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Assessment of Biochar as a carbon Capture Storage method, and evaluation of potential negative effects

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Abstract

When biomass is treated through pyrolysis, intense heating in the near absence of oxygen, the end product is called biochar: a black carbon-rich substance with a vast surface area and high porosity. It has successfully been implemented in many fields. Studies in urban areas in Thailand, Burma, and Africa, found biochar to be an economical and sustainable mean to provide access for clean water through a simple and cheap filtration system, as well as a potent fertilizer (Sparrevik et al., 2014). In China, India, and in sub-Saharan Africa, the production of biochar through pyrolysis has the potential to act as a waste management system for agricultural residue, and because of this reduce its emissions by almost 10% (1Gt of CO₂ per year) (Tan, 2019; Nair et al., 2020). The production of biochar produces two important by-products: syngas and bio-oil. These two renewable energy sources have the potential to be used as, among others, a mean of transport and as a heating agent (Lehmann, 2007). This study aims to review the positive and negative effects of biochar and found that as a mean of carbon storage biochar is highly effective since production is simple and economically sustainable, work as a mean for waste management, and is seen to be preserved in a solid durable form for 10³ years (Schmidt et al., 2002). By reviewing previous studies, this study found that biochar has shown to be effective for plant growth rate and soil health, i.e., improved water holding capacity, increase in microbe activity, and a more stable pH. However, the result of this literature review has found that biochar could have a negative effect on the greenhouse gas emissions (GHG) though an increase of N₂O soil emissions. This seems to depend on soil type and biochar biomass origin.

Keywords

Biochar; Biomass; Fertilization; Carbon Capture Storage (CCS); Pyrolysis; Water treatment; Sustainability.

Abstrakt (Swedish)

När biomassa är behandlad genom pyrolys, intensiv uppvärmning i en syrefattig miljö, blir slutprodukten biochar. En svart kol-rik substans med en stor yt-area och hög porositet. Biochar har kunnat implementeras i flera fält. Undersökningar i Thailand, Burma och Afrika visade biochar som en ekonomisk och hållbar produkt när den användes som vatten-renare genom ett enkelt och billigt filtrationssystem, och även som ett gödslingsmedel (Sparrevik et al, 2014). I Kina, Indien och söder om Sahara i Afrika, har produktionen av biochar genom pyrolys potential att fungera som ett avfallshanteringssystem för jordbruksrester. Resultatet av detta är upp till 10% (1Gt av CO₂ per år) minskade utsläpp av växthusgaser (Tan, 2019; Nair et al, 2020). När biomassa behandlas genom pyrolys, så produceras två produkter utöver biochar: biogas och bio-olja. Dessa två förnybara energikällor har potential att användas inom flera områden, bland annat för transport och som en värmekälla (Lehmann, 2007). Denna studie avser att se över de positiva och negativa effekter som följer användandet av biochar, och fann att biochar är en högst effektiv metod för att binda kol på grund av att: produktionen är enkel och ekonomisk hållbar, produktionen fungerar som avfallshantering samt att slutprodukten är en stabil produkt som förblir i fast form i över 10³ år (Schmidt et al., 2002). Biochar har visat sig effektiv för vattenrenlighet, en ökad fotosyntes och ett sätt att öka skicket på brukbar jord genom att främja mikrobhälsa, bevattningsbehov, samt att stabilisera pH. Dock, vid användandet av biochar inom jordbruk följer eventuella negativa effekter. Ett ökat utsläpp av N₂O beroende på pH och näringsinnehåll i jorden har påträffats, till en förmodad följd av att felaktig biochar har använts i felaktig jord.

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1. Introduction

1.1 Background

When biomass such as wood, pellets, and crop residue is exposed to a thermochemical, oxygen-poor environment the final product is biochar. Biochar is a lightweight black product composed almost entirely of carbon. The product is a stable, solid mass that can endure in solid form for thousands of years (Schmidt et al., 2002). This is a promising carbon capturing solution (CCS) since it captures carbon dioxide from the atmosphere and binds it in solid form. It differs from the short-term carbon cycle, which works as follows: Atmospheric CO₂ is turned to biomass through photosynthesis ($H_2O + CO_2 \rightarrow <CH_2O> + O_2$). This biomass is later decomposed by microorganisms and CO₂ is returned to the atmosphere through their respiration. However, when implementing the use of biochar, the cycle changes, as biochar has a reduced effect on the carbon cycle since it captures CO₂ from the atmosphere in solid form and doesn't let it return unless oxidised either through burning or respiration. When used as part of fertilizing biochar aids the future capture of CO₂ through the increased growth rate of vegetation, see **figure 1**. The complete process is carbon negative since the net effect of biochar production is removal of carbon dioxide from the atmosphere.

