [*5*][53]. Moreover, they also meet the conditions of the regulation on organic production as they present the EBC-AgroOrganic certification [*5*][53].

Germany harvested a value of 42 million tonnes of cereals in 2021 which included grain maize and wheat among others [54]. Likewise, it is observed through the statistical data of the Federal Statistical Office of Germany [*16*] that approximately 50% of field crops correspond to cereal crops. Moreover, about 50% of these crops are wheat followed by barley with 25% and grain maize with 9% [*16*].

Due to their admissibility and availability in Germany, the study is decided to be focused on cereal crops. Although there is a major production of barley over grain maize, Sedmihradská, A., et al. (2020) conclude in their experimental research that the results of barley straw biochar were similar to wheat straw [37]. Therefore, corn stover and wheat straw biomass are chosen for this current study.

"*Corn stover is the stalks, leaves, and husks that remain in the field after corn harvest"* (Ruan, Z. et al., 2019, p. 2) [55]. Moreover, being an herbaceous biomass, it is composed by approximately a 35% of cellulose, 20% of hemicellulose and 12% lignin [*34*][55]. In countries such as the United States, corn stover is mainly fed to animals for livestock. However, there is also a part that is left in the field to maintain soil productivity [55].

"*Wheat straw is the main by-product of wheat production*" (Xu, Y. et al., 2019, p. 2) [56]. It is composed by internodes, nodes, leaves, chaffs and rachis presenting up to 40% of cellulose, 25% of hemicellulose and 20% of lignin [57]. Moreover, a portion of this biomass is used for animal husbandry or as a household fuel while the majority is burnt in the field [56]. However, it can also be utilised as a renewable resource for industrial application or as an agricultural supplement, giving agricultural waste an added value as usable products [56][57].

Both of these harvest residues correspond to two of the most plentiful lignocellulosic biomasses produced in the world [58]. An experimental research study executed by Zhao W. et al. (2021) conclude that biochar derived from corn stover biomass reduce the migration of mercury contained in the Hg-contaminated soil to the leaching solution and the spinach [59]. Thus, being mercury (Hg) a concerning pollutant that is harmful to human beings, corn stover biochar represents a solution for decreasing Hg mobility in soil and preventing its damage on food quality and safety [59]. Moreover, this type of biochar supplements calcium, magnesium and iron nutrients to the soil [59].

Likewise, a research study performed by Cui, L. et al. (2019) conclude that wheat straw biochar diminishes cadmium (Cd) bioavailability from contaminated waters and soils [60]. Cadmium environmental pollution can lead to its accumulation in the food chain and consequently, may harm animals and human health, e.g., it can conduct to kidney dysfunction, skeletal damage and cancers [60]. Thus, wheat straw biochar can solve these issues as its organic functional groups dimmish Cd bioavailability from the solution and the contaminated soil [60].

2.1. Agriculture in Saxony

Numerical agriculture data from the Federal Statistical Office of Germany (Destatis) and the Food and Agriculture Organization of the United Nations (FAO) has been collected in order to later present the results of each biochar Life Cycle Assessment (LCA) in a real scale, i.e., respectively to each biomass yearly production in Saxony region. Likewise, this data offers the possibility to analyse the different factors of agriculture in respect of the procurement of the selected biomass.

Therefore, with the purpose of studying the LCA results for Saxony region, an analysis has been performed to compare the percentage of land agriculture use in the different German regions. Thus, as it is shown in Figure 19, Saxony constitutes a 5,5% of Germany's agriculture being this percentage utilised to estimate the numerical data for this region in reference to the country's database.

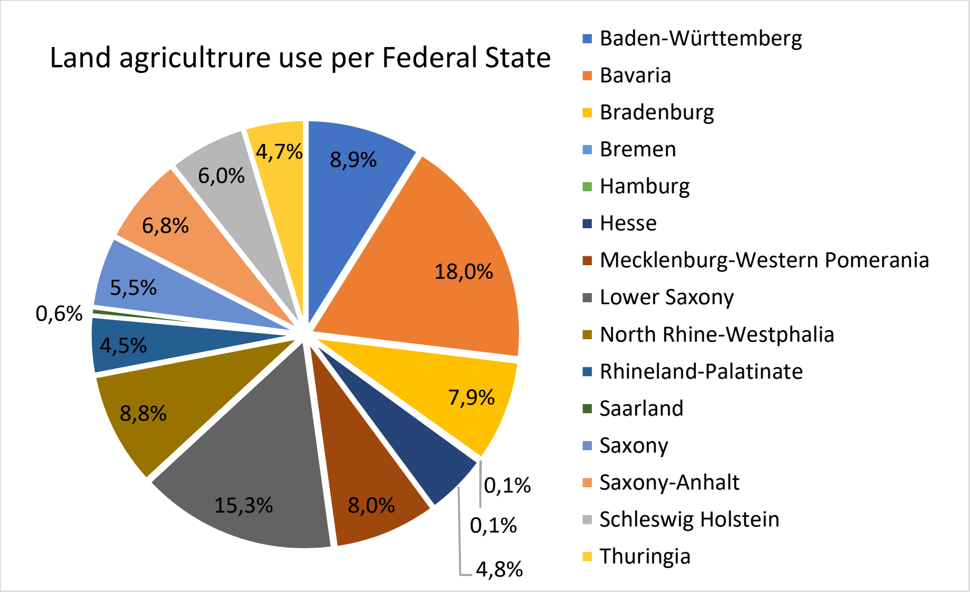


Figure 19. Land agricultural use per Federal States of Germany. [16]

Firstly, an analysis on the amount of agricultural land in Saxony for the selected cereal crops has been made (Figure 20). The surface of arable land employed for crops growth of wheat descended around 20% from 2010 to 2019 approximately, remaining after more or less stable until this current year. Nevertheless, cereal crops of grain maize including corn-cob mix prevail similar through the years.

In this manner, the surface of arable land corresponding to wheat and grain maize crops has been about 164.041 and 25.133 hectares (ha) respectively in 2022.

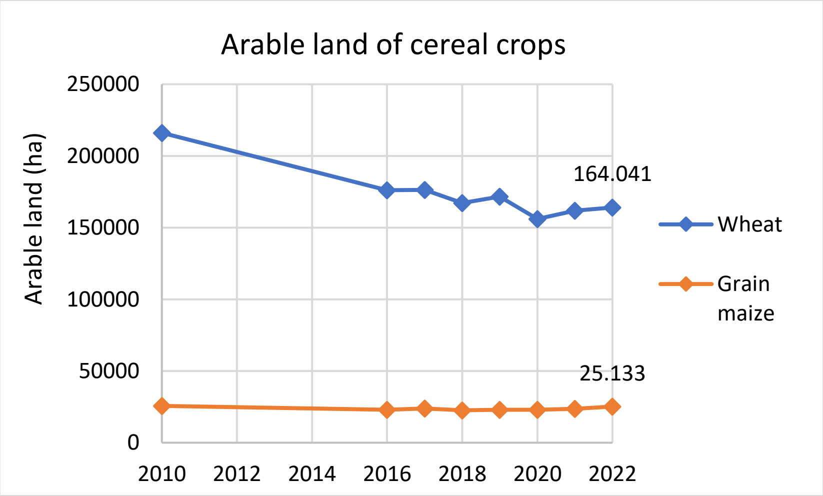


Figure 20. Arable land of selected cereal crops. [16]

Crop yield determines the crop production per harvested area, also known as arable land [18]. For that reason, this factor defines the performance and efficiency of the correspondent agricultural lands which will have a direct effect on the amount of crop residues obtained after harvest.

Figure 21 manifests a slight superiority of yield grain maize crop over wheat's which implies that having the same amount of arable land, the production of grain maize will be superior. Thus, as it is represented in this next graph, the performance of the later is around 26,3% higher than the one corresponding to wheat.

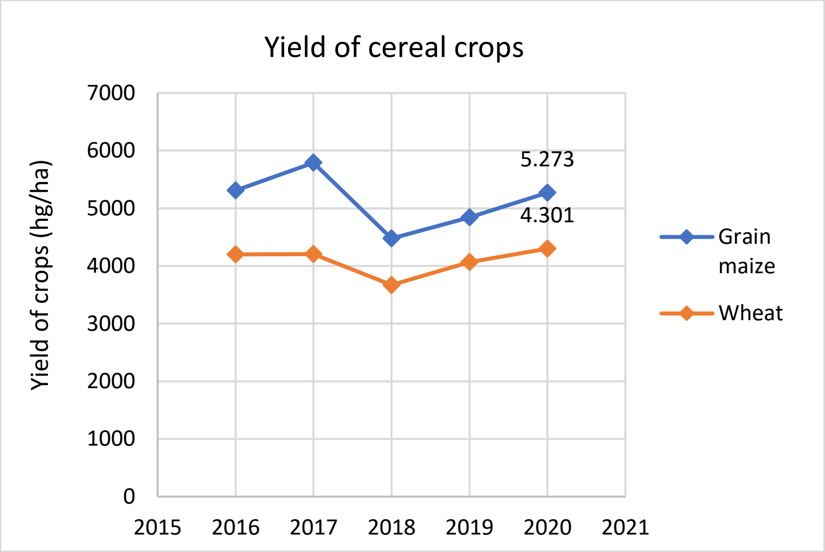


Figure 21. Yield of selected cereal crops. [17]

However, as wheat crops have greater quantity of arable land such as it is illustrated in Figure 20, the harvest volume of wheat acquired is more significant. In recent years, Figure 22, the production of wheat has been close to 1,2 million tonnes while for grain maize the harvest volume has been approximate to 220.000 tonnes in Saxony region.

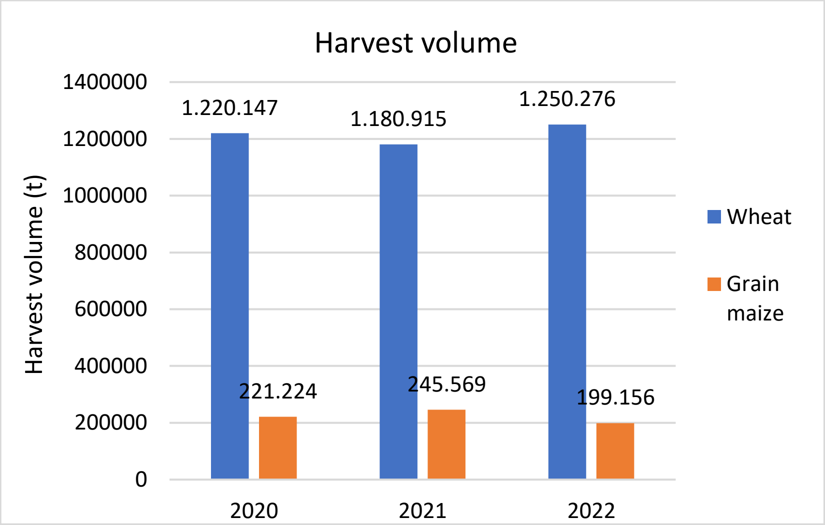


Figure 22. Harvest volume of selected cereal crops. [16]

Nevertheless, agricultural waste from wheat crops presents a larger scale (Figure 23). This is clearly caused by the superior amount of harvested area for this type of cereal in comparison to grain maize, but it is also due to the crop yield. Wheat crop residues constitute about a 1,2% of wheat production while waste from grain maize harvest corresponds approximately to the 0,8%. Thus, the next graph shows the quantity of residues for both products in tonnes of nutrients. Likewise, these crop residues will be considered as wheat straw and corn stover biomass obtained from the harvest process of the agricultural land.

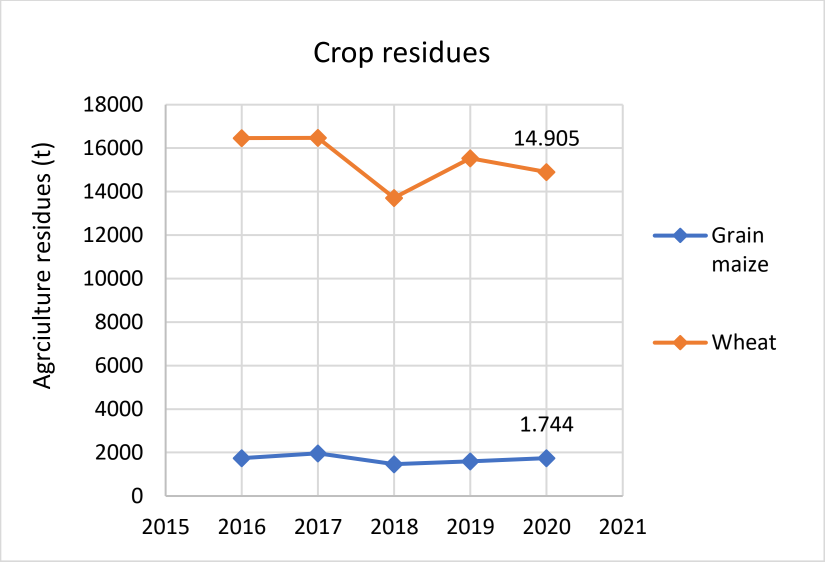


Figure 23. Crop residues of selected cereal crops. [17]

2.2. Corn stover and wheat straw biomass

The procurement of biochar goes through different stages. Firstly, starting from the crop planting and harvesting in which wheat straw and corn stover biomass are obtained as agricultural waste. In this manner, continuing with the storage and transport of these biomasses followed by their pyrolysis process in a pyrolysis plant in which their corresponding biochar is generated and, finally, biochar storage and transport in order to be applied again in agriculture soils to achieve circular economy based in sustainable production that reduces emissions and environmental impacts.

For that reason, the distinct methods and elements utilised in the life cycle of biochar produced from the pyrolysis of these two biomasses are studied through articles, reports and statistical data in order to elaborate a much realistic Life Cycle Assessment.

Furthermore, numerical data from these different processes is established by taking into consideration the percentage of Saxony's agricultural land with respect to the whole German agriculture (Figure 19), the percentage that cereal crops constitute in Saxony's agriculture (Figure 24) and the weight that grain maize and wheat have in respect of these crops.

In this manner, as it is represented in Figure 24, cereals correspond to a 52,4% of German crop agricultural land. Likewise, grain maize and wheat constitute respectively a 7,5 % and 48,8% of these types of crops [*16*].

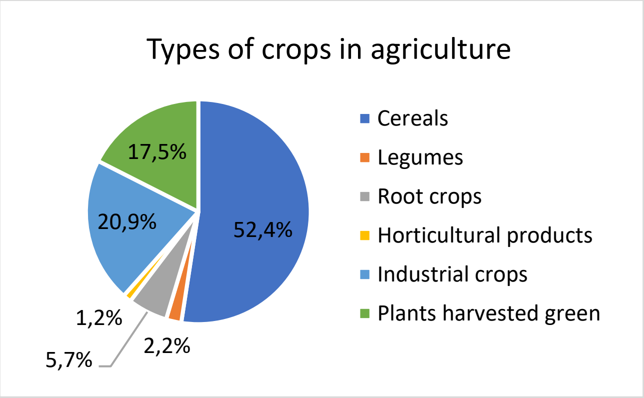


Figure 24. Types of crop production in German agriculture. [16]

2.2.1. Crop production

The first step in crop production is land preparation in which agricultural land is being arranged for seeding and plantation [19]. Normally this phase is based on soil tillage which is defined as the mechanical manipulation of the soil in order to increase the fertility of agricultural soils to achieve greater crop production, having the disadvantage of reducing soil organic matter in the long term and for that reason, risking agriculture as it provides nutrients for the crop [*20*][21].

Traditionally soil tillage methods have been focused on, for example, ploughing or slash and burning [22]. Ploughing the field consist in digging the land with a plough making furrows in the soil in order to prepare it for sowing [23]. This type of land preparation can be labour intensive with low mechanized conditions. Nevertheless, other methods such as harrowing are an alternative that can be less laborious as it employs a large equipment which breaks the earth into small pieces [22][*24*].

However, even though these types of soil tillage technics can be aggressive, as it is indicated in Figure 25 and Figure 26, conventional methods such as ploughing and harrowing are more utilised in German agriculture than organic farming. That is why, the German government is promoting the later in order to reduce the risks in the soil.

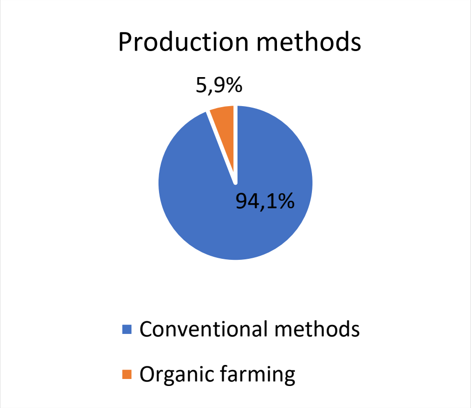


Figure 25. Percentage of production methods. [16]

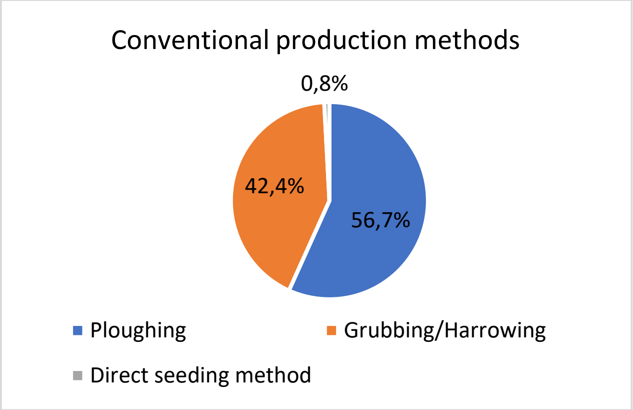


Figure 26. Percentage of conventional production methods. [16]

After getting the land ready, nutrients are added to the soil through mineral or organic fertilisers, such as manure. These products are utilised to apply the nutrients needed in the soil for the crop growth and compensate their removal after harvesting. However, employing a heavy improper fertilisation provokes environmental impacts as mineral fertilisers with nitrogen and phosphorous content can affect to soil fertility and waterbody quality and, manure produces ammonia and nitrous oxide emissions which contribute to climate change [25].

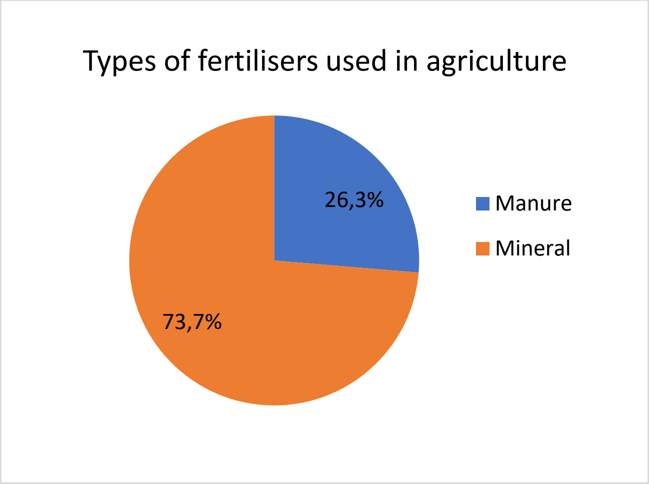


Figure 27. Types of fertilisers used in agriculture. [17]

The use of manure is distinguished in some areas of north-western Germany such as in Lower Saxony and North Rhine-Westphalia [12]. However, as it is represented in Figure 27, around 74% of German agricultural land is exposed to mineral fertilisers which can be classified depending on their nutrient content. Nitrogen is the more utilised of all in the whole German agriculture followed by potash and phosphate content fertilisers (Figure 28). In this manner, considering that all Saxony's agricultural land employs this type of fertilisers, around 17.800 and 2.700 tonnes of nitrogen fertilisers are used for wheat and grain maize crops respectively (Figure 29).

Furthermore, after the fertilisation process, unwanted plants are removed by the weeding process in order to prevent crop damage and consecutively, seeds are planted in the field with an adequate spacing and placement as to achieve a good development of the plant [22].

Approximately 67.100 tonnes of wheat and 12.200 tonnes of maize seeds for sowing are placed in the arable land with respect to the crop yield for the production of these two types of crops (Figure 30).

