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Environmental impact assessment of biochar in anaerobic digestate

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Abstract

Climate change and unsustainable crop production are among the most prominent environmental issues and viable solutions must be looked for. A circular economy approach by recycling biochar-digestate back to agriculture as a fertilizer can be one of the means for tackling these problems. This thesis presents a Gate-to-Cradle life cycle assessment (LCA) for the global warming potential (GWP) of biochar-amended digestate in agriculture compared to mineral fertilizer.

The LCA was performed as case a study for Lindum where digestate was obtained from The Magic Factory (TMF) and biochar from Lindum's facility. The biochar-to-digestate ratios of 0.07% w/w, 6.25% w/w, and 12.5% w/w were able to mitigate greenhouse gases (GHGs) by 88 kg CO_2-eq./daa (80%), 323 kg CO_2-eq./daa (296%), and 592 kg CO_2-eq./daa (542%), respectively. The two emission-mitigating keys were the reduced N_2O fluxes and the C storage from biochar and digestate. C storage counterbalanced other emissions such as spreading, transport, agricultural emissions, and pyrolysis resulting in total environmental benefits. One of the LCA hotspots is the amount of biochar applied, because of its significant contribution to C abatement and reduced N_2O fluxes. Another important thing emphasized in this thesis is the agricultural benefits of applying biochar to digestate such as nutrient retention and increased soil C.

Furthermore, this thesis exhibits clear results that biochar-amended digestate can serve benefits for the climate. In addition, biochar in digestate can achieve positive agricultural effects which are important for sustainable food production.

Preface

This thesis marks the end of my two-year master's program in Energy and Environmental Technology at the University of South-Eastern Norway. The thesis is submitted to the Faculty of Technology, Natural Sciences, and Maritime Sciences as a part of the final subject FMH606 and accounts for 30 credits.

The reason for writing this thesis is my bachelor's thesis, which was a part of my study in renewable energy at the University of Agder. The bachelor thesis concerned the effects of biochar in anaerobic digestion in terms of biogas production and methane yield, as well as stability issues during digestion. This master thesis also concerns biochar in anaerobic digestion but with a focus on the digestate and the environmental impact.

My motivation for doing this master thesis is my interest in circular economy and sustainable waste management. Anaerobic digestion is a viable solution for treating organic wastes with two products: renewable energy, biogas, and a sustainable fertilizer product, digestate. Today, the world is facing problems regarding excessive amounts of mineral fertilizer for sustaining the growing food production demand. Upcycling the effluent from biogas production into agriculture, provides a more sustainable food production and a shift toward a circular economy.

The realization of this thesis is made upon the suggestion of Lindum, and I would like to extend my gratefulness to Lindum for this opportunity in doing this study and research. I will thank my external supervisor Dr. Ketil Stoknes at Lindum for all help and guidance in making this thesis possible. I would also thank my supervisor Associate Professor Wenche Hennie Bergland for advice and help during the writing of this thesis. I also want to extend my thanks to my other supervisor Professor Marianne Sørflaten Eikeland for her advice and support.

I also want to extend my sincere gratitude to my family who has been a great support for me during the writing of this thesis. My special thanks to my friend Dr. Marilex Llave for the advice in the finalization of this thesis. Lastly, my thanks to all my friends and fellow students for their support and encouragement.

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Nomenclature

AD	Anaerobic digestion
CH_4	Methane
CO_2	Carbon dioxide
Daa	Decare (1 daa= 1000 m^2)
LCA	Life cycle assessment
GHG	Greenhouse gas
GWP	Global warming potential
N_2	Dinitrogen
NH_3	Ammonia
NH_4^+	Ammonium ion
NH_4^+-N	Nitrogen in ammonium (the concentration does not take into account the mass of oxygen atoms in the molecule)
N_2O	Nitrous oxide
N_2O-N	Nitrogen in nitrous oxide (the concentration does not take into account the mass of oxygen atoms in the molecule)
NO_2^-	Nitrite ion
NO_3^-	Nitrate ion
PAH	Polycyclic aromatic hydrocarbons
TMF	The Magic Factory (biogas facility ran by Lindum)
TS	Total solids
VFA	Volatile fatty acids
w/w	Weight/total weight

1 Introduction

Today, agricultural soil is fed with excessive amounts of chemical fertilizers, and due to the high energy intensity of production, it will not be sustainable in the long term (Greenberg et al., 2019). The use of inorganic fertilizer has increased rapidly in the last decades and today synthetic nitrogen fertilizer accounts for 2% of the world's energy consumption (Walling & Vaneeckhaute, 2020). Using a circular economy approach where organic waste such as digestate is recycled back into the soil reduces the dependency on synthetic fertilizers. Digestates are abundant in macronutrients, micronutrients, and organic material which are important for the soil ecosystem (Lukehurst, Frost, & Al Seadi, 2010). However, digestate has some problems regarding N_2O volatilization which is a dangerous greenhouse gas that is 298 times more potent than CO_2 (IPCC, 2007). Another obstacle is leaching/runoff as this can jeopardize the aquatic ecosystem and have negative environmental impacts such as being a precursor for N_2O emissions (Möller, Stinner, Deuker, & Leithold, 2008). The amendment of biochar in digestate can potentially reduce leaching and N_2O emissions by adsorption and can thereby improve nutrient retention (Borchard et al., 2019).

Biochar is a product of thermal degradation of organic material with restricted concentrations of oxygen. The substance is known to be a soil additive with the benefits of improving plant growth and cleaning contaminated water (Fagbohungbe et al., 2017). Biochar can function as an adsorbent which can adsorb useful nutrients for plant growth thus sustaining soil fertility (Borchard et al., 2019). One of the major advantages of biochar apart from soil benefits is the resistance to decay meaning that biochar can sequestrate carbon for several decades (Shackley, Ruysschaert, Zwart, & Glaser, 2016).

It is critical to evaluate the entire life cycle to address the real contribution of biochar and digestate's potential for greenhouse gas (GHG) reduction. The life cycle involves biochar production, distribution, and utilization of biochar-digestate as a fertilizer product. Life cycle assessment (LCA) is a well-established and standardized method that is widely employed to assess the environmental impact of biogas as a replacement for conventional fossil fuels. However, digestate management and quality can have a crucial impact on the net emission balance of the overall LCA. The analysis is assessed for digestate from The Magic Factory (TMF) owned by Greve Biogas. TMF is an anaerobic digestion (AD) facility treating organic wastes from industry and households in the eastern part of Norway. The products from the AD at TMF are biogas with biofuel quality and biofertilizer which can replace mineral fertilizer. In addition, TMF is run by Lindum which is a waste management company. Lindum provides biochar from wastes received at the facility such as garden waste. Furthermore, it is crucial to evaluate the environmental impact of the two waste streams and assess the potential benefits of biochar-digestate in the agroecosystem.

1.1 Research Question

In order to address the issues presented above, this thesis will investigate the environmental impact of biochar in anaerobic digestate with the research question:

"What is the global warming potential of using biochar in digestate as a fertilizer product on agricultural soil?"

To gain a better understanding of biochar's perspectives in digestate, this thesis will specifically investigate the following research sub-questions:

SQ1: What is the global warming potential of biochar-amended digestate on agricultural soil compared to synthetic fertilizer for a specific case in Norway?

SQ2: Which categories in the LCA are identified to have the greatest impact and how does the biochar-to-digestate ratio influence the global warming potential of the mixture?

SQ3: What are the potential agricultural benefits of applying biochar in the digestate?

Sub-questions 1 and 2 will be answered through an LCA analysis of digestate received from TMF and biochar obtained from Lindum's facility. The last sub-question will be investigated through a literature search.

1.2 Thesis Outline

This thesis is structured according to the presented research motivations and questions and comprises seven chapters. Chapter 1 introduces the motivation and research questions. Chapter 2 introduces the literature about agricultural soil, digestate, biochar, and LCA. Chapter 3 goes through the system boundaries and data inventory. Chapter 4 presents the results obtained from the LCA and chapter 5 discusses the acquired results. The next chapter (6) deduces conclusions from the results and the discussion provided in the thesis. Finally, the last chapter (7) provides an overview of suggestions for future work.

2 Theory

This chapter provides an overview of literature related to the research questions in this thesis. Subchapter 2.1 examines the value of biogas production and digestate in a circular economy. Subchapter 2.2 gives an overview of what agricultural soil is and what it needs for crop growth. Subchapter 2.3 examines the digestate characteristics and its prospect as a fertilizer. The following subchapter (2.4) outlines the properties and functions of biochar on the soil. Subchapter 2.5 evaluates biochar's benefits in anaerobic digestion (AD), in digestate, and its influence on nitrous oxide (N_2O) emissions. The last subchapters of the literature review are regarding LCA and LCAs of similar work.

2.1 Circular Economy and Emission Reduction Potential

The Norwegian Government states that they want to fulfill the Paris agreement, which aims to prevent the global temperature from rising more than two degrees. Norway is obligated to reduce 40% of its GHG emissions by 2030 compared to 1990 (Ministry of Climate and Environment, 2017). This obligation was implemented on the 1st of January 2018 and this goal is one of the precursors to the final goal of a low-carbon society in 2050 (Ministry of Climate and Environment, 2017). Therefore, it is critical to look for sustainable and eco-friendly technologies. Among these technologies is AD which treats organic waste and produces biogas. Biogas is a renewable fuel and can be used for the production of thermal energy (cooking, water heating, etc.), electrical energy (gas turbines, engines, fuel cells, etc.), and for transportation (which requires $\geq$ 97% methane (Morken, Briseid, Hovland, Lyng, & Kvande, 2017)).

Biogas utilization can support the Norwegian Government's climate goal by reducing emissions from manure storage and replacement of fossil fuels. Norwegian Environment Agency (2020b) estimated that if 25% of all livestock manure from pits and barns went to biogas plants within 2030, it can reduce GHG emissions by a total of 253 000 tons of CO_2-eq. from 2021 to 2030. This GHG saving is an effect of reduced storage time and emissions from manure spreading on the field. In the case where fossil fuel replacement is taken into account and 10% of hauling vehicles use biogas as transportation fuel, it can be possible to have an additional saving of 470 000 tons of CO_2-eq. (Norwegian Environment Agency, 2020b).

Biogas can therefore be a meaningful contribution toward a more sustainable future, as well as a support for a circular economy. A circular economy is a resilient economy that tackles global challenges such as climate change, waste, pollution, and biodiversity, but also maintains prosperity (Ritchie & Freed, 2021). This type of economy emphasizes the necessity for a flow of nutrients back to the biosphere and being a feedstock for a new biological cycle (MacArthur, 2015). Biogas production may contribute to a circular bioeconomy by utilizing waste and providing valuable nutrients to re-enter the ecosystem. Figure 1 presents an example of how biogas production and its by-product, digestate, can be a valuable approach for a circular bioeconomy. This approach exhibits organic waste as a substrate for a biogas plant and that the digestate is a fertilizer for nutrient recycling.

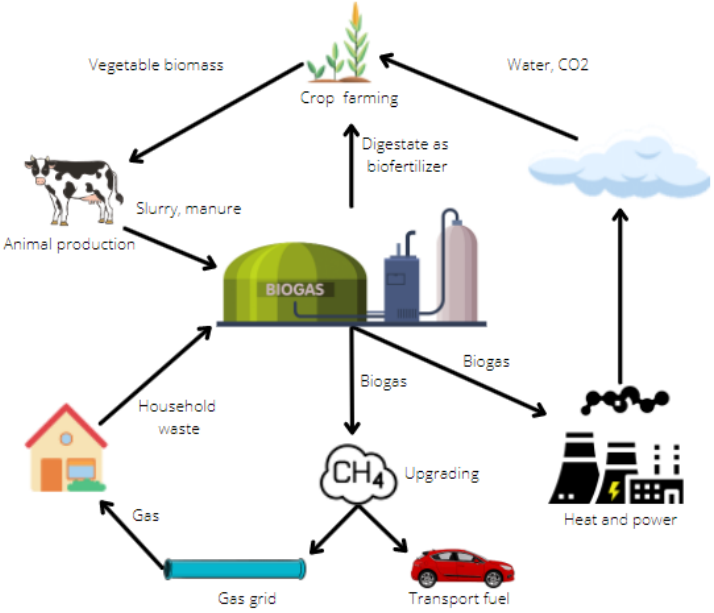

Figure 1: How biogas and digestate can be a meaningful approach toward a circular bioeconomy. Inspired by Fagerström, Al Seadi, Rasi, and Briseid (2018).

2.2 Agricultural Soil

The agricultural soil is necessary for food, fuel, feeds, and fiber production, and therefore proper soil management for sustaining its purpose is of great interest. The soil is a composite mixture of minerals, air, water, and organic matter which covers most of the earth's surface. It is the main source of organic wastes: both directly such as plants and indirectly such as animal wastes (Gilbert, Ricci-Jürgensen, & Ramola, 2020). The soil varies in composition and can take thousands of years to form, but can through poor land management practices be destroyed within decades (Gilbert et al., 2020). Therefore, it is important to understand how to sustain agricultural soil and what the agricultural soil needs to be efficient for production.

Agricultural soil should develop an environment that favors plant growth such as being rich in organic matter and containing vital nutrients for plant growth. There are 16 essential elements for plant growth: C, H, O, N, P, S, K, Ca, Mg, Fe, Mn, Zn, Cu, Mo, B, and Cl (Deng, Liu, & Wang, 2020). C, H, and O are taken from the air during photosynthesis while the other elements are found in dissolved salts (Deng et al., 2020). Soil's physical properties and biological life are also important parameters for sustaining plant growth. Physical properties such as moisture retention and soil structure help determine root functions and water retention, while soil organisms are important for soil structure such as creating pores and channels for water drain and/or giving roots space for growth (Shackley et al., 2016).

2.3 Digestate

Digestate is one of the two economically useful products of animal manures, food waste, and agricultural waste after AD. AD is the process where organic matter is decomposed by microorganisms in the absence of oxygen. One of the products of this process is biogas, which can produce thermal energy, electrical energy, or replace transportation fuel. The other product is digestate which is a potential fertilizer and soil amendment (Nkoa, 2014).

2.3.1 Digestate Characteristics

The composition of the digestate is dependent on the feedstock and the process (retention time and process temperature) thus the digestate varies from the digester to digester. In addition, the digestate composition from the same digester may vary with time (Wellinger, Murphy, & Baxter, 2013). The biogas residue consists of minerals, nitrogen, phosphorous, organic matter, and microorganisms which possess strong benefits on soil and plant growth (Deng et al., 2020; Fagbohungbe et al., 2017). Utilizing digestate as a biofertilizer serves as a natural nutrient cycle of macronutrients such as N, P, K, Ca, Mg, and S, and micronutrients such as B, Co, Cu, Cl, Fe, Mn, Mo, Ni, Se, and Zn which are vital minerals for crop growth (Lukehurst et al., 2010).

A major advantage of digestate is the high concentration of ammonium (NH_4^+) which is plant available (Odlare, 2005). Nitrogen enters the digester as NH_4^+ and organic nitrogen and due to the reducing environment, some of the organic nitrogen is transformed to NH_4^+ thus the concentration of NH_4^+ in the effluent is higher than in the inlet. Holm-Nielsen, Halberg, Huntingford, and Al Seadi (1997) found that the concentration of NH_4^+-N in digestate was 20% higher than for undigested cattle slurry. Digestate's content of NH_4^+ is about 60-80% of the total nitrogen content (Makádi, Tomócsik, & Orosz, 2012).

Digestate closes the loop of phosphorous recycling, which is necessary due to the world's reserves of phosphorus are rapidly depleting. In 2014, the European Union declared that phosphorus was on the European commission's list of critical commodities (European commission, 2014). It was stated that phosphorous recycling is essential due to the few reserves and the cost of mining. The depletion of phosphorus is very critical for food production because it is an indispensable mineral for plant growth.

Digestate contains both a liquid and a solid phase which have different compositions due to their different physical state. The liquid part of the digestate contains the largest amount of nutrients, about 87% of total Kjeldahl nitrogen, 72% of available phosphorous, and 90% of available potassium (Deng et al., 2020). The solid phase is richer in organic matter, humic acid, phosphorous, and other components that act as humus precursors (Schnurer & Jarvis, 2010; Wellinger et al., 2013). In light of these facts, it is evident that the solid fraction has greater potential as a soil amendment and the liquid fraction has greater potential as a fertilizer.

Besides the available nutrients in the digestate, there are other beneficial and adverse compounds in the digestate. Amino acids can be present due to inadequate conversion of amino acids to ammonia/ammonium (Morken, Briseid, Hovland, Lyng, et al., 2017). Fertilizers containing amino acids can strengthen seedlings and enhance the stress resistance of crops (Deng et al., 2020). A study conducted by He et al. (2019) showed that amino acids increased shoot and root weight thus improving plant growth. Similar results were obtained by Noroozlo, Souri, and Delshad (2019) who experienced increased plant growth but also increased leaf chlorophyll content. Plant hormones can also be found in the digestate and are important for plant growth and development. Digestate contains four major plant hormones: auxin, gibberellin, cytokinin, and abscisic (Deng et al., 2020). On the contrary, digestate might have some impurities which are unwanted in agriculture such as heavy metals. Norway is concerned with the following heavy metals: zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), lead (Pb), chromium (Cr), and mercury (Hg) (Ministry of Agriculture and Food, Ministry of Climate and Environment, & Ministry of Health and Care Services, 2003). Most heavy metals come from anthropogenic sources such as animal feed additives, food industry, fat residues, and domestic sewage (Makádi et al., 2012). Physical impurities in the biogas effluent are plastic, rubber, glass, stone, sand, and lignocellulosic materials. These impurities can cause stability problems in AD and decrease the quality of digestate. Plastics are the most abundant impurity and are drawing negative attention because of visible plastic pieces from undegradable collection bags (Aspray, Dimambro, & Steiner, 2017; Wellinger et al., 2013).

AD is also known to have some sanitation effect depending on the process temperature and retention time in the digester. It is reported that plant and animal pathogens are effectively inactivated or destroyed in the digester even in mesophilic digesters which have a lower process temperature than thermophilic digesters (Lukehurst et al., 2010). In addition, AD has been proven to reduce weed seeds (Johansen et al., 2011). Apart from the suppression of hazardous organisms and weed seeds, AD reduces odors compared to an undigested slurry (Morken, Briseid, Hovland, Lyng, et al., 2017).