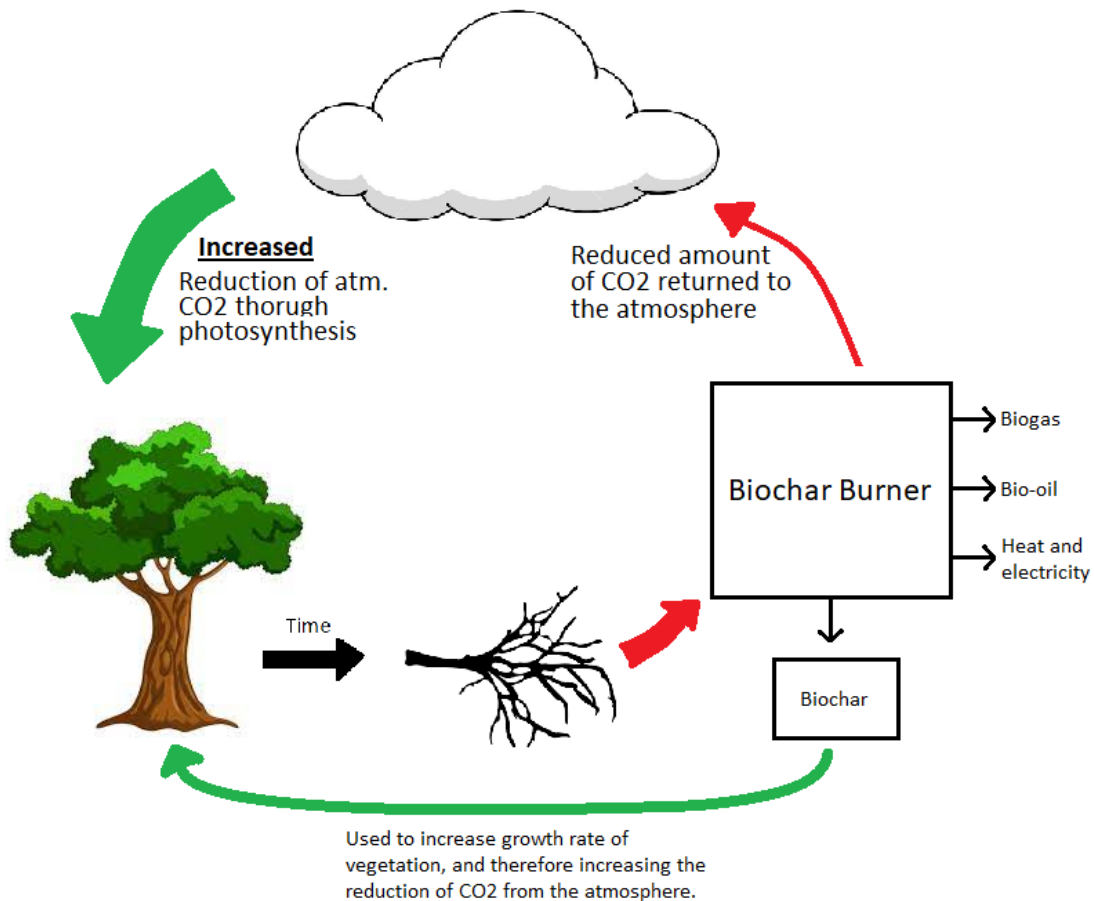


Figure 1: How the production and use of biochar help to restore a healthy CO₂-balance in the atmosphere by **a)** save carbon within biomass from decomposition by converting to biochar, and **b)** use biochar as a fertilizer to enhance soil health and microbial life, and further aid capture of atmospheric CO₂.

The treatment of biomass to char was used as early as the 1600's and was mainly used as a source of heat when forging iron. The production process is based on the same idea that is used today. The wood was piled and covered in sand, soil, grass, and peat (**figure 2**, Tekniska Museet, 1899) before ignited. By covering the wood, the amount of oxygen could be controlled through small vent holes in the sides. It was important for the wood not to be set aflame, only pyre since much of the biomass would be wasted in the form of ash. With only a small amount of oxygen this is avoided, and the biomass would stay in solid form. But with only a small amount of oxygen this would be avoided, and the carbon would stay in reduced form. After oil was struck in the USA in the mid 1800's, people turned their attention to this new source of energy, and the use of pyrolyzed biomass decreased until it finally ceased around 1945 after the second world war. It is only now in the last few decades that biochar has been rediscovered and its properties studied.



Figure 2 (Tekniska Museet 1899): Coal miles such as this has been used since the 1600's.

Through pyrolysis in low-oxygen conditions organic materials, such as plant-waste and wood, will undergo vaporization where the organic material will dry and be empty of gases and water (Glaser et al., 2009). The final product is called biochar and it consists of ~85% carbon with eventual traces of oxygen, hydrogen and small amounts of ash (Basu, 2018). Charcoal is not to be confused with biochar, for it is different in both use and origin. Further, Charcoal is mostly used as a heating agent. It is primarily produced of wood, while biochar can be produced from all types of biomasses. Charcoal has a lower surface area and porosity, as well as a higher pH (9-11), making it less suitable for agricultural usages, such as a fertilizer. Both biochar and charcoal, with the exception of mined coal, are produced through pyrolysis. However, there is

a difference in temperature and production emissions. Charcoal is treated in lower temperature, often over several days, and the gases released from the biomass is emitted to the atmosphere. When producing biochar, the syngas is either captured (to be used as biogas) or returned to the heating chamber to be used as fuel to further aid the pyrolysis burner (figure 1). The purpose of heating biomass in an oxygen poor environment is to prevent the oxidation of carbon, i.e., the production of carbon dioxide. When burning biomass in an oxygen-rich environment the carbon absorbs molecules of oxygen. This reaction of carbon surface oxidation produces carbon monoxide (CO) and carbon dioxide (CO₂) (Zhou, 2018).

Both biochar and charcoal works as an excellent water treater through their porous microstructure and charged surface area. It removes not only pathogens, but also chemical, physical and biological contaminants from unsafe drinking water (Gwenzi et al., 2017). As ~600 million people live without access to clean water, studies on biochar as a cleaning agent is encouraged. The production and use of biochar is not only a cheap solution for water treatment, but it also comes with other positive usages in agriculture, waste management and energy production.

Another important use of biochar is as a fertilizer. Firstly, the biochar must be charged with the right nutrients. Like a sponge biochar will absorb nutrients and if added to soil without being activated it can have a negative effect and harm the crops (Agegnehu et al., 2017). Biochar is activated by adding the right nutrients through mixing it with manure, grass clippings, rock dust, synthetic fertilizer, or other sources of nutrients. Schulz et al. (2013) mixed biochar with compost and used the biochar as a fertilizer, and with positive results. Vegetational growth rate was found to be increased, as soil health improved with the adding of biochar, even compared to soil fertilized only with compost. According to Duan et al. (2019), biochar as a soil fertilizer seems to enhance richness, accelerate degradation, and alter bacterial communities through stimulating the microbe activity. Cornelissen et al. (2018) performed a long-term study which showed that biochar made from cacao shells balanced the acid ultisol to a more favourable pH, alongside a more supporting calcium and aluminium ratio.