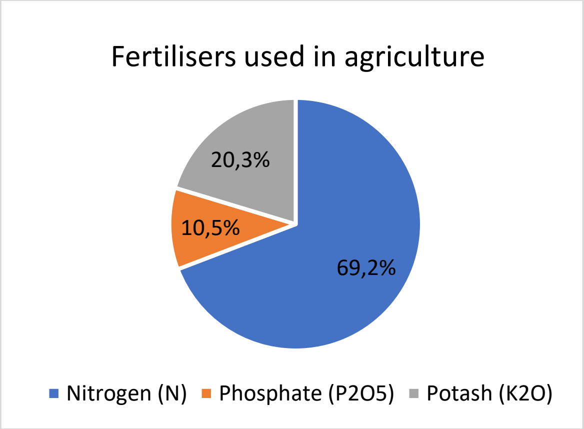


Figure 28. Fertilisers used in agriculture. [17]

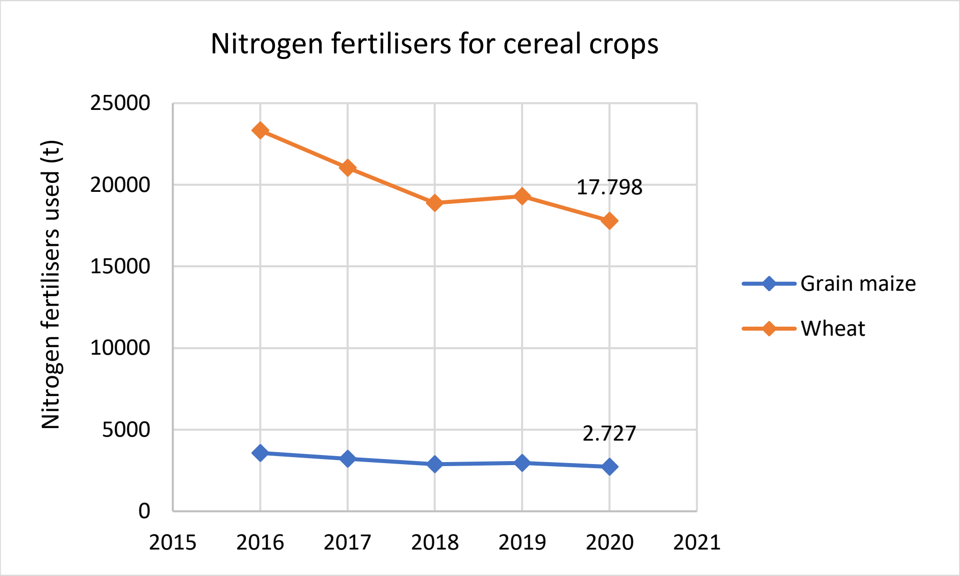


Figure 29. Fertilisers used for grain maize and wheat crops. [16]

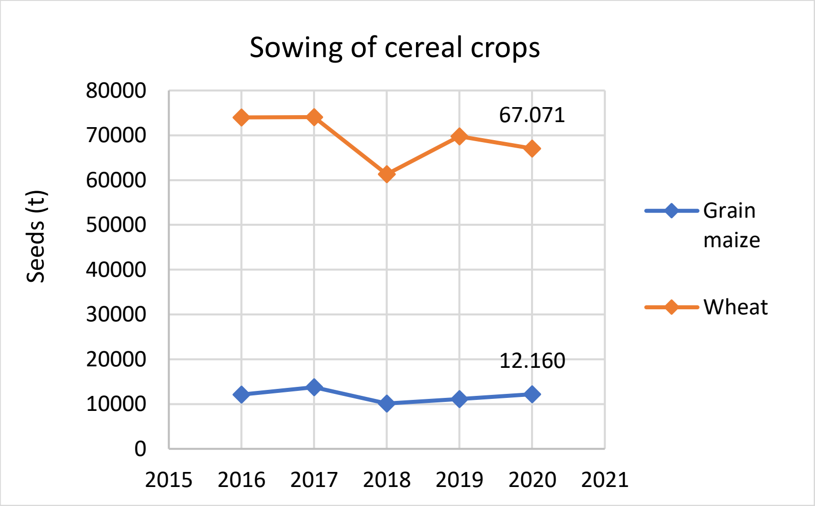


Figure 30. Sowing of grain maize and wheat crops.

After planting seeds, the agricultural land is supplied with water through the irrigation process in order to reach crop growth [27]. However, as it is shown in Figure 31, irrigated agricultural holdings in Saxony only represent 1% of those in whole Germany.

In this manner, through the data of water abstraction used for German agriculture obtained from the European Environment Agency [26], the volume of water utilised for grain maize and wheat crops in Saxony is determined considering the percentage of irrigated farms in this region and the percentage that these cereal crops represent with respect to the whole crop production. Likewise, Figure 32 indicates that in 2019 about 695.100 m^3 and 106.500 m^3 of water were used respectively for wheat and grain maize crop irrigation.

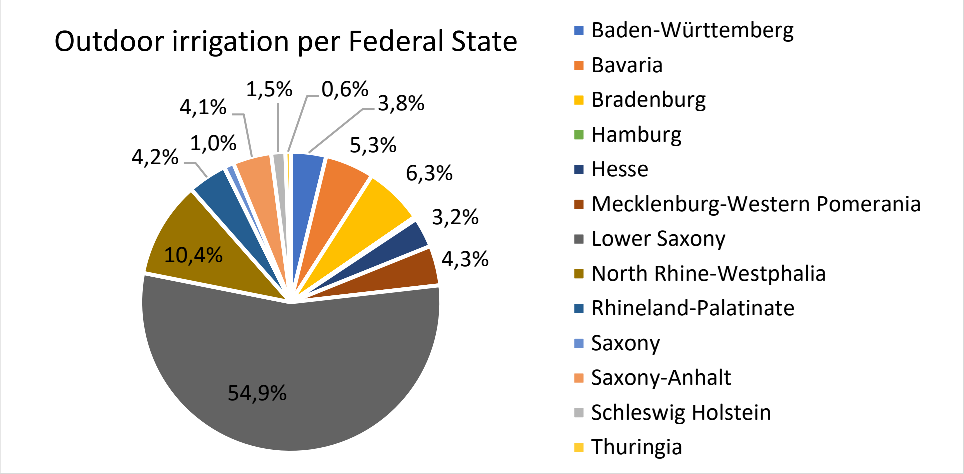


Figure 31. Percentage of holdings with irrigation per Federal States of Germany. [16]

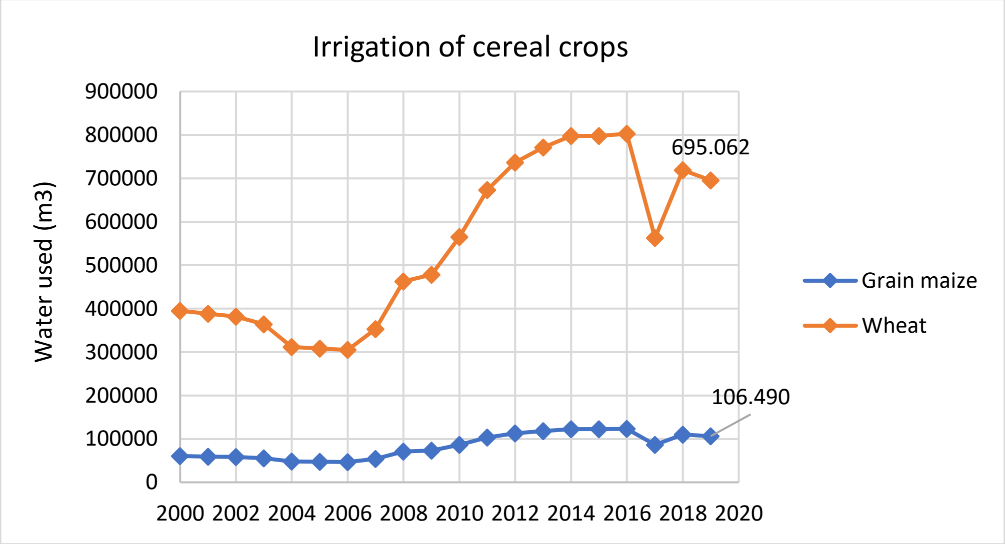


Figure 32. Water used for irrigation in agriculture. [26]

Furthermore, plant protection products are employed for crop cultivation as for secure the plants from undesirable organisms [28]. Pesticides are the most used in German agriculture (Figure 33) corresponding to more than a half of these utilised plant protection products. For that reason, considering that only these products are applied in the whole Saxony's agriculture, 675 and 103 tonnes of pesticides protect wheat and grain maize crops respectively (Figure 34).

Finally, regarding the machinery used for crop cultivation and harvest, approximately is estimated that 14.500 and 2.200 tractors contribute in the land preparation of wheat and grain maize crops respectively while around 1.600 and 245 combine harvesters are utilised for the harvest of production of these mentioned cereal crops (Figure 35).

Combine harvesters cut the plants and place them in a grain tank where unwanted crop residues are separated from the grains which are conducted to be unloaded into a truck for their transportation while residues are chopped and thrown back into the field behind the moving combine [29]. However, in this case, instead of leaving there these crop residues corresponding with corn stover and wheat straw biomass, they will be collected to perform their pyrolysis process for biochar production.

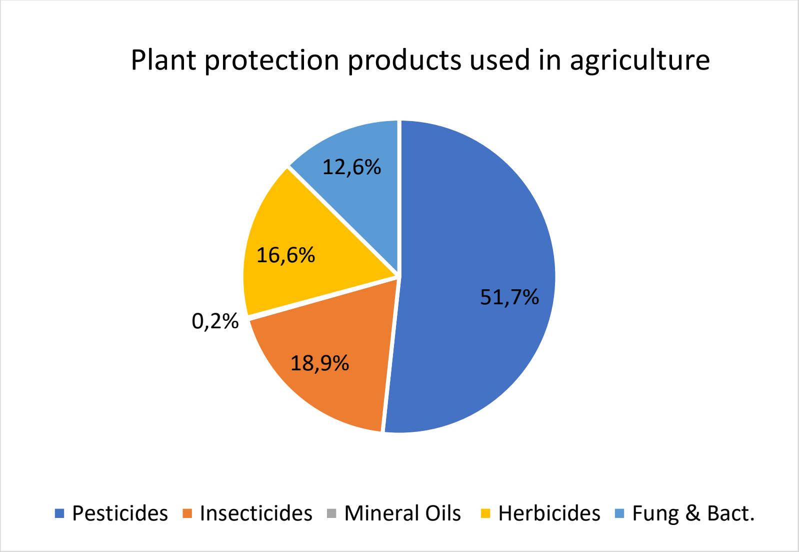


Figure 33. Plant protection products used in agriculture. [16]

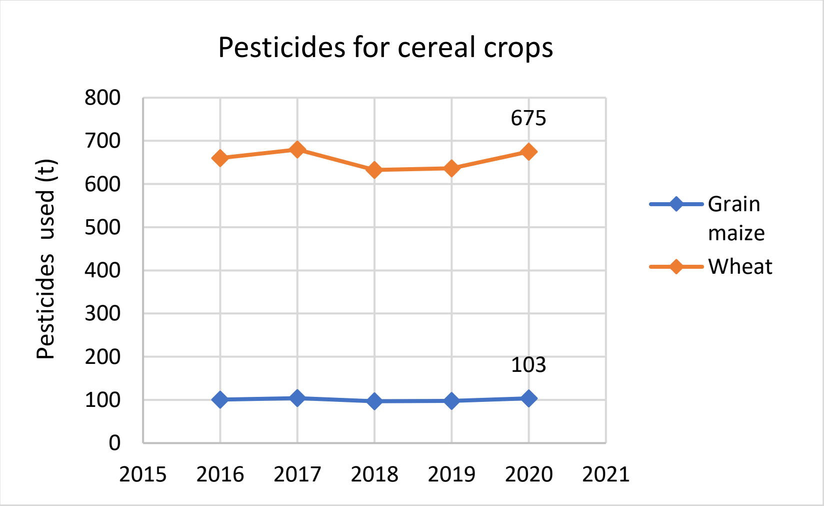


Figure 34. Pesticides used for grain maize and wheat crops. [16]

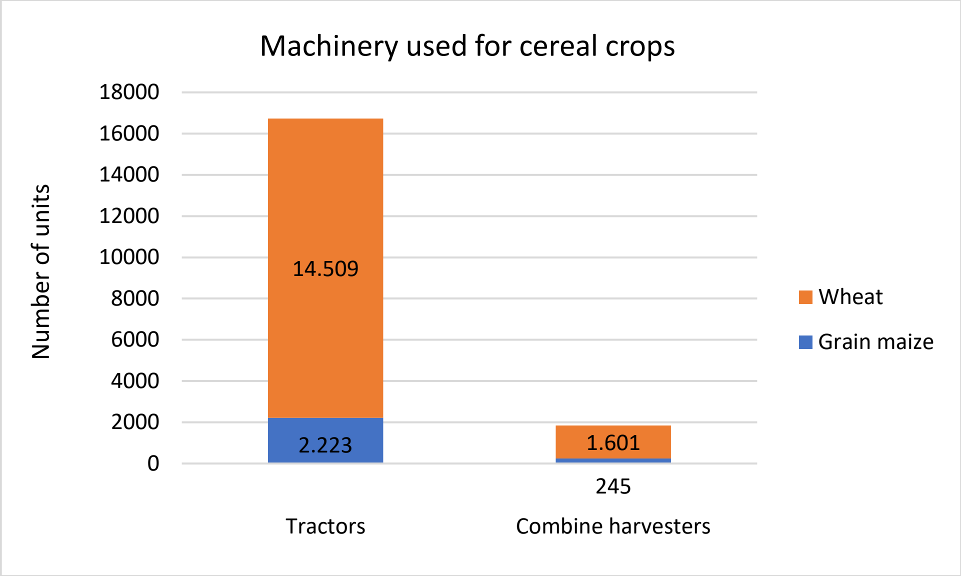


Figure 35. Machinery used in agriculture. [17]

2.2.2. Pyrolysis

Pyrolysis consists in a thermochemical process in which carbon-rich materials such as crop residues at heated in an inert atmosphere without the presence of oxygen in order to obtain biochar, bio-oil and gas (syngas) as products (Figure 36). There are different types of pyrolysis technologies, being three of them fast, slow and microwave pyrolysis (MWP) which are distinguished by their heating rate, temperature, residence time, reaction environments and heating methods [*30*]. The temperature range of pyrolysis is established around 350 and 700 °C [31]. This parameter has a direct effect on biochar yield as it decreases while augmenting the pyrolysis temperature [32].

Experimental data from slow pyrolysis process with an approximate temperature of 600 °C for both corn stover and wheat straw biomass has been gathered through scientific papers in which although it is proven that crop yield is reduced with higher temperatures, carbon content in biochar increases reducing O:C molar ratio.

For that reason, a slightly higher pyrolysis temperature was selected for the analysis as CO_2 long-term sequestration is directly proportional to carbon content of biochar which implies a greater carbon sequestration. Moreover, also H:C molar ratios present lower values which achieves high aromaticity and resistance to microbial and chemical degradation [*34*].

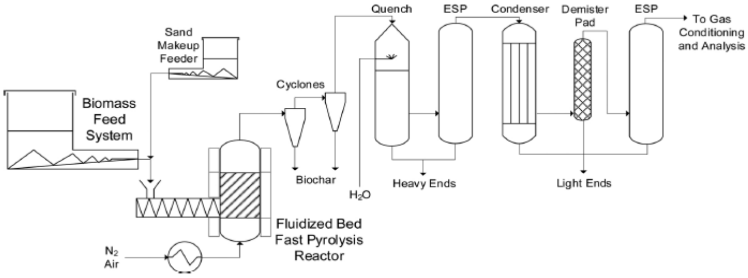


Figure 36. Scheme of conventional pyrolysis plant. [33]

Additionally, as the experimental processes studied employed laboratory pyrolysis systems, the model BST-05 Pro from Beston Group [35] has been chosen in order to collect its technical data and execute a much realistic life cycle assessment for the pyrolysis processes of both corn stover and wheat straw biomass.

The main stages that occur in every pyrolysis plant for biomass remain the same, only varying their inputs and outputs. First, a different type of gas, nitrogen or helium for example, goes into the reactor to create an inert atmosphere which eliminates the presence of oxygen in the air. After that, a mass of biomass is heated in the reactor at a certain pyrolysis temperature producing three different products: biochar, bio-oil and syngas. Biochar is collected, the heavier volatiles are condensed into liquid bio-oil by applying cooling water into a condenser and the lighter volatiles escape as syngas [31].

2.2.2.1. *Corn stover*

In respect of the pyrolysis process of corn stover biomass, experimental data from an article in microwave-assisted pyrolysis for the production of biochar corn stover (Zhu, L. et al., 2015) has been collected to execute a life cycle assessment with real results [*31*].

Previously to initiating the pyrolysis process, the corn stover residues derived from crop production are dried (pre-treatment) until presenting the characteristics shown in Figure 37. In this case, dried corn stover biomass has a 6,29% of moisture content which indicates that 93,71% of water content of the initial biomass is removed (1).

$$r_{H_2O} = m_{CS} \cdot \left(1 - \frac{6{,}29}{100}\right) \tag{1}$$

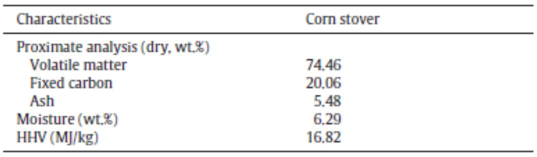
Being:

$\mathrm{r}_{\mathrm{H_2O}}: removed\ water\ (l)$

$m_{CS}: total\ corn\ stover\ biomass\ (kg)$

Nitrogen gas (N_2) is introduced during 30 min with a flow rate of 1000 mL·min^{-1}, as it is previously mentioned, to create an inert atmosphere in the reactor. Then corn stover biomass is inserted into the reactor with a capacity of 300 kg·h^{-1} as it is indicated in the technical data of the pyrolysis plant model BST-05 Pro [35] and it is heated with a temperature of 650 °C. Consequently, biochar is obtained and heavier volatiles are condensed into liquid bio-oil with a condenser with cooling water at 5 °C, leaving lighter volatiles (syngas) to escape.

In this manner, data for corn stover (CS) biomass pyrolysis is established for the yearly biomass production which corresponds to 1.744 tonnes of corn stover as it is represented in Figure 23. Likewise, as the results and characteristics of the rest inputs and outputs of pyrolysis, corn stover properties (Figure 37) are defined through the initial analysis of raw feedstock made for the experiment described in the mentioned article [*31*] of the *Journal of Analytical and Applied Pyrolysis (JAAP)*.



Characteristics	Corn stover
Proximate analysis (dry, wt.%)	
Volatile matter	74.46
Fixed carbon	20.06
Ash	5.48
Moisture (wt.%)	6.29
HHV (MJ/kg)	16.82

Figure 37. Proximate analysis of initial raw feedstock. [31]

Furthermore, in respect of determining the yearly quantity of nitrogen gas as input, a calculation has been done with the known data of its flow rate, time of introduction in the reactor and residence time of biomass in the pyrolysis process before the repetition of the cycle with the entry of a new flow of nitrogen, multiplying these values by the number of hours in a whole year as it is represented in the next equation (2).

$$\dot{V} \cdot t \cdot \frac{m_{CS}}{C_r} \cdot 60 \frac{min}{(r_t + t)} \cdot 10^{-3} = m_{N_2} \tag{2}$$

Being:

$\dot{V}: N_2\ flow\ rate\ (mL \cdot min^{-1})$

$t: time\ (min)$

$r_t: residence\ time\ (min)$

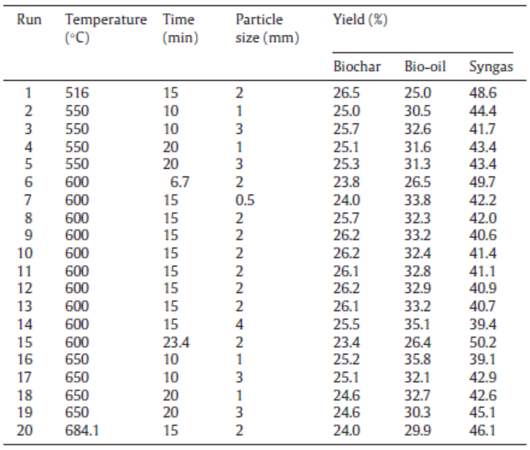
$m_{N_2}: mass\ of\ nitrogen\ (kg)$

$m_{CS}: total\ corn\ stover\ biomass\ (kg)$

$C_r: pyrolysis\ reactor\ capacity\ (kg \cdot h^{-1})$

Thus, as it is indicated in the investigation of this paper, the residence time (r_t) for a pyrolysis temperature of 650 °C with the highest biochar yield in this condition corresponds to 10 minutes (Figure 38) resulting in a yearly mass of 261.600 kg which is equivalent to 261,6 tonnes of nitrogen.