2.3.2 Digestate as a Fertilizer and Soil Improver

Recycling digestate back to agriculture as an organic fertilizer or soil improver is the most sustainable employment of digestate (Alburquerque, de la Fuente, & Bernal, 2012). The application of digestate on soil provides prominent effects on soil's physical, chemical, and biological properties (Makádi et al., 2012). However, only digestate from pure substrates such as animal manures and/or food waste could be used as biofertilizers for food production (Schnurer & Jarvis, 2010). Digestate from wastewater is not suitable for that purpose due to the content of heavy metal and/or organic pollution.

Regarding soil biological effects, microorganisms are crucial for maintaining soil fertility by mineralizing organic matter and facilitating plant nutrient uptake (Schnurer & Jarvis, 2010). Studies show that biogas residues on soil can enhance soil microbial activity (Abubaker, Risberg, & Pell, 2012; Petersen et al., 2003). Odlare, Pell, and Svensson (2008) did a four-year trial of digestate's effect as a fertilizer and compared it to different fertilizing compounds. The study showed that biogas residues increased substrate-induced respiration, the portion of active microorganisms, and the nitrogen mineralization capacity relative to other treatments. This suggests that digestate has positive effects on soil chemical and microbiological variables. In terms of soil physical properties, Garg, Pathak, Das, and Tomar (2005) conducted a field experiment and concluded that biogas slurry from agricultural waste increased saturated hydraulic conductivity, reduced bulk density, and increased moisture retention capacity in soil.

Given that digestate has positive effects on soil and that the digestate possesses significant amounts of nutrients, it is evident that digestate has beneficial effects on crops, fruits, and vegetable production. The fertilizer value of anaerobic digestate can be recognized through the field performance with other recognized organic or inorganic fertilizers. Anaerobic digestate has been proven to be at least as effective as undigested feedstock on crop performance (Möller et al., 2008; Odlare, 2005), and digestate has also shown similar or better performance as mineral fertilizer (Furukawa & Hasegawa, 2006; Nkoa, 2014; Walsh, Jones, Edwards-Jones, & Williams, 2012). A study by Haraldsen, Andersen, Krogstad, and Sørheim (2011) showed that liquid digestate had the same effects on barley yield and NPK uptake in barley grain as Fullgjødelsel®.

Crop yield is a very important parameter for the food industry, but quality can also be considered a significant and valuable factor. The quality of the crop is evaluated on a range of parameters depending on if the crop is a fruit, vegetable, or grain. Panuccio, Papalia, Attinà, Giuffrè, and Muscolo (2019) demonstrated that digestate increased antioxidant capacity, phenols, and vitamin C in cucumber compared to unfertilized control. Another field experiment showed that digestate can increase amino acids, protein, soluble sugars, β-carotene, vitamin C, and tannins in fruits compared to mineral fertilizer (Yu, Luo, Song, Zhang, & Shan, 2010). Similar results were obtained by Barzee et al. (2019) who also found that the soluble content in the digestate-treated tomatoes was higher than the ones treated with mineral fertilizer.

2.3.3 Problems with Digestate as a Fertilizer

Although there are some benefits of utilizing digestate, there are also some risks. Nutrient losses from the digestate to the atmosphere and water can have critical effects on the environment and aquatic life. Möller et al. (2008) emphasize the importance of the correct application rate of nitrogen regarding supply and demand for enhancing the nitrogen use efficiency but also for reducing negative impacts. The European Commission restricted a maximum supply of 150-250 kg N/ha/year and/or 22-80 kg P_2O_5 in agriculture (Saveyn & Eder, 2014). Despite the right application amount, there are also risks regarding nitrogen losses during application and storage. Inappropriate storage and/or application can lead to atmospheric pollution of ammonia (NH_3) and nitrous oxide (N_2O), and other nutrient losses. Application of digestate during seasons where there is little plant uptake such as autumn and winter can lead to nutrient leaching or runoff into surface and ground waters (Lukehurst et al., 2010). Soil properties are also important in terms of nutrient losses, soils with little water retention capacity can lead to nutrient leaching.

Digestate increases the concentration of NH_4^+, but also the equilibrium partner NH_3. Temperature and pH are two factors influencing the shift in equilibrium, where an increase in pH and/or temperature promotes NH_3 production. The pH of the digestate tends to be in the alkaline range, thus the potential for nitrogen volatilization is high (Nkoa, 2014). NH_3 deposits back to the surface as a dry deposit of NH_3 or as a wet deposit of NH_4^+ (Asman, Sutton, & Schjørring, 1998). These deposits can have critical consequences for the aquatic ecosystem due to acidification and eutrophication. In addition, these deposits can be critical for human health as NH_3-derived fine particulate matter (PM2.5) can enter the lungs causing serious health issues (Nkoa, 2014). Another important gas is N_2O which is produced during nitrification and denitrification. The former is the microbial oxidation of NH_4^+ to nitrite (NO_2^-) and nitrate (NO_3^-) with the help of the bacterial genera Nitrosomonas and Nitrospira (Shackley et al., 2016). N_2O is formed when there are unbalances between the transformation of NO_2^- to NO_3^-. NO_2^- is toxic to microbes thus N_2O volatilization is a path to avoid the accumulation of NO_2^- (Sommer, Møller, & Petersen, 2001). Denitrification reduces NO_3^- to N_2O and dinitrogen (N_2) in the absence of oxygen. N_2 is a harmless gas but N_2O is a critical greenhouse gas with a global warming potential of 298 times CO_2 over 100 years (IPCC, 2007). Excess concentration of NO_3^- promotes the volatilization of N_2O instead of N_2 (Sommer et al., 2001). There are several factors influencing nitrification and denitrification, such as organic substrates, oxygen, nitrogen availability, and temperature (Barnard, Leadley, & Hungate, 2005). The most important factors are nitrogen availability and oxygen availability as nitrification is aerobic while denitrification is anaerobic. Temperature is also an important factor because an increase in temperature enhances microbial activity. Increased amounts of easily degradable organic matter and NO_3^- availability tends to stimulate denitrification because microbes use carbon as an energy source and NO_3^- as an electron acceptor (Barnard et al., 2005).

Unlike digestate, mineral fertilizers are chemically stable with a slow release of nutrients thus reducing the possibility of leaching (Fagbohungbe et al., 2017). To avoid leaching and runoff both the correct application rate and season are important. A study by Petraityte, Arlauskiene, and Ceseviciene (2022) showed that dry seasons can have negative impacts on nitrogen uptake of crops by the use of digestate while under normal seasons digestate was as effective as mineral fertilizer.

2.4 Biochar

Biochar is a carbon-rich solid material made from the pyrolysis of organic material. It is categorized by its large surface area and porous structure. International Biochar Initiative (2013) defines biochar as:

"Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used as a product itself or as an ingredient within a blended product, with a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution, and as an avenue for greenhouse gas mitigation."

Today, biochar has gained interest due to its soil amendment properties and its possibility to be an atmospheric cleaner. The following subchapters will go through how biochar is produced, biochar properties, its effects on soil, and possible negative properties of biochar.

2.4.1 Biochar Production

Biochar is made from the thermochemical decomposition of organic material in the absence or limited amounts of oxygen. When the equivalent ratio (ratio of oxygen supply to oxygen required for combustion) is 0 then the process is referred to as pyrolysis, while an equivalence ratio less than 0.15 is assigned as pyrolytic gasification, and 0.15-0.3 is called gasification (Lehmann & Joseph, 2015). Pyrolysis is the most promising technology for biochar production because of its yield (Hersh & Mirkouei, 2019). The products of pyrolysis are biochar (HHV=18 MJ/kg), bio-oil (medium to high energy density product, HHV=17 MJ/kg), and syngas (a low energy density product, HHV=6 MJ/kg) (Crombie & Mašek, 2014). Pyrolysis is categorized by the heating rate which determines if the process is slow, intermediate, fast, or flash, see Table 1.

Table 1: Different pyrolysis processes and products (Shackley et al., 2016).

Process	Temperature (°C)	Time	Heating rate (°C/s)	Char (wt. %)	Liquid (wt. %)	Gas (wt. %)
Slow pyrolysis	350-400	2-30 min.	0.1-2	25-35	20-50	20-50
Intermediate pyrolysis	350-450	4 min.	2-5	30-40	35-45	20-30
Fast pyrolysis	450-550	1-5 s.	10-200	10-25	50-70	10-30
Flash pyrolysis	500-600	< 1s.	> 200	13-23	50-60	10-25
Gasification	850	1-5 min.	1-1000	5-10	1-3	85-95

One of the products of pyrolysis is biochar which is very carbon-enriched. The properties are dependent on the pyrolysis process and the feedstock. Biochar's carbon content is dependent on the feedstock but is usually >50% of the mass (Shackley et al., 2016). Biochar is predominated by stable carbon, but there is also some labile carbon that can be mineralized in the soil to CO_2. The biochar also contains N, P, and K in lower yields but also unwanted impurities such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) (see chapter 2.4.5). Process temperature can influence biochar production whereby biochar production decreases with an increase in temperature resulting in an increase in gas and liquids (Shackley et al., 2016). Lower process temperatures will therefore provide more biochar, but the carbon is less stable and biomass carbonization is slower (see Figure 2).

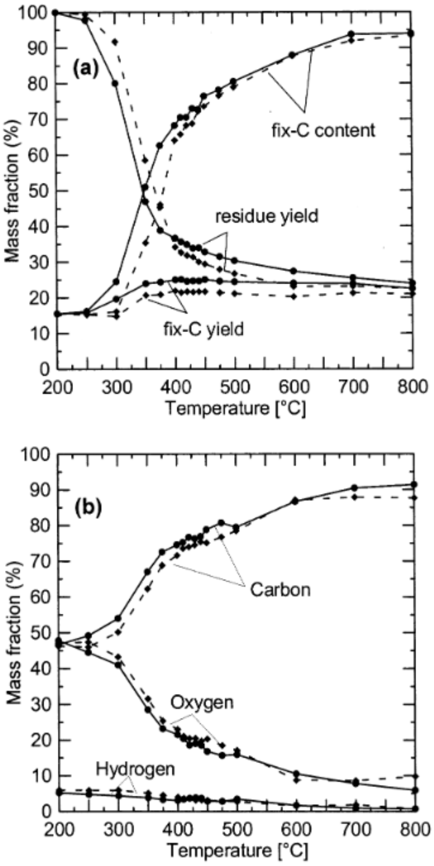

Figure 2: Effects of temperature on yield and CHO content in chars (Antal & Grønli, 2003).

2.4.2 Prospect in Norway

Biochar in the agricultural sector is relatively new in Norway, but the industry is rapidly increasing and evolving where biochar is an important contributor to the national emission-mitigation goals (Prestvik & Lilleby, 2021). In Klimakur 2030, it is estimated that biochar on soil can mitigate emissions by 0.8 million tons of CO_2-eq. in the period 2021-2030 (Norwegian Environment Agency, 2020b). Carbon sequestration and increased soil carbon are some of the main promoters for applying biochar to the soil in Norway. The value chains for biochar in Norway are in fertilizer products, animal feeds, pet food, urban planting, asphalt and concrete, biogas production, as a filter and adsorption medium, and as a reduction medium in the process industry. Biochar in fertilizers and animal feed are the most important products in agriculture, where biochar in fertilizer can improve soil quality and potentially increase crop yield, and biochar in animal feed can improve animal health (Prestvik & Lilleby, 2021). Moreover, the agricultural use of biochar is dependent on the farmers' willingness to pay. Today, the market price of biochar is 8000 NOK/ton biochar, which is relatively high, but subsidies and carbon credits can help enhance biochar's value (Prestvik & Lilleby, 2021).

2.4.3 Biochar Properties: Physical and Chemical

There are some desirable and interesting features of biochar that are drawing attention in the agronomical studies for soil amendment and carbon sequestration (Kizito et al., 2015). The most important properties are the porous structure and its aromatic ring structure (Shackley et al., 2016).

Fresh biomass only contains a few stable C molecules, which means that biomass applied to the soil will not remain there for a long time. Only a few percent of C will remain stable on soil and form humus (Shackley et al., 2016). On the contrary, biochar is abundant with highly stable C molecules formed during the pyrolysis. During pyrolysis, the aliphatic chain structure which consists of bounds that are readily available for microbial enzymes is converted to an aromatic ring structure (Shackley et al., 2016). This aromatic ring structure consists of strong bonds that are hard for microbes to decompose which features the resistance of mineralization (to CO_2). Biochar has also resistance to reduction (to methane (CH_4)) in anaerobic conditions. The stable aromatic ring structure features the biochar’s capacity to store C for several hundreds to thousands of years (Shackley et al., 2016). As biochar is a carbon-negative solution, it became one of the finalists in the Virgin earth challenge. This prize aims at developing technologies able to pull a gigaton or more of CO_2 out of the atmosphere annually (Lehmann & Joseph, 2015).

One of the most defining features of biochar is the porous structure which gives biochar a high specific surface area. The specific surface area is the accessible surface of the biochar, such as through pores or tunnels. Woody biochar tends to have the largest surface areas which can be from 400-600 m^2/g whereas manure biochar has 260 m^2/g (Shackley et al., 2016). The porous structure composes of a complex connection between macropores, mesopores, and micropores. Given the structure of the biochar, it can act as an adsorbent which is a process where the adsorbate associate at the surface of the biochar until equilibrium is achieved (Fagbohungbe et al., 2017). This feature promotes nutrient retention, and the structure can also support the growth of microorganisms.

An important characteristic of biochar is the cation exchange capacity. Biochar tends to be negatively charged, which means that it attracts positively charges cations or molecules. The ions are in a weak bond with the surface which can be broken and the ions can be used as nutrients for plants (Shackley et al., 2016). The adsorption capacity of biochar depends on different factors such as feedstock, particle size, pH, and pyrolysis temperature. Kizito et al. (2015) found that rice husk biochar can have a more amorphous and less porous structure compared to woody biochar due to its cellulose content. Thus, woody biochar has a higher surface area which facilitates adsorption. Similar results were discovered by Yang et al. (2018) who found that pyrolyzed pine sawdust removed more NH_4^+ than pyrolyzed wheat straw at the same pyrolysis temperature. Kizito et al. (2015) also discovered that maximum absorption appeared in the pH range of 6.5-7.0 and with particle sizes of 0.25-0.5 mm. According to Fagbohungbe et al. (2017), the sorption rate of biochar increases with a decrease in the particle size, which is because larger biochar particles may cause blockages of smaller sorption sites. Kizito et al. (2015) experimented with biochar in pure NH_4^+ solution and slurry with the same

NH_4^+ concentration where biochar had a higher removal rate in the pure solution. The authors argued that competing ions in the slurry interfered with the adsorption rate through competition with NH_4^+ for the adsorbent active sites. High pyrolysis temperature is also an important factor that facilitates the formation of micropores and increases the surface area (Shackley et al., 2016). Aligning with this theory, Yang et al. (2018) found that pine sawdust pyrolyzed at 550°C had a higher adsorption rate at 300°C.

Furthermore, another feature of biochar is the pH, the alkaline pH of biochar can prevent soils to become acidic. Agricultural soils tend to become acidic over time due to losses of base cations, but applying biochar to soil can neutralize it (Shackley et al., 2016).

2.4.4 Biochar on Agricultural Soil

Biochar is not a new scientific term and is dated back to the ancient Amazon region where the Amerindian populations made dark earth soils, also known as Terra Preta (Rajapaksha, Mohan, Igalavithana, Lee, & Ok, 2016). These spots of soil were more fertile than the surrounding soil, and even hundreds of years after the population's abandonment, the soil is more fertile than its surrounding land (Lehmann & Joseph, 2015). The enhanced fertility is given by the higher level of soil organic matter, nutrients, nutrient holding capacity, higher pH value, and greater water retention (Shackley et al., 2016).

It is understood that biochar has some positive effects on soil such as increased pH, porosity, and water retention, which can create a favorable environment for the microbial community and root development (Joseph et al., 2021). In addition, biochar's cation exchange capacity leads to an affinity for micro-and macronutrients (Masebinu, Akinlabi, Muzenda, & Aboyade, 2019). These properties are beneficial for crop growth, and studies have been done to quantify the benefits of biochar application. A meta-analysis done by Joseph et al. (2021) showed that biochar increased crop yield by 10-42%. Another meta-analysis by Jeffery, Verheijen, van der Velde, and Bastos (2011) found that biochar application increased crop yield by -28- 39%. The two meta-analyses are conflicting on the average crop yield increase, but both analyses agreed that biochar application has the greatest potential on acidic and coarse soil. This confirms that biochar increases pH, nutrient retention, and water holding capacity.

2.4.5 Negative Properties of Biochar

The adverse health and environmental impact of biochar's properties and how they can be avoided are important to understand. These negative properties are polycyclic aromatic hydrocarbons (PAHs), heavy metals, and dioxins.

PAHs are one of the most discussed potential pollutants of biochar (Lehmann & Joseph, 2015). It consists of two to six benzene-type rings which are difficult to decompose and are formed during incomplete combustion, gasification, or pyrolysis of biomass (Shackley et al., 2016). The PAH concentration in biochar is influenced by temperature, time, production process, and biomass source (Shackley et al., 2016). Hale et al. (2012) reported that an increase in process temperature or residence time decreased the PAH concentration. A report from Sintef (2017) highlighted that biochar made from a process temperature above 350˚C does not represent any risk regarding PAHs. PAHs are critical to human health because they can inhibit the metabolic functions of the cells and can be carcinogenic (Panjwani, Andersson, Wittgens, & Olsen, 2017).

Another important consideration is heavy metals, especially in food production, where pure biochar is required. O, H, N, and C be volatilized during pyrolysis, while heavy metals such as Cd, Pb, Cr, As, etc. will be concentrated (Shackley et al., 2016). Apart from heavy metals, dioxins are toxic to human health. Dioxins can be produced if the process temperature is too low and/or if the feedstock contains Cl such as salts (O`Toole et al., 2022).

2.5 Effects of Biochar in AD and Digestate

This subchapter scrutinizes the effects of biochar as an AD amendment and as a digestate additive for soil and nutrient retention improvement.