1.2 Purpose

This study aims to provide a review of the advantages and disadvantages of biochar, and discover the most promising substrate and production methods for biochar from an environmental, agricultural and CCS (Swedish and global) perspective. Is the discovered process economically feasible, both national and internationally?

2. Method

The review is mainly conducted by analysing scientific articles and reports from the last two decades, with some exceptions before the year 2000. The two main databases used for finding these articles and reports were ScienceDirect (www.sciencedirect.com) and Google Scholar (<https://scholar.google.com/>). Additional information on biochar production also came from the German manufacturer of biochar burners Biomacon's website (www.biomacon.com) as well as their Swedish partners at Svenskt Biokol (www.biokol.se). First, the biochar production process is reviewed, later followed by usage areas such as CCS, fertilization, and water treatment. Lastly then potential negative effects of biochar, as well as an economical perspective, is reviewed.

The most used search terms were: Biochar, Carbon Capture Storage (CCS), Pyrolysis, Carbon sequestration, Fertilization, Soil health, Water purifier, and Economical sustainability.

3. Result

3.1 Production of biochar

Biochar can be obtained from several different types of procedures, and some give higher yields than others. Pyrolysis is the most common treatment to produce biochar, it is time efficient and is able to produce high yields of product in lower temperatures. The process changes the chemical composition of biomass through thermal decomposition where the sample is heated in an oxygen-poor environment. Pyrolysis can be subdivided in three categories: slow pyrolysis, fast pyrolysis, and flash pyrolysis. They vary in their different temperatures (300-800°C, 400–800°C, 400-1000°C, respectively). Slower pyrolysis is used to increase the yield of biochar, and fast pyrolysis is used to increase the yield of bio-oil (Panchasara & Ashwath, 2021). See **table 1**.

| <u>Pyrolysis</u> | <u>Operating conditions</u> | <u>Product yield</u> |
|-------------------------|------------------------------------|-----------------------------|
| Slow Pyrolysis | Temperature: 300-800°C | Biochar yield: ~35% |
| | Heating rate: 0.1-1°C/s | Bio-oil yield: ~30% |
| | | Biogas yield: ~35% |
| Fast Pyrolysis | Temperature: 400-800°C | Biochar yield: ~20% |
| | Heating rate: 10-200°C/s | Bio-oil yield: ~50% |
| | | Biogas yield: ~30% |
| Flash Pyrolysis | Temperature: 800-1000°C | Biochar yield: ~12% |
| | Heating rate: 1000°C/s | Bio-oil yield: ~75% |
| | | Biogas yield: ~13% |

Table 1: The yield of biochar depends on the operation temperature of the pyrolysis.

The lower the temperature, the higher yield of biochar, as well as a more developed microporosity and higher surface area (Chen et al., 2017). From an agricultural perspective, both high surface area and porosity is important when biochar is used as a fertilizer. Leng et al. (2021) explains how biochar produced in temperatures between 300-1000°C commonly provides a surface area of 8-132m²/g, and a porosity of 0.016-0.083cm³/g. In some cases, surface area and porosity can reach up to 490.8m²/g and 0.25cm³/g respectively (**figure 3**, Leng et al., 2021). The biochar's remarkable surface has high potential in adsorbing metals, nutrients and contaminants. Depending on pyrolysis temperature the surface can either be positively or negatively charged, and can attract anions, cations, hydrogen bonds, and exchange ions (Vikrant et al., 2017) (**figure 4**).

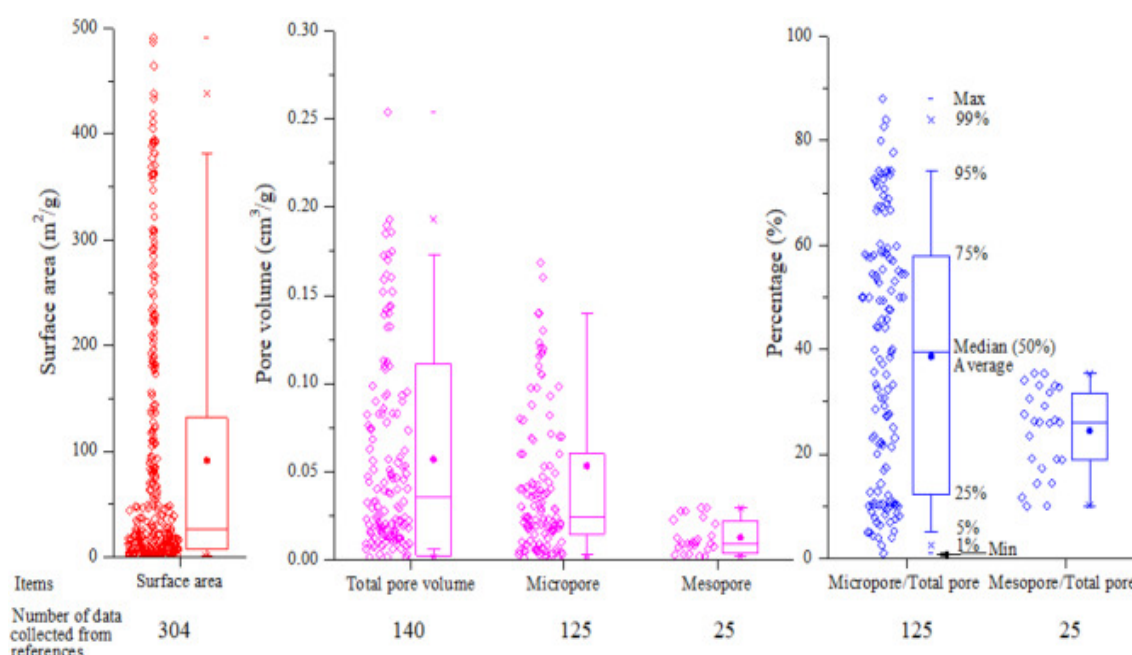


Figure 3 (Leng et al., 2021): Surface area (m²/g) and pore volume (cm³/g) of treated biochar.