Additionally, working this type of model of pyrolysis plant with its full capacity during 24 hours through the 365 days of the year, it is proven that one of these plants is enough to execute the pyrolysis process for the total quantity of corn stover biomass. Therefore, data for the construction of this type of plant has been estimated considering its location inside of an industrial building which presents the characteristics shown in Table 1.



Run	Temperature (°C)	Time (min)	Particle size (mm)	Yield (%)		
				Biochar	Bio-oil	Syngas
1	516	15	2	26.5	25.0	48.6
2	550	10	1	25.0	30.5	44.4
3	550	10	3	25.7	32.6	41.7
4	550	20	1	25.1	31.6	43.4
5	550	20	3	25.3	31.3	43.4
6	600	6.7	2	23.8	26.5	49.7
7	600	15	0.5	24.0	33.8	42.2
8	600	15	2	25.7	32.3	42.0
9	600	15	2	26.2	33.2	40.6
10	600	15	2	26.2	32.4	41.4
11	600	15	2	26.1	32.8	41.1
12	600	15	2	26.2	32.9	40.9
13	600	15	2	26.1	33.2	40.7
14	600	15	4	25.5	35.1	39.4
15	600	23.4	2	23.4	26.4	50.2
16	650	10	1	25.2	35.8	39.1
17	650	10	3	25.1	32.1	42.9
18	650	20	1	24.6	32.7	42.6
19	650	20	3	24.6	30.3	45.1
20	684.1	15	2	24.0	29.9	46.1

Figure 38. Reaction conditions and product yield distribution. [31]

Component	Value	Unit
Pyrolysis plant land occupation	80	m^2
Industrial building land occupation	360	m^2
Steel pillars	16	units
Pillars length	5	m
Steel beams	16	units
Beams length	5	m
Steel profile	IPE 300	
Total mass of steel	6.752	kg
Foundations	16	units
Foundation area	1,44	m^2
Foundation depth	0,5	m
Total foundation mass	11.520	kg
Reinforcement steel bars	192	units
Total mass of reinforcement steel	100	kg

Table 1. Pyrolysis plant construction characteristics.

Furthermore, as it is represented in Figure 38, run 16 which corresponds with the selected experimental conditions indicates the biochar, bio-oil and syngas yield that also determines the proportion of these products with the pyrolysis of corn stover biomass as it is indicated in the next function (3).

$$Initial\ corn\ stover = weight\ of\ syngas + bio\ oil\ mass + biochar\ mass \tag{3}$$

In this manner, the mass of syngas, bio-oil and biochar with respect to the initial quantity of corn stover biomass (1.744 tonnes) are the following expressed in Table 2 which are calculated as it is indicated in the next function (4).

Component	Value	Unit
Biochar	439.488	kg
Bio-oil	624.352	kg
Syngas	680.160	kg

Table 2. Biochar, bio-oil and syngas products.

$$m_i = \left(\frac{y_i}{100}\right) \cdot m_{CS} \tag{4}$$

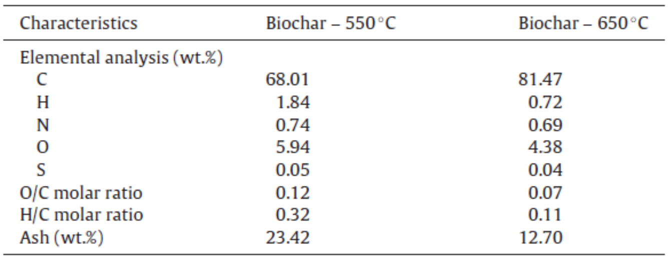
Being:

$m_i: mass\ of\ each\ product\ (kg)$

$y_i: yield\ of\ each\ product$

$m_{CS}: total\ corn\ stover\ biomass\ (kg)$

Moreover, as it was previously mentioned and it appears in Figure 39, biochar at the selected pyrolysis temperature (650 °C) contains a higher quantity of carbon (C) with a lower O:C and H:C molar ratio which indicates that there is a greater carbon sequestration, aromaticity and resistance to microbial and chemical degradation which are the key factors for the improvement of organic matter content in soil and the reduction of CO_2 emissions to the atmosphere.



Characteristics	Biochar – 550 °C	Biochar – 650 °C
Elemental analysis (wt.%)		
C	68.01	81.47
H	1.84	0.72
N	0.74	0.69
O	5.94	4.38
S	0.05	0.04
O/C molar ratio	0.12	0.07
H/C molar ratio	0.32	0.11
Ash (wt.%)	23.42	12.70

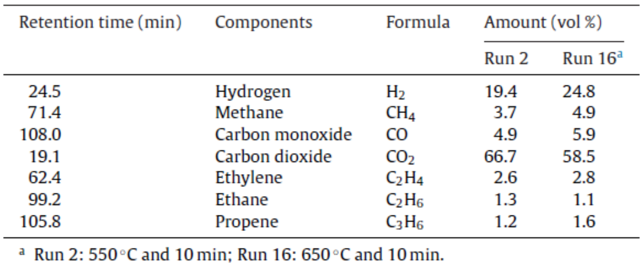
Figure 39. Biochar composition derived from corn stover. [31]

Likewise, with respect of the total mass of biochar produced from the pyrolysis process of corn stover which it is indicated in Table 2, the composition of biochar in respect of the contribution of each element shown in Figure 39 is the following illustrated in Table 3.

Component	Value	Unit
C	358.051	kg
H	3.164	kg
N	3.032	kg
O	19.250	kg
S	176	kg

Table 3. CS biochar composition at 650 °C.

However, although carbon sequestration exits due to biochar, non-condensable gases are produced along with bio-oil being one of them carbon dioxide as it is represented in Figure 40 and Table 4 where the mass of each component is calculated with respect of its amount (vol.%) in syngas composition (5).



Retention time (min)	Components	Formula	Amount (vol %)	
			Run 2	Run 16[a]
24.5	Hydrogen	H_2	19.4	24.8
71.4	Methane	CH_4	3.7	4.9
108.0	Carbon monoxide	CO	4.9	5.9
19.1	Carbon dioxide	CO_2	66.7	58.5
62.4	Ethylene	C_2H_4	2.6	2.8
99.2	Ethane	C_2H_6	1.3	1.1
105.8	Propene	C_3H_6	1.2	1.6

[a] Run 2: 550 °C and 10 min; Run 16: 650 °C and 10 min.

Figure 40. Major components of non-condensable gases derived from corn stover pyrolysis. [31]

$$m_i = \left(\frac{a_i}{100}\right) \cdot m_{sg} \tag{5}$$

Being:

m_i: $mass\ of\ each\ gas\ (kg)$

a_i: $amount\ of\ each\ component$

m_{sg}: $total\ mass\ of\ syngas\ (kg)$

Component	Value	Unit
Hydrogen (H_2)	168.680	kg
Methane (CH_4)	33.328	kg
Carbon monoxide (CO)	40.129	kg
Carbon dioxide (CO_2)	397.894	kg
Ethylene (C_2H_4)	19.044	kg
Ethane (C_2H_6)	7.482	kg
Propene (C_3H_6)	10.883	kg

Table 4. Non-condensable gases composition derived from corn stover pyrolysis at 650 °C.

Nevertheless, the resulted long-term carbon sequestration of biochar achieves a higher value than this carbon dioxide production. This quantity of carbon dioxide long-term capture of biochar has been determined as it is described by Shackley, S. et al. (2016) [*36*] (6) resulting in the value indicated in Table 5.

$$kg\ CO_2 = kg\ C \cdot \frac{ma_{CO_2}}{ma_C} = kg\ C \cdot \frac{44}{12} = kg\ C \cdot 3{,}67 \qquad (6)$$

	Value	Unit
Carbon sequestration	1.312.853	kg CO_2

Table 5. Carbon dioxide sequestration of corn stover biochar.

2.2.2.2. Wheat straw

In respect of the pyrolysis process of wheat straw biomass, in order to study real results, experimental data from a research paper regarding the pyrolysis of wheat and barley straw biomass (Sedmihradská, A. et al., 2020) has been collected [37].

The pyrolysis process in this investigation (Sedmihradská, A. et al., 2020) is similar to the previous process described for corn stover biomass. However, in this case, an inert atmosphere without the presence of oxygen is achieved by introducing helium (He) before heating the wheat straw biomass [37].

Equally to the previous case regarding CS biochar production, wheat straw residues are dried (pre-treatment) until showing the characteristics represented in Figure 41. In this manner, dried wheat straw biomass presents an 8,20% of water content which indicates that 91,80% of H_2O is removed from the initial biomass (7).

$$r_{H_2O} = m_{CS} \cdot \left(1 - \frac{8{,}20}{100}\right) \qquad (7)$$

Being:

$r_{H_2O}: removed\ water\ (l)$

$m_{WS}: total\ wheat\ straw\ biomass\ (kg)$

Helium is introduced with a flow rate of 150 $cm^3 \cdot min^{-1}$ in the reactor containing wheat straw biomass with the presented characteristics illustrated in Figure 41. Then, this reactor is placed into a hot furnace which is previously heated with the selected pyrolysis temperature (600 °C) and after 90 minutes, biochar is obtained and pyrolysis primary products, liquid and gases, are released. Therefore, considering that this process lasts this amount of time, it is estimated that the utilised yearly mass of helium corresponds to a value of 78.840 kg for each pyrolysis plant.

Furthermore, as it was described for the previous case, the same pyrolysis plant model BST-05 Pro from Beston Group [35] has been considered for the LCA applying its data in SimaPro software as this allows to execute a much certain analysis by utilising a real pyrolysis plant instead of a prototype.

In the contrary to the previous case respective to the production of corn stover biochar, an approximate number of 6 pyrolysis plants are needed to execute the pyrolysis of the total yearly production of wheat straw biomass estimated for Saxony region (8).

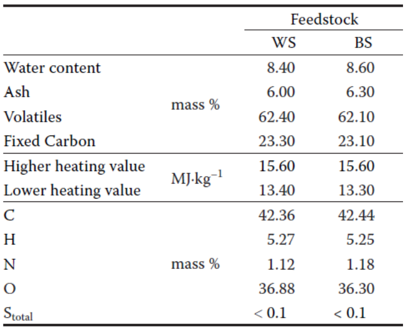
$$n = {}^{m_{WS}}/_{(C_r \cdot 24\,h \cdot 365\,days)} = 5{,}67 \approx 6 \tag{8}$$

Being:

$n: number\ of\ pyrolysis\ plants$

$m_{WS}: total\ wheat\ straw\ biomass\ (kg)$

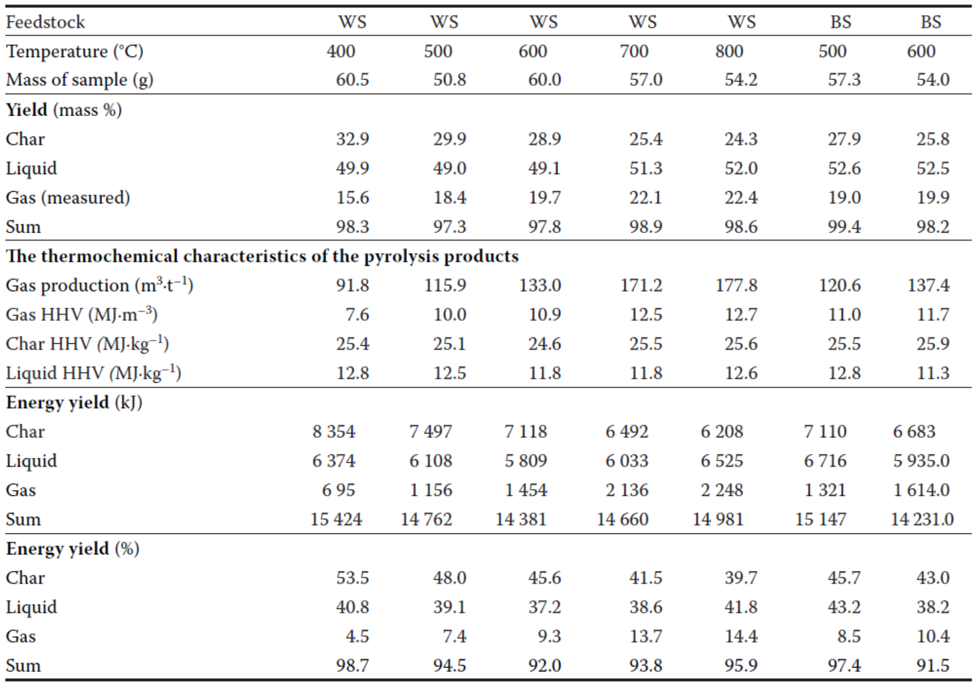
$C_r: pyrolysis\ reactor\ capacity\ (kg \cdot h^{-1})$



		Feedstock	
		WS	BS
Water content	mass %	8.40	8.60
Ash		6.00	6.30
Volatiles		62.40	62.10
Fixed Carbon		23.30	23.10
Higher heating value	$MJ{\cdot}kg^{-1}$	15.60	15.60
Lower heating value		13.40	13.30
C	mass %	42.36	42.44
H		5.27	5.25
N		1.12	1.18
O		36.88	36.30
S_{total}		< 0.1	< 0.1

Figure 41. Proximate analysis of wheat straw feedstock. [37]

The total amount of biomass which is considered to be used for the pyrolysis process of a yearly production is the one indicated in Figure 23 which corresponds to 14.905 tonnes of wheat straw (WS). In this manner, the pyrolysis of this quantity of biomass at 600 °C results in the production of char, liquid and gas with the following properties defined in Figure 42. Likewise, the yield of these products expressed in mass percentage determines their mass (Table 6) in proportion to the total mass of feedstock biomass previously mentioned. Therefore, these values are calculated as it is indicated in the next function (9).



Feedstock	WS	WS	WS	WS	WS	BS	BS
Temperature (°C)	400	500	600	700	800	500	600
Mass of sample (g)	60.5	50.8	60.0	57.0	54.2	57.3	54.0
Yield (mass %)							
Char	32.9	29.9	28.9	25.4	24.3	27.9	25.8
Liquid	49.9	49.0	49.1	51.3	52.0	52.6	52.5
Gas (measured)	15.6	18.4	19.7	22.1	22.4	19.0	19.9
Sum	98.3	97.3	97.8	98.9	98.6	99.4	98.2
The thermochemical characteristics of the pyrolysis products							
Gas production ($m^3 \cdot t^{-1}$)	91.8	115.9	133.0	171.2	177.8	120.6	137.4
Gas HHV ($MJ \cdot m^{-3}$)	7.6	10.0	10.9	12.5	12.7	11.0	11.7
Char HHV ($MJ \cdot kg^{-1}$)	25.4	25.1	24.6	25.5	25.6	25.5	25.9
Liquid HHV ($MJ \cdot kg^{-1}$)	12.8	12.5	11.8	11.8	12.6	12.8	11.3
Energy yield (kJ)							
Char	8 354	7 497	7 118	6 492	6 208	7 110	6 683
Liquid	6 374	6 108	5 809	6 033	6 525	6 716	5 935.0
Gas	6 95	1 156	1 454	2 136	2 248	1 321	1 614.0
Sum	15 424	14 762	14 381	14 660	14 981	15 147	14 231.0
Energy yield (%)							
Char	53.5	48.0	45.6	41.5	39.7	45.7	43.0
Liquid	40.8	39.1	37.2	38.6	41.8	43.2	38.2
Gas	4.5	7.4	9.3	13.7	14.4	8.5	10.4
Sum	98.7	94.5	92.0	93.8	95.9	97.4	91.5

WS – wheat straw; BS – barley straw; HHV – higher heating value

Figure 42. Mass and energy balance of pyrolysis products. [37]

$$m_i = \left(\frac{y_i}{100}\right) \cdot m_{WS} \qquad (9)$$

Being:

$m_i: mass\ of\ each\ product\ (kg)$

$y_i: yield\ of\ each\ product$

$m_{WS}: total\ wheat\ straw\ biomass\ (kg)$

Component	Value	Unit
Biochar	4.307.545	kg
Liquid	7.318.355	kg
Gas	2.936.285	kg

Table 6. Pyrolysis products of wheat straw biomass.

Moreover, WS biochar produced by pyrolysis at 600 °C presents the following composition represented in Figure 43. Thus, the mass of the different components of this biochar correspond to the quantities shown in Table 7. These values are calculated as it is indicated in function (10).

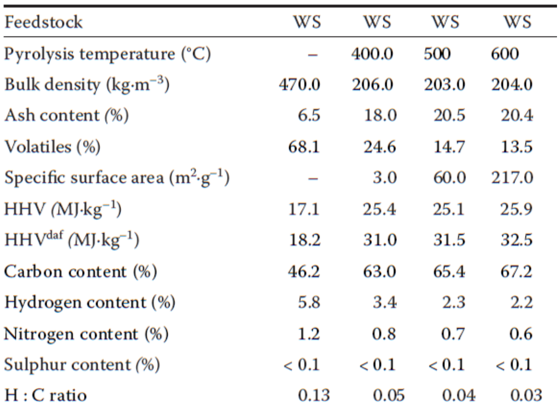
$$m_i = \left(\frac{c_i}{100}\right) \cdot m_{WS,BC} \qquad (10)$$

Being:

$m_i: mass\ of\ each\ component\ (kg)$

$c_i: content\ of\ each\ component$

$m_{WS,BC}: total\ wheat\ straw\ biochar\ (kg)$



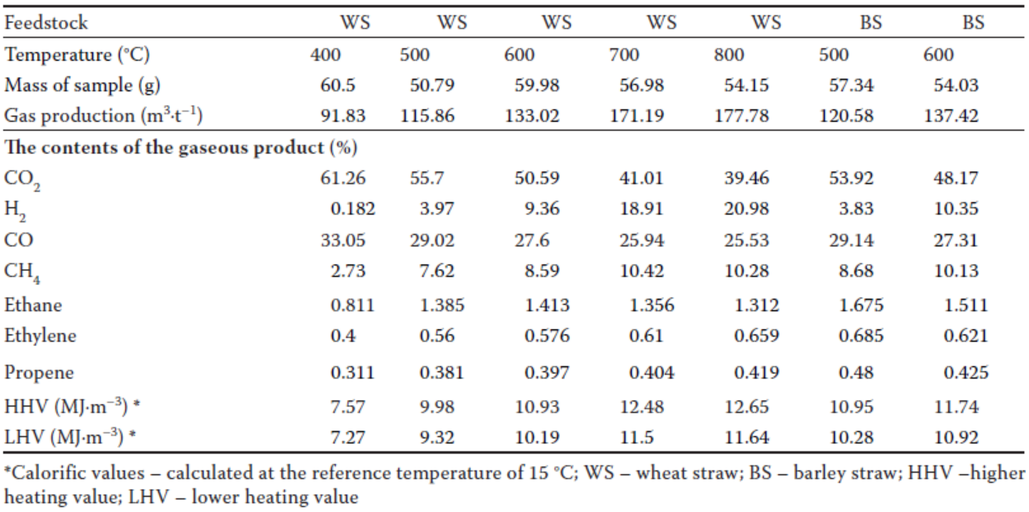
Feedstock	WS	WS	WS	WS
Pyrolysis temperature (°C)	–	400.0	500	600
Bulk density (kg·m^{-3})	470.0	206.0	203.0	204.0
Ash content (%)	6.5	18.0	20.5	20.4
Volatiles (%)	68.1	24.6	14.7	13.5
Specific surface area (m^2·g^{-1})	–	3.0	60.0	217.0
HHV (MJ·kg^{-1})	17.1	25.4	25.1	25.9
HHV^{daf} (MJ·kg^{-1})	18.2	31.0	31.5	32.5
Carbon content (%)	46.2	63.0	65.4	67.2
Hydrogen content (%)	5.8	3.4	2.3	2.2
Nitrogen content (%)	1.2	0.8	0.7	0.6
Sulphur content (%)	< 0.1	< 0.1	< 0.1	< 0.1
H : C ratio	0.13	0.05	0.04	0.03

Figure 43. Analysis and composition of wheat straw biochar. [37]

Component	Value	Unit
C	2.894.670	kg
H	94.766	kg
N	25.845	kg
O	409.217	kg
S	4.308	kg

Table 7. WS biochar composition at 600 °C.