2.5.1 In the AD process

Biochar-assisted biogas digesters have been extensively researched in the last few years (Qiu, Deng, Wang, Davaritouchaee, & Yao, 2019). The most important factors for biogas production are gas yield, methane production, and process stability. Several articles report that biochar-amended digesters improve the biogas production and methane yield (Fagbohungbe et al., 2017; Qiu et al., 2019). Shen, Linville, Urgun-Demirtas, Schoene, and Snyder (2015) showed that biochar increased methane content to 88-96.7%, reaching almost pipeline-quality biogas, compared to 67.9% for non-amended digesters. Similar results were obtained by Viggi et al. (2017) who used lignocellulosic biochar in food waste and demonstrated that biochar increased methane production 4.6 times compared to unamended digesters.

Nitrogen-rich substrates such as slaughterhouse- and fish waste are desirable for biogas production because of their methane yield (Mumme, Srocke, Heeg, & Werner, 2014). These substrates are rich in proteins which are precursors for ammonium/ammonia production where an increase in pH and/or temperature promotes ammonia accumulation. Ammonia can inhibit AD by penetrating the cell membrane of microbes causing methanogenic inactivity which can prevent volatile fatty acids (VFA) consumption (Qiu et al., 2019). VFA is an intermediate product in the AD process and is essential for methane production. However, VFA accumulation can decrease pH and make an undesirable environment for microorganisms. One possible solution to prevent ammonia inhibition is to use a carbonaceous sorbent such as biochar, which can achieve a slow release of ammonium. Mumme et al. (2014) report that biochar can prevent mild ammonia inhibition (2.1g Total Ammonium-N/kg). Kizito et al. (2015) report that wood and rice husk biochar can prevent ammonia inhibition in high ammonium concentrations of 1000-1400 mg N/L by adsorbing 60% and 53% of ammonium-N in slurry, respectively. There are various techniques for mitigating and controlling ammonia inhibition, such as using zeolite, carbon fibers, textiles, and activated carbon (Lü, Luo, Shao, & He, 2016; Qiu et al., 2019). These solutions are expensive on a large scale and must be removed from the digestate to be economically feasible. Using biochar instead as an AD amendment can be an alternative solution and cost-effective replacement, and due to the relatively low cost, it does not have to be removed. Instead, biochar may have a positive impact on the digestate quality through nutrient recovery (Fagbohungbe et al., 2017).

Apart from ammonia inhibition, VFA inhibition is mainly caused by rapid accumulation which can lead to low methane yield and in the worst case lead to reactor failure (Qiu et al., 2019). Biochar may prevent this pH drop in AD because of its nature as an acid buffer (Fagbohungbe et al., 2017). Sunyoto, Zhu, Zhang, and Zhang (2016) reported that biochar provided a stable pH during the AD process, reduced lag phase, and enhanced microbial metabolism and growth. Luo, Lü, Shao, and He (2015) found that biochar promoted acid production and degradation. In addition, biochar can also support the colonization of microbial communities on their surface by forming a biofilm that can prevent washout and support their growth (Fagbohungbe et al., 2017).

2.5.2 Digestate and Biochar's Effects on Agricultural Soil

Digestate naturally contains less carbon than its initial feedstock due to the degradation of organic matter and volatilization of CH_4 and CO_2. Adding biochar to the digestate can increase the C:N ratio which is an essential property for crop growth. Mineral nitrogen will be released to the plants if the C:N ratio is below 20-24, while a higher C:N ratio will immobilize the nitrogen and the microbes will consume it for their growth (Shackley et al., 2016). In the case where C:N is too high, less nitrogen is available for plants, and this situation is referred to as microbial immobilization. Moreover, one of the major goals of adding biochar to the soil is the long-lasting increase in soil carbon which serves as a carbon sink (Greenberg et al., 2019; Holatko et al., 2021; Shackley et al., 2016).

Biochar amended digestate has shown beneficial effects on soil and plant growth. Budai, O'Toole, Weldon, and Rivier (2021) did a field trial of biochar and digestate for spring onion production on arenaceous soil. The results showed that the organic fertilizers with the biochar-to-digestate ratios of 6.25% w/w and 12.5% w/w increased marketable crops by 37% and 24% compared to NPK-fertilizer, respectively. In addition, results showed that biochar and digestate had higher crop yield than just digestate. Also, similar results were obtained by Ronga et al. (2020), who did a field experiment with tomato crops fertilized with liquid digestate and liquid digestate-biochar compared to unfertilized control. Thus, results showed that liquid digestate-biochar recorded the maximum marketable yield with a 54% increase, and liquid digestate recorded a 26% increase.

Other studies have been focusing on biochar for nutrient recovery. Biochar has been extensively researched for nutrient recovery in synthetic solutions such as ammonium, potassium, and phosphate (Hu et al., 2020; Modin, 2021; Shang, Xu, Huang, & Zhang, 2018). These articles compare the sorption capacity of biochar with biochar alteration (acid wash) or from different feedstocks. In general, these articles show that biochar is a feasible absorbent for nutrient recovery. Moreover, few reports focus on biochar's nutrient recovery in digestate. Plaimart et al. (2021) studied the sorption capacity of coconut husk biochar in dairy/pig slurry digestate. Results showed that biochar slowed down nitrification resulting in reduced leaching and biochar retained nutrients for a longer period, thus minimizing the risk of groundwater pollution. The results also showed that biochar did not affect ammonia losses, but this could be because biochar was applied on the surface of the soil, and digestate was applied on top of that. Another study by Kizito et al. (2015), found that woody biochar can adsorb 44.64 mg NH_4^+-N/g in pig manure digestate and was a sufficient nutrient filter.

For the soil fauna, biochar can act as an energy source depending on the amount of labile and recalcitrant carbon. Most of the carbon will remain in the soil, but some will be available for microorganisms over time acting as a slow release of energy. Studies show that biochar increases microbial biomass which suggests that microorganisms utilize the labile carbon as an energy source (Shackley et al., 2016). In addition, biochar's pores can be a refuge for soil microorganisms and can protect themselves from predation.

Biochar supplement in digestate has also increased nutrient content in the digestate due to the elemental composition in the biochar ashes. Shen, Forrester, Koval, and Urgun-Demirtas (2017) experienced a 33 times increase in P, K, Ca, Mg, and Fe compared to just digestate. Similar results were obtained by Shen, Linville, Ignacio-de Leon, Schoene, and Urgun-Demirtas (2016) who found a 162- 367% increase in K, and other nutrients such as Ca, Mg, and Fe were significantly increased. An increased amount of nutrients increases the fertilizer value.

2.5.3 Biochar's Influence on the Nitrogen Cycle

Agriculture accounts for approximately 60% of the global N_2O emissions which is largely due to organic and mineral nitrogen fertilizer use (Borchard et al., 2019). In Norway, agriculture accounts for 77% of total N_2O emissions which is also due to the consumption of fertilizers (Environment Norway, 2021). A first meta-analysis studying biochar's ability to reduce N_2O emissions was conducted by Cayuela et al. (2014) who found a 54% reduction potential. The same authors updated the meta-analysis and found that biochar reduced N_2O emissions by 49% (Cayuela, Jeffery, & van Zwieten, 2015). Two more recent meta-analyses found 38% (Borchard et al., 2019) and 32% (Liu et al., 2018) N_2O emission reduction. Field studies have shown lower reduction potential, 28% and 12.4%, which can be explained by lower biochar application rate and lower moisture content (Cayuela et al., 2015; Verhoeven et al., 2017). The soil type, pyrolysis temperature, and the amount of biochar applied to the soil are factors influencing emission mitigation (Liu et al., 2018). In addition, biochar made from high-N feedstocks can generate additional short-term N_2O emissions. The structure of biochar and its porosity is largely influenced by pyrolysis temperature (Shackley et al., 2016). However, Cayuela et al. (2014) found no significant impact of pyrolysis temperature on the extent of N_2O mitigation, even though there were higher variabilities for <400˚C and >600˚C.

One of the major problems of digestate is leaching and one of the ways to prevent this is to increase the C:N ratio. Raising the C:N ratio is not the only effective approach because the slowness of the microbial processes does also jeopardize leaching (Fagbohungbe et al., 2017). When digestate is applied directly to the soil, the nutrients are released fast and beyond the utilization rate of the microorganisms thus leaching and runoff are unavoidable. Nitrogen leaching is easily soluble in soil pore water and can infiltrate the soil causing soil acidification, exhausting soil fertility, and reducing crop yield, and can also jeopardize aquatic life through eutrophication (Xu, Tan, Wang, & Gai, 2016). Nitrogen leaching is largely due to excessive and inappropriate timing of nitrogen fertilizer application (Borchard et al., 2019). The porous structure of biochar makes it suitable as an adsorbent that can adsorb nitrogen and can control nitrification and denitrification (Cayuela et al., 2014). A meta-analysis by Borchard et al. (2019) found that biochar reduced NO_3^- leaching by 13% and that a greater leaching reduction potential (>26%) took place after one month. Similar results were obtained from a meta-analysis by Liu et al. (2018) who found that NO_3^- leaching was reduced by 29% and that NH_4^+ leaching was reduced by 22%. Biochar made from wood experienced the greatest reduction potential for leaching compared to straw biochar (slightly less efficient) and manure biochar (no effect) (Liu et al., 2018). Martin, Clarke, Othman, Ramsden, and West (2015) found that biochar in digestate increased the NH_4^+ concentration with time and the concentration was at the highest at the end of the incubation period, which indicates a slow release of nutrients.

Organic fertilizers such as digestate can be influenced by biochar which has an alkaline pH. Digestate contains significant amounts of NH_4^+ which is in equilibrium with NH_3 and an increase in pH promotes NH_3 volatilization. Thus, increasing nitrogen losses and reducing the fertilizer value of the digestate. A report by Cottis, Solberg, Myrvang, and Mousavi (2022) experienced a decrease in crop yield where the authors argued that the biochar adsorbed the nutrients and made them unavailable for plants. However, a new report from O`Toole et al. (2022) discusses that the possible reason for this was not the adsorption capacity but the NH_3 volatilization. There were no measurements of pH and NH_3 during storage thus there is no clear demonstration of this statement. Moreover, there are conflicting studies on whether biochar enhances or reduces NH_3 volatilization. Liu et al. (2018) report that biochar increases NH_3 volatilization by 19%. Different results were obtained by Le Leuch and Bandosz (2007) who found that biochar immobilizes NH_4^+ by adsorption thus reducing NH_3 volatilization. Similar results were obtained by Budai et al. (2021) who showed that NH_4^+ and NO_3^- in soil were higher for digestate and biochar than in the control (mineral fertilizer). Thus, these experiments demonstrate that biochar enhancement reduces nutrient losses.

2.6 Life Cycle Assessment (LCA)

The increased interest in sustainable products has developed methods for quantifying the environmental impact of the given product both manufactured and consumed. Life cycle assessment (LCA) is one of the most used and promising methods for establishing the sustainability of the process and its possibilities for improvement. The International organization for Standardization (ISO) has made a series of standards, referred to as the ISO-14040 series. This method is commonly used to address the environmental impact during the life cycle of raw material from production until disposal (i.e. Cradle-to-Grave).

The LCA framework recommends four steps for the assessment (Standard, 2006):

- Definition of goal and scope
- Inventory analysis
- Impact assessment
- Interpretation of results

The following subchapters will briefly explain the different steps of the LCA method.

2.6.1 Definition of Goal and Scope

The definition of goal and scope is the first step for using the LCA method and is the foundation of the entire process. Characteristics such as system boundaries, intended application, assumptions, and constraints will have an impact on the final goal of the process.

The assessment system boundaries can be Cradle-to-Grave, Cradle-to-Gate, or Cradle-to-Cradle (Krishna, Manickam, Shah, & Davergave, 2017). Cradle-to-Grave can be defined as the full cycle assessment from the manufacturer (cradle) until disposal (grave) where all inputs and outputs are considered. Cradle-to-Gate is a partial LCA such as from manufacturer (cradle) to factory gate. Cradle-to-Cradle is a sophisticated modification of the Cradle-to-Grave approach where the disposal step is a recycling process. There are also modifications such as Gate-to-Cradle which is a partial LCA such as from factory gate to disposal.

Another important aspect in the first phase is the functional unit. Environmental impact is measured by the functional unit which has the main purpose of quantifying the product's function and making it comparable to other systems. For example, an AD facility can use the treatment of 1 ton of food waste as a functional unit for assessing the environmental impact of treating food waste. Another example is to analyze all products and services achieved during an entire year for finding the greatest environmental impact and improvements.

2.6.2 Inventory Analysis

After the functional unit and system boundaries are defined, the life cycle inventory (LCI) phase begins. The inventory involves data collection of input and output for all the processes that compose the system. Data include material, energy, chemicals, etc. but also air and water emissions. The LCI phase also includes the description and verification of data to have an intelligible modeled system.

2.6.3 Impact Assessment

The aim of the life cycle impact assessment (LCIA) phase is to evaluate the contribution of environmental, human, and health impacts. This phase includes some mandatory elements which are selection, classification, and characterization (Standard, 2006). The selection of impact categories, category indicators, and characterization models are relevant for the goal and scope of the analysis. In the classification step, LCI results are assigned to the selected impact category. Characterization is used to calculate the potential impacts and make them comparable, such as to use CO_2-equivalents for evaluating the global warming potential.

2.6.4 Interpretation of Results

The last phase of the LCA tool is the interpretation of results. This phase includes the identification of significant issues in the past phases, evaluation of the completeness, sensitivity, consistency, conclusions, limitations, and recommendations (Standard, 2006). The interpretation phase involves a thorough analysis of all the phases included in the analysis leading to conclusions (Figure 3).

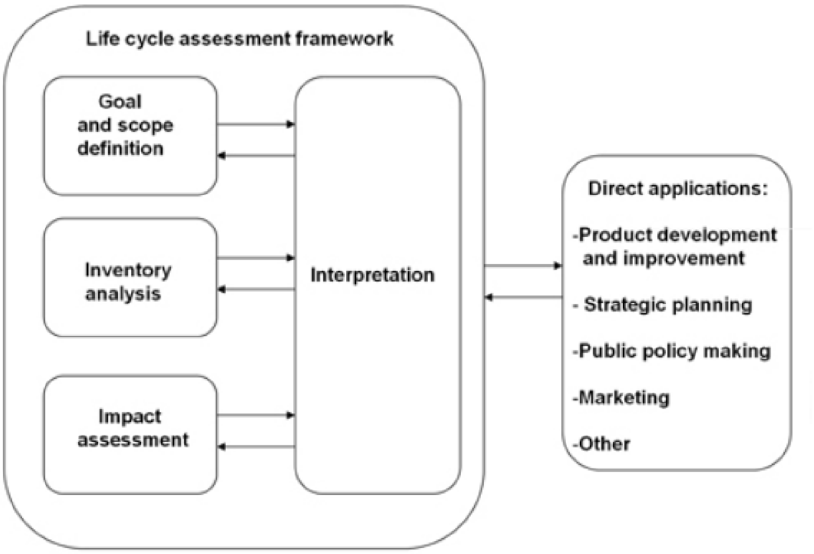

Figure 3: Connection between the interpretation phase and the other phases in the LCA method (Standard, 2006).

2.7 LCA of Digestate and Biochar

LCAs have so far been focusing on biogas in AD as a displacement of conventional fossil fuel (Breunig, Amirebrahimi, Smith, & Scown, 2019). However, quantifying the amount and management of digestate can have a significant impact on the LCA’s emission balance. Digestate quality, management strategy, and net emissions or sequestration are critical parameters for evaluating the environmental impact of organic waste treatment. This thesis focuses on biochar-amended digestate, but there are very few studies available regarding this topic because it is a relatively new topic. However, this section will review LCAs for digestate, biochar, and the few studies on biochar and digestate as a blended product.

Studies regarding the replacement of synthetic fertilizer with digestate have been evaluated for TMF. Lyng and Saxegård (2020) conducted an LCA on products and services supplied by TMF such as biofuel, biofertilizer, bio-CO_2 for a greenhouse, treatment of food waste, and treatment of manure. The results showed that emissions from field application of organic fertilizer were one of the categories with the greatest environmental impact. However, the substitutional effect of mineral fertilizer was one of the greatest greenhouse gas (GHG) reductions, with -3961 t CO_2-eq./year. Similar results were obtained by Morken, Briseid, Hovland, Stensgård, and Saxegård (2017) who also did an LCA for TMF and found that substitution of synthetic fertilizer can reduce GHG by -5192 t CO_2-eq./year.

Another approach is to evaluate digestate production as opposed to other waste treatment methods. Logan and Visvanathan (2019) found that digestate had a GHGs emission of 139 g CO_2-eq./kg waste while conventional treatment of organic municipal solid waste had an emission of 568 g CO_2-eq./kg waste. This led to a GHG emission reduction of 75% which suggested that AD was a sustainable method for waste management. In addition, the authors emphasized the benefits of digestate such as a stabilization of waste, pathogen removal, and improved nutrient availability.

Very few articles report the environmental impact of digestate and biochar as a product, and these are briefly reviewed here. Breunig et al. (2019) did an LCA with dewatered digestate and biochar in California and estimated the CO_2, CH_4, and N_2O emissions over time and the C sequestration potential from land application. This article emphasized that C sequestration, increase soil C, and reduction of natural N_2O fluxes are the three categories with the greatest emission reduction potential. Authors found that digestate and biochar have a net GHG impact of -1.3 MMTCO_2-eq./year for a long-term (100 years) aspect in the state of California.

Another approach for estimating the environmental impact was done by Patel, Rathore, and Panwar (2021) who used the biochar-digestate's NPK-composition as a substitution for mineral fertilizer. The nutrient content in the fertilizer was a direct saving of GHG emissions and resulted in a saving of 6.5 tons of CO_2-eq. if it replaces synthetic fertilizer.

Some studies do LCAs of biochar production and C sequestration potential, where pyrolysis of organic wastes has been proved to be a significant approach for mitigating CO_2 emissions (Zhao, Yang, He, Zhao, & Wei, 2021). Ji, Cheng, Nayak, and Pan (2018) analyzed biochar production from crop straw after harvest and reported a 0.94 t CO_2-eq./ton straw emission reduction. An LCA analysis by Muñoz, Curaqueo, Cea, Vera, and Navia (2017) found that biochar fertilization on soil was able to reduce GHG emissions of 2.74 t CO_2-eq./ton biochar. This study also emphasized that the climate change impact category represented the greatest relative importance in the LCA due to the C storage potential of biochar. Matustik, Hnatkova, and Koci (2020) did a review of biochar-to-soil systems and found that the results exhibited a clear trend that biochar-soil amendments have benefits such as neutralizing the impact of crop production in terms of GHG emissions. The authors also stated that biochar production and handling are always counterbalanced by the C sequestration of biochar and/or energy production of syngas and bio-oil.