When biochar is produced through pyrolysis the sample undergoes chemical transformation when heated to temperatures between 300 and 1000°C in an oxygen-controlled environment (Lord et al., 2012). During pyrolysis solid or liquid sources of carbon turn into smaller unstable molecules through thermal degradation. During this process the material does not interact with oxygen or other oxidants. Unlike phase change the process of thermal degradation degrades big molecules to small ones through chemical reactions. Lignocellulose (plant dry matter, biomass) is a collective term covering cellulose, lignin, and hemicellulose, each with their own features such as different crystallinity and branching. These compounds found in all vegetation on land and is also found as a by-product from different industrial processes. The different features of these compounds will lead to various pyrolysis mechanisms (Cheng & Li, 2018). The pathway of cellulose through a pyrolysis process is illustrated in **figure 5** (Cheng & Li, 2018). Depending on the biomass and the heat of the pyrolysis process the ratio of biochar, biogas, and bio-oil will differ, as well as the surface morphology of the biochar (see **table 2**, Septiana et al., 2018).

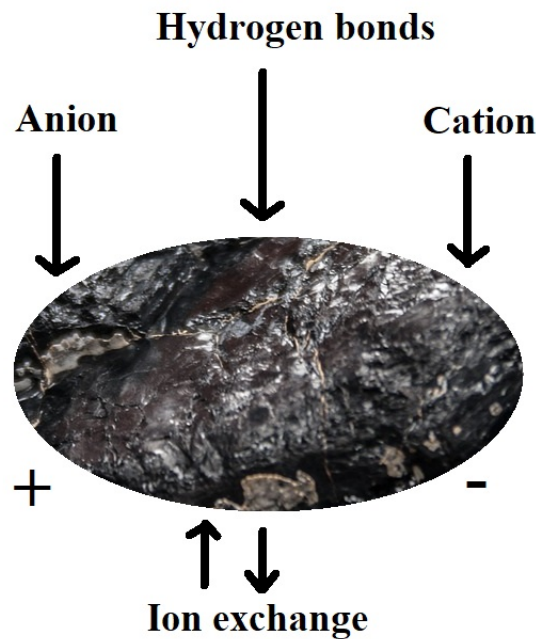


Figure 4: The potentials of a biochar surface where anions, cations and hydrogen bonds are shown, as well as ion exchange.

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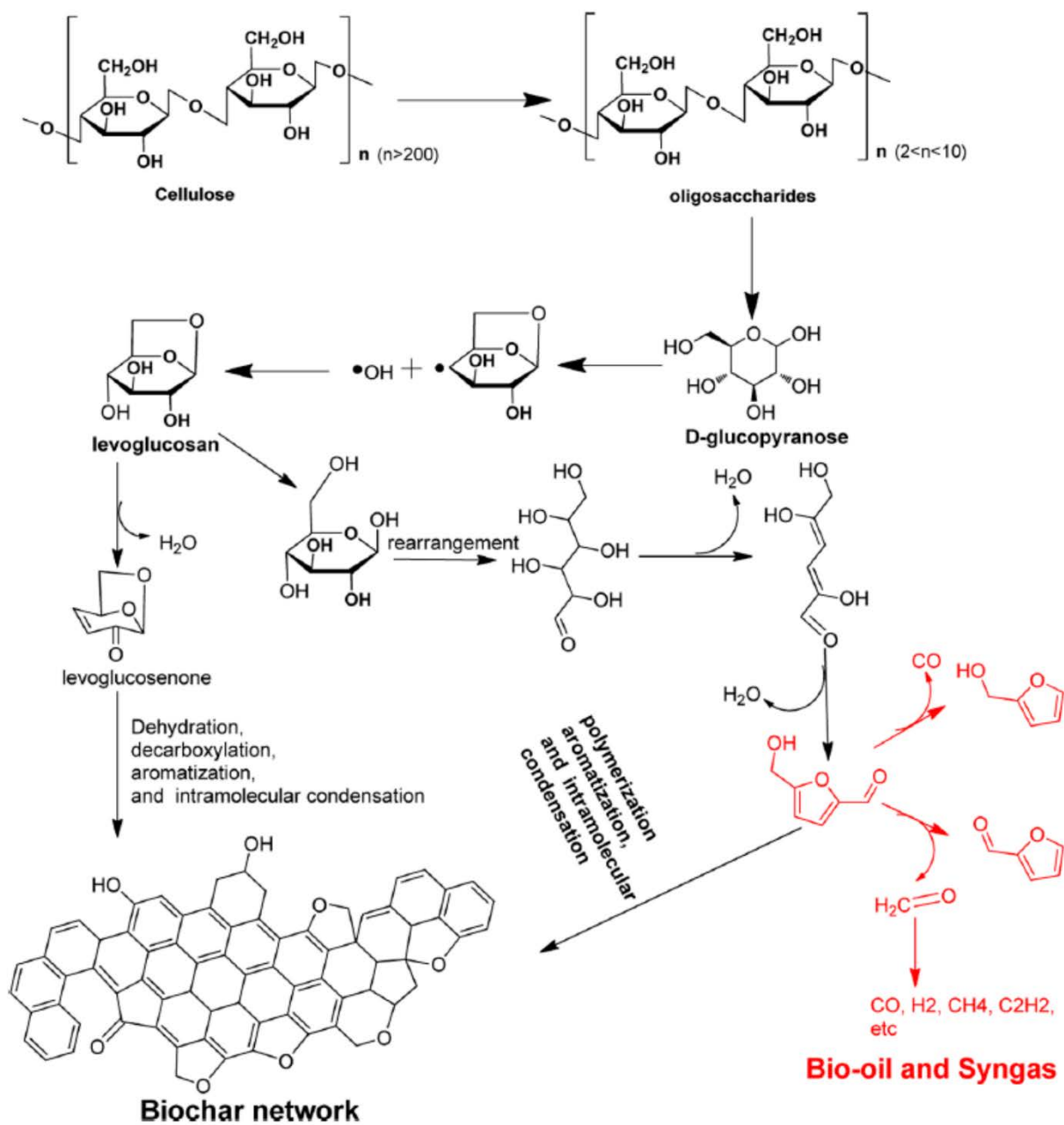