Along with the production of liquid products after condensation, gases are also released in the process containing non-condensable gases with a specific proportion as it is represented in Figure 44. Therefore, with respect to the calculation defined in the next equation (11), the mass of the most significant non-condensable gases is determined as it is shown in Table 8.



Feedstock	WS	WS	WS	WS	WS	BS	BS
Temperature (°C)	400	500	600	700	800	500	600
Mass of sample (g)	60.5	50.79	59.98	56.98	54.15	57.34	54.03
Gas production (m^3·t^{-1})	91.83	115.86	133.02	171.19	177.78	120.58	137.42
The contents of the gaseous product (%)							
CO_2	61.26	55.7	50.59	41.01	39.46	53.92	48.17
H_2	0.182	3.97	9.36	18.91	20.98	3.83	10.35
CO	33.05	29.02	27.6	25.94	25.53	29.14	27.31
CH_4	2.73	7.62	8.59	10.42	10.28	8.68	10.13
Ethane	0.811	1.385	1.413	1.356	1.312	1.675	1.511
Ethylene	0.4	0.56	0.576	0.61	0.659	0.685	0.621
Propene	0.311	0.381	0.397	0.404	0.419	0.48	0.425
HHV (MJ·m^{-3}) *	7.57	9.98	10.93	12.48	12.65	10.95	11.74
LHV (MJ·m^{-3}) *	7.27	9.32	10.19	11.5	11.64	10.28	10.92

*Calorific values – calculated at the reference temperature of 15 °C; WS – wheat straw; BS – barley straw; HHV –higher heating value; LHV – lower heating value

Figure 44. Average contents of most significant gaseous products. [37]

$$m_i = \left(\frac{c_i}{100}\right) \cdot m_g \tag{11}$$

Being:

$m_i: mass\ of\ each\ gas\ (kg)$

$c_i: content\ of\ each\ component$

m_g: total mass of gas products (kg)

Component	Value	Unit
Hydrogen (H_2)	274.836	kg
Methane (CH_4)	252.227	kg
Carbon monoxide (CO)	810.415	kg
Carbon dioxide (CO_2)	1.485.467	kg
Ethylene (C_2H_4)	16.913	kg
Ethane (C_2H_6)	41.490	kg
Propene (C_3H_6)	11.657	kg

Table 8. Non-condensable gases composition derived from wheat straw pyrolysis at 600 °C.

Although, there is a production of carbon dioxide (CO_2) after the pyrolysis process, the total yearly production of wheat straw biochar achieves a long-term carbon sequestration with an approximate value of 10.614 tonnes of CO_2 (Table 9) calculated as it is presented in equation (6) Shackley, S. et al. (2016) [*36*].

	Value	Unit
Carbon sequestration	10.613.791	kg CO_2

Table 9. Carbon dioxide sequestration of wheat straw biochar.

2.2.3. Transport and storage

A slight analysis has been performed to visualize which is the largest type of goods transport employed in Germany. In this manner, this study is executed by using statistical data from the Federal Statistical Office of Germany [*16*].

Therefore, as it can be seen in Figure 45, road transport by national lorries is the main type of transportation of agricultural goods used in Germany. Moreover, national transportation appears to be the most frequent in respect of traffic relations (Figure 46).

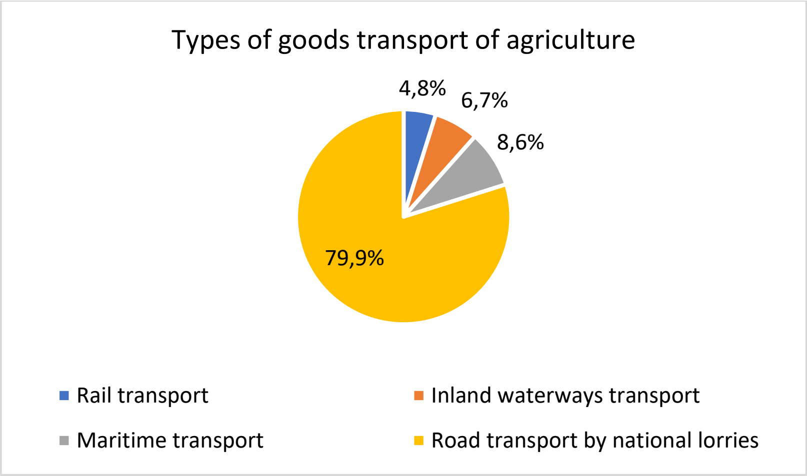


Figure 45. Types of goods transport of agriculture in Germany. [16]

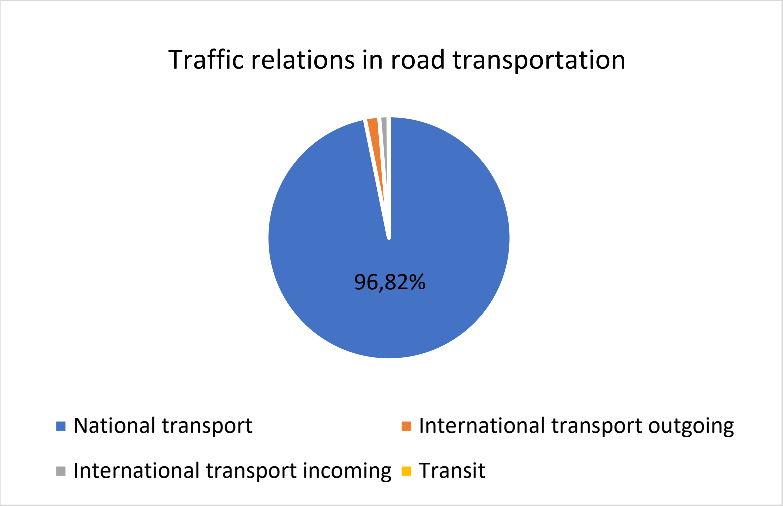


Figure 46. Types of traffic relations in road transportation of Germany. [16]

Thus, it is assumed that produced biochar is transported by national lorries throughout the different regions of Germany. Therefore, the total performance of road transportation for the yearly production of corn stover and wheat straw biochar is 439,5 tkm and 4307,5 tkm respectively. These values are considered by knowing the total amount of biochar (Table 2 and Table 6) obtained throughout the pyrolysis process of CS and WS biomass generated in Saxony's agriculture.

Furthermore, as the Federal Statistical Office of Germany (2019, p. 13) indicates in respect of heavy-duty transport, lorries fuel consumption can be estimated for this analysis as 32,6 l/100 km. Thus, after travelling 100 km each lorry will need a refill of 0,0326 tonnes of diesel [46]. This assumption is made considering that diesel is the fuel that lorries use for transport.

Likewise, it is assumed that each lorry travels the maximum distance from north to south of Germany which is approximately 800 km [47]. Therefore, the total amount of diesel needed for this path is estimated to be about 0,26 tonnes after travelling 800 km.

2.2.4. Application of biochar in agriculture

In respect to this stage of the life cycle of biochar, the values of crop production in Saxony described in sections 2.1 Agriculture in Saxony and 2.2.1 Crop production are supposed to remain constant. However, in this case, corn stover and wheat straw biochar (Table 2 and Table 6) are applied to the agricultural soil achieving a long-term carbon sequestration (Table 5 and Table 9).

3. Data summary

In accordance with the previous argumentation exposed in section 2. Selected biomass, a summary of the data is presented for the values of yearly production of CS and WS biomass (Table 10 and Table 15) and, their total biochar production throughout the pyrolysis process (Table 11 and Table 16). The purpose of presenting this data is to view how CS and WS biochar's production would affect the environment in a realistic scale. Moreover, it helps to determine the corresponding values of the different products and processes involved in the generation of 1 tonne of biochar of each type of biomass (Table 12, Table 13, Table 17 and Table 18).

The goal of having a representation of these values based on the production of 1 tonne of biochar for both types of biomasses is to analyse the results of their LCA for the same quantity of end product. Therefore, there can be a clearer conclusion on which of these products presents a larger amount of negative environmental impacts.

3.1. Corn stover

Table 10 and Table 11 illustrate a summary of the significant data respective to the crop production of corn in Saxony region and the pyrolysis process of its total value of corn stover residues. These values are estimated through the statistical data of the Federal Statistic Office of Germany (Destatis) [*16*] and the Food and Agriculture Organization of the United Nations (FAO) [*17*] as it is explained in section 2.1 Agriculture in Saxony.

Component	Value	Unit
Arable land	25.133	ha
Crop yield	0,53	ton/ha
Sowing	12.160	ton
Nitrogen fertiliser	2.727	ton
Irrigation	106.490	m^3
Pesticides	103	ton
Maize production	221.983	ton
Corn stover biomass	1.744	ton

Table 10. Saxony's estimated yearly data of CS biomass production.

Component	Value	Unit
Pyrolysis plant	1	unit
Corn stover biomass	1.744	ton
Removed H_2O content	1.634.302	l
Total yearly pyrolysis time	5.813	h
Nitrogen gas (N_2)	261,6	ton
Biochar	439,5	ton
C	358	ton
Bio-oil	624,4	ton
Syngas	680,2	ton
Hydrogen (H_2)	168,7	ton
Methane (CH_4)	33,3	ton
Carbon monoxide (CO)	40,1	ton
Carbon dioxide (CO_2)	397,9	ton
Ethylene (C_2H_4)	19	ton
Ethane (C_2H_6)	7,5	ton
Propene (C_3H_6)	10,9	ton

Table 11. Saxony's estimated yearly data of CS biomass pyrolysis.

Similarly, Table 12 and Table 13 present the corresponding data for these mentioned stages of the life cycle of biochar with the only difference that these values refer to the production of 1 tonne of biochar.

The values represented in the following tables result of dividing the previous numbers shown in Table 10 and Table 11 by the total quantity of biochar produced by the pyrolysis of Saxony's agriculture CS biomass (439,5 tonnes of biochar). However, as an exception, the crop yield value remains constant in both cases (Table 10 and Table 12).

Component	Value	Unit
Arable land	52,5	ha
Crop yield	0,53	ton/ha
Sowing	27,7	ton
Nitrogen fertiliser	6,2	ton
Irrigation	242,4	m^3
Pesticides	0,23	ton
Maize production	505	ton
Corn stover biomass	**3,97**	ton

Table 12. Data of CS biomass production to generate 1 tonne of biochar.

Component	Value	Unit
Pyrolysis plant	1	unit
Corn stover biomass	3,97	ton
Removed H_2O content	3.719	l
Total pyrolysis time	13,23	h
Nitrogen gas (N_2)	0,59	ton
Biochar	**1**	ton
C	0,82	ton
Bio-oil	1,42	ton
Syngas	1,55	ton
Hydrogen (H_2)	0,38	ton
Methane (CH_4)	0,08	ton
Carbon monoxide (CO)	0,09	ton
Carbon dioxide (CO_2)	0,91	ton
Ethylene (C_2H_4)	0,04	ton
Ethane (C_2H_6)	0,02	ton
Propene (C_3H_6)	0,03	ton

Table 13. Data of CS biomass pyrolysis to produce 1 tonne of biochar.

Furthermore, Table 14 defines the quantity of long-term carbon sequestration that can be achieved through the application of 1 tonne of CS biochar in the agricultural soils. Therefore, similarly to the previous cases, this value is obtained from dividing the long-term carbon sequestration of the total yearly production of corn stover biochar (Table 5) in tonnes by the total amount of biochar produced (439,5 tonnes of biochar).

Component	Value	Unit
Long-term carbon sequestration	0,003	ton

Table 14. Data of 1 tonne of CS biochar long-term carbon sequestration.

3.2. Wheat straw

Similarly, to the previous case, Table 15 and Table 16 show a summary of the data in respect to the yearly production of wheat in Saxony region and the pyrolysis of its residues which is also estimated through the statistical data of the Federal Statistic Office of Germany (Destatis) [*16*] and the Food and Agriculture Organization of the United Nations (FAO) [*17*].

Component	Value	Unit
Arable land	164.041	ha
Crop yield	0,43	ton/ha
Sowing	67.071	ton
Nitrogen fertiliser	17.798	ton
Irrigation	695.062	m^3
Pesticides	675	ton
Wheat production	1.217.113	ton
Wheat straw biomass	14.905	ton

Table 15. Saxony's estimated yearly data of WS biomass production.

Component	Value	Unit
Pyrolysis plant	6	units
Wheat straw biomass	14.905	ton
Removed H_2O content	13.682.790	l
Total yearly pyrolysis time	8.760	h
Helium (He)	447,2	ton
Biochar	4.307,5	ton
C	2.894,7	ton
Bio-oil	7.318,4	ton
Syngas	2.936,3	ton
Hydrogen (H_2)	274,8	ton
Methane (CH_4)	252,2	ton
Carbon monoxide (CO)	810,4	ton
Carbon dioxide (CO_2)	1.485,5	ton
Ethylene (C_2H_4)	16,9	ton
Ethane (C_2H_6)	41,5	ton
Propene (C_3H_6)	11,7	ton

Table 16. Saxony's estimated yearly data of WS biomass pyrolysis.

Likewise, Table 17 and Table 18 show the values of these previous components in reference to the obtaining of 1 tonne of biochar which result from dividing the values of annual crop production in Saxony (Table 15 and Table 16) by the total amount of WS biochar (4.307,5 tonnes of biochar).

Component	Value	Unit
Arable land	36,2	ha
Crop yield	0,43	ton/ha
Sowing	15,6	ton
Nitrogen fertiliser	4,13	ton
Irrigation	161,4	m^3
Pesticides	0,16	ton
Wheat production	283	ton
Wheat straw biomass	**3,46**	ton

Table 17. Data of WS biomass production to generate 1 tonne of biochar.

Component	Value	Unit
Pyrolysis plant	1	unit
Wheat straw biomass	3,46	ton
Removed H_2O content	3.177	l
Total pyrolysis time	11,53	h
Helium (He)	0,10	ton
Biochar	**1**	ton
C	0,67	ton
Bio-oil	1,7	ton
Syngas	0,68	ton
Hydrogen (H_2)	0,06	ton
Methane (CH_4)	0,06	ton
Carbon monoxide (CO)	0,19	ton
Carbon dioxide (CO_2)	0,34	ton
Ethylene (C_2H_4)	0,004	ton
Ethane (C_2H_6)	0,01	ton
Propene (C_3H_6)	0,003	ton

Table 18. Data of WS biomass pyrolysis to produce 1 tonne of biochar.

Additionally, Table 19 establishes the quantity of long-term carbon sequestration that can be obtained through the application of 1 tonne of WS biochar in the soils for crop production. Likewise, this value is obtained from dividing the long-term carbon sequestration of the total yearly production of wheat straw biochar (Table 9) in tonnes by the total amount of biochar produced (4.307,5 tonnes of biochar).

Component	Value	Unit
Long-term carbon sequestration	0,0025	ton

Table 19. Data of 1 tonne of WS biochar long-term carbon sequestration.

4. SimaPro's LCA

4.1. Corn stover and wheat straw biochar

4.1.1. Goal and scope

The goal of each Life Cycle Assessment (LCA) of both types of biochar, derived from corn stover and wheat straw biomass, is to identify the environmental impacts of the production of these biochars (BCs) and compare them in order to discuss which one of them causes less damage to the environment, specially to the ecosystem quality and the human health.

The analysed systems are set with system boundaries which define the different stages that are included in the analysis. These steps correspond to the crop production, the pyrolysis process of biomass, the transportation and storage of biochar and the application of the latter in the agricultural soil. In this manner, the assessment of life cycle of both of these types biochar includes the respective inputs and outputs from the production of biomass through agriculture to the transportation of the end product (biochar).

Thus, data in respect of the life cycle of these products is collected with the disadvantage of having some limitations. Due to the lack of collecting experimental data from the laboratory, the inventory data in respect of the stage of pyrolysis is gathered through experimental data from other scientific research studies. Furthermore, LCI databases such as Ecoinvent 3 [48] or Agri-footprint [49] do not include data of biochar, the pyrolysis process and the pyrolysis plant among others. Therefore, this conduces to the increase of uncertainties as this particular inventory data needs to be created or based on a similar process or product.

Additionally, the intention of these assessments is to contribute along with other research studies in the conclusion of which of the selected biomasses is preferred for the production of biochar as it may have fewer negative effects on the environment, i.e., reduces the environmental impacts.

4.1.1.1. *Life Cycle Assessment (LCA) model*

The model which is selected to guide the scope and the methodology of the Life Cycle Assessment (LCA) [44] is the cradle-to-cradle analysis. In this manner, as it is described in section 1.3.2. Goal and scope (p. 20), this type of model (Figure 47) defines the life cycle of the product from the extraction of raw materials and their manufacture (cradle) to the recycling of waste so that it can be reused for another products life cycle. Likewise, the product of this LCA (biochar) is considered to be applied in agricultural lands after its production.

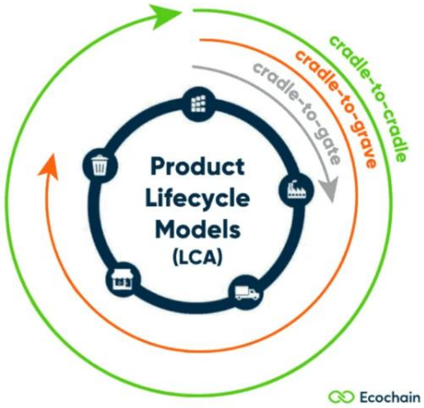


Figure 47. Life cycle models in LCA. [44]

In this case, the extraction of raw materials corresponds to the production of biomass throughout the crop production while the stage of processing is equivalent to the pyrolysis process. The transportation step is characterized by the displacement of biochar to the agricultural land followed by the usage phase in which biochar is integrated in the agricultural soil. Finally, the disposal and recycling of waste is referred to the discarding and reuse of the co-products obtained in the pyrolysis process.

4.1.1.2. *System boundaries*

As it was previously defined in section 1.3.2. Goal and scope (p. 20), system boundaries define the parts and processes that are included in the analysed system. Separating these factors from the rest of the technosphere and setting a boundary with the ecosphere.

Therefore, as it is represented in Figure 48, the analysed system of this Life Cycle Assessment (LCA) is defined by the different stages of biochar's life cycle, starting from the obtaining of biomass throughout crop production (growth and harvest) and ending with the utilisation of produced biochar in agriculture by adding it to the soils for crop production.

Likewise, stage 1 corresponds to the phase of crop production which is combination of different steps that include land preparation, fertilisation, sowing, irrigation, application of pesticides and harvest. The main inputs and outputs of this stage are the applied fertilisers, water, pesticides and machinery and, the released emissions and the disposal of waste produced throughout the whole process (Figure 48).

Furthermore, stage 2 is defined by the pyrolysis process which is composed of the pre-treatment and the pyrolysis process itself. In this manner, the inputs of this phase correspond to the respective biomass, the chemicals utilised in the process, the pyrolysis plant and the type of resource used to supply energy to the plant. The outputs are the emissions released after the process, the disposal of waste generated and the end-product (biochar) obtained (Figure 48).

Finally, stage 3 comprehends the biochar (end product) storage and transportation where vehicles with their respective fuels are the principal inputs and the outputs correspond to their emissions. During this phase, biochar is transported to the agricultural land where it will be integrated into the soil, stage 4 (Figure 48).