For the LCA of biochar-digestate, some aspects should be evaluated. One of the most important aspects is the long-term C storage of biochar. Another aspect is the GHG emission balance where digestate emits CO_2, N_2O, and CH_4. CO_2 emissions from fossil fuels are considered to have a net addition to GHG, while CO_2 from organic sources is considered neutral because it is a part of the carbon cycle (Dietrich, Fongen, & Foereid, 2020). Thus, CO_2 is not taken into account because it is part of the natural carbon cycle. Digestate does also emit some CH_4 due to the presence of methanogenic bacteria, where it is unclear if biochar promotes CH_4 volatilization (Breunig et al., 2019). The last GHG digestate emit is N_2O where biochar has been proven to mitigate this pollutant (Liu et al., 2018). Moreover, a GHG balance is given in Figure 4.

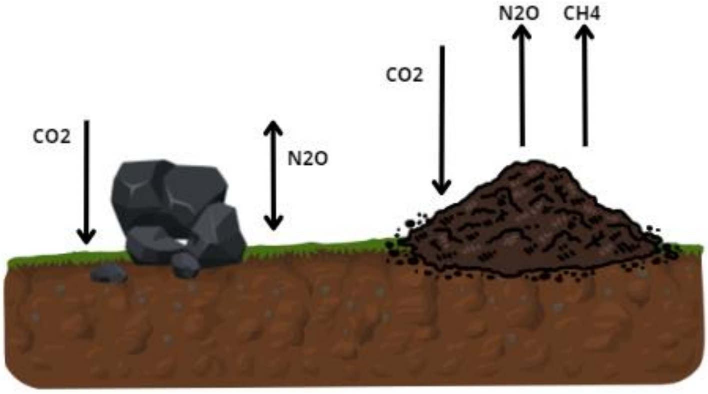

Figure 4: GHG balance of biochar and digestate.

3 Methodology

This chapter presents the overall vision of the research methodology applied in this study. Chapter 3.1 exhibits the system boundaries of the model which are made for evaluating the total emissions of applying biochar-digestate to the agricultural soil. This model can be used to evaluate the GWP of biochar-digestate as a fertilizer product compared to the LCA of synthetic fertilizer and digestate. The following chapters present the data inventory of the systems, biochar-to-digestate ratios, and the impact category.

3.1 LCA Framework

This chapter presents the LCA framework for the systems. LCA is a standardized method for evaluating the environmental impact of a product's life cycle and this method is applied in this thesis for specifically analyzing biochar-digestate, mineral fertilizer, and digestate applied to agricultural soil. The methodology is following the procedure explained in chapter 2.6.

3.1.1 Definition of Scope and Goal

Goal: The goal is to assess the GWP of applying biochar in the digestate and use it as a fertilizer in agriculture. Moreover, the fertilizer value is determined by the N cycle, C sequestration potential, and emissions related to handling the products.

System boundaries: The assessment begins with the digestate and the pyrolysis of feedstock and includes all emissions related to transports, preparations, and application of the fertilizer product. Moreover, the last step of the process is the utilization of the fertilizer product, and the total emissions from the system are compared to the use of mineral fertilizer. The system boundaries are shown in Figure 5. Note that the life cycle of the AD facility and digestate storage is omitted in the assessment as these are considered to be built and operated irrespectively of the digestate disposal pathway.

The analysis can be defined as a Gate-to-Cradle assessment because the analysis evaluates the digestate after the AD. Moreover, the environmental impact of the products and processes before digestate handling is omitted.

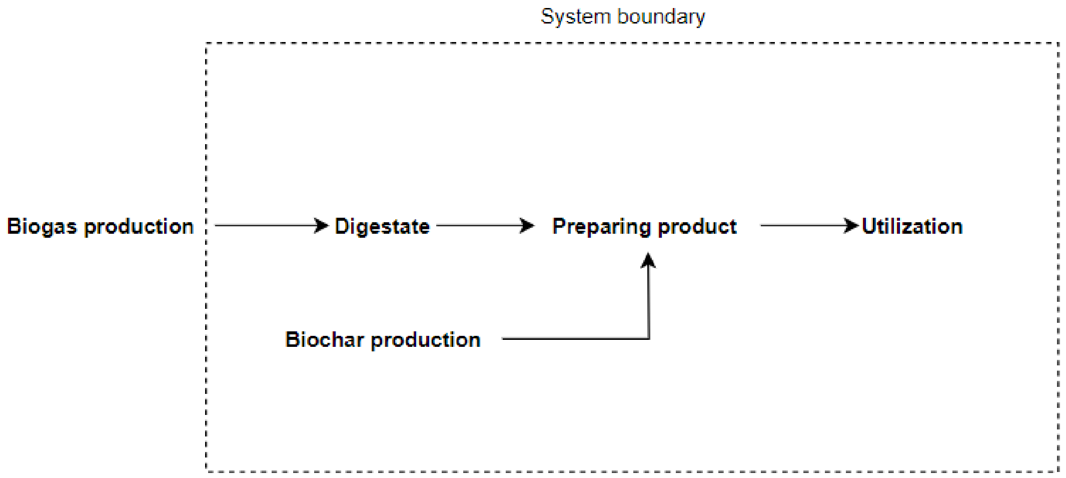

Figure 5: System boundaries for the environmental impact of digestate and biochar as a fertilizer product.

Functional unit: The functional unit for fertilizers is usually the weight of raw material or product (kg or ton) or surface area (decare (daa) or hectare) (Skowrońska & Filipek, 2014). According to Yara (2020), the N application rate depends on the crop type and when the crop is set into the soil. It is more common to sow seeds during spring and fertilization is done one or more times during the growing season. For barley and oat, it is common to fertilize with 11.1 kg N/daa which expects a crop production of 500 crops/daa. Wheat requires 12.1 kg N/daa for the same crop production. Data for barley is used because it is one of the main harvested crops in Norway.

Furthermore, the functional unit of this system is 11.1 kg N/daa. The functional unit will therefore be CO_2-eq./(11.1 kg N/daa) but is written as CO_2-eq./daa in the results.

3.1.2 System Boundaries

The model follows the digestate and biochar through the value chain. There are two additional scenarios for comparison: mineral fertilizer and digestate. Figure 6 shows the general value chain of the systems. All the scenarios' life cycle phases are explained in the following section.

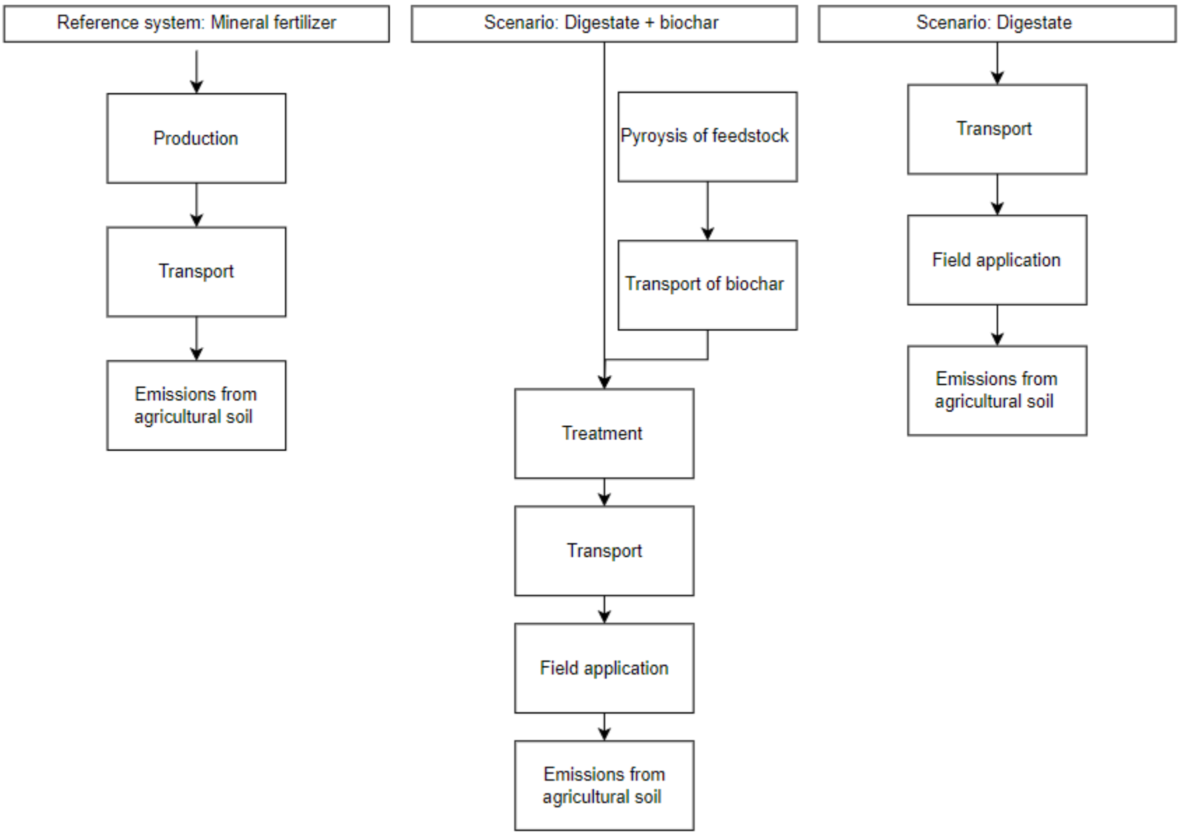

Figure 6: The system boundaries of the three scenarios: Mineral fertilizer, biochar-digestate, and digestate.

Biochar-digestate is the main system to be analyzed. The assessment starts with the digestate leaving the AD facility. It is assumed that the digestate is separated before biochar is added thus the emissions emitted for this stage are omitted. In addition, emissions from the storage of digestate are not considered. Bransjenormen's methodology for digestate characterization in relation to the inlet feedstock is used to assess the digestate composition. The digestate composition is used to evaluate the N and C for then assessing the N losses and C stored. Moreover, there is no transport of digestate to the stirring facility as it is assumed that the stirring tank is located at the AD facility. Biochar production starts with the pyrolysis of the feedstock, which means emissions involving the transport or pretreatment before the pyrolysis is not included. After pyrolysis, the biochar is transported to the AD facility for stirring and preparation. Biochar-digestate is transported from the AD facility to the farmland for field application. The application involves pumping and spreading on the field. For simplification, stirring, pumping, and spreading of biochar-digestate is one category in the final results. The last phase of the value chain is the emissions from agricultural soil which involve CH_4 emissions and direct and indirect N pollution.

Digestate (0% biochar) is a scenario for comparison. This analysis involves the same steps as biochar-digestate besides those phases of biochar production and transport.

Mineral fertilizer is the reference system of the model. The first phase involves the emissions of producing the product. It is assumed that the NH_4^+-N in the mineral fertilizer should be equivalent to the digestate's content, which coincides with the methodology of Hanssen, Arnøy, Morken, Briseid, and Sørby (2016). The second phase is the transportation of the mineral fertilizer to the farm while the last phase accounts for emissions relating to applying the fertilizer to the soil.

3.2 Life Cycle Inventory

This chapter presents the data selected for the Excel file including assumptions and estimates. The methodology and structure are the same as for Bransjenormen, which is a tool made by Carbon Limits to calculate the climate impact of the entire value chain of production and use of biogas and digestate. Bransjenormen is an excel tool where the user is meant to insert data such as feedstock, biogas yield, transport, etc. for their production facility. This thesis gives an additional Excel tool for calculating the environmental impact of biochar-amended digestate. The aim is to obtain the net GWP of biochar in digestate and compare that to mineral fertilizer.

3.2.1 Emissions from Electricity and Fuel

The emissions relating to fuel are source dependent, such as electricity derived from fossil fuels has a greater environmental impact than electricity from renewable energy. The data used in this module is collected from Bransjenormen.

Electricity is used for the pyrolysis of raw material to biochar. Two types of electricity mixtures are used for comparison, one for a more general case in Norway and one for Lindum specifically. EL- Nordic mixture is very common in Norway and the emission factor is 35.56 g CO_2-eq./MJ_{EL}. The other type of electricity mixture is EL-Norway (BIOGRACE), which is the electricity mixture Lindum uses (personal communication) and the emission factor is 2.72 g CO_2-eq./MJ_{EL}.

Diesel is used in machinery for spreading, pumping, and stirring the digestate mixture. The emission from diesel for machinery is 79.30 g CO_2/MJ. Moreover, diesel is also used for the transport of fertilizer to the farm and the emission factor for transport is 75.04 g CO_2/MJ.

The LCA includes transport of digestate, biochar-digestate, and mineral fertilizer to the spreading site but also transport of biochar to TMF. Moreover, the energy consumption is dependent on the transport distance, the size of the truck, the type of fuel, and if the truck will have return freight. It is assumed that there will be a return freight for the digestate transport, meaning that manure or other agricultural wastes will be transported to the AD facility after digestate disposal. This coincide with what Morken, Briseid, Hovland, Stensgård, et al. (2017) stated in their report. For the biochar and the mineral fertilizer, it is assumed that there is no return freight. Data for energy consumption was collected from Bransjenormen and is given in Table 2.

Table 2: Energy consumption for the transport of fertilizers. Data is taken from Branjenormen.

Transport	**FULL** (MJ/t.km)	**Empty** (MJ/t.km)	**Total for roundtrip** (MJ/t.km)
Truck 12 ton, liquid fuel	0.72	0.50	1.22
Truck 33 ton, liquid fuel	0.56	0.26	0.82

3.2.2 Digestate Characteristics

The data about the feedstock characteristics are taken from Bransjenormen and are used to determine the digestate composition for further analysis (see Table 3). The total solid (TS) content in the feedstocks is determined by Lindum and is given in chapter 3.2.7.

Table 3: Digestate composition determined by the inlet feedstock. Data is taken from Bransjenormen.

Type of feedstock	**Description**	**VS (%TS)**	**VS removed (%VS)**	**C (%TS)**	**Total N (kg N/ton TS)**	**NH_4^+-N (%N)**	**P (kg P/ton TS)**
Organic household waste	Food waste etc.	85 %	70 %	49 %	41	60 %	4.7
Organic institutional household waste	Food waste from institutions and companies.	85 %	70 %	49 %	41	60 %	4.7
Swine manure	-	90 %	55 %	52 %	64	74 %	17
Grease	Grease from grease remover from food production	95%	90%	55%	0	0%	0

The NH_4^+ content will likely increase after digestion, but this is not a sure expectation, thus it is assumed that the NH_4^+ will remain constant during digestion, which corresponds to Bransjenormen's assumption. It is also assumed that the N and P will remain the same after digestion. For the C, it is assumed that the remaining C in the digestate is following this relation:

$$C_{digestate}[kg] = C_{feedstock} - C_{gas}$$

It is assumed that C_{gas} includes C losses from storage.

Regarding the distribution of plant-available N, it is assumed that the total liquid fraction will go through the separation process in the biogas production plant while some of the solid fraction will be removed. Currently, TMF uses a fiber separation unit to remove plastics in the digestate resulting in little organic solid separation. Fiber separation allows safe disposal of digestate where the digestate value remains. This is not a typical solid-liquid separation, where conventional solid-liquid separation tends to have some NH_4^+ in the solid phase as well, approximately 20-30% (Logan & Visvanathan, 2019). However, fiber separation does not remove solids in the same way as conventional separation. Thus it is assumed that the entire liquid fraction and most of the solid fraction will remain in the digestate for further use as a fertilizer. Fiber separation is mainly removing plastics, but some digestate solids are also removed and a final TS value of 4.5% is estimated (personal communication with Lindum). Moreover, it is assumed that the liquid fraction will go unchanged through the fiber separation.

Some C in the digestate will be stored for long-term storage, and this thesis estimates that 20% of total C will be sequestrated (Hanssen et al., 2016). According to Bransjenomen, the humification factor ranges from 27% (for manures) to 67% (for garden and agricultural waste). Another study suggested that the C sequestration potential was 2-14% (Galgani, van der Voet, & Korevaar, 2014). Taking into account these data, there is a variety and uncertainty regarding estimating the C sequestration factor, however, 20% can be seen as a value in the middle of all other data, and therefore it is used.

3.2.3 Soil N_2O and CH_4 Emissions from Digestate

Nitrogen emissions from soil have two pathways: direct and indirect. N_2O emissions can directly come from the soil where fertilizer is applied and can come indirectly from NH_3 and NO_x volatilization, and leaching and runoff, mainly as NO_3^- (IPCC, 2006). Direct N_2O emission is estimated to be 0.01 kg N_2O-N/kg N (IPCC, 2006). The indirect N_2O emission from volatilization is 0.21 (kg NH_3-N + NO_x-N)/kg N applied (Norwegian Environment Agency, 2020a). In addition, some indirect emission is associated with leaching/runoff and approximately 22% of applied N will be leached/runoff which has an environmental impact of 0.0075 kg N_2O/kg N leached/runoff (Norwegian Environment Agency, 2020a).

Following Breunig et al. (2019), CH_4 emissions are estimated to be 0.05% of total labile C in digestate. Breunig et al. (2019) suggest that biochar addition in digestate enhances C losses in the form of CH_4, but because of limited studies on biochar's effect on CH_4 volatilization, it is not considered. Therefore, CH_4 emissions will be the same for just digestate application and biochar-digestate application.

3.2.4 Biochar

Pyrolysis temperature is an important factor for both the mineralization of C, but also for the biochar properties. Biochar made at lower temperatures has different properties compared to biochar made at higher temperatures. Given the recalcitrant nature of biochar, it is very stable in the soil compared to organic matter. However, biochar is not entirely inert and some C is labile and can mineralize through biotic and abiotic processes (Goswami, Pant, Mansotra, Sharma, & Joshi, 2021). Biochar pyrolyzed at lower temperatures mineralizes faster than biochar formed at a higher temperature, because the temperature increases aromaticity (Goswami et al., 2021). According to IPCC (2006), 65% of initial C will remain in biochar after 100 years if biochar is pyrolyzed at 350°C, and 89% will if biochar is pyrolyzed at 650°C. In addition, the adsorption capacity is influenced by the pyrolysis temperature. High pyrolysis temperature facilitates the formation of micropores and increases the surface area (Shackley et al., 2016). Aligning with this theory, Yang et al. (2018) found that pine sawdust pyrolyzed at 550°C had a higher adsorption rate at 300°C. Therefore, this thesis uses biochar made at 600°C because of the beneficial properties experienced at greater pyrolysis temperature. In addition, scientific works widely employ biochar made at 600°C in their experiments (Budai et al., 2021; Kizito et al., 2015).