Figure 5 (Cheng and Li, 2018): Formation of biochar, bio-oil, and syngas through cellulose pyrolysis. Through pyrolysis Cellulose is turned to saccharides (oligosaccharides \rightarrow D-glucopyranose \rightarrow levoglucosan \rightarrow levoglucosenone), then a network of biochar is formed through dehydration, decarboxylation, aromatization and intramolecular condensation from levoglucosenone. The by-products bio-oil and syngas is formed by the chemical rearrangement of levoglucosan.

| No. | Kind of Biochar | Temperature | Surface Area (m ² /g) | Total Pore Volume (%) | Average Pore Radius (Å) |
|-----|---------------------------|-------------|----------------------------------|-----------------------|-------------------------|
| 1 | Sawdust of albazia wood | 250°C | 10.40 | 2.39 | 15.06 |
| | | 350°C | 142.35 | 0.45 | 11.79 |
| 2 | Sawdust of maesopsis wood | 250°C | 24.93 | 16.97 | 34.89 |
| | | 350°C | 113.01 | 32.30 | 15.93 |
| 3 | Sawdust of mahogany wood | 250°C | 125.35 | 62.49 | 25.56 |
| | | 350°C | 277.15 | 73.88 | 13.67 |
| 4 | Rice husk | 250°C | 21.85 | 0.22 | 21.58 |
| | | 350°C | 109.67 | 1.15 | 16.09 |
| 5 | Corn cob | 250°C | 100.35 | 0.07 | 23.31 |
| | | 350°C | 142.93 | 2.53 | 0.91 |
| 6 | Empty oil palm bunch | 250°C | 7.98 | 6.74 | 100.89 |
| | | 350°C | 49.07 | 14.02 | 35.61 |
| 7 | Baggase | 250°C | 1.24 | 16.95 | 279.76 |
| | | 350°C | 4.62 | 15.69 | 155.58 |

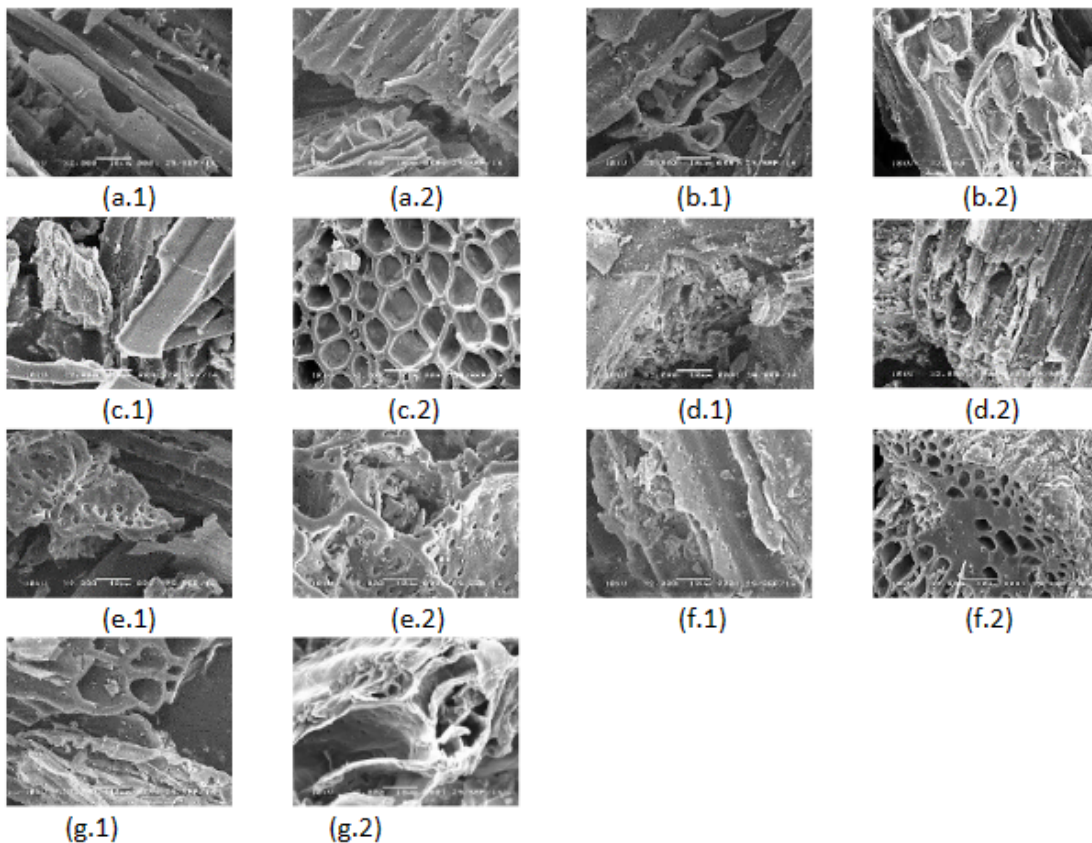
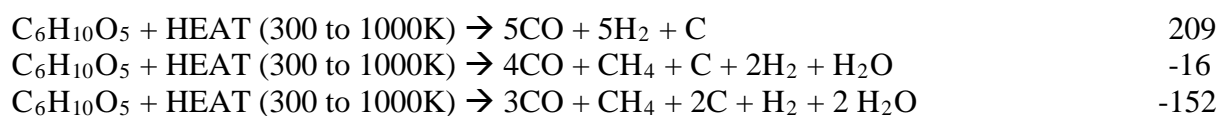


Table 2 (Septiana et al., 2018): Variety of surface morphology of biochar depending on biomass source (images through Scanning Electron Microscopy, SEM): a) Albizia sawdust, b) maesopsis sawdust, c) mahogany sawdust, d) rice husk, e) corn cob, f) bagasse, g) empty oil palm bunch. Pyrolyzed at 1: 250°C, and 2: 350°C. Images at 2000x magnification.