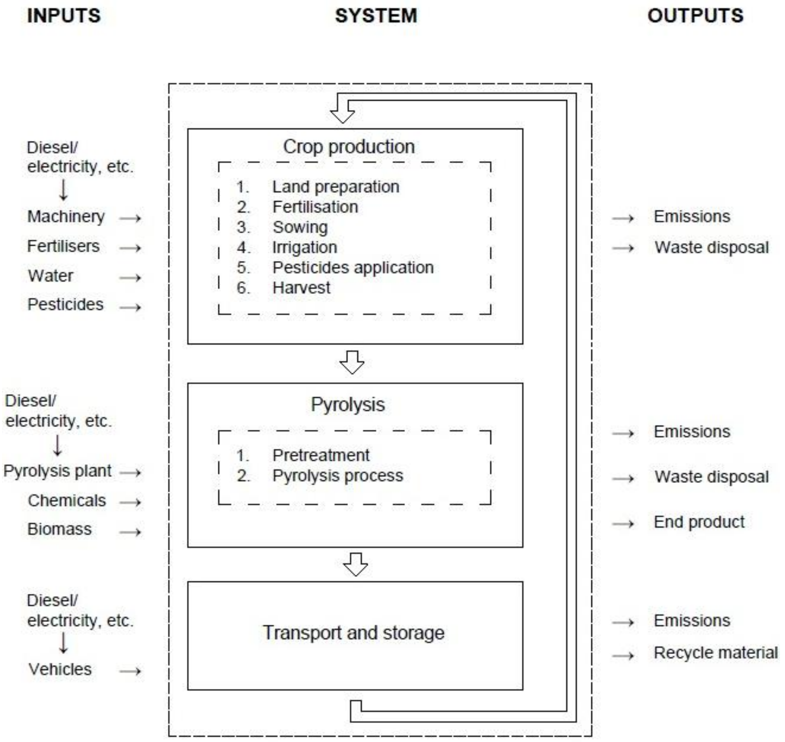


Figure 48. System boundaries of biochar production and application for an LCA.

4.1.1.3. Functional unit

The chosen functional unit should quantify the significant properties and the performance of the system [*38*], relating the LCA results to this same selected function [*41*].

In this case, a mass-based functional unit is defined for the LCA of both corn stover and wheat straw biochar. Considering that the performance of the system is studied by its end product, the functional unit of both cases corresponds to 1 tonne of biochar. Therefore, the results with respect to the environmental impacts and their respective areas of protection will be assessed in reference to the production of 1 tonne of biochar.

4.1.1.4. Allocation

The allocation method used in the stages in which agriculture is implicated corresponds to an economic allocation which distributes the value of the environmental impacts of each product in respect to its economic value [*42*]. This method is applied through Ecoinvent [48] and Agri-footprint [49] which are life cycle inventory (LCI) databases for the agriculture and food sector.

However, the rest of inputs and outputs which are not a product of the agricultural process are excluded of using an allocation method. This implies that there is no allocation utilised and these products or systems take the all the environmental burden [*42*].

4.1.2. Inventory analysis

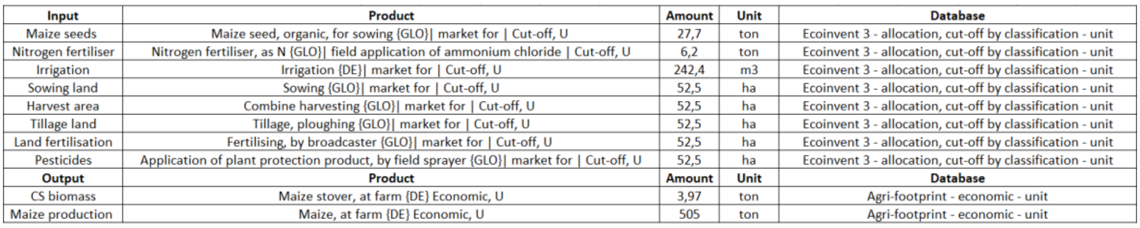
The Life Cycle Inventory (LCI) of this Life Cycle Assessment (LCA) has been divided in the four stages of the life cycle of biochar which are previously described in section 4.1.1.2. System boundaries.

The inventory analysis recollects the data of the production of 1 tonne of biochar defined in section 3. Data summary. The reason for establishing this data in respect of this mentioned value is that 1 tonne of biochar corresponds to the functional unit of the Life Cycle Assessment (LCA) developed in this current project.

4.1.2.1. Crop production

4.1.2.1.1. Corn stover

Table 20 represents the inputs and the outputs which are involved in the stage of corn production that are also illustrated in Table 12. The inputs in this phase correspond to the different processes and products that are applied to the land and the crop in order to obtain corn and corn stover biomass as products (outputs).

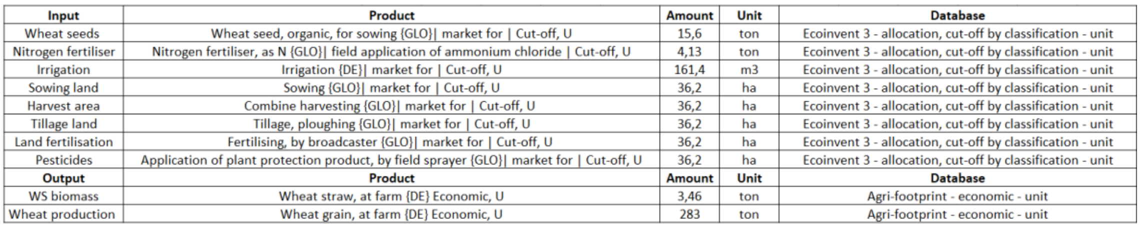


Input	Product	Amount	Unit	Database
Maize seeds	Maize seed, organic, for sowing {GLO}| market for | Cut-off, U	27,7	ton	Ecoinvent 3 - allocation, cut-off by classification - unit
Nitrogen fertiliser	Nitrogen fertiliser, as N {GLO}| field application of ammonium chloride | Cut-off, U	6,2	ton	Ecoinvent 3 - allocation, cut-off by classification - unit
Irrigation	Irrigation {DE}| market for | Cut-off, U	242,4	m3	Ecoinvent 3 - allocation, cut-off by classification - unit
Sowing land	Sowing {GLO}| market for | Cut-off, U	52,5	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Harvest area	Combine harvesting {GLO}| market for | Cut-off, U	52,5	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Tillage land	Tillage, ploughing {GLO}| market for | Cut-off, U	52,5	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Land fertilisation	Fertilising, by broadcaster {GLO}| market for | Cut-off, U	52,5	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Pesticides	Application of plant protection product, by field sprayer {GLO}| market for | Cut-off, U	52,5	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Output	**Product**	**Amount**	**Unit**	**Database**
CS biomass	Maize stover, at farm {DE} Economic, U	3,97	ton	Agri-footprint - economic - unit
Maize production	Maize, at farm {DE} Economic, U	505	ton	Agri-footprint - economic - unit

Table 20.Inventory data of CS biomass production applied in SimaPro.

4.1.2.1.2. Wheat straw

Similarly, in this case, Table 21 presents the inputs and the outputs which are implicated in the wheat production that correspond to the data represented in Table 17. Equally to the previous case, the inputs are the components and the processes involved in the stage of crop production while the outputs are the products which are obtained after this phase, wheat grain and wheat straw biomass.



Input	Product	Amount	Unit	Database
Wheat seeds	Wheat seed, organic, for sowing {GLO}| market for | Cut-off, U	15,6	ton	Ecoinvent 3 - allocation, cut-off by classification - unit
Nitrogen fertiliser	Nitrogen fertiliser, as N {GLO}| field application of ammonium chloride | Cut-off, U	4,13	ton	Ecoinvent 3 - allocation, cut-off by classification - unit
Irrigation	Irrigation {DE}| market for | Cut-off, U	161,4	m3	Ecoinvent 3 - allocation, cut-off by classification - unit
Sowing land	Sowing {GLO}| market for | Cut-off, U	36,2	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Harvest area	Combine harvesting {GLO}| market for | Cut-off, U	36,2	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Tillage land	Tillage, ploughing {GLO}| market for | Cut-off, U	36,2	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Land fertilisation	Fertilising, by broadcaster {GLO}| market for | Cut-off, U	36,2	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Pesticides	Application of plant protection product, by field sprayer {GLO}| market for | Cut-off, U	36,2	ha	Ecoinvent 3 - allocation, cut-off by classification - unit
Output	**Product**	**Amount**	**Unit**	**Database**
WS biomass	Wheat straw, at farm {DE} Economic, U	3,46	ton	Agri-footprint - economic - unit
Wheat production	Wheat grain, at farm {DE} Economic, U	283	ton	Agri-footprint - economic - unit

Table 21.Inventory data of WS biomass production applied in SimaPro.

4.1.2.2. Pyrolysis

Regarding the stage of pyrolysis of the Life Cycle Assessment, different aspects are taken into consideration. Due to the limited database found in the software of SimaPro, there has not been a possibility to access to references of products such as pyrolysis facilities or processes. Therefore, by editing references of similar systems these excluded inputs are defined (Table 22, Table 24 and Table 26).

Table 22 indicates all the inputs related to the technosphere and the ecosphere that are implicated in the construction of the pyrolysis facility. Likewise, this data is established following the construction characteristics of the pyrolysis plant that are illustrated in Table 1.

The land occupation corresponds to the area which the industrial building is occupying, while the land transformation is the area that is transformed to place the pyrolysis plant. The total section that covers the pyrolysis plant is defined through the technical data of the model BST-05 Pro from Beston Group [35], as it was argued in section 2.2.2. Pyrolysis.

However, the data related to the industrial building, in which the pyrolysis facility is located, is estimated considering that the dimensions of the building (20x18 m) are an increment of 10 m in length and width in respect of the dimensions of the pyrolysis facility (10x8 m). Therefore, as it is represented in Table 1, the structured is constructed with a number of 16 pillars and 16 beams made of steel which need reinforcement and foundation for its stability.

Moreover, it is reckoned that the plant is supplied with electricity generated with the biogas produced by the pyrolysis process (Table 22). Equally to the value of the area of the pyrolysis plant, the energy consumption of the plant is defined by the technical data of the model BST-05 Pro from Beston Group [35].

Pyrolysis plant	Pyrolysis facility {DE}| construction | Cut-off, U	1	p
Input (ecosphere)	**Product**	**Amount**	**Unit**
Land occupation	Occupation, industrial area	360	m2
Land occupation	Occupation, construction site	360	m2
Land transformation	Transformation, from unspecified	80	m2
Land transformation	Transformation, to industrial area	80	m2
Input (technosphere)	**Product**	**Amount**	**Unit**
Foundation	Cement, unspecified {CH}|market for cement, unspecified|Cut-off, U	11520	kg
Reinforcement	Reinforcing steel {GLO}|market for|Cut-off, U	104	kg
Structural steel	Steel, chronium steel 18/8, hot rolled {GLO}|market for|Cut-off, U	6752	kg
Energy consumption	Electricity, biomass, at power plant/US	31	kWh

Table 22.Inventory data of the pyrolysis plant applied in SimaPro.

4.1.2.2.1. Corn stover

Table 23 shows the corresponding inputs and outputs to the pyrolysis stage of the life cycle of corn stover biochar. Therefore, as it is represented in Table 23, the construction of the pyrolysis facility, the pre-treatment of corn stover biomass previous to the pyrolysis process and the pyrolysis process itself are the inputs in this phase of the Life Cycle Assessment (LCA).

Likewise, corn stover biochar and bio-oil are the main outputs (Table 23) along with non-condensable gases (Table 24). Furthermore, each product in the inventory data of the pyrolysis phase corresponds with the values represented in section 3. Data summary, Table 13.

The pre-treatment process consists in the removal of water content from corn stover biomass through a drying procedure. This product as well as the produced corn stover biochar and bio-oil are established in the software of SimaPro in reference to similar products found in the database.

In the case of bio-oil, it is clear that used vegetable cooking oil is different to this component (Table 23). However, the treatment of both of these products for their reuse and application in other technologies presents a similarity. Therefore, this resemblance has been the reason for utilising this product as a reference in order to execute the Life Cycle Impact Assessment (LCIA).

Contrary to the case of bio-oil, corn stover biochar is defined in SimaPro by editing a carbon sequestration component and simply changing its rate of carbon sequestration (Table 23).

Input	Product	Amount	Unit	Database
Pyrolysis plant	Pyrolysis facility {DE}| construction | Cut-off, U	1	p	CS biochar production
CS pyrolysis process	Pyrolysis process, corn stover {DE}| process-biomass | Cut-off, U	1	ton	CS biochar production
Pre-treatment	Drying of maize straw and whole-plant {GLO}| market for | Cut-off, U	3719	l	Ecoinvent 3 - allocation, cut-off by classification - unit
Output	**Product**	**Amount**	**Unit**	**Database**
CS biochar	Corn stover biochar (3.67 tonnes CO2/kg biochar)	1	ton	CS biochar production
Bio-oil use	Used vegetable cooking oil {GLO}| market for | Cut-off, U	1,42	ton	Ecoinvent 3 - allocation, cut-off by classification - unit

Table 23.Inventory data of CS biochar production (pyrolysis) applied in SimaPro.

The pyrolysis process of corn stover biomass is outlined by inputs that come from the technosphere and outputs that are released to the ecosphere (Table 24). Likewise, corn stover biomass obtained through corn production and nitrogen gas correspond with the products applied in the pyrolysis process (i.e., the inputs) while the non-condensable gases represented in Table 24 are the products released to the ecosphere (i.e., the outputs).

CS pyrolysis process	Pyrolysis process, corn stover {DE}| process-biomass | Cut-off, U	1	ton
Input (technosphere)	**Product**	**Amount**	**Unit**
CS biomass	Maize stover, at farm {DE} Economic, U	3,97	ton
Nitrogen gas	Nitrogen, gas {RER}|market for|Cut-off, U	0,59	ton
Output (ecosphere)	**Product**	**Amount**	**Unit**
CO2	Carbon dioxide	0,91	ton
CO	Carbon monoxide	0,09	ton
CH4	Methane	0,08	ton
C3H6	Propene	0,03	ton
H2	Hydrogen	0,38	ton

Table 24.Inventory data of CS pyrolysis process applied in SimaPro.

4.1.2.2.2. Wheat straw

In the same manner as the previous case, Table 25 illustrates the different inputs and outputs encountered in the pyrolysis stage of the LCA. The inventory data of the pyrolysis facility is defined in Table 22 as it was formerly described.

Likewise, as it was explained for the case of the pyrolysis of corn stover biomass, the pre-treatment process previous to the pyrolysis process and the bio-oil resulting from the pyrolysis itself are established in SimaPro by selecting a similar product found in its database (Table 25). Moreover, wheat straw biochar is determined alike corn stover biochar.

Input	Product	Amount	Unit	Database
Pyrolysis plant	Pyrolysis facility {DE}| construction | Cut-off, U	1	p	WS biochar production
WS pyrolysis process	Pyrolysis process, wheat straw {DE}| process-biomass | Cut-off, U	1	ton	WS biochar production
Pre-treatment	Drying of bread grain, seed and legumes {GLO}| market for | Cut-off, U	3177	l	Ecoinvent 3 - allocation, cut-off by classification - unit
Output	**Product**	**Amount**	**Unit**	**Database**
WS biochar	Wheat straw biochar (3.67 tonnes CO2/kg biochar)	1	ton	WS biochar production
Bio-oil use	Used vegetable cooking oil {GLO}| market for | Cut-off, U	1,7	ton	Ecoinvent 3 - allocation, cut-off by classification - unit

Table 25.Inventory data of WS biochar production (pyrolysis) applied in SimaPro.

Furthermore, the pyrolysis process input presents sub-inputs which correspond to the introduced wheat straw biomass and helium in the pyrolysis plant. Additionally, this product is also defined by sub-outputs which are the non-condensable gases released to the ecosphere along with the production of wheat straw biochar (Table 26).

WS pyrolysis process	Pyrolysis process, wheat straw {DE}| process-biomass | Cut-off, U	1	ton
Input (technosphere)	**Product**	**Amount**	**Unit**
WS biomass	Wheat straw, at farm {DE} Economic, U	3,46	ton
Helium	Helium {GLO}|market for|Cut-off, U	0,1	ton
Output (ecosphere)	**Product**	**Amount**	**Unit**
CO2	Carbon dioxide	0,34	ton
CO	Carbon monoxide	0,19	ton
CH4	Methane	0,06	ton
C3H6	Propene	0,003	ton
H2	Hydrogen	0,06	ton

Table 26.Inventory data of WS pyrolysis process applied in SimaPro.

4.1.2.3. Transport and storage

The LCI of the transport and storage stage of the life cycle of biochar is almost identical for both cases, the transportation of corn stover and wheat straw biochar, being the only difference the type of product that is being stored and transported (Table 27 and Table 28).

Thus, as it was described in section 2.2.3. Transport and storage, national transportation by lorry and its diesel consumption are defined as inputs of this phase of the life cycle. The performance of the lorry presents a value of 1 tkm as the LCA is executed in reference to the production of 1 tonne of biochar, i.e., the functional unit (Table 27 and Table 28).

Moreover, as there is no database that allows to establish corn stover and wheat straw biochar at storage as an input, these products are applied in SimaPro as corn and wheat obtained from crop production, dried and stored (Table 27 and Table 28).

4.1.2.3.1. Corn stover

Input	Product	Amount	Unit	Database
Transport	Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, U	1	tkm	Ecoinvent 3 - allocation, cut-off by classification - unit
Fuel	Diesel {Europe without Switzerland}| market for | Cut-off, U	0,26	ton	Ecoinvent 3 - allocation, cut-off by classification - unit
CS and corn storage	Maize, dried, at storage {DE} Economic, U	1	ton	Agri-footprint - economic - unit

Table 27.Inventory data of CS biochar transportation (SimaPro).

4.1.2.3.2. Wheat straw

Input	Product	Amount	Unit	Database
Transport	Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, U	1	tkm	Ecoinvent 3 - allocation, cut-off by classification - unit
Fuel	Diesel {Europe without Switzerland}| market for | Cut-off, U	0,26	ton	Ecoinvent 3 - allocation, cut-off by classification - unit
WS and wheat grain storage	Wheat grain, dried, at storage {DE} Economic, U	1	ton	Agri-footprint - economic - unit

Table 28.Inventory data of WS biochar transportation (SimaPro).

4.1.2.4. Application of biochar in agriculture

This stage of the LCA of biochar presents the same inputs determined for the stage of crop production (Table 20 and Table 21). However, in this phase of the life cycle biochar is also established as an input in the system (Table 29 and Table 30).

Both corn stover and wheat straw biochar are defined by the same rate of carbon sequestration as it was previously explained through function (6). However, as the quantity of C is different for each type of biochar (Table 13 and Table 18), the total carbon sequestration in the long-term would be slightly dissimilar (Table 14 and Table 19).

4.1.2.4.1. Corn stover

Input	Product	Amount	Unit	Database
CS biochar	Corn stover biochar (3.67 tonnes CO2/kg biochar)	1	ton	CS biochar production

Table 29.Inventory data of CS biochar application in agriculture (SimaPro).

4.1.2.4.2. Wheat straw

Input	Product	Amount	Unit	Database
WS biochar	Wheat straw biochar (3.67 tonnes CO2/kg biochar)	1	ton	WS biochar production

Table 30.Inventory data of WS biochar application in agriculture (SimaPro).

4.1.3. Impact assessment

The LCIA relates the environmental aspects (i.e., raw materials, emissions, etc.), which result from the LCI, to their corresponding environmental impacts. These impacts are classified by mid-point impact categories that are associated to their respective areas of protection, damage or end-point categories (Figure 49).

The LCIA of both corn stover and wheat straw biochar is executed in SimaPro by employing the IMPACT World+ Endpoint V1.02 methodology. This method analyses the environmental impacts related to the impact categories (mid-point categories) which affect the human health and the ecosystem quality (damage or end-point categories). Therefore, the studied impact categories range from human toxicity down to land occupation (Figure 49) [50].

Furthermore, in order to support the interpretation of the results, the environmental impacts of each stage of the LCA are established by utilising the normalisation method. Thus, the results are represented in proportion to a reference value of the annual elementary flows of the certain region or country indicated for each inventory data. This geographic location is defined by abbreviations which are written in brackets, e.g., {DE} represents Germany [51].

Therefore, as it was illustrated in section 4.1.2. Inventory analysis, the majority of the inventory data is established in reference to Germany yearly elementary flows. However, due to the limitations of database of this country in SimaPro, several inputs and outputs present a global {GLO} or European {RER} reference [51].