Lindum's facility provides biochar from garden waste processed at 600°C. Data for the elemental composition of biochar is taken from a master thesis who experimented at Lindum's facility. Pine and spruce were pyrolyzed for 3 hours in a microwave-assisted pyrolysis unit and the C content was 92.4% (dry weight) (Fallas Yamashita, Martinsen, & Stoknes, 2021).

Both process parameters and feedstocks are important for the biochar properties (Shackley et al., 2016). Garden waste which is abundant in wood is used as feedstock for biochar production because only pure feedstocks such as wood are allowed in agriculture in Norway (Prestvik & Lilleby, 2021). Also, woody biochar is characterized to have a higher surface area as opposed to other biochar feedstocks which is a very beneficial property in terms of water and nutrient retention (Kizito et al., 2015; Shackley et al., 2016). Process conditions are some of the major factors for deciding the biochar properties and product yield. Both process temperature and heating rate such as slow or fast pyrolysis have some impact on the biochar production, however, it was difficult to find a correlation and use that in the analysis. The pyrolysis process is done by a microwave-assisted unit, where little information is found regarding the production yield. Therefore, it is assumed that the process yield is the same as for a slow pyrolysis process. Data about feedstock input was found in Crombie and Mašek (2015), where 2.23 kg and 3.03 kg of wood were pyrolyzed at 350°C and 650°C, respectively, to obtain 1 kg biochar. It is assumed that the input is linear to the temperature, thus biochar made at 600°C requires 2.90 kg of lignocellulosic material. The yield correlates to the yields approximated by Shackley et al. (2016), given in Table 1. Also, Meyer, Glaser, and Quicker (2011) state that biochar production is approximately 30% of the dry wood feedstock (in mass). The energy required for woody biochar is approximately 0.57 kWh/kg of wood for an effective pyrolysis process (Joseph, Taylor, & Cowie, 2018).

The biochar-to-digestate ratios are given in either by w/w (weight of biochar/total weight) or L/ton separated digestate. In the latter case, it is necessary to know the density of biochar. Lindum provides biochar at 675 g/L at approximately 50% TS (from personal communication with Lindum).

For the C balance of biochar, it is understood that the biochar is very resistant to oxidation, but some C is labile. It is assumed that no CH_4 is emitted during the decay of biochar thus all C not remaining in the biochar after 100 years are emitted as CO_2 (Breunig et al., 2019). According to IPCC (2006), the labile fraction of biochar is dependent on process temperature, where the amount of C remaining in the biochar after 100 years is 89% for biochar produced at 600˚C. It is assumed that the C is oxidized linearly in the 100 years, but no records can be found.

For the N_2O mitigation of biochar, it is assumed that N is immobilized in the biochar thus preventing it to volatilize and that the biochar releases the NH_4^+-N slowly into the agricultural soil. Data about the biochar's adsorption capacity is taken from Kizito et al. (2015) who found that biochar (at pyrolysis temperature at 600 ˚C) could adsorb 44.64 mg NH_4^+-N/g in an anaerobic digestate slurry of piggery manure.

3.2.5 Spreading on Field

The energy consumption for spreading on the field involves mixing, pumping, and spreading with a hose. These data are taken from Hanssen et al. (2016) and are found in Table 4. The energy in diesel is 37.3 MJ/L (Simonsen, 2009). Stirring, pumping, and spreading are involved in the digestate mixtures whereas only pumping and spreading are used for mineral fertilizer.

Table 4: Diesel consumption for stirring, pumping, and spreading the fertilizers (Hanssen et al., 2016).

Diesel consumption	**Value (l diesel/m^3)**	**Comments**
Stirring	0.045	Assuming a diesel consumption of 15 l/h and 2-3 h of stirring.
Pump	0.1	Diesel consumption by tractor involves pumping from storage to tank or hose for spreading.
Spreading	0.28	For tanks greater than 15 m^3.

3.2.6 Synthetic Fertilizer

Data about the synthetic fertilizer production was found in Bransjenormen (see Table 5). For the soil emissions, data from IPCC (2006) were used. The direct N_2O emission factor for synthetic fertilizers, organic amendments, crop residues, and N mineralized from mineral soil as a result of loss of soil carbon is 0.01 kg N_2O-N/kg N applied. For the indirect N_2O emission factor, NH_3 and NO_x volatilization from synthetic fertilizer has the emissions factor of 0.11 kg (NH_3-N + NO_x-N)/kg N applied. The amount of nitrogen leached/runoff for synthetic fertilizer is according to IPCC the same as for organic amendment thus data from the Norwegian Environment Agency (2020a) is used, see chapter 3.2.3.

Table 5: Fertilizer data. Data is taken from Bransjenormen.

Fertilizer type	**Value**	**Unit**
Fullgjødsel 22-2-12	3.81	kg CO2-eq./kg N
Fullgjødsel 22-2-12	4.19	kg product/kg N

3.2.7 TMF Data Input and Output

Data for the transport of digestate and biochar-digestate was suggested by Lindum (personal communication). It was estimated a transport distance of 30 km and that the truck had a capacity of 33 tons whereas the factual capacity is 25 tons and uses diesel as fuel.

For the transportation of mineral fertilizer, it is assumed that the truck size of 12 tons and the factual capacity is 10 tons. The transport distance is assumed to be the distance between Yara and TMF where the transport distance is approximately 130 km.

The biochar is transported from Lindum to TMF, which is a short distance and is approximately 200 meters. It is assumed that the biochar transportation uses a 12-ton truck where the factual capacity is 10 tons.

Characteristics of feedstock supplied to TMF were given by Lindum and were data for 2021, see Table 6. The livestock manure module in the table is a collection of manure from livestock, swine, and poultry and is used as process water and has a stabilizing effect on AD (Lyng & Saxegård, 2020).

Table 6: Feedstock composition received at TMF for 2021 (from personal communication with Lindum).

Feedstock for AD	**Mass (ton (wet)/year)**	**TS**
Household food waste	49 919	33%
Institutional food waste	14 753	24%
Livestock manure	80 078	8%
Household food waste*	7 306	15%
Grease	5 369	12%

*Two types of household food waste are listed, with unknown reasons besides different TS.

Besides feedstock, output characteristics were also given by Lindum, and those are given in Table 7. It is assumed that the biogas consists of CH_4 and the rest is CO_2, even though there might be some percent of NH_3, H_2S, etc.

Table 7: Output parameters from the AD process at TMF for 2021 (from personal communication with Lindum).

Output parameters	**Value**
Digestate	150 153 tons annually
Digestate TS	4.5%
Biogas	16 383 tons annually
Methane (CH_4)	64%
Carbon dioxide (CO_2)	36%

3.2.8 Summary of Data Inventory

A summary of inventory data is given in Table 8, excluding input and output data for TMF.

Table 8: A summary of inventory data used in this analysis.

LCA characteristics	**Emission factor/data**	**Reference and comments**
EL- Nordic mixture	35.56 gCO_2-eq./MJ_{EL}	Bransjenormen (Excel tool)
EL- Norway (BIOGRACE)	2.72 gCO_2-eq./MJ_{EL}	Bransjenormen (Excel tool)
Transport		
Transportation fuel, diesel	75.04 gCO_2/MJ.	Bransjenormen (Excel tool)
Synthetic Fertilizer		
Fullgjødsel 22-2-12	3.81 kg CO2-eq/kg N	Bransjenormen
Emissions from field application		
Digestate direct N_2O emission	0.01 kg N_2O-N/kg N	(IPCC, 2006)
Digestate indirect N_2O emission	*Volatilization:* 0.21 (kg NH_3-N + NO_x-N)/kg N 0.01 kg N_2O-N/(kg NH_3-N + NO_x-N volatilized) *Leaching:* 0.0075 kg N_2O/kg N $Frac_{Leach}$ 0.22	(Norwegian Environment Agency, 2020a)
Digestate CH_4 emissions	0.05% of total labile C	Breunig et al. (2019)
Synthetic fertilizer direct N_2O emission	0.01 kg N_2O-N/kg N	IPCC (2006): Includes synthetic fertilizer, organic amendments and crop residues, mineralized N.

Synthetic fertilizer indirect N_2O emission	*Volatilization:* 0.11 (kg NH_3-N + NO_x-N)/kg N 0.01 kg N_2O-N/(kg NH_3-N + NO_x-N volatilized) *Leaching:* 0.0075 kg N_2O/kg N $Frac_{Leach}$ 0.22	IPCC (2006), (Norwegian Environment Agency, 2020a)
Biochar		
Biochar adsorption	44.64 mg NH_4^+-N/g	Kizito et al. (2015)
Spreading		
Emission factor for machinery (diesel)	79.30 g CO_2/MJ	Bransjenormen
Diesel consumption for stirring	0.045 L/m^3	Hanssen et al. (2016)
Diesel consumption for pumping	0.1 L/m^3	Hanssen et al. (2016)
Diesel consumption for spreading	0.28 L/m^3	Hanssen et al. (2016)

3.3 Biochar-to-Digestate Ratios

Three different biochar-to-digestate ratios are used for this assessment (see Table 9). The biochar-to-digestate ratios are given by Lindum's template and by an experiment conducted by Budai et al. (2021). The results from the experiment conducted by Budai et al. (2021) are evaluated in chapter 2.5.2.

Another important aspect is the electricity mixture because it is used to evaluate the emissions from pyrolysis. Lindum uses EL-Norway (BIOGRACE) for their biochar production (personal communication), but it is also interesting to evaluate the LCA for a more general case by using a more common electricity mixture in Norway (EL- Nordic mixture). Both electricity mixtures will be applied to all of the biochar-to-digestate scenarios.

Table 9: Biochar-to-digestate ratios used in the LCA. The first case is according to a template given by Lindum and the other cases are from field experiments conducted by Budai et al. (2021).

Biochar-to-digestate ratios	**Reference**
1 L/ton (0.07 % w/w)	According to Lindum's template
6.25 % w/w	Budai et al. (2021)
12.5 % w/w	Budai et al. (2021)

3.4 Global Warming Potential (GWP)

The GWP is often given in CO_2-equivalents, and a factor is used to convert GHGs to CO_2-eq. IPCC (2007) has developed conversion factors for different GHGs such as N_2O has a factor of 298 kg CO_2-eq./kg N_2O which means that N_2O is 298 times more potent than CO_2. CH_4 is 25 times more potent than CO_2. Other gases mentioned in this thesis are NH_3 and NO_x but these do not have any direct climate change impact, however, they are precursors for N_2O. The emissions factor of NH_3 and NO_x is 0.01 kg N_2O-N/(kg NH_3-N + NO_x-N volatilized) leading to 3.86 kg CO_2-eq./kg NH_3 and 1.43 kg CO_2-eq./kg NO_x (IPCC, 2006).

Most of the emissions are given in terms of N, which must be converted. One example is:

$$N_2O = N_2O\text{-}N \cdot 44/28.$$

An LCA usually includes the assessment of several impact categories such as excessive fertilization and acidification in soil (Lyng & Saxegård, 2020). This thesis only focuses on the GWP category. It is important to be aware that assessments done with other impact categories can give other conclusions.

4 Results

This chapter presents the results of the LCA conducted in this thesis. The purpose of this LCA was to evaluate the GWP of biochar-digestate on agricultural soil. The data gathered in this study was collected through literature research with the aim to validate the LCA results with similar studies.

4.1 Digestate Composition and Synthetic Fertilizer

The digestate characteristic is used to estimate the equivalent amount of synthetic fertilizer.

The amount of organic fertilizer and synthetic fertilizer applied per daa:

- Organic fertilizer: 1.82 tons of digestate for 11.1 kg N/daa with or without biochar.
- Synthetic fertilizer: 46.5 kg product/daa correspond to 11.1 kg N/daa.

Digestate characteristics produced at TMF and applied per daa are given in Table 10. The digestate has a total nitrogen content of 9.10 kg N/ton and the amount of plant-available nitrogen is 6.09 kg NH_4^+-N/ton.

Table 10: Estimated digestate characteristics for digestate at TMF.

Characteristic	**Value**
TS	4.5%
C	71.9 kg C
C stable	14.4 kg C
Total N	16.6 kg N
NH_4^+-N	11.1 kg NH_4^+-N
P	2.5 kg P
Mass	1.82 ton

4.2 LCA Results

This subchapter exhibits the results obtained after the LCA of the three different biochar-to-digestate ratios. Moreover, the values for each impact are tabulated in Appendix B.

4.2.1 Reference System

The reference system is mineral fertilizer application in the amount of 11.1 kg N/daa. Emissions related to mineral fertilizer are production, transport, spreading, and N_2O emissions. Moreover, the total emissions related to mineral fertilizer are 109 kg CO_2-eq./daa (see Figure 7).

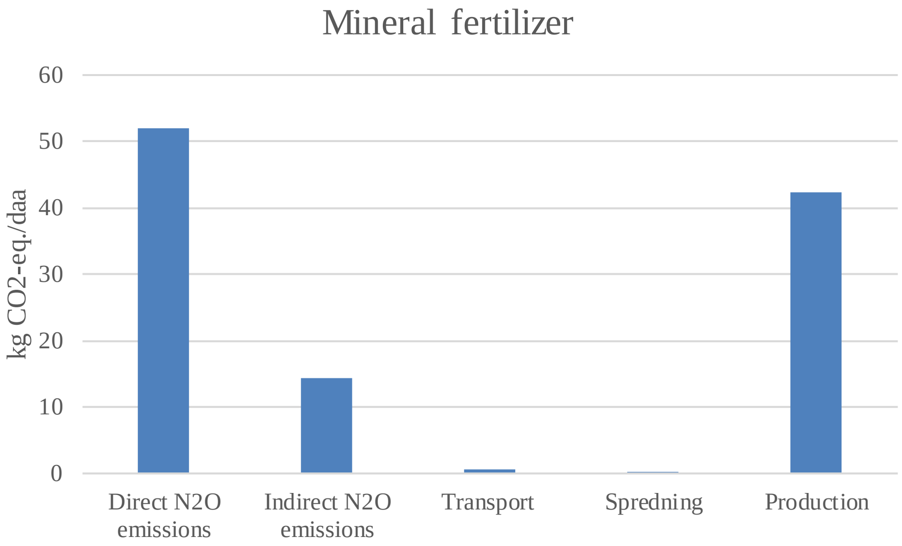

Figure 7: Emissions related to applying mineral fertilizer to the soil. The application rate on agricultural soil is 11.1 kg N/daa.

4.2.2 Digestate Scenario

Another scenario is to evaluate the GWP of digestate to compare it with synthetic fertilizer and biochar-digestate. Digestate emissions are related to spreading, soil emissions (N_2O and CH_4), transport, and digestate C sequestration (see Figure 8). The total emissions of digestate as a fertilizer is 24 kg CO_2-eq./daa resulting in a 78% emission reduction compared to the reference system.

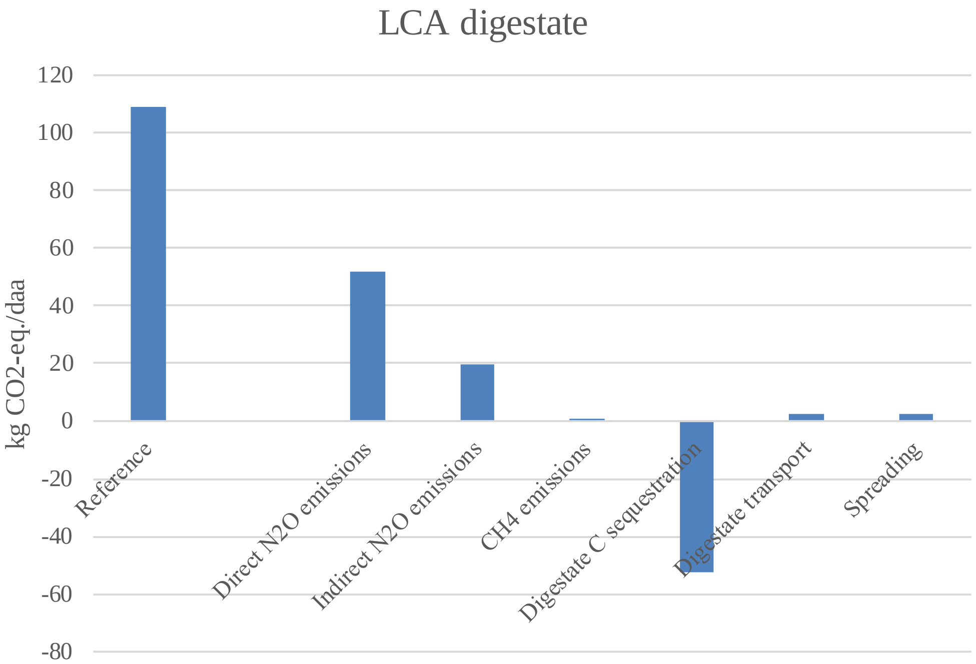

Figure 8: Emissions related to digestate as a fertilizer. The application rate on agricultural soil is 11.1 kg N/daa. The reference system is mineral fertilizer.

4.2.3 Biochar-to-Digestate Ratios

The three biochar-to-digestate ratios are 0.07% w/w, 6.25% w/w, and 12.5% w/w, where all three cases are evaluated for two types of electricity mixtures: EL-Norway (BIOGRACE) and EL-Nordic mixture. Emissions related to these scenarios are transport, soil emissions (N_2O and CH_4), spreading, and C sequestration (biochar and digestate).

Figure 9 and Figure 10 show the results obtained for 0.07% biochar with the two types of electricity mixtures, respectively. Total emissions for both these systems are 22 kg CO_2-eq./daa.