The biomass is decomposed to release a vapour phase, while the solid phase remains (biochar). During the vapour phase, compounds with heavy molecules and polar charges produce a liquid phase (bio-oil) while cooling. Contrarily to this, the lighter molecules (CO₂, CO, CH₄ and more) stay in gas form. Nitrogen on the other hand has shown high stability during slow pyrolysis up to 450°C, and remains as a structural part (black nitrogen) of the charred biomass (Knicker, 2010). In nature the most common organic substance is cellulose, as this polysaccharide is the main component in the cellular walls of vegetation (Lee et al., 2019). Below are three chemical reactions representing the pyrolysis of cellulose (C₆H₁₀O₅) in idealized conditions. Through pyrolysis the carbon is oxidised, and hydrogen are formed as well as light hydrocarbon gases and methane. (Putro et al, 2016).

Enthalpy change (ΔH) (kJ g⁻¹ mol⁻¹)



CO = Carbon monoxide H₂ = Hydrogen gas CH₄ = Methane
 C = Carbon H₂O = Water

Even though the reactant (cellulose) and max temperature (1000K) is the same, a difference in enthalpy is seen. If the heating rate is high, then the change in enthalpy (ΔH) will be positive and the reaction will be endothermic. If the heating rate is low, then the change in enthalpy will be negative and the reaction is exothermic. A change in biochar yield is seen depending on if the reaction in endo- or exothermic, where the yield seems to be highest in exothermic conditions (Cho et al., 2010). The author informs that attempts has been made to quantify the change in enthalpy during pyrolysis, but are still controversial. If the formation of biochar is an endothermic or exothermic reaction is still not certain.

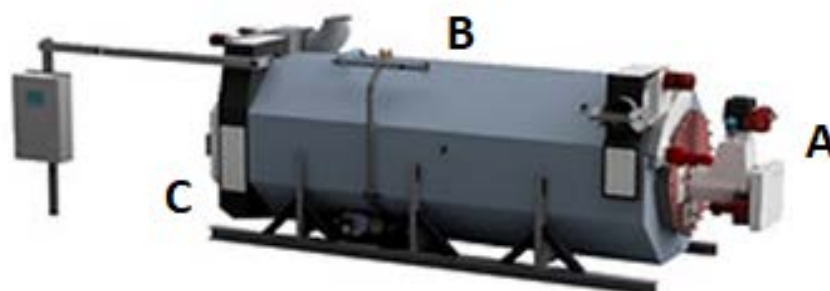


Figure 6 (Biomacon, 2020): A pyrolysis burner suited for industrial use with a heating power of 250-400kW.

As previously stated, biochar is most commonly produced through pyrolysis and for this a biochar burner is needed. Lippel (Brazil) offers a wide range of different burners from 200-1000kW (Lippel, 2023). There are also smaller ones provided by Bestongroup whom produces pyrolysis burners with a heating power of 16.65kW (Bestongroup, 2023). A common burner used in Sweden is provided by a German company named Biomacon, **figure 6** (Biomacon, 2020). They offer two burners, one suitable for farms and a larger one for industrial use, with heating powers from 40-160kW and 250-400kW respectively. Local biomass originated from a regenerative source (wood, leaf, stems from crops etc.) is added into the system (**A**). The biomass undergoes slow pyrolysis in an oxygen-poor environment, and syngas (CO_2 , CO , CH_4 , H_2) is produced. The syngas is burned in the combustion chamber (**B**). During the combustion up to 80% of the heat is absorbed by the heat exchanger to be used as energy. After the pyrolysis process approximately 50% of the carbon is left within the burner as biochar (**C**) to be used further. When carbon dioxide is captured by vegetation, and then conserved as biochar through a pyrolysis burner like Biomacon, the net carbon profit is 50%, provided that the biomass originates from a regenerative source. With the use of burners like this the carbon-cycle is broken, and industries and farms can easily help drain the atmosphere of carbon dioxide to prevent further environmental problems caused by the climate crisis. The energy needed to run these burners differ depending on brand, but also type of feedstock. The energy needed to pyrolyze biomasses such as oat hulls and pine wood are 0.8MJ/Kg and 1.6MJ/Kg respectively (Daugaard & Brown, 2023).

3.2 Uses of biochar

3.2.1 Biochar as a Carbon Capture Storage (CCS)

For several decades, the idea of carbon capture has been more and more interesting in both science and in politics. Experts argue that a long-term system of carbon sequestration is vital to prevent further climate change and to avoid a global mean temperature of 1.5-2°C above pre-industrial average in the years 1850-1900 (IPCC, 2018). The year 2022 was the sixth hottest year measured with a mean annual temperature of 1.15°C above the pre-industrial average (WMO, 2022). Negative emission technologies, NETs, are technologies focused on CO_2 removal from the atmosphere, and these are needed to achieve the Paris agreements: to keep the global rise of temperature below 2°C. There are different types of NETs such as ocean fertilization: where nutrient is added to the ocean to enhance growth of marine vegetation; burial of anaerobic biomass: to prevent carbon oxidation; direct air capture (DAC): the extraction of CO_2 from the air; bioenergy coupled with carbon capture solutions such as the production of biochar to capture and hold carbon, and in the process producing bioenergy in the form of bio-oil and biogas (Tan, 2019)

Biochar as a carbon storage system is considered a geoengineering solution for active removal of carbon dioxide from the atmosphere. The biochar system acts as a carbon sink, where agricultural vegetation is grown and later pyrolyzed to form biochar. The biochar charged with nutrients (such as mixing biochar with compost or manure) and is later added to the soil to further aid in carbon fixation through increased growth rate of vegetation due to increased microbe activity, balanced pH, and increased the water holding potential of the soil. Carbon dioxide is sequestered as carbohydrates as the plants grow, later the carbohydrates are fixed as biochar through pyrolysis. Under normal circumstances, in the carbon cycle, 99% of the stored carbon in vegetation will return to the atmosphere through either decomposition or burning (days to thousands of years). But in the biochar cycle (**figure 7**) decomposition of carbon is

delayed several thousands of years since the carbon is stabilized as biochar. To follow the example of figure 1 then 50% of the vegetational carbon is stored as biochar and used as a product of fertilization, water purifier, and more. The other 50% is turned to renewable energy (biogas and biooil) to be used as heat, transport, and much more, before returning to the atmosphere again.