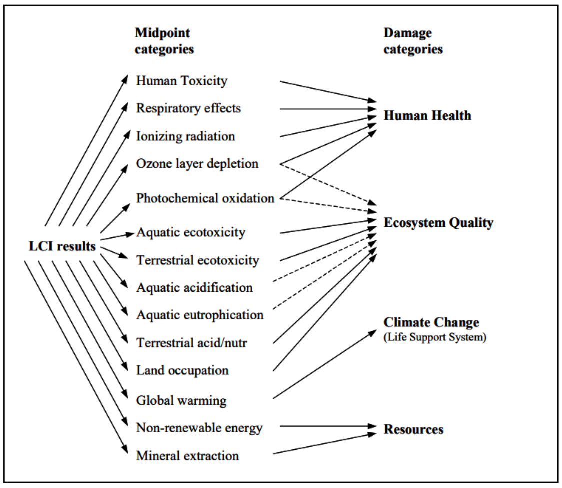


Figure 49. Impact categories and pathways covered by the IMPACT 2002+ methodology. [45]

4.1.3.1. Crop production

4.1.3.1.1. Corn stover

Figure 50 illustrates the most relevant environmental impacts in corn production which affect the ecosystem quality. Thus, as it is represented in this following graph, each of the products that contribute in this stage of the life cycle of corn stover biochar show a higher score of freshwater ecotoxicity in the long-term. Especially the maize, the maize seeds for sowing and the nitrogen fertilisers have a greater impact on the ecosystem quality by having a significant effect in freshwater ecotoxicity.

Additionally, the production of maize (corn) also indicates a considerable value in respect of the impact category “Land occupation, biodiversity” (Figure 50). This implies that corn production has a relevant effect on the ecosystem due to the use of the land for agricultural purposes that generate biodiversity losses [45].

Figure 51 manifests the most significant environmental impacts in human health. Likewise, as it is revealed in its corresponding graph, the impact category labelled as “Water availability, human health” corresponds to the main impact that affects this area of protection (end-point). Thus, there is a greater risk of depletion of freshwater resources that are consumed by the population [45].

Impacts on the ecosystem quality are slightly superior than impacts on human health (Figure 52). However, if this is specified for each product that is involved in the stage of crop production, this difference might differ. Thus, as it is illustrated in Figure 52, maize production distinguishes the damage to the ecosystem quality from the damage to human health. This product has a higher impact on the ecosystem while have less relevance.

Contrary to the of maize production, the maize seeds and the nitrogen fertilisers show a higher impact score for the damage category of human health as their environmental impacts of this area of protection are more significant for these products (Figure 52).

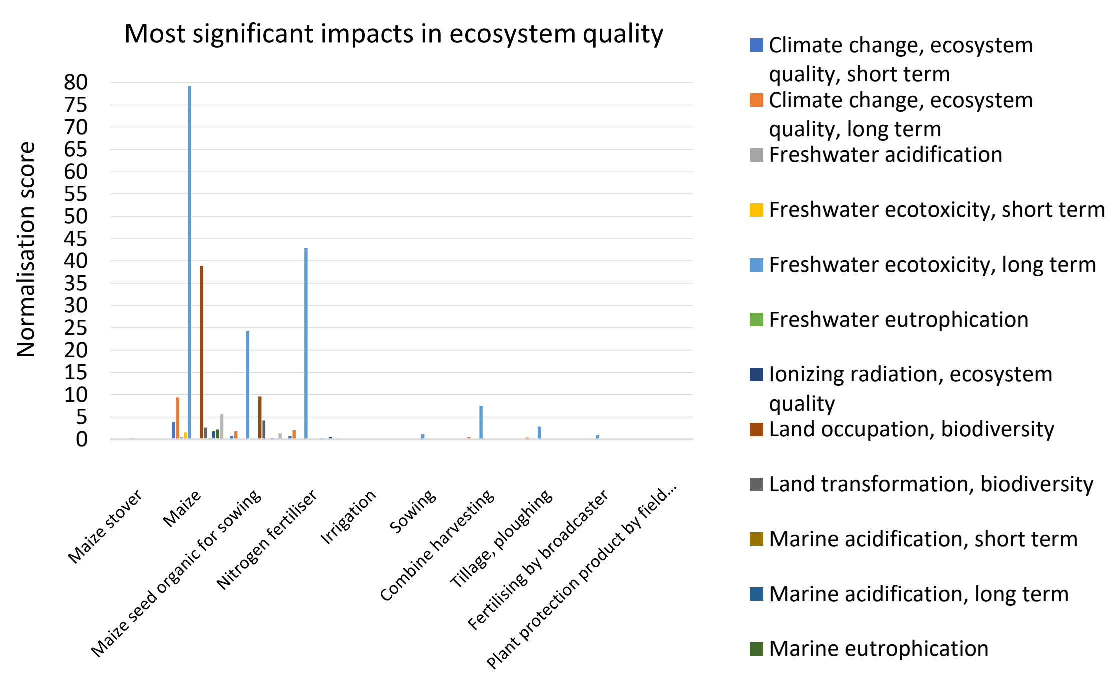


*Figure 50. Most significant impacts in ecosystem quality of corn stover production. **Source**: SimaPro*

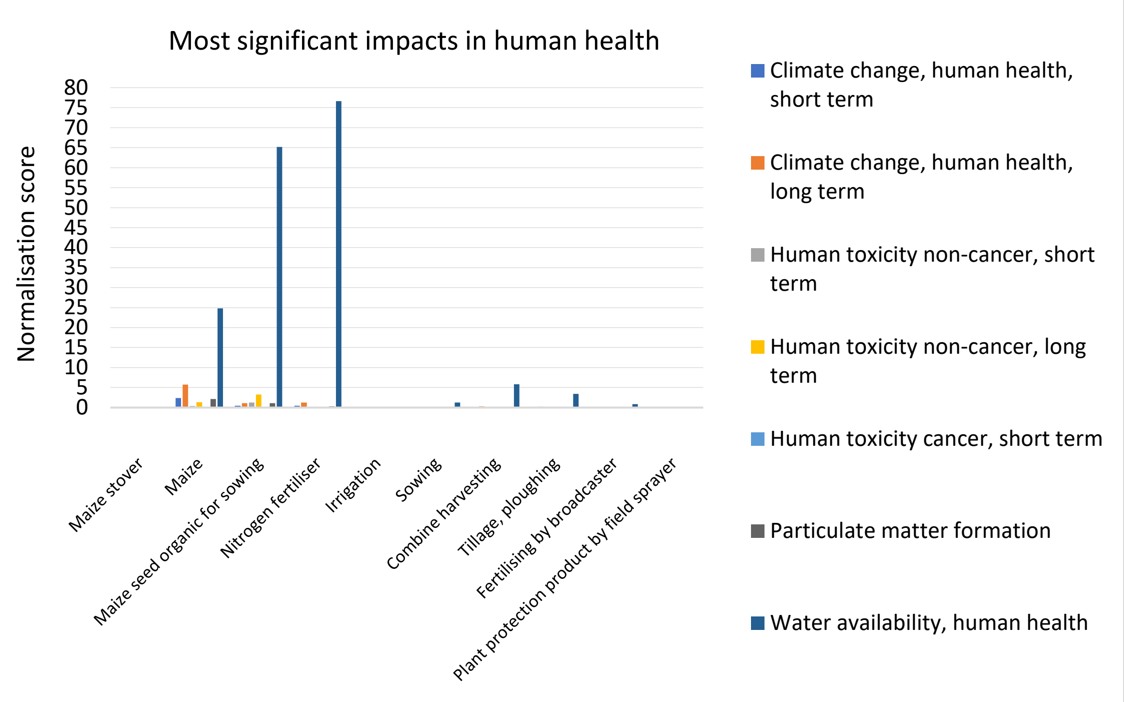


*Figure 51. Most significant impacts in human health of corn stover production. **Source**: SimaPro*

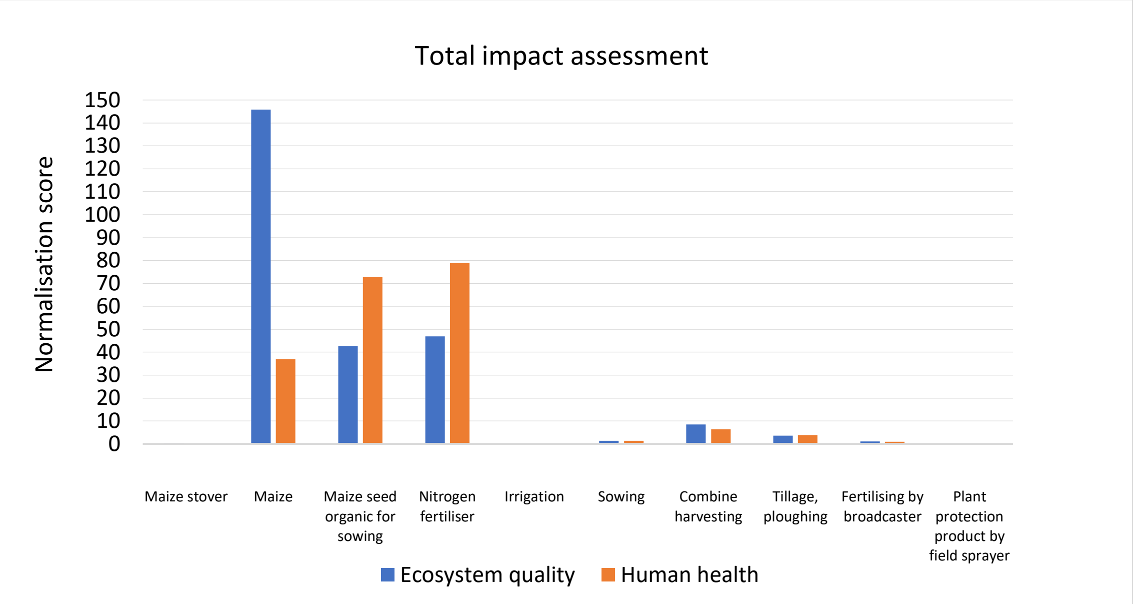


*Figure 52. Total impact assessment of corn stover production. **Source**: SimaPro*

4.1.3.1.2. Wheat straw

Figure 53 is a graphical representation of the most significant environmental impacts in wheat production that damage the ecosystem quality. In this case, land transformation presents the highest impact score among the others. Thus, as it is illustrated in Figure 53, applying wheat seeds for sowing has a greater effect on the biodiversity through land transformation in comparison with the previous case where the application of maize seeds showed superiority of long-term freshwater ecotoxicity and land occupation impacts over land transformation.

Furthermore, similarly to the previous case, Figure 53 manifests wheat grain, wheat seeds and nitrogen fertilisers as the products that constitute the highest score in environmental impacts. Long-term freshwater ecotoxicity related to wheat grain and nitrogen fertilisers also presents a relevance on the impact assessment of the ecosystem quality. However, due to the notable difference with the land transformation impact, this latter impact category appears to be less pertinent.

Additionally, Figure 54 illustrates the most relevant environmental impacts in human health. Equally to the study of corn production (Figure 51), there is a greater impact on water availability that affects human health. However, comparing both of these cases a slight dissimilarity is perceived. The normalisation score of water availability in corn production presents bigger values provoking a largest damage on human health.

Thus, contrasting Figure 55 with Figure 52 there can be seen that both situations manifest more damage to the ecosystem quality. Corn stover production through harvest presents its largest impact through the production and the market of corn while wheat seeds are the main promoters of environmental impacts in the ecosystem. Although wheat seeds represent the largest impact in this area of protection, the rest of components that are involved in wheat production show smaller damage values for the two areas of protection (Figure 55). Therefore, this means that the damage of this stage of the life cycle of wheat straw biochar relies on the application of wheat seeds in the agricultural soil.

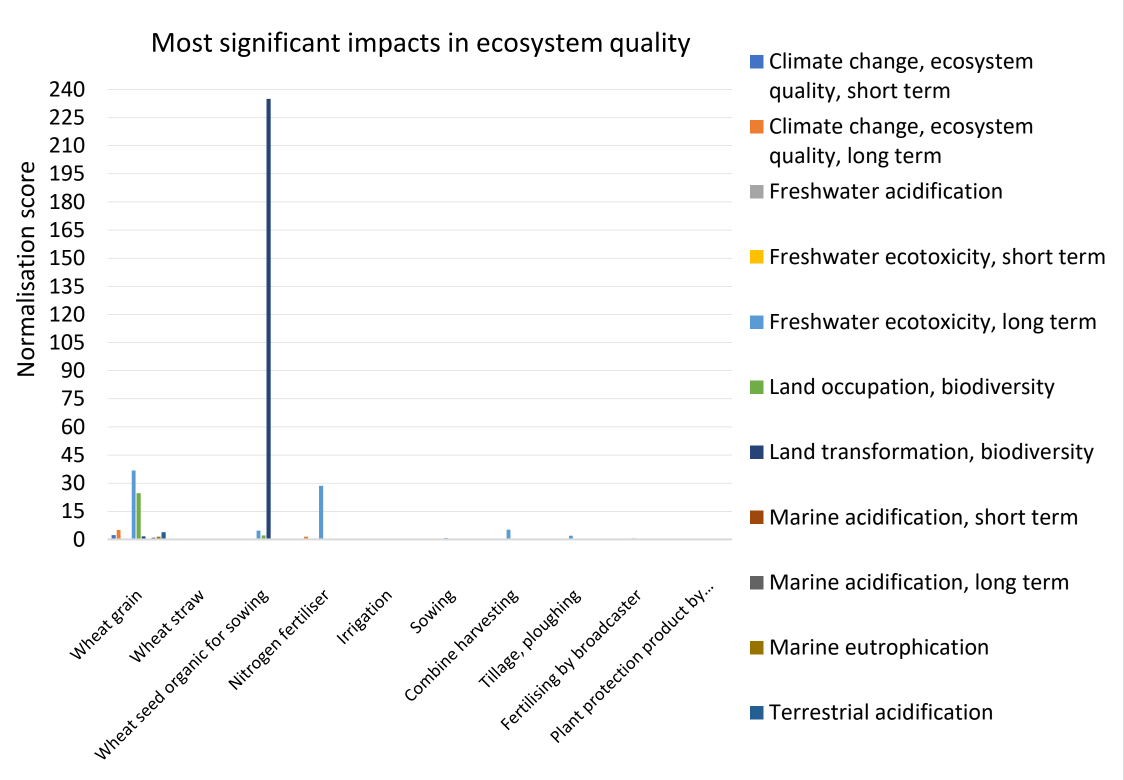


*Figure 53. Most significant impacts in ecosystem quality of wheat straw production. **Source**: SimaPro*

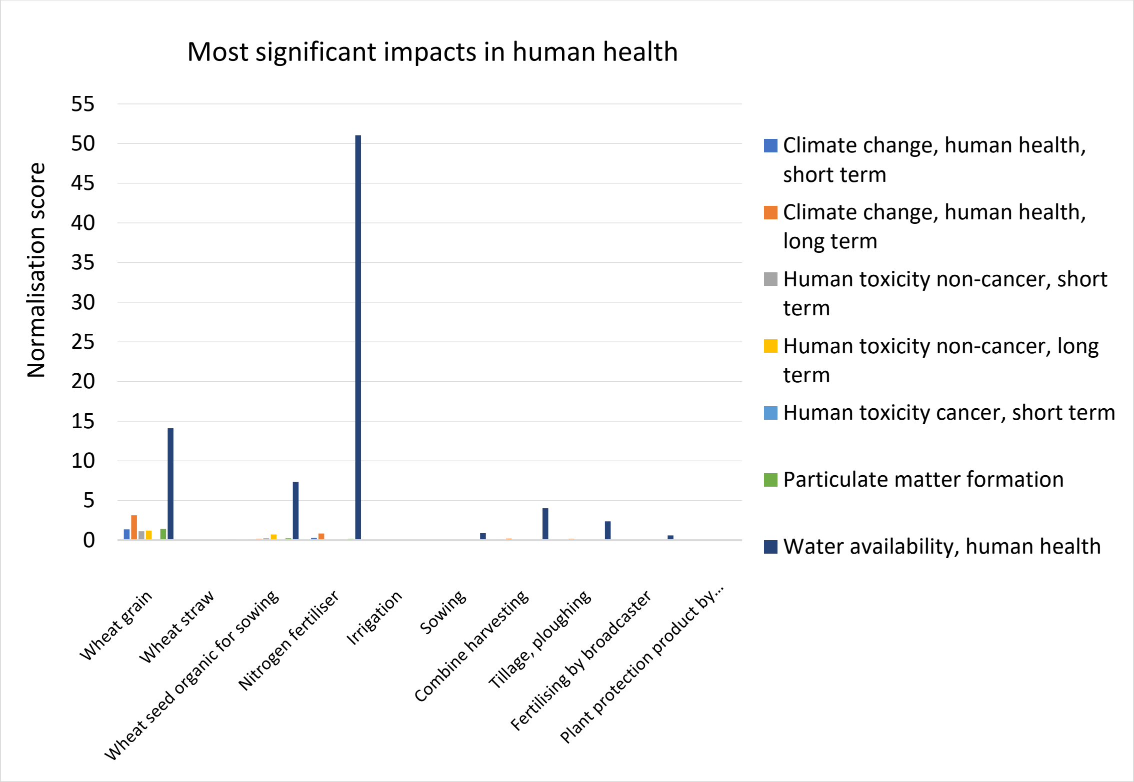


Figure 54. Most significant impacts in human health of wheat straw production. ***Source***: *SimaPro*

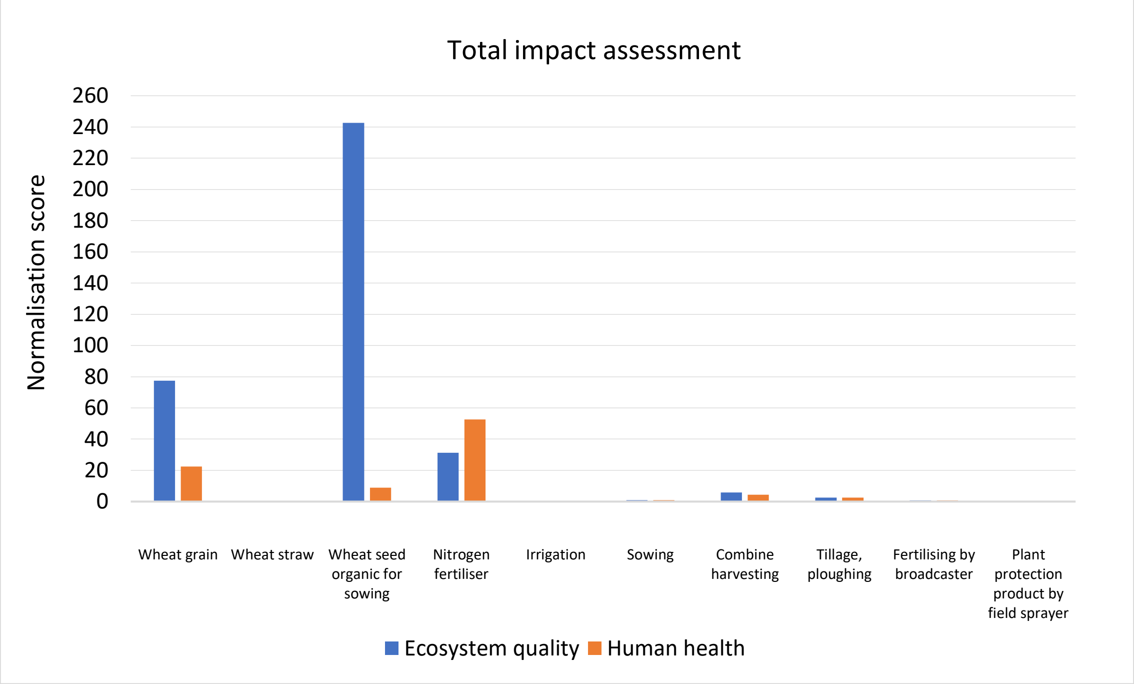


Figure 55. Total impact assessment of wheat straw production. ***Source***: *SimaPro*

4.1.3.2. Pyrolysis

The phase of pyrolysis in the life cycle of both corn stover and wheat straw biochar manifests quite similar results in respect of their impact assessment. Thus, as it is illustrated in Figure 56 and Figure 59, long-term freshwater ecotoxicity is the impact category with the highest value in the damage assessment of ecosystem quality. Likewise, a greater risk of producing this type of impact in the long-term is due to the construction of the pyrolysis facility.

Although the results of corn stover and wheat straw biomass pyrolysis are nearly identical, there is a slightly variation between the impact in the areas of protection produced by the pre-treatment process of corn stover and wheat straw biomass. Comparing Figure 56 with Figure 59 and Figure 57 with Figure 60, it can be seen that drying wheat biomass generates a higher impact in the ecosystem quality and the human health.