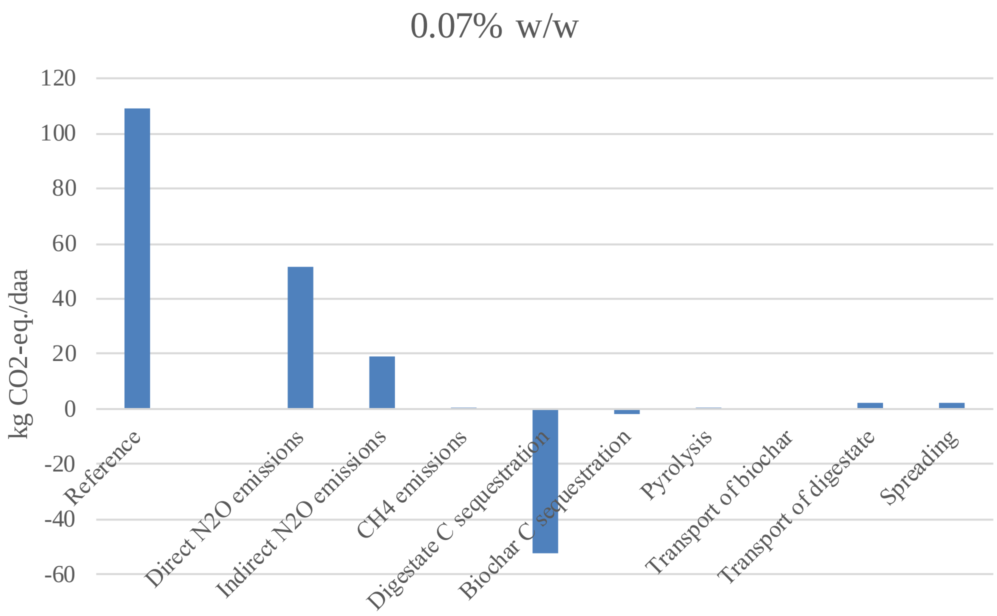

Figure 9 Results from the LCA of 0.07% w/w biochar in digestate. The electricity mix is EL-Norway (BIOGRACE) which has an emission factor of 2.72 g CO_2-eq./MJ. The organic mixture is applied to agriculture by surface area: 11.1 kg N/daa. Mineral fertilizer is the reference system.

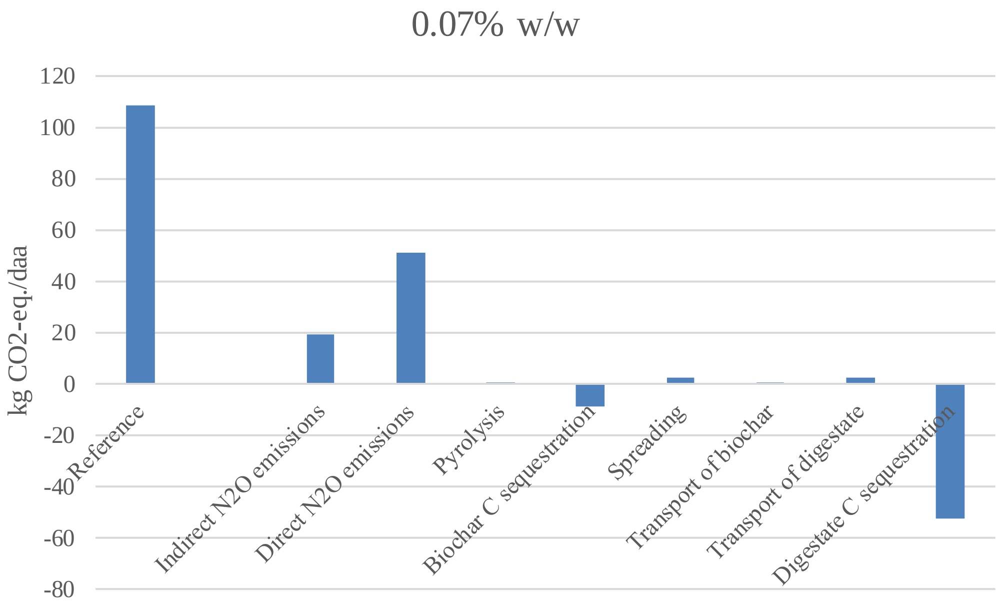

Figure 10: Results from the LCA of 0.07% w/w biochar in digestate. The electricity mix is a Nordic mixture with an emission factor of 35.56 g CO_2-eq./MJ. The organic mixture is applied to agriculture by surface area: 11.1 kg N/daa. Mineral fertilizer is the reference system.

Another case is 6.25% w/w biochar, and the results from the LCA are given in Figure 11 and Figure 12. The total emissions for these cases are -214 kg CO_2-eq./daa and -190 kg CO_2-eq./daa, respectively.

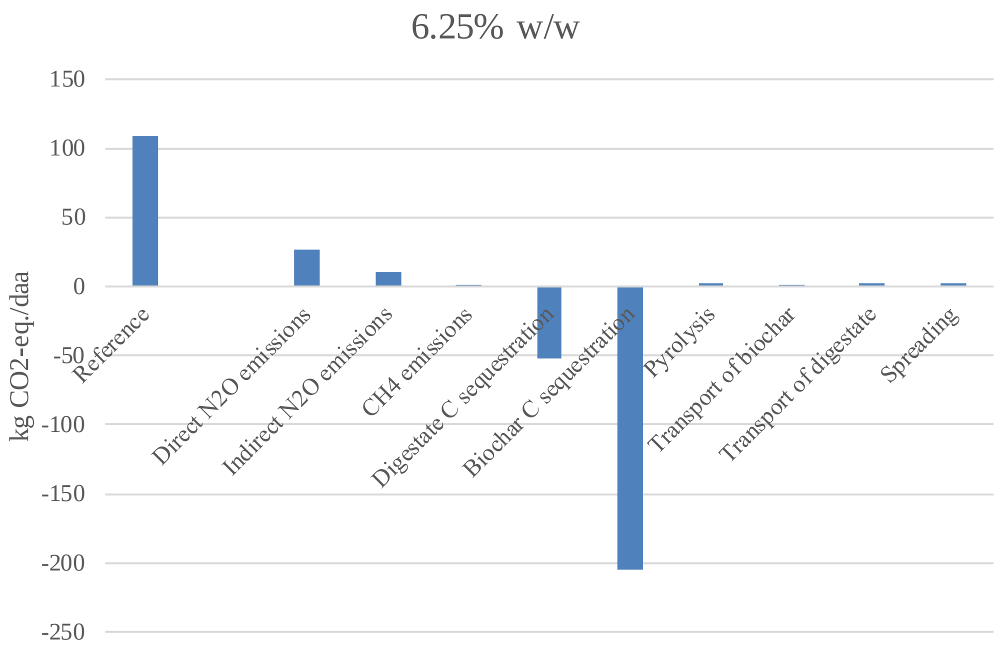

Figure 11: Results from the LCA of 6.25% w/w biochar in digestate. The electricity mixture is EL-Norway (BIOGRACE) with an emission factor of 2.72 g CO_2-eq./MJ. The organic mixture is applied to agriculture by surface area: 11.1 kg N/daa. Mineral fertilizer is the reference system.

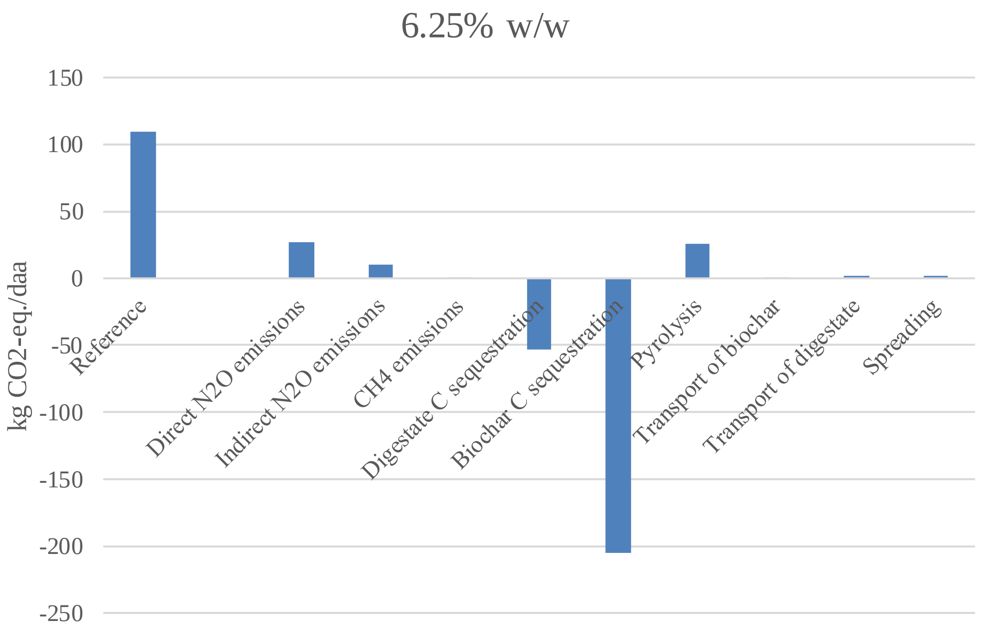

Figure 12: Results from the LCA of 6.25% w/w biochar in digestate. The electricity mixture is a Nordic mixture with an emission factor of 35.56 g CO_2-eq./MJ. The organic mixture is applied to agriculture by surface area: 11.1 kg N/daa. Mineral fertilizer is the reference system.

The last scenario is the case where the biochar-to-digestate ratio is 12.5% w/w and the results from the LCA are given in Figure 13 and Figure 14. Total emissions are -483 and -432 kg CO_2-eq./daa for the two EL mixtures, respectively.

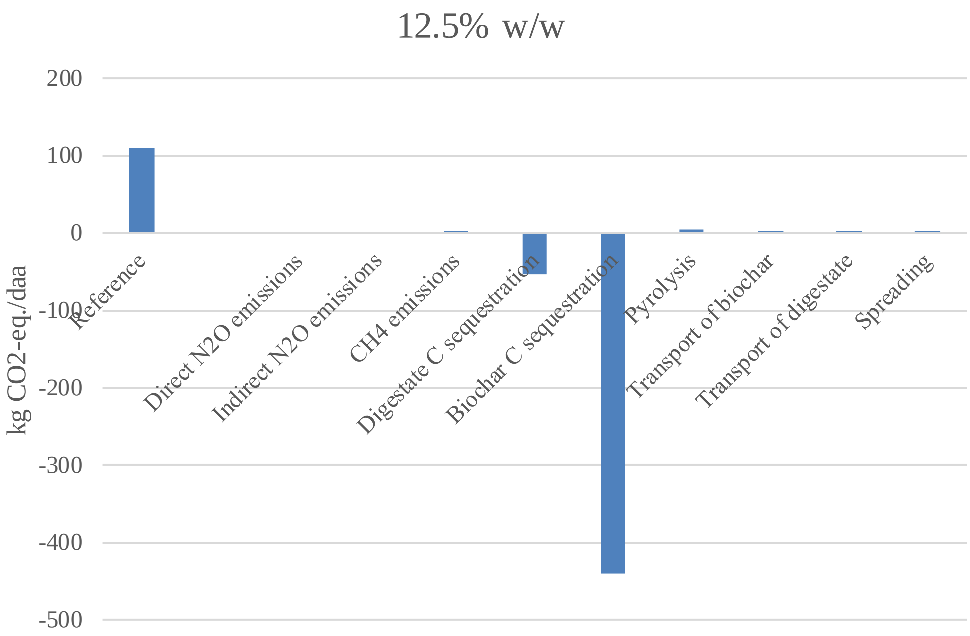

Figure 13: Results from the LCA of 12.5% w/w biochar in digestate. The electricity mixture is EL-Norway (BIOGRACE) with an emission factor of 2.72 g CO_2-eq./MJ. The organic mixture is applied to agriculture by surface area: 11.1 kg N/daa. Mineral fertilizer is the reference system.

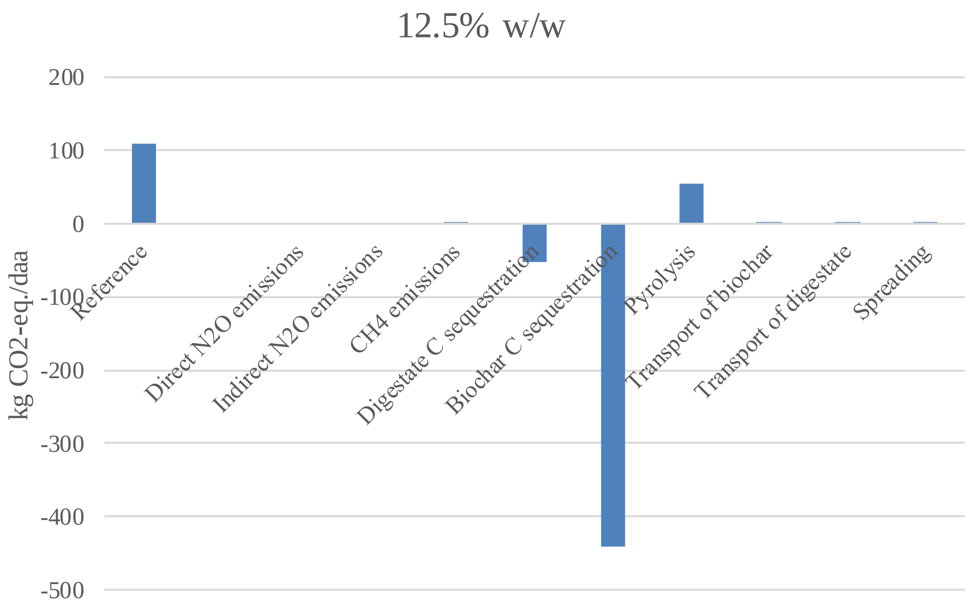

Figure 14: Results from the LCA of 12.5% biochar in digestate. The electricity mixture is a Nordic mixture with an emission factor of 35.56 g CO_2-eq./MJ. The organic mixture is applied to agriculture by surface area: 11.1 kg N/daa. Mineral fertilizer is the reference system.

4.2.4 Comparing LCA Results

The LCA results in the previous subchapters are summarized in Figure 15.

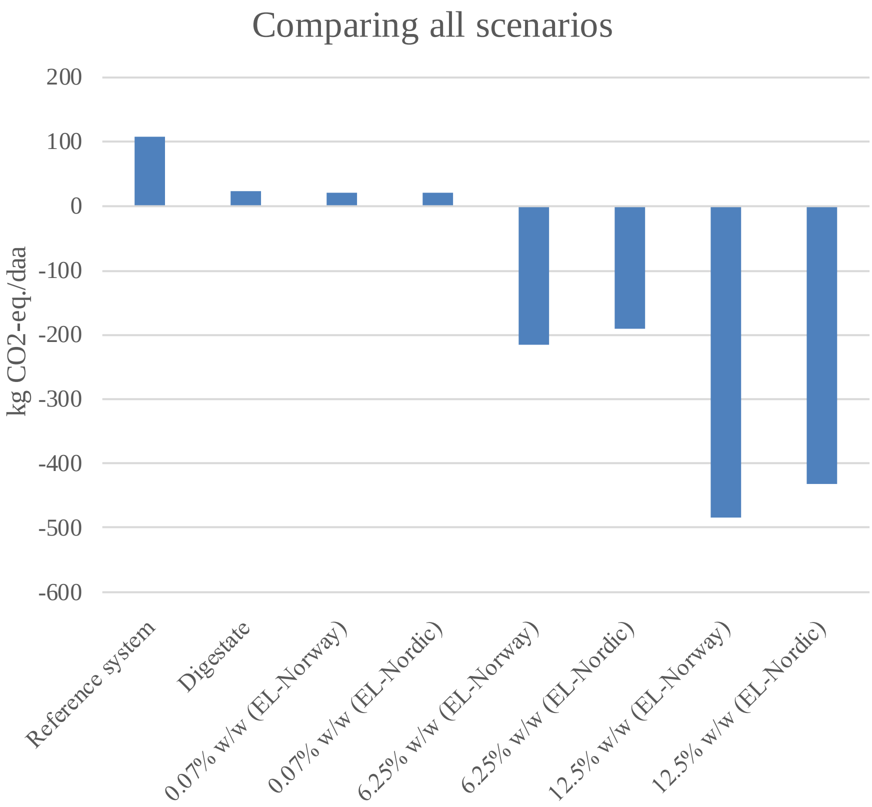

Figure 15: Comparison between all the LCA results. The reference system in mineral fertilizer.

5 Discussion

This chapter examines the results obtained from the LCA of the three different biochar-to-digestate ratios and discusses the data selection, uncertainties, and GWP of the results. Moreover, the last part of the chapter provides a prospect of biochar in the future.

5.1 The Digestate Characteristics

The most important digestate characteristic in this thesis is the plant-available nitrogen which was determined by Bransjenormens' method and data set. Ammonium concentration was estimated to be 6.09 kg NH_4^+-N/ton which corresponds to 6090 mg NH_4^+-N/L and 0.61% of fresh matter weight. This value is considerably high in comparison to what Cottis et al. (2022) found for their experiment, 1.76 kg N/ton. Another article also experienced lower plant-available nitrogen in the digestate, 1108.8 mg/L (Zhang et al., 2020). A review by Nkoa (2014) estimated that the ammonium-N concentration range from 0.12-0.53% of fresh matter weight. The estimated ammonium concentration is above the range of what Nkoa (2014) found. In addition, the digestate can in this thesis substitute mineral fertilizer by a factor of 25.5 kg mineral fertilizer/ton while Lyng and Saxegård (2020) estimated 18 kg/ton. Furthermore, the plant-available nitrogen concentration is dependent on the inlet feedstock, but based on other findings, the estimated concentration in this thesis is assumed to be high.