It is due to the strong carbon-bonds, and the absence of oxygen within the biochar structures that makes it highly stable product that can be expected to endure in the natural environment for long periods of time. Untreated biomass, such as a branch on the forest floor, will survive for 50-100 years before degraded. According to Schmidt et al. (2002), biochar is found to survive for 1160 – 5040 years before being degraded. It is the absence of oxygen that keeps charred materials from decaying at a “normal” rate. Biochar is praised by for its highly stable characteristics and has demonstrated that biochar production may reduce net GHG emissions up to 1.8 Pg CO₂ annually without disturbing food security or the stabilities of ecosystems (Wang et al., 2016).

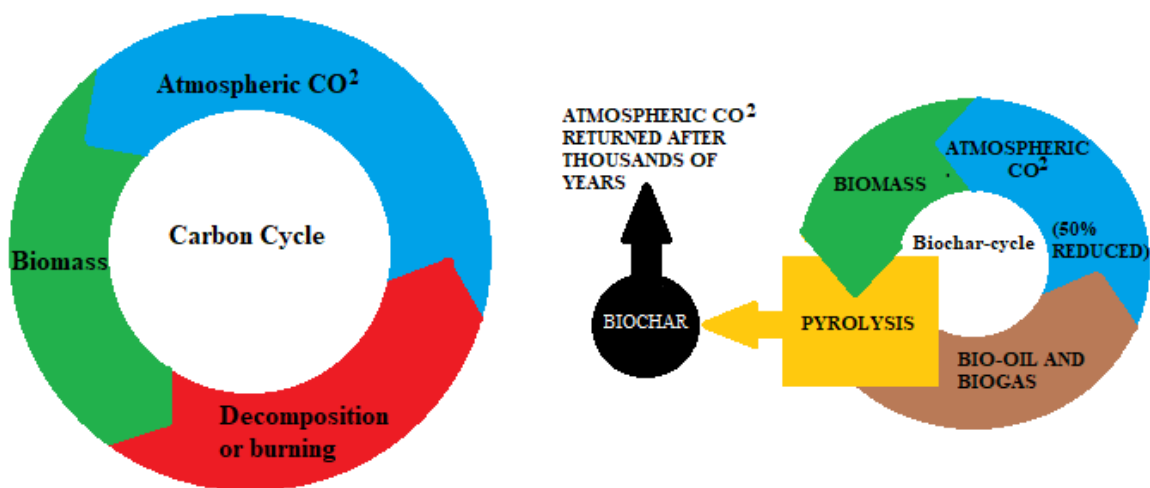


Figure 7: Comparison of the carbon cycle (to the left) and the biochar cycle (to the right)

Lui et al. (2013) performed an experiment where biochar was exposed to a simulated degradation, both in mild and harsh conditions, in both a biotic (living environment such as effected by microorganisms) and abiotic environment (non-living, such as affected by pH, temperature and salts). 10g of biochar, along with a small amount of sterile water was aerobically incubated at 30°C for 374 days. They found that biochar produced a mild degradation. When biochar is exposed to the environment initially, no oxidation would be expected. But after time the sample showed reduction in pore volumes and surface area. In the harsh experiment, the biochar was added to nitric acid, HNO₃, with a weight ratio of 1:10, the flask was then heated to 80°C and shaken in a water bath with a constant temperature for 48 hours. They found that the sample of biochar showed greater degradation through affected surface area, pore volume, adsorption properties, morphology, and changed chemical properties. The author also informs that the degradation rate of biochar in a natural environment has been poorly investigated, and encourages further studies.

The biochar cycle is a sustainable system of energy thanks to the use of biochar as a fertilizer. When mixed with the soil, the rate of the photosynthesis increases i.e., the binding of

atmospheric carbon increases, which means that the biochar cycle is not only neutral, but negative. The adding of biochar to soil gives a negative flow of CO₂ due to the carbon storage of 10³ years. Biochar reacts differently to different soil, and in some cases the negative flow of CO₂ is increased further due to the changes in the soil where a CH₄ and N₂O emissions are reduced. An experiment in China found that when biochar was added to the soil of rice husks, the CH₄ emissions was decreased by 30.7% and 35.6% due to an increased abundance of methanotrophic proteobacteria (procaryotes that metabolizes methane), and/or a reduced methane-producing ability of the soil at the same time as an increased level of pH was measured. This indicates that the level of pH affects the CH₄ emissions of soil (Lui et al., 2014). Sean Case along with his partners published in 2013 a study on how much effect biochar could provide on soil CO₂ emissions and net soil CO₂ equivalent emissions. In the field, a two year long experiment was performed where biochar was mixed with a soil intended for grass growth. The result of this field study was a reduced CO₂ emission by 33%, and an annual reduction of net soil CO₂ equivalent emissions (CO₂, CH₄, and N₂O) by 37% over two years. In a laboratory with a controlled temperature, the effect of biochar showed a decrease of 53% soil emissions, and a 55% decrease on net soil CO₂ equivalent emissions.

More positive effects on the use of biochar are found, such as: reduced use of industrial fertilizers (now at 1.4% of annual CO₂ emissions, CarbonBrief, 2022), reduced water demand, and the use of renewable syngas and bio-oil from biochar production (Tan, 2019). The potential emission reduction of biochar-based systems is 130Gt of CO₂ before the year 2100. Of this is roughly 60% from carbon storage, and the remaining 40% are from the secondary effects of biochar listed above (Woolf et al., 210). McLaren (2012) supports the idea of emission reductions through his own calculations that the use of biochar has the potential of reducing CO₂ by 0.9-3.0Gt per year of a cost of 8 - 300 USD (82 – 3096 SEK) .