Furthermore, in this stage of the life cycle of both biochars, water availability is the most affected impact category that implies a risk to human health (Figure 57 with Figure 60). Equally to the damage assessment of ecosystem quality, the construction of the pyrolysis facility produces the largest damage to human health.

Additionally, these statements are also proven through a comparison between Figure 58 and Figure 61. A slight distinction is encountered for the pyrolysis and the pre-treatment process of the two biomasses. The pyrolysis and the pre-treatment process of wheat straw biomass have more impact, specially, on human health. Therefore, contrary to the stage of crop production, the phase of pyrolysis implies a major damage on human health over the damage on the ecosystem.

4.1.3.2.1. Corn stover

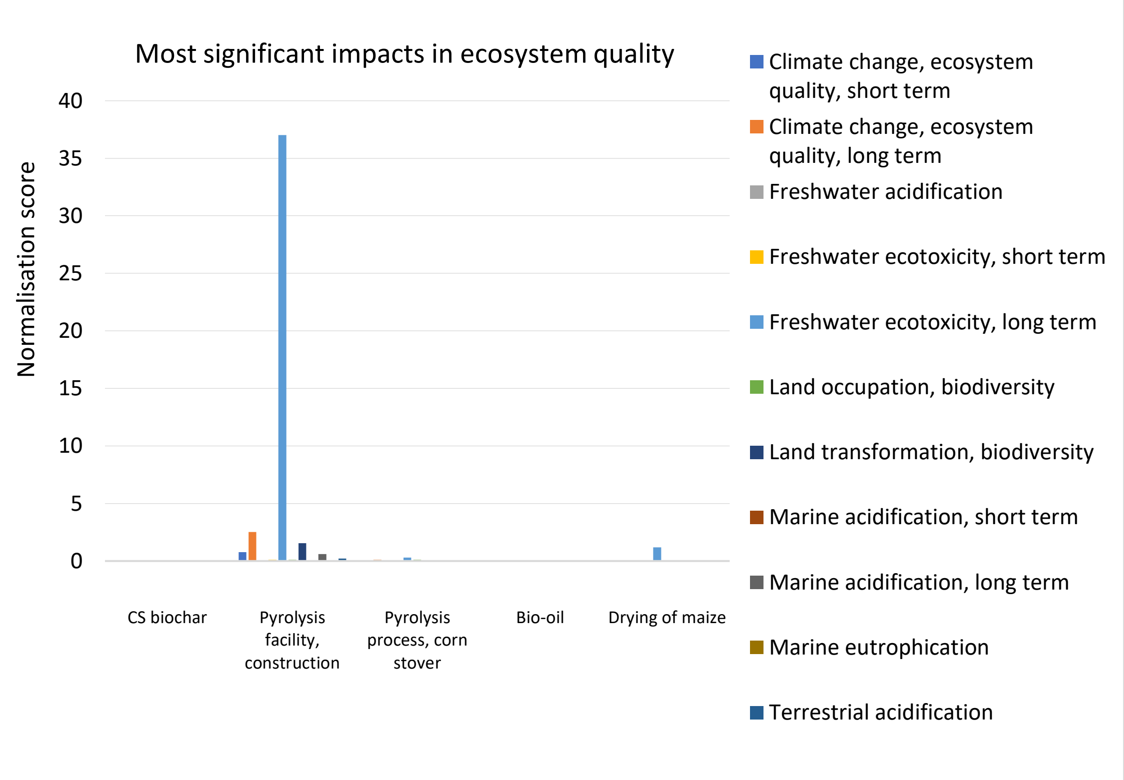


Figure 56. Most significant impacts in ecosystem quality of corn stover pyrolysis. ***Source****: SimaPro*

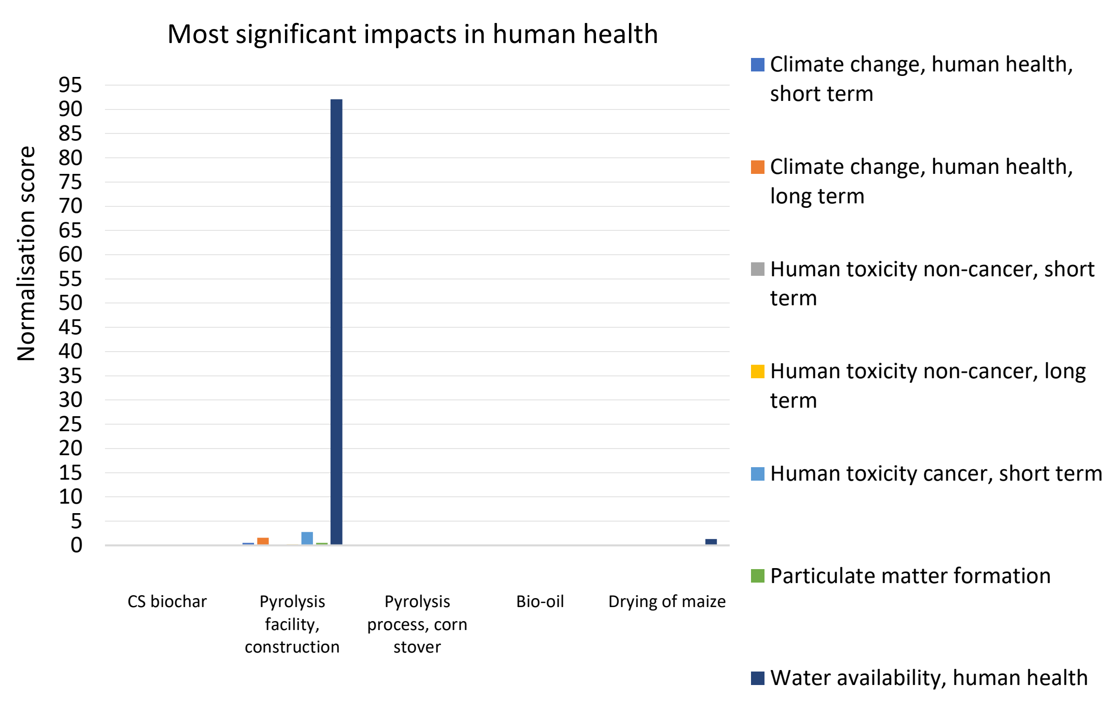


Figure 57. Most significant impacts in human health of corn stover pyrolysis. ***Source****: SimaPro*

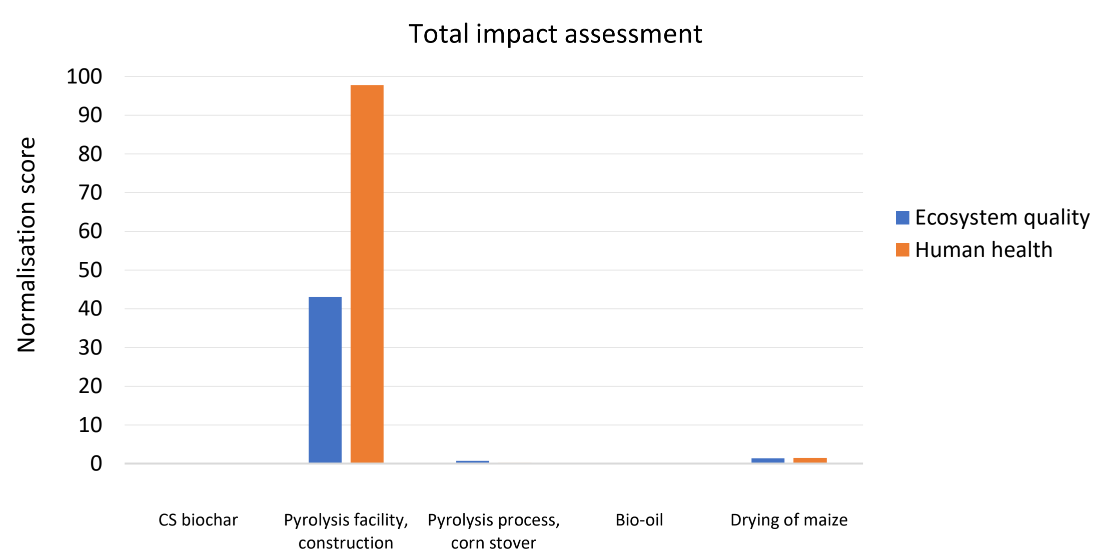


Figure 58. Total impact assessment of corn stover pyrolysis. ***Source****: SimaPro*

4.1.3.2.2. Wheat straw

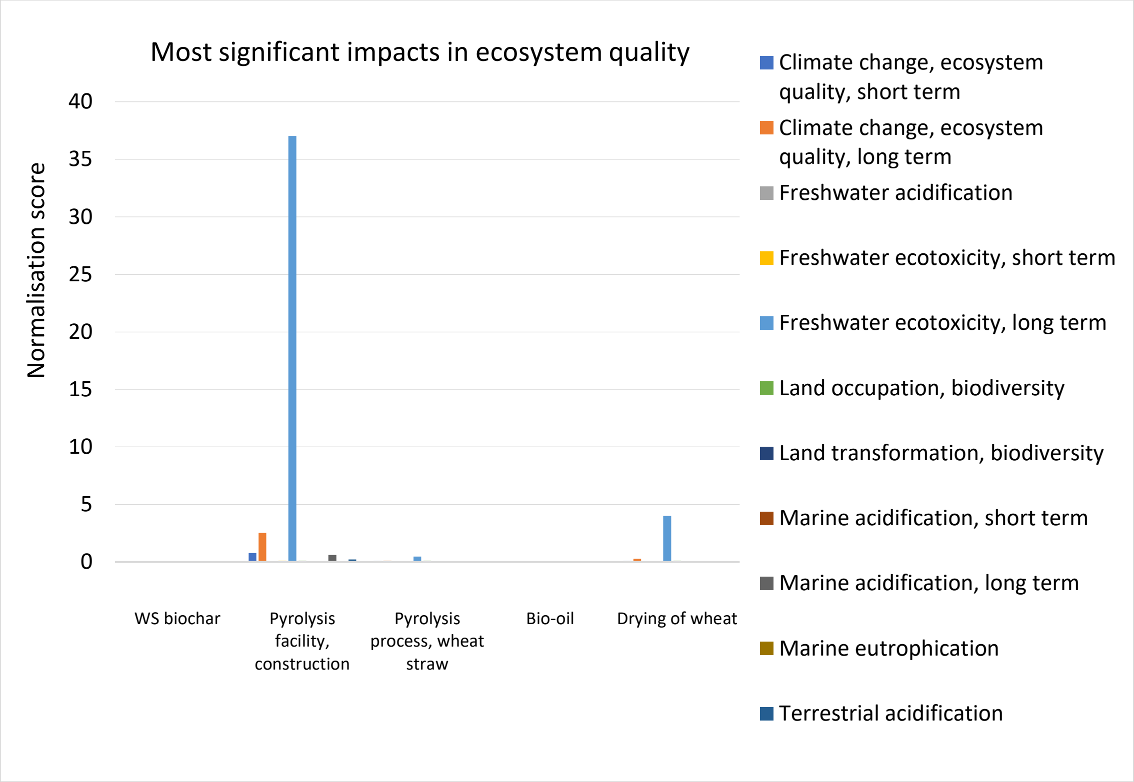


*Figure 59. Most significant impacts in ecosystem quality of wheat straw pyrolysis. **Source**: SimaPro*

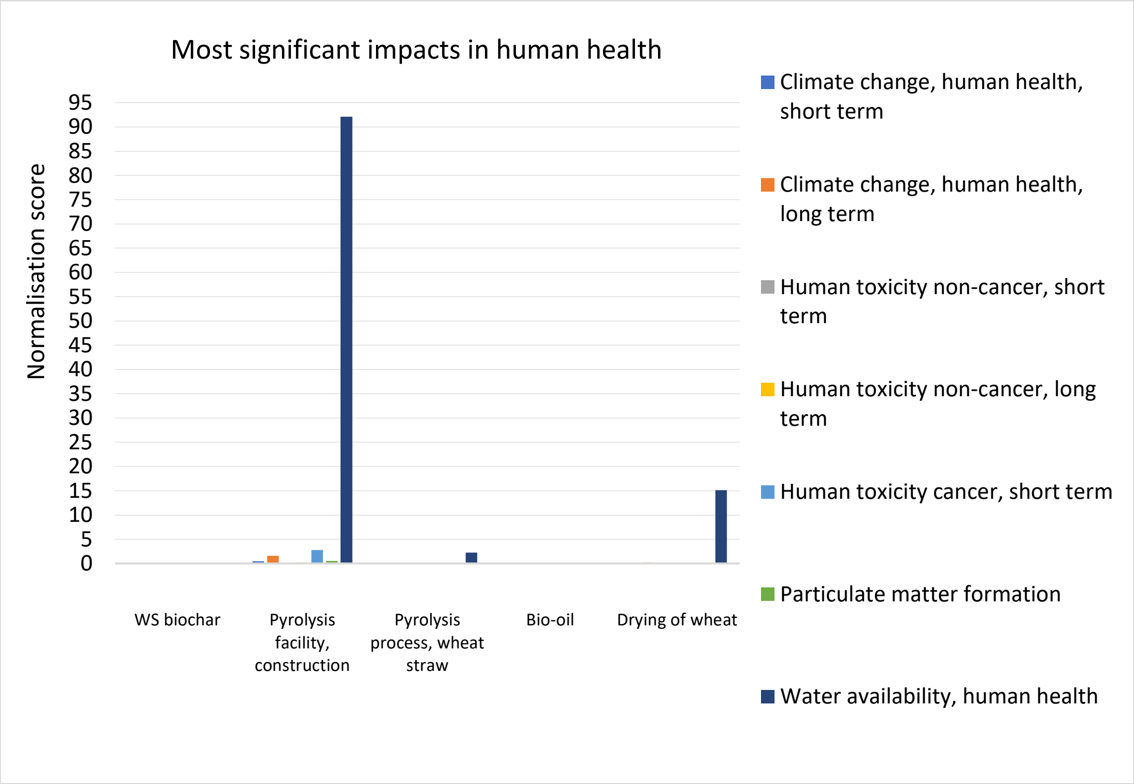


*Figure 60. Most significant impacts in human health of wheat straw pyrolysis. **Source**: SimaPro*

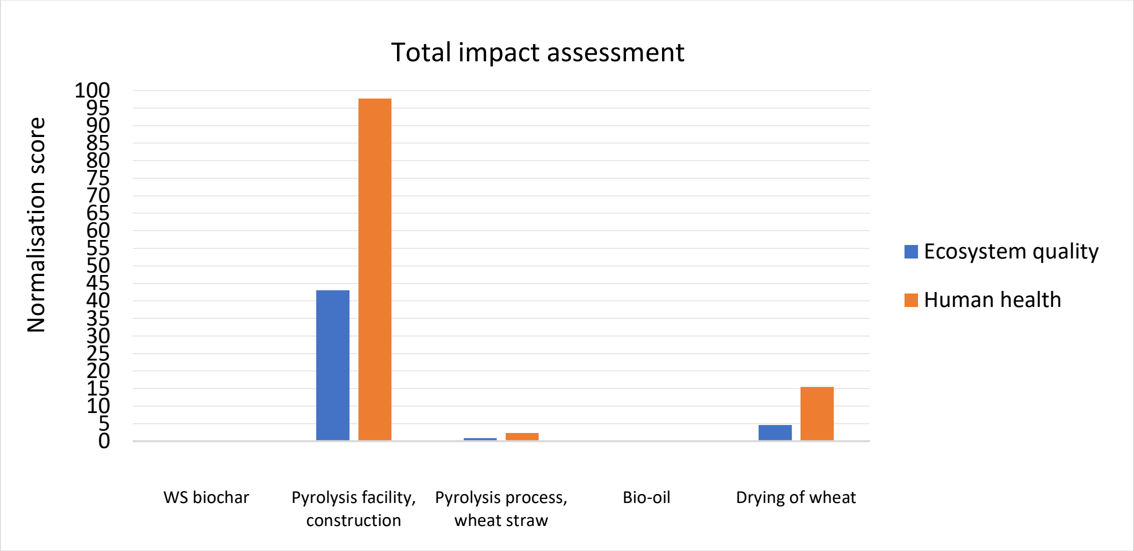


*Figure 61. Total impact assessment of wheat straw pyrolysis. **Source**: SimaPro*

4.1.3.3. Transport and storage

The impact assessment of the stage of transport and storage of biochar presents almost identical results for both types of biochar. Therefore, they have been illustrated by common graphs. Figure 62 reveals long-term freshwater ecotoxicity as the main impact that affects the ecosystem quality, followed by land occupation which provokes losses of biodiversity in the ecosystem. In this case, the component that presents the major quantity of environmental impacts corresponds with the phase of drying and storage of biochar.

However, as it is shown in Figure 63, diesel is the product which has the largest effect on water availability that diminishes the freshwater resources damaging human health.

Nevertheless, Figure 64 proves that the phase of drying and storage of biochar yet constitutes the biggest damage in this part of the life cycle. Moreover, there can be seen that the impact score of the distinct products in this step is significant smaller than in the previous stages.

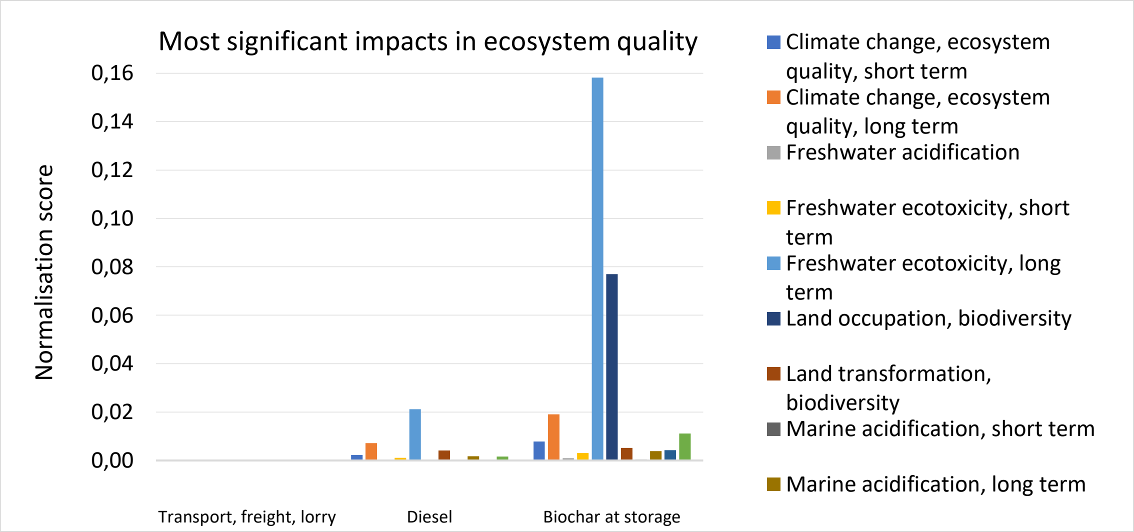


*Figure 62. Most significant impacts in ecosystem quality of biochar transportation. **Source**: SimaPro*

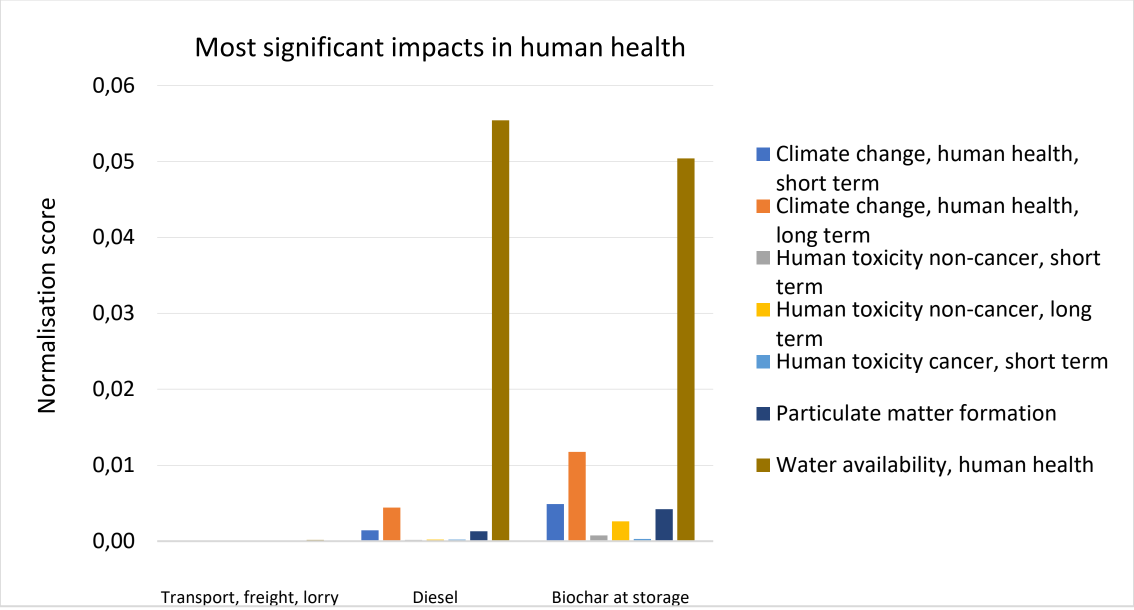


Figure 63. Most significant impacts in human health of biochar transportation. ***Source****: SimaPro*