5.2 Feedstock for Biochar Production

Exploring other types of feedstocks for biochar production could be interesting for evaluating the environmental impact of other biochar and digestate mixtures. Other feedstocks can give biochar different structures and other concentrations of recalcitrant or labile C. According to IPCC (2006), wastewater sludge has the lowest level of recalcitrant C at 35% and lignocellulosic material has the highest level of 77%. Data used for this analysis is from a master thesis where the author did an elemental analysis of biochar made from pine and spruce at Lindum's facility with a process temperature of 600°C in a microwave-assisted pyrolysis unit. The author found that the biochar composition was 92.4% C, 1.5% H, 4.1% O, 0.22% N, 0.05% S, and 0.03% P (on dry basis) (Fallas Yamashita et al., 2021). This thesis does not use pine and spruce directly as feedstock but uses garden waste, however, it is assumed that garden waste is abundant in lignocellulosic material. The C content in the reported biochar is relatively high, but other authors reported that woody biochar has a C content of >90% (dry basis) (Lehmann & Joseph, 2015). A critical review estimated that woody biochar during slow pyrolysis had a C content of 95% (dry basis) (Meyer et al., 2011). Due to the high C content, lignocellulosic biochar exhibits a greater C sequestration resulting in a greater climate change impact compared to other feedstocks. This statement is also supported by Moreira, Noya, and Feijoo (2017) who did a review of different biochar systems and found that lignocellulosic waste had the highest environmental impact benefits.

In general, lignocellulosic biochar presents a positive energy balance due to the feedstock's high energy content (Chiappero et al., 2020). However, lignocellulosic waste can as opposed to purpose-grown organic material, have contaminants such as heavy metals, dioxins, and PAHs. This risk is not taken into account in the LCA, but there is a relatively low chance of experiencing PAHs when the feedstock is pyrolyzed at temperatures above 350°C (Sintef, 2017).

Using waste as feedstock for pyrolysis also faces the advantage of avoided waste management which serves additional environmental benefits (Matustik et al., 2020). Moreover, taking into regard that the feedstock used in this thesis is garden waste meaning that most of the waste is lignocellulosic material, the environmental impact benefit is at its greatest and will probably be lower with other types of feedstocks.

5.3 Discussion of LCA Results

This subchapter examines the results obtained from the LCA with the aim to compare the results to similar studies.

5.3.1 LCA of the Reference System

The reference system is mineral fertilizer and the LCA of mineral fertilizer includes transport, soil emissions, and production. Mineral fertilizers have a significant energy consumption due to the production of nitrogen, where 90% of the global energy input is used to produce nitrogen in the fertilizer (Skowrońska & Filipek, 2014). The production of mineral fertilizer in this thesis accounted for 39% of the emissions in the total system, the direct N_2O emissions for 48%, indirect N_2O emissions for 13%, and transport and spreading accounted for less than 1%. Hasler, Bröring, Omta, and Olfs (2015) did an LCA of different mineral fertilizer types and found that the production of mineral fertilizer had the largest impact on the LCA due to the use of fossil fuels. These authors found that N_2O emissions from field applications accounted for approximately 15-20% of the system's emissions (Hasler et al., 2015). The N_2O emissions have a significantly lower impact than the results obtained for the LCA in this thesis, but this might be due to the lower application rate of nitrogen (5.1 kg N/daa). In addition, Hasler et al. (2015) found that production accounted for 70-80% of the total system, which is significantly higher than the results in this thesis. This effect can be explained by the type of fuel used for production since Norway has a lower emission factor for its electricity production than other countries in Europe. In addition, Hasler et al. (2015) did include emissions from the extraction and mining of raw material which is not included in this thesis. Moreover, Hasler et al. (2015) estimated that the total GHG emissions from NPK 17-5-13 were 95-110 kg CO_2-eq./(5.1 kg N/daa), which is higher than what this thesis suggests, 109 kg CO_2-eq./(11.1 kg N/daa).

One of the uncertainties with the LCA analysis in this thesis is the transport distance because it was difficult to evaluate. The transport distance is now evaluated as the distance from TMF to Yara, but the different minerals such as P and K are transported for longer distances (from mines in different countries). However, no data was found for the transportation distance of mineral fertilizer, thus transportation from Yara is assumed. Transport accounts for 0.5% of the emissions, which is significantly low compared to 1-3% of total emissions as Hasler et al. (2015) estimated.

Furthermore, the results obtained for the mineral fertilizer had the greatest impact in the N_2O emission category and the second was the production. Mineral fertilizer production had a lower impact than assumed and compared to other studies.

5.3.2 GWP of Digestate Compared to Mineral Fertilizer

The conversion of data for digestate and mineral fertilizer to annual values is necessary for comparing results to other studies (see Appendix C). The GWP of all digestate produced at TMF is 1784 t CO_2-eq., where the direct N_2O emissions have the greatest impact, and digestate C sequestration counterbalances this impact. Digestate C sequestration itself had a reduction potential of 3096 t CO_2-eq. which is close to the value Lyng and Saxegård (2020) found. The authors found that digestate can sequestrate 3897 t CO_2-eq. Mineral fertilizer in this thesis has a total GWP of 8088 t CO_2-eq. for the equivalent amount of available N. The largest impacts of the mineral fertilizer analysis are the N_2O emissions (4912 t CO_2-eq.) and the production of mineral fertilizer (3134 t CO_2-eq.). Lyng and Saxegård (2020) estimated that digestate replacement of mineral fertilizer resulted in a GWP of -3961 t CO_2-eq., which is based on the plant-available N in the food waste fraction of the digestate. According to these findings, Lyng and Saxegård (2020) estimate greater emissions of synthetic fertilizer production than this thesis, which might be a result of another emission factor for production (authors are using Fullgjødsel 18-2-15 and Fullgjødsel 22-3-10). Moreover, results show that applying digestate can reduce GHGs by 6303 t CO_2-eq. compared to mineral fertilizer, resulting in a 78% emission saving. For comparison to other studies which only assess the GWP of mineral fertilizer production and digestate C sequestration, the substitution effect is -7014 t CO_2-eq. This estimation is greater than what Morken, Briseid, Hovland, Stensgård, et al. (2017) estimated, -5192 t CO_2-eq., and can be explained by that the amount of digestate produced in 2017 was 18% lower than for 2021 and/or another emission factor for the production of fertilizer. The substitution effect estimation in this thesis is comparable to the value experienced by Lyng and Saxegård (2020), who found an emission reduction of 7858 t CO_2-eq. Moreover, digestate is more environmentally friendly than mineral fertilizer which is largely due to the C sequestration of digestate and the high energy consumption of producing mineral fertilizer.

5.3.3 GWP of Biochar-Digestate Scenarios

The biochar-digestate scenarios included emissions on soil, pyrolysis, transports, C sequestration, and spreading, without considering the production of digestate and the storage of the mixtures. Total emissions from the scenarios are summarized in Table 11. Mineral fertilizer emits 109 kg CO_2-eq./daa and digestate emits 24 kg CO_2-eq./daa.

Table 11: Results obtained from the LCA of the different biochar-to-digestate ratios.

Biochar-to-digestate (w/w)	EL- Nordic Mixture (kg CO_2-eq./daa)	EL- Norway (BIOGRACE) (kg CO_2-eq/daa)
0.07%	21.9	21.6
6.25%	-190.4	-214.2
12.5%	-432.2	-483.1

The categories having the greatest GHG emissions are N_2O volatilization for the lowest biochar-to-digestate ratio scenario, and because of the low biochar production required, the emissions from pyrolysis were non-significant in the assessment. Moreover, the greatest emission reduction was experienced by digestate C sequestration. In the other scenarios, the biochar production was more significant due to the amount of biochar utilized in the fertilizer product. For the 6.25% w/w scenario, the N_2O volatilization and pyrolysis had the greatest GHG emissions, while the credits (avoided CO_2 emissions) of biochar and digestate had the greatest GHG mitigation. Because of the long-term C storage, the overall total emissions of 6.25% w/w biochar addition resulted in GHG reduction. For the 12.5% w/w, there is almost no effect of agricultural emissions. The pyrolysis of feedstock has some GHG emissions, but the emissions are counterbalanced by digestate C sequestration. Moreover, the biochar C sequestration has the greatest impact and results in a total of -440 kg CO_2/daa. In general, the effect of biochar's C sequestration had the greatest GHG mitigation potential when the amount of biochar was significant. In addition, biochar's potential for N_2O flux reduction is also important.

The biochar mixtures' GWP compared to mineral fertilizer and digestate is given in Table 12.

Table 12: Results obtained from the LCA of biochar-digestate compared to mineral fertilizer and digestate.

Biochar-to-digestate (w/w)	Compared to mineral fertilizer (kg CO_2-eq./daa)	Compared to digestate (kg CO_2-eq./daa)
0.07% (EL-Nordic)	-87	-2.2
0.07% (EL-Norway (BIOGRACE))	-87.5	-2.4
6.25% (EL-Nordic)	-300	-215
6.25% (EL-Norway (BIOGRACE))	-323	-238
12.5% (EL-Nordic)	-541	-456
12.5% (EL-Norway (BIOGRACE))	-592	-507

These results address sub-question 1 (SQ1) which investigates the GWP of biochar-digestate compared to synthetic fertilizer in agriculture. The ratios of 0.07% w/w, 6.25% w/w, and 12.5% w/w could reduce emissions by 80%, 296%, and 542% compared to mineral fertilizer. 12.5% w/w had the largest GHG mitigation potential which is due to the C sequestration in digestate and biochar and N_2O volatilization reduction. C storage itself counterbalances other emissions in both 6.25% w/w and 12.5% w/w scenarios and results in negative emissions. Breunig et al. (2019) highlighted that the benefits of using biochar in digestate are C sequestration, increased soil C, and reduced natural N_2O fluxes. This thesis emphasizes the importance of C storage which is one of the major benefits in terms of GHG mitigation. Biochar can act as a negative emission technology as it stores C from organic resources long-term. It is also shown that biochar can reduce N_2O emissions which is a potent GHG. Moreover, both the N_2O mitigation and the C sequestration address sub-question 2 (SQ2) which aims to identify the greatest contribution to the GWP of biochar-digestate.

Comparing biochar-digestate to just digestate exhibits similar trends as to comparing biochar-digestate to mineral fertilizer. The main promoters for using biochar in digestate are the N_2O reduction and the C storage capacity of biochar. Moreover, the biochar-to-digestate ratios of 6.25% w/w and 12.5% w/w demonstrated greater mitigation potential than 0.07% w/w. The 0.07% w/w had no significant influence on GHG reduction compared to just digestate. This suggests that one of the main hotspots in this thesis is the biochar-to-digestate ratio as this influence the C storage capacity and the N_2O volatilization. Moreover, this addresses sub-question 2 (SQ2) which aims to evaluate the effects of biochar-to-digestate ratios.

5.3.4 Emissions Related to Pyrolysis

The pyrolysis was evaluated for two different electricity mixtures: EL- Nordic mixture and EL-Norway (BIOGRACE). The EL-Nordic mixture is 13 times more polluting than the EL-Norway (BIOGRACE). Emissions resulting from pyrolysis are small for the low biochar-to-digestate ratio, while greater biochar-to-digestate ratios had some impact. An LCA study by Homagain, Shahi, Luckai, and Sharma (2015) found that pyrolysis emitted 96 kg CO_2-eq. per ton of dry feedstock. This is comparable to what is calculated in this thesis, 73 kg CO_2-eq. per ton of feedstock for EL-Nordic. When the electricity mixture is changed to EL-Norway, this results in only 6 kg CO_2-eq. per ton of feedstock, suggesting that the emission factor of electricity is important. The emission factors used in this thesis are relatively low compared to other electricity emission factors in Europe and the world, thus the emissions related to pyrolysis is low and can be significantly higher in other studies.

There is also some uncertainty regarding the energy needed for pyrolysis as this is dependent on the moisture content. A study found that the energy needed for pyrolysis was 0.53 kWh/t woody biochar and 1.01 kWh/t pig manure biochar (Rajabi Hamedani et al., 2019), which is lower than the 1.66 kWh/t biochar used in this thesis. There is considerable uncertainty regarding the energy needed for pyrolysis because of the unknown moisture content.

5.3.5 Emissions Related to Transport

Transport accounts for 10% of the total emissions in the case of 0.07% w/w and accounts for less than 1% for both 6.25% w/w and 12.5% w/w. The emission from transport is related to the transport fuel and for this analysis, it is assumed that all trucks use diesel (according to personal communication with Lindum). One way to reduce emissions from transport is to use renewable energy as a fuel such as methane from TMF. Lyng and Saxegård (2020) suggested in their environmental impact assessment of TMF that 30% of trucks used diesel as transport fuel while 70% used biogas. With this assumption, it is possible to reduce the emissions by 1.56 kg CO_2-eq./daa.

5.3.6 Emissions Related to Spreading

The emissions related to spreading were non-significant for the reference system and all biochar-to-digestate ratios. In comparison to other results, Lyng and Saxegård (2020) reported that digestate distribution (transport and spreading) was 731 tons CO_2-eq. annually. This thesis estimates that digestate only emits 340 tons of CO_2-eq. annually for distribution (the same for the biochar-digestate scenarios). The spreading of mineral fertilizer accounts for approximately 0 tons of CO_2-eq. annually, due to the low mineral fertilizer amount needed. Few reports are found for comparing the emissions related to spreading, but the emissions are considered to be lower than expected.

5.3.7 Comparing LCA Results to Literature

The results are so far compared to LCA studies conducted for the digestate and the different values in the LCA are also compared to other data. For the biochar-digestate, few reports have conducted similar LCAs. Only Breunig et al. (2019) did a similar type of LCA but this study disallows direct comparison of systems due to the amount of biochar-digestate used in that analysis. However, trends in the different emission categories are compared in this study. The results in this thesis are further compared to other LCAs conducted with biochar in other organic amendments or with biochar-soil systems.

This thesis suggests that both the use of digestate and biochar-digestate are environmentally superior alternatives in comparison to the use of mineral fertilizer. Similar results were obtained by Oldfield et al. (2018) who did an LCA of compost, biochar, and biochar-compost and found that all three amendments were sustainable solutions compared to mineral fertilizer. These authors evaluated the environmental impact (GWP, eutrophication, and acidification) and found that biochar had the lowest environmental impact due to electricity generated from syngas and C abatement. The amount of biochar applied to soil for the mixtures had significant importance here. Moreover, the authors emphasized that in order to have beneficial use of the amendment, a positive effect on crop yield is required. Biochar-compost showed significant agronomic benefits such as C and nutrient recycling in comparison to just biochar and compost. Moreover, Oldfield et al. (2018) emphasized the benefits of electricity production from syngas. This thesis does not take into account the energy produced during pyrolysis, which can displace grid energy and result in additional GWP reduction. An LCA considering the energy potential in bio-oil and syngas could be considered in future research.

Other LCA studies are conducted on utilizing biochar as a soil amendment. Muñoz et al. (2017) found that biochar on soil could reduce GHG by 2.59 to 2.74 t CO_2-eq./t biochar. The authors identified that the C storage, natural gas avoided (syngas substitution), and urea avoided generated total GHG mitigation. In addition, the authors emphasized that the amount of biochar applied to soil is the main hotspot in the LCA, which is also experienced in this thesis. Moreover, C storage of biochar accounts for 90% of the total savings in the system, which is 2.3 to 2.47 t CO_2/t biochar. In this thesis, C sequestration range from 2% to 80% of the total systems' emissions due to different biochar ratios applied to the soil. The calculations in this thesis suggest that each ton of biochar can mitigate 1.7 t CO_2 which is lower than what Muñoz et al. (2017) found. Another study by Hammond, Shackley, Sohi, and Brownsort (2011) examined that biochar could sequestrate approximately 1.2 to 1.8 t CO_2/t biochar made from straw and wood which are values closer to what is reported in this thesis. Furthermore, biochar shows significant potential for GHG mitigation due to its C storage potential and the values used in this thesis are comparable to other LCAs on biochar.

5.4 Discussion of GHG Volatilization

Digestate emissions are CO_2, N_2O, and CH_4, but CO_2 is not accounted for because it is a part of the natural cycle (Dietrich et al., 2020). In the following section, CH_4 and N_2O emissions in the LCA results will be evaluated.

5.4.1 CH_4 Emissions

CH_4 is expected to be low when digestate is supplied with sufficient amounts of oxygen such as on aerobic soil, but some bacteria from the methanogenic AD phase will be present in the digestate and induce emissions (Dietrich et al., 2020). In addition, biochar is proven to promote CH_4 in the digester which can also be the case for digestate. CH_4 accumulation in digestate is a result of incomplete digestion of organic waste which might be due to instability of AD or too short hydraulic retention time (Masebinu et al., 2019). TMF has operated for a long time and it is assumed that the process is stable with complete digestion. Moreover, an experiment conducted by Dietrich et al. (2020) showed no significant accumulation of CH_4 for digestate in the soil. Goswami et al. (2021) stated that biochar addition increases aeration in the soil thus reducing the anaerobic zones in the digestate which prevents CH_4 emissions. Breunig et al. (2019) neglected the effects of biochar due to limited studies on biochar's interaction in digestate on CH_4 volatilization and this assumption is also used for this thesis. Plaimart et al. (2021) showed that biochar-amended soil had a lower abundance of methanogenic microbes compared to non-amended soil, suggesting less methane loss with biochar application, thus supporting the neglect of additional CH_4 emissions. Moreover, the CH_4 emissions from biochar-digestate are assumed to be the same as for digestate, but there are some uncertainties regarding this because biochar has been proven to promote CH_4 in digesters.

5.4.2 N_2O Emissions from Digestate and Mineral fertilizer

The N_2O emissions account for 71 kg CO_2-eq./daa in the digestate scenario while synthetic fertilizer contributes 66 kg CO_2-eq./daa. Both fertilizers have the same GHG emission of direct N_2O emissions which is in accordance with what the IPCC (2006) suggested. IPCC (2006) suggested 0.01 kg N_2O-N/kg N for synthetic fertilizer, organic amendments, crop residues, and N mineralized from mineral soil as a result of loss of carbon. The direct N_2O emissions will therefore be the same (52 kg CO_2-eq./daa) for digestate and mineral fertilizer because both fertilizers are applied with the same amount of nitrogen. This effect can be inaccurate over a longer period due to digestate's C content. Digestate provides readily available C as an energy source for denitrifying microbes thus stimulating microbial growth and activity (Verdi et al., 2019). However, this effect occurs in the long-term, whereas in the short-term N_2O accumulation can be greater than for mineral fertilizer due to the moisture content in digestate. Trost et al. (2013) found that precipitation or irrigation increased N_2O emissions by 50% to 140%. Moreover, increased soil water-filled pores reaching 65-85% enhances N_2O production (Hauge, Haukås, Rivedal, & Deelstra, 2020). Digestate has a significant water content which can increase soil water-filled pores and promote N_2O production. This effect was also experienced by Verdi et al. (2019) who found that digestate emitted 23% more N_2O than the equivalent N content in solid mineral fertilizer. After precipitation, mineral fertilizer increased N_2O emissions and remained higher than digestate. Moreover, the N losses of mineral fertilizer were higher than of digestate due to a significantly higher NH_3 volatilization. The authors suggested that digestate could reduce total N-losses, but digestate can experience higher N_2O production due to the moisture content in the digestate. Verdi et al. (2019) examined N_2O volatilization over 25 days, and a longer period can be necessary to examine the effects of C in digestate. Moreover, it is interesting to compare the N_2O emission to other literature. The results estimate that digestate emits 239 g N_2O/daa/year while mineral fertilizer emits 222 g N_2O/daa/year. International studies estimated 4 g to 2 kg N_2O/daa/yr while Norwegian studies suggested less than 100 g to 1 kg N_2O/daa/yr due to organic and synthetic fertilization (Nibio, 2016). Furthermore, the total N_2O emissions estimated for this LCA fall into the range of what other reports suggested, but there are some uncertainties regarding digestate's emissions in the long-term and short-term.

5.4.3 Biochar's N_2O Reduction Estimations

N_2O emission is of significant interest for this thesis due to biochar's ability to mitigate N_2O emissions. There are two pathways for N_2O emissions, and it is assumed that biochar mitigates N losses by adsorbing N thus preventing it to volatilize.

It was found that 0.07% w/w, 6.25% w/w, and 12.5% w/w can reduce N_2O emissions by 0.5%, 49% and 100% compared to digestate, respectively. It is possible to compare these results to literature, however, these data are a consequence of biochar's adsorption capacity and not experimental data. One important thing to consider is that biochar is not selective in its adsorption and competing ions can interfere with the adsorption rate (Kizito et al., 2015). Other literature reported that biochar in slurry at the rate of 1% w/w and 3% w/w can mitigate N_2O

fluxes by 18% and 59%, respectively (Martin et al., 2015). This article experienced a higher mitigation rate than this thesis which is difficult to explain, but Martin et al. (2015) found that biochar increased nitrification rate thus reducing N_2O fluxes. This effect is not considered for this thesis and more assessments are needed on this effect to quantify its efficiency.

Moreover, it is estimated that the 12.5% w/w biochar addition has no N_2O volatilization, which is not realistic. Biochar has an alkaline pH and can promote local NH_3 emissions which is a precursor for N_2O emissions (Shackley et al., 2016). The amount of biochar can have a significant effect on increasing the pH and thus experiencing NH_3 losses. In addition, the report by Budai et al. (2021) which used 12.5% w/w in their assessment experienced a lower crop yield than 6.25% w/w which can be due to N volatilization in the form of NH_3. However, this is not considered in this thesis because of the unknown quantity of biochar required to increase pH. Another important thing to note is that it is assumed that all N adsorbed will be slowly released and will be rapidly consumed by plants thus there is no leaching. However, this is not a sure expectation because the utilization rate of N is not determined and the desorption rate of biochar is not known. In addition, it is assumed that all N is adsorbed for 12.5% w/w, which is uncertain due to competing ions. Thus, there can be leaching and direct N_2O emissions from the digestate. Moreover, the biochar can increase pH and the desorption rate of biochar can be beyond the utilization rate of plants and can induce N_2O volatilization which is not considered in this thesis. Thus, the N_2O reduction potential of 12.5% w/w is expected to be too high and should be investigated further.

5.5 Agricultural Benefits of Biochar in Digestate

The third research sub-question (SQ3) addresses the agricultural benefits of applying biochar in digestate and is partially discussed in the theory part of this thesis. However, a brief assessment will be discussed here as well since it is considered one of the main promoters for applying biochar to digestate.

Applying biochar to digestate for enhancing crop yield appears to be a relatively new research topic, and only three reports are found regarding this topic. Budai et al. (2021) showed that biochar-digestate increased crop yield in comparison to NPK-fertilizer, biochar-NPK, and digestate. Ronga et al. (2020) reported that biochar-digestate increased crop yield by 22% compared to just digestate. A more recent experiment done by Cottis et al. (2022) showed that there were no significant differences between crop yield of biochar-digestate in comparison to conventional fertilizer and digestate. Moreover, the results from the experiments showed mainly positive results in terms of crop yield. All the extant articles found that biochar in digestate had equal or better fertilizer potential than non-amended digestate. However, there are relatively few reports within this field and more research should be done to be more certain of the biochar-digestate's effects on crop yield performance.

Biochar in digestate also has some agricultural benefits such as nutrient recovery (Kizito et al., 2015; Plaimart et al., 2021). Another important agricultural benefit is the increased C in the digestate and soil which can serve as a C sink and as an energy source for microorganisms

(Shackley et al., 2016). Breunig et al. (2019) indicated in their LCA of biochar-digestate that one of the important categories was the increase of soil C because it enhances net primary productivity. Net primary productivity is influenced by water, organic matter, and nutrient availability, and is a relatively new topic that is an active field of research. This thesis does not include this parameter in the LCA because of the limited data available. Moreover, Breunig et al. (2019) emphasized that the soil benefits and reduced N_2O fluxes are the main promoters for applying biochar to digestate. These properties should be considered for applying biochar to digestate instead of prioritizing selling biochar to other markets. These effects can be highlighted in this thesis as well.

Furthermore, biochar-digestate's benefits on agricultural soil should not be overlooked, although this issue is relatively new, and more research should be done. Moreover, the N_2O reduction and agricultural benefits of applying biochar to digestate are one of the main promoters for using this product in agriculture.

5.6 Future Perspective

One of the recommended strategies for biochar addition in digestate is to apply it before digestion rather than after. Biochar in AD has been extensively reviewed and exhibits great results in terms of methane yield and process stability (Fagbohungbe et al., 2017). This amendment can improve methane yield to almost pipeline quality. In terms of process stability, it can alleviate acid and ammonia inhibition for preventing reactor failure (Mumme et al., 2014). These benefits can reduce the dependency on upgrading technology and the cost of expensive additives for stabilizing the process. Today, biochar is relatively expensive, but an expanded value chain, carbon credits, and understanding of the benefits of biochar can outweigh the cost and can reduce costs in the long term.

There is major attention on biogas optimization and methane extraction. Biogas production is focused on as the key driver for organic waste management and digestate is an auxiliary driver. Reactors are optimized for the best yields of biogas and methane, and take limited regard to the digestate quality, even though overlooking the digestate quality is a setback for the purpose of organic waste management. Biogas is a major contributor to GHG reduction due to the displacement of conventional fossil fuels, but also digestate can have significant benefits regarding the substitution of mineral fertilizer. In terms of GHG reduction, biogas utilization for substituting conventional fossil fuels has often the greatest environmental benefits and digestate has also a significant contribution and often carries the second greatest GHG reduction potential (Lyng & Saxegård, 2020; Morken, Briseid, Hovland, Stensgård, et al., 2017). Digestate quality has a meaningful impact on GHG mitigation and reactors should also be optimized to enhance the quality. Biochar amendment can be a solution for both enhancing the digestate quality and reducing GHG emissions. Several articles report biochar's benefits in digestate, it can act as a sorbent for better nutrient and water retention which increases the fertilizer value compared to just digestate. In addition, the plant-available N is immobilized and prevents N_2O volatilization thus reducing the GHG emissions. Biochar-amended digestate as a fertilizer exhibit benefits mostly for the environment but also for soil. More investigation on the full LCA with biochar addition before and after AD should be conducted for a better picture of the environmental impact of this fertilizer product.

In terms of an economic viewpoint, biochar should be evaluated alone or with an organic amendment on agricultural soil. Several studies have been focusing on high biochar application (>10 t/ha) on agricultural soil, but this is not economically feasible (Hagemann et al., 2017). Pyrolysis technology is known to be expensive and biochar's value is currently 8000 NOK/ton (Prestvik & Lilleby, 2021). More recent studies recommend that biochar should be mixed with an organic amendment for increasing soil agroecosystem benefits (Hagemann et al., 2017). Moreover, this thesis suggests that both digestate and biochar-digestate are viable substitutes for mineral fertilizer. Biochar-digestate shows clear benefits in terms of C abatement, nutrient retention, and N_2O volatilization. In addition, biochar-digestate production is a viable waste management method that ensures nutrient recycling and reduces the dependency on synthetic fertilizers.

6 Conclusion

This thesis is one of the few studies investigating the GWP of biochar-digestate. The main objective was to perform an LCA as a case study for TMF and Lindum: "*What is the global warming potential of using biochar in digestate as a fertilizer product on agricultural soil?"*. To address this question, a Gate-to-Cradle LCA was conducted using Excel where the framework was including transport, biochar production, field application, soil emissions (N_2O and CH_4), and C sequestration for both digestate and biochar.

The first sub-question addressed the GWP of biochar-digestate from TMF and Lindum compared to synthetic fertilizer on agricultural soil. Three different biochar-to-digestate ratios were used for comparison and to investigate the effects of biochar ratios. These three ratios were 0.07% w/w, 6.25% w/w, and 12.5% w/w and were able to mitigate GHG by 88 kg CO_2-eq./daa, 323 kg CO_2-eq./daa, and 592 kg CO_2-eq./daa compared to mineral fertilizer. This led to a total GHG reduction of 80%, 296%, and 542% and showed that biochar-digestate was more environmentally friendly than mineral fertilizer. The second sub-question was about identifying the main contributors to the LCA, and it was found that the most important GHG reduction categories in the LCA were the reduction of natural N_2O fluxes and the C sequestration of digestate and biochar. In addition, the second sub-question did also concern the influence of the biochar-to-digestate ratios on the GWP, and it was found that it was one of the main hotspots in the system because of biochar's C abatement and N adsorption capacity. The third sub-question was regarding biochar-digestate's potential benefits on agricultural soil. It was found that biochar in digestate can be beneficial in terms of nutrient recovery and increased C in digestate which can be a nutrient source for microorganisms. However, biochar-digestate's effect on crop yield is a relatively new topic and more research should be done to evaluate the benefits. Moreover, the main promoters for applying biochar to digestate in agriculture are the reduced N_2O fluxes, C sequestration, and the potential agricultural benefits.

In conclusion, biochar-amended digestate exhibits significant GHG reduction potential compared to mineral fertilizer which can contribute to more sustainable food production. This product offers a climate-smart agricultural practice by utilizing benefits from both systems: digestate for nutrient recovery and biochar for carbon storage and enhanced nutrient efficiency.

7 Future Work

One uncertainty of this study is the effect of biochar in digestate on N_2O volatilization. The assumption now is that N is immobilized in the biochar and thus prevents it from emitting. However, this is not a sure expectation due to the pH and adsorption/desorption rate of biochar. Therefore, it is suggested that future work should consider the influence of biochar in anaerobic digestate on N_2O emissions.

For future work, it is interesting to evaluate a full Cradle-to-Grave analysis of biochar application before and/or after digestion. Biochar in AD can serve benefits such as stabilization and increased methane yield, in addition to potential agricultural benefits such as increased soil C and increased nutrient retention. However, adding biochar to the reactor can require some volume and promote NH_3 volatilization which should be carefully examined.

Another suggestion for future work is to examine the LCA of pyrolyzing the solid fraction of the digestate and use it in the liquid fraction of the digestate for increased nutrient retention. Pyrolyzing the solid fraction can reduce the concentration of plastics in the digestate which is beneficial for agriculture.

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Appendices

Appendix A: Task description

University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Environmental impact assessment of biochar in AD digestate

USN supervisor: Wenche Bergland and Marianne Eikeland

External partner: Ketil Stoknes at Lindum

Task background:

Lindum runs several different R&D projects to improve energy efficiency and resource recovery. One of their latest interests is combining pyrolysis and anaerobic digestion (AD). One important step in this is evaluating the use of combined pyrolysis and AD products.

Digestate is used as a fertilizer where addition of biochar from pyrolysis to the digestate both adds to the carbon storage and improve the soil properties for farming.

Life cycle analysis (LCA) can be done for biogas production [1] where the environmental effect can be calculated using tools [2, 3] already available. The possible use of biochar in Norway is evaluated [4] where carbon storage in soil is of particular interest in this thesis proposal.

[1]: Kari-Anne Lyng in Norsus (LCA on two biogas production sites) https://norsus.no/publikasjon/livslopsvurdering-av-produktene-og-tjenestene-til-den-magiske-fabrikken/ https://norsus.no/publikasjon/livslopsvurdering-av-produktene-og-tjenestene-levert-av-romerike-biogassanlegg/

[2]: Excel tool for analysing environmental impact in biogas production
https://avfallnorge.no/bransjen/nyheter/ny-bransjestandard-for-rapportering-klimanytte-fra-biogass-og-biogjodsel
https://www.carbonlimits.no/project/tool-for-calculating-the-climate-impact-of-production-and-use-of-biogas-and-biodigestate/

[3]: Open LCA https://www.openlca.org/

[4]: Nibio report «Verdikjeder for biokull i Norge» https://nibio.brage.unit.no/nibio-xmlui/bitstream/handle/11250/2763655/NIBIO_RAPPORT_2021_7_138.pdf?sequence=1

Task description:

- Literature survey.
- Choose process scenarios producing AD digestate (bio fertilizer) modified with biochar from pyrolysis.
- Calculate and evaluate the environmental impact assessment of AD digestate modified with biochar and compare with artificial fertilizer.

Student category: Reserved for EET student Thea Indrebø

Is the task suitable for online students (not present at the campus)? No

Practical arrangements:

The work will be done in Porsgrunn. Possible visit to Lindum in Drammen and/or Lindum/DMF in Tønsberg.

Supervision:

As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature): 24.03.22 Wenche Bergland

Student (write clearly in all capitalized letters): THEA INDREBØ

Student (date and signature): 23.03.22 Thea Indrebø

Appendix B: Results from LCA

The following tables are tabulated values from the LCA of mineral fertilizer, digestate, and biochar-digestate.

Table 13: Results obtained from the LCA of mineral fertilizer.

Category	Value (kg CO_2-eq./daa)
Direct N2O emissions	52
Indirect N2O emissions	14
Transport	1
Spreading	0
Production	42
Total emissions	**109**

Table 14: Results obtained from the LCA of digestate.

Category	Value (kg CO_2-eq./daa)
Direct N2O emissions	52
Indirect N2O emissions	19
CH4 emissions	1
Digestate C sequestration	-53
Digestate transport	2
Spreading	2
Total emissions	**24**

Table 15: Results obtained from the LCA of 1 L/ton biochar in separated digestate where the electricity mixture is EL-Norway (BIOGRACE) with an emission factor of 2.72 gCO_2/MJ_{EL}.

Category	Value (kg CO_2-eq./daa)
Direct N2O emissions	52
Indirect N2O emissions	19
CH4 emissions	1
Digestate C sequestration	-53
Biochar C sequestration	-2
Pyrolysis	0
Transport of biochar	0
Transport of digestate	2
Spreading	2
Total emissions	**22**

Table 16: Results obtained from the LCA of 1 L/ton biochar in separated digestate where the electricity mixture is a Nordic mixture with an emissions factor of 35.56 g CO_2/MJ_{EL}.

Category	**Value (kg CO_2-eq./daa)**
Direct N2O emissions	52
Indirect N2O emissions	19
CH4 emissions	1
Digestate C sequestration	-53
Biochar C sequestration	-2
Pyrolysis	0
Transport of biochar	0
Transport of digestate	2
Spreading	2
Total emissions	**15**

Table 17: Results obtained from the LCA of 6.25% w/w biochar in digestate where the electricity mixture is EL-Norway (BIOGRACE) with an emissions factor of 2.72 g CO_2/MJ.

Category	**Value (kg CO_2-eq./daa)**
Direct N2O emissions	27
Indirect N2O emissions	10
CH4 emissions	1
Digestate C sequestration	-53
Biochar C sequestration	-205
Pyrolysis	2
Transport of biochar	0
Transport of digestate	2
Spreading	2
Total emissions	-214

Table 18: Results obtained from the LCA of 6.25% w/w biochar in digestate where the electricity mixture is a Nordic mixture with an emissions factor of 35.56 g CO_2/MJ.

Category	**Value (kg CO_2-eq./daa)**
Direct N2O emissions	27
Indirect N2O emissions	10
CH4 emissions	1
Digestate C sequestration	-53
Biochar C sequestration	-205
Pyrolysis	26
Transport of biochar	0
Transport of digestate	2
Spreading	2
Total emissions	**-190**

Table 19: Results obtained from the LCA of 12.5% w/w biochar in digestate where the electricity mixture is EL-Norway (BIOGRACE) with an emissions factor of 2.72 g CO_2/MJ.

Category	**Value (kg CO_2-eq./daa)**
Direct N2O emissions	0
Indirect N2O emissions	0
CH4 emissions	1
Digestate C sequestration	-53
Biochar C sequestration	-440
Pyrolysis	4
Transport of biochar	0
Transport of digestate	2
Spreading	2
Total emissions	-483

Table 20: Results obtained from the LCA of 12.5% w/w biochar in digestate where the electricity mixture is a Nordic mixture with an emissions factor of 35.56 g CO_2/MJ.

Category	**Value (kg CO_2-eq./daa)**
Direct N2O emissions	0
Indirect N2O emissions	0
CH4 emissions	1
Digestate C sequestration	-53
Biochar C sequestration	-440
Pyrolysis	55
Transport of biochar	0
Transport of digestate	2
Spreading	2
Total emissions	**-432**

Appendix C: Results from LCA (one year)

Table 21: the digestate characteristics for one year.

Characteristic	**Value**
TS	4.5%
C	5 326 980 kg C
C stable	1 065 396 kg C
Total N	1 230 224 kg N
NH_4^+-N	822 703 kg NH_4^+-N
P	187 310 kg P
Mass	135 138 ton

Table 22: Results obtained from the LCA of mineral fertilizer.

Category	**Value (ton CO_2-eq./year)**
Direct N2O emissions	3853
Indirect N2O emissions	1059
Transport	41
Spreading	0
Production	3134
Total emissions	**8088**

Table 23: Results obtained from the LCA of digestate.

Category	**Value (ton CO_2-eq./year)**
Direct N2O emissions	3853
Indirect N2O emissions	1445
CH4 emissions	53
Digestate C sequestration	-3906
Digestate transport	170
Spreading	170
Total emissions	**1784**