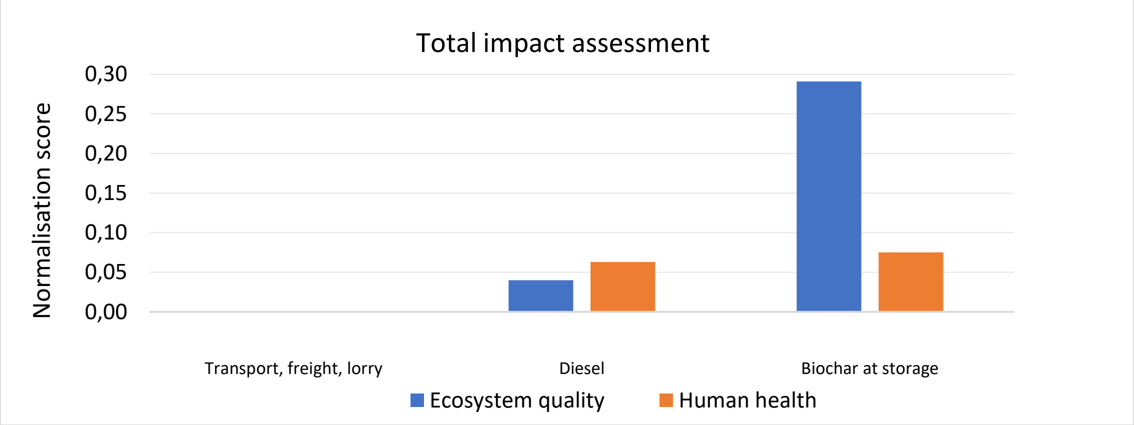


Figure 64. Total impact assessment of biochar transportation. ***Source****: SimaPro*

4.1.3.4. Application of biochar in agriculture

The step of the application of biochar in the agricultural soils is characterised by having the same inputs and outputs which are involved in crop production. The only distinction is the implementation of biochar as an input in the system. Thus, the following graphs are focused on manifesting the environmental impacts of biochar.

Figure 65 shows the diverse impact categories that affect the ecosystem quality. Therefore, as it appears in this graph, biochar contributes mainly to the climate change in the long-term altering the ecosystem. Likewise, Figure 66 defines the impact score of biochar in respect of the impact on climate change that influences human health.

Although biochar has an effect on both ecosystem quality and human health, Figure 67 demonstrates that applying biochar in agriculture produces an impact on the ecosystem that doubles the impact on the human health.

Furthermore, in difference with the rest of products of the LCA, biochar is the single one that presents negative values in the impact assessment. This implies that biochar avoids impacts that damage negatively the environment, i.e., negative scores in impact assessment indicates positive effects or improvements [52].

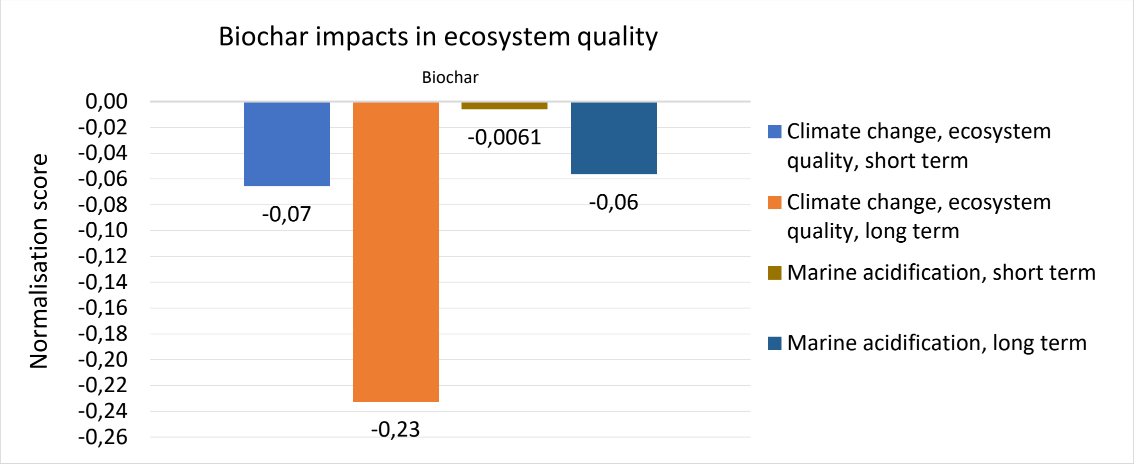


*Figure 65. Biochar impacts in ecosystem quality. **Source**: SimaPro*

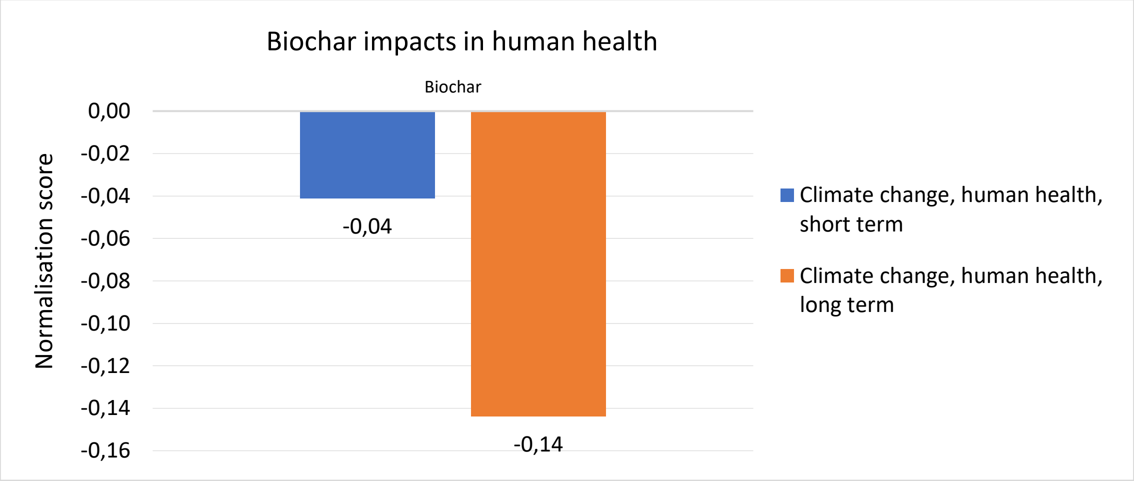


*Figure 66. Biochar impacts in human health. **Source**: SimaPro*

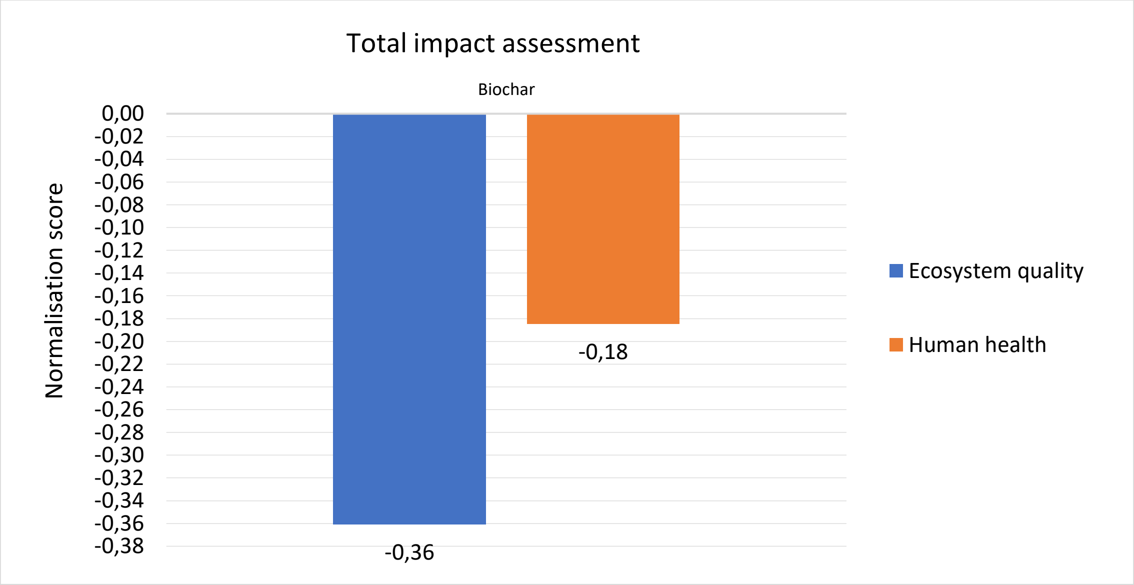


*Figure 67. Biochar total impact assessment. **Source**: SimaPro*

4.1.3.5. Life Cycle Impact Assessment

Finally, adding up the impact scores of each product, the total damage on the two different areas of protection is represented for the distinct stages of the LCA (Figure 68 and Figure 69).

In comparison to the rest of stages of the life cycle of corn stover biochar, crop production has a greater repercussion for the ecosystem and the human health (Figure 68). However, the phase respective to the transportation and the storage of this end-product is almost unnoticeable. Moreover, the pyrolysis procedure constitutes approximately a 50% of the damage on human health in respect of the maximum harm caused by the crop production. Yet it only presents about an 18% of damage score in the ecosystem quality.

In the matter of the LCIA of wheat straw biochar, crop production also produces a higher effect on the ecosystem quality with respect to the rest of stages of the life cycle. However, contrary to the occurrence of corn stover biochar, pyrolysis is the step that has a greater impact on human health in lieu of crop production (Figure 69). This is due to the bigger effect that the pyrolysis process has on the depletion of freshwater resources, i.e., water availability (Figure 54 and Figure 60).

Furthermore, as it is shown in both graphs (Figure 68 and Figure 69), the application of biochar in agriculture presents a similar impact score as the step of crop production. This is caused as the same procedures and products are considered for both stages of the life cycle. However, there is a slightly minor impact applying biochar in the agricultural land due to the avoidance of negative damages that biochar achieves [52].

4.1.3.5.1. Corn stover biochar

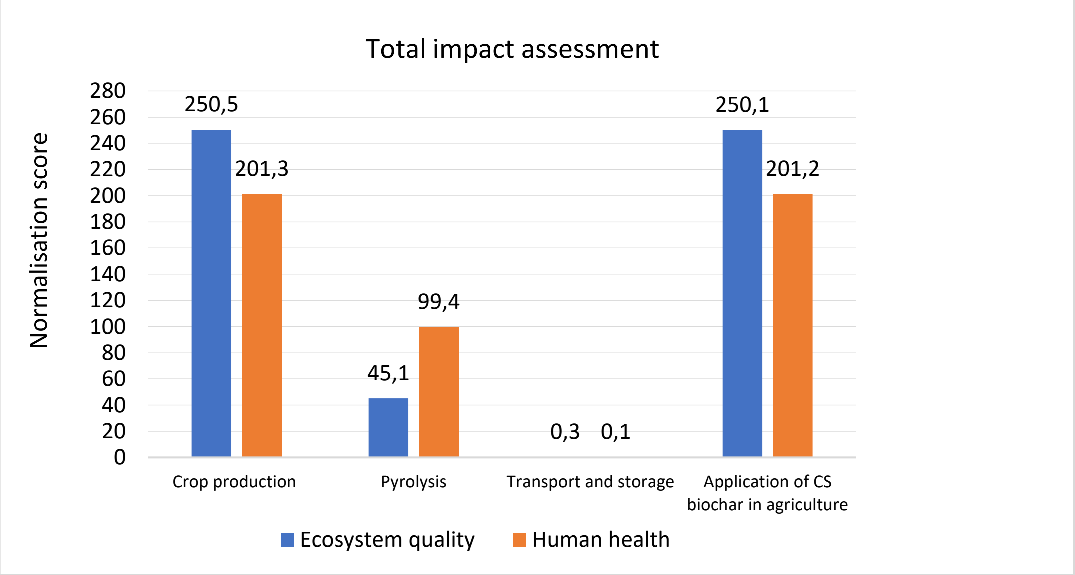


*Figure 68. LCIA of CS biochar. **Source**: SimaPro*

4.1.3.5.2. Wheat straw biochar

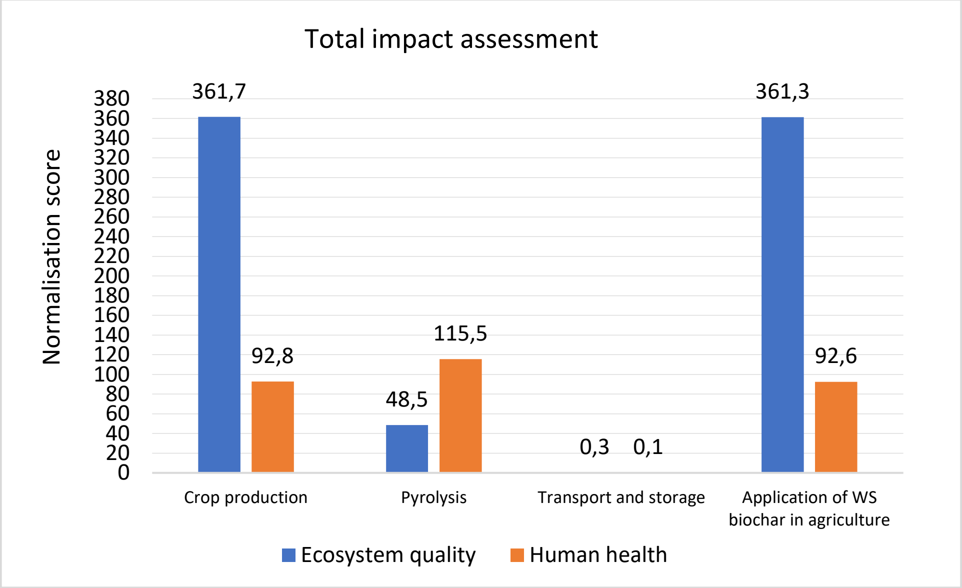


Figure 69. LCIA of CS biochar. ***Source****: SimaPro*

4.1.4. Interpretation

The significant issues of these LCAs are mainly generated through the collection of data that is applied in the LCI. The use of statistical data and experimental data from other research studies increases the uncertainties of the results. This is because the data is based on data collected by other scientific researchers or statistical institutions instead of data that is obtained directly from an experimental process in a laboratory. Thus, it gathers the previous errors produced in these referential scientific analyses and the errors generated in this current project.

The possible errors that may be founded in this project can be also produced by the conversion of the collected data to an equivalent data to 1 tonne of biochar and the limitations of the SimaPro database regarding these new technologies, biochar and pyrolysis. Consequently, these factors affect the LCIA, diminishing the precision of the final results.

A sensitivity analysis should be performed to detect these issues and thus, assessing the reliability of the final results so that necessary changes are implemented in the LCA phases. However, due to limitations, a basic completeness check is developed by comparing the results of this project to results from other studies.

The research review of LCA of biochar-to-soil systems done by Matustík, J. et al. (2020) also states that the main cause of impacts is the stage of crop production, followed by the pyrolysis system and the processing of feedstock [65]. However, the phase of transportation presents negligible results. Moreover, with respect to acidification, eutrophication and ecotoxicity impact categories, this research paper concurs that the agricultural processes are the main sources of negative impact. In addition, it also describes biochar as neutralizer of the impacts of crop production due to its positive impact on climate change.

5. Discussion

The outcomes of this project intended to help analyse and compare the significance of the environmental impacts generated through the life cycle of corn stover and wheat straw biochar. Thus, an impact assessment is executed for the distinct stages of the life cycle of 1 tonne of biochar which is selected as the functional unit for both LCAs for a proper comparison of their results.

Corn stover biochar presents higher impact results, for both ecosystem quality and human health, in the stage of crop production (Figure 68). The damage on the ecosystem quality is mainly provoked by the effects of long-term freshwater ecotoxicity and land occupation while in the case of human health, the depletion of water availability presents the greatest relevancy (Figure 50 and Figure 51).

On the contrary, although the stage of wheat production also shows greater impact results on the ecosystem quality in the life cycle of wheat straw biochar, the pyrolysis process is more harmful to human health (Figure 69). In the present case, the ecosystem quality is affected mainly by the land transformation that the application of wheat seeds in the soil produces and, the long-term freshwater ecotoxicity. Meanwhile, there is a major risk in human health due to the depletion of water resources generated by the step of pyrolysis.

Comparing the impact assessment of the two types of biochar, a difference is found between their values of damage on the two areas of protection. It is noticeable that the production of WS biochar represents a higher risk to the ecosystem while the life cycle of CS biochar is more harmful to human health. Thus, if a global impact score is considered, both cases present a similar risk with the only difference that each one of them affects in a bigger scale a distinct area of protection (Figure 68 and Figure 69).

Nevertheless, there is a slightly major difference between the total impact score in the ecosystem quality determined for both cases. Thus, although the total impact score in human health is similar to the case of CS biochar, it can be considered that wheat straw biochar generally can be more hazardous to the ecosystem.

Likewise, although the application of biochar in the agricultural soil constitutes a close positive effect for both cases (Figure 67), corn stover biochar achieves a rather larger long-term carbon sequestration than wheat straw biochar (Table 14 and Table 19). However, this is not completely certain as biochar inventory data has been collected from other research experimental studies and not directly from an executed laboratory experiment. Therefore, uncertainties can be found in the results diminishing the possibilities to come to a clear conclusion regarding carbon sequestration.

Thus, in order to reduce these uncertainties, it would be preferable to execute a real experiment in the laboratory and gather direct data from this process. In this manner, there would be a clearer result of the biochar characteristics which consequently, would improve the comparison between the two biochars.

6. Conclusion

The aim of this study was to perform a LCA model for the production of both corn stover and wheat straw biochar in order to analyse and compare the results of the environmental impacts produced in both cases and, their effect on the different areas of protection.

The results of the LCAs showed that each product presented a slight relevancy over the other, on a distinct damage category. Likewise, there was more risk to human health due to the production of corn stover biochar and a bit bigger risk to the ecosystem quality due to wheat straw biochar production.

Thus, the importance of the environmental impacts for both cases was quite similar. However, comparing the results of the two end-point categories, the total impact score in human health manifested less difference between the two biochar products. Therefore, the damage on ecosystem quality has been considered as one of the decisive factors to reach a conclusion.

The overall impact of the life cycle of wheat straw biochar and its superiority with respect to the ecosystem damage demonstrated that the life cycle of this product had more repercussion for the environment. However, the difference between both LCAs was not much significant. Thus, other factors such as the availability of the biomass had to be considered in the conclusion.

Wheat straw biomass yearly production in Germany was more abundant as approximately half of the field crops were utilised for wheat production. Therefore, a greater amount of biochar can be produced by wheat straw biomass pyrolysis which consequently, increase the availability and the application of biochar in agricultural soils.

In conclusion, it can be said that corn stover biochar is less harmful to the environment as the environmental impacts produced through its life cycle have less repercussion. Moreover, it presents a higher carbon content than wheat straw biochar which translates in more stability and long-term carbon sequestration. Therefore, applying it in the agricultural soil can be beneficial. However, wheat straw biomass is more available due to German crop production which augments the possibility to produce and apply wheat straw biochar to the soil of Saxony region.

Thus, depending on the purposes of biochar and considering the uncertainties due to the limitations founded in this project, it can be said that any of these biochars could be an adequate option to be applied in the agricultural soil.

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