India and China had a combined agricultural residue of 1.4Gt/y in 2010. If this residue were to be used in a biochar system, they would be able to lower their annual CO₂ emissions with more than 1Gt/y (12.7Gt/y of CO₂ that same year). If implemented in Scotland, the effect of a biochar system would be able to decrease their emissions with 10%. There are several studies done in the area of biochar as a carbon capture storage method, and they provide varying answers. Further studies are recommended, but with the existing ones at hand, it is safe to say that biochar is a NET system that when used on a large scale, would be able to offset a significant amount of the greenhouse gas emissions in many countries (Tan 2019).

Biochar systems are not a “quick-fix” of the climate problems, but it is an easy and quick way of carbon sequestration, and keeping it stored for a long time. Gupta et al. (2020) states that out of the many options of greenhouse mitigation, the use of biochar is more and more popular thanks to its many advantages as the fact that biochar is an easy way for carbon sequestration and its many uses apart from carbon storage: efficiency in reducing soil CH₄ and N₂O emission, providing an efficient way of managing organic residue, and increasing crop yield, and as an agent of clean water.

Depending on biomass origin and pyrolytic temperature, biochar has different characteristics and will behave differently in different soil types depending on soil storage capacity which include: soil depth, land area, and carbon content. Nutrients and pH are also of importance if biochar is to be used as a fertilizer. Studies has to be conducted to evaluate which biochar is best suited for which soil (Tan, 2019).

3.2.2 Biochar as a fertilizer

As previously stated by Agegnehu et al. (2017) biochar works as a good fertilizer when charged with the right nutrients, such as mixing biochar with organic manure, industrial fertilizers, or minerals containing phosphorus (P) to increase root growth, nitrogen (N) to increase sunlight capture, potassium (K) to aid in water and nutrient absorption, sulphur (S) to form amino acids, as well as other micronutrients like zinc or other metals to aid in the formation of chlorophyll. Thanks to the adsorbing potential of the great surface area of biochar (see figure 2 and figure 4), it can adsorb nutrients and act as a colonization surface for microbes (Leng et al., 2021). When nutrients are adsorbed on the biochar surface, they will not leach away with rain. Instead, they will offer a slow-release of nutrients over long periods of time. Nutrients desorb from biochar primarily through ion exchange and electrostatic interactions (Marcinczyk et al., 2022). When adding char in soil, it has shown to counteract the degradation of soil, and improve the health of already degraded soils (Garber & Elad, 2013). Listed below are four case studies of biochar fertilization's effects on Crop yield:

Zhang et al. (2011) used biochar (both with and without added nitrogen) as a fertilizer to measure crop yield (maize) as well as soil emissions (CO_2 , N_2O , and CH_4). At the end of the season, they found that nutrient poor biochar had increased the crop yield by 7.3 - 15.8%, and the nitrogen charged biochar had increased the yield by 8.8 - 12%. This difference in yield between charged and uncharged biochar contradicts the statement by Agegnehu in 2017 that uncharged biochar should be harmful to crops. Zhang et al. (2011) also reported decreased emissions of CH_4 and N_2O by 9.8 - 41.5% with uncharged biochar, and 23.8 - 47.6% with charged biochar. However, CO_2 emissions were increased by 12% with uncharged biochar; no report of CO_2 emissions in charged biochar is to be found. The group concludes that adding charged and uncharged biochar to dry, calcareous, and infertile croplands both increase crop yield and reduces the total greenhouse gases (GHG's).

Glaser et al. (2014) also performed a study of maize yield, but in a sandy cambisol, but in Germany. They compared crop yield by fertilizing different slots with different fertilizers. Here they used compost, minerals, biogas digestate, and microbially inoculated biogas digestate, both alone and also mixed with biochar. Compost mixed with biochar increased the yield by 26% compared to pure compost. Minerals mixed with biochar increased the yield by 20% compared to only minerals. Biogas digestate mixed with biochar increased the yield by 30% compared to only pure biogas digestate. Lastly when biochar was added to soil with microbially inoculated biogas digestate increased the yield by 42%, but decreased the yield by 50% when biochar was fermented along with biogas digestate. They found that biochar combined with other fertilizers increased the uptake of K, Zn, and Mg, and reduced the uptake of Cu, Na, Ni, and Cd in maize. They conclude with the statement that biochar mixed with other fertilizers not only increase the yield of crops, But also, the uptake of important nutrients.

Bai et al. (2022) summarized the data of 57 articles regarding biochar as a fertilizer on crop yield. They found that biochar increased the crop yield with 25.3 (+/- 3.2%), and organic fertilizers increased the crop yield of 21.9% (+/- 4.4%). However, when biochar and organic fertilizers were used together, the crop yield increased by 179.6% (+/- 18.7%). The author emphasizes that these are rough numbers due to the low amount of data, and encourages further studies. The meta-analysis concludes with the statement that the co-application of biochar and organic and/or non-organic fertilizer greatly increases crop yield compared to the use of only biochar or other fertilizer. Another important aspect of the use of biochar as a fertilizer, aside from growth rate, is plant nutrient uptake. A study performed by Chew et al. (2020), mixed biochar with soil in the rhizosphere (soil directly influenced by roots) on rice crops in China,

found that not only did the plant biomass increase by 67%, but nitrogen (N) uptake increased by 40% and phosphorus (P) uptake increased by 46% when biochar-based compound fertilizers (BCF) was used, compared to when conventional fertilizers were used.

3.2.3 Biochar as a water purifier

Char has properties other than energy, fertilization, and carbon storage. Since 400 B.C coal has been used as a water purifier. Through its charged surface area, coal adsorbs chemicals through complexation, precipitation, electrostatic attraction, H-bonding, and electron donor-acceptor interactions (Palansooriya et al., 2019). The adsorbing capacity also seems to increase with pH 6 or higher, especially concerning calcium, potassium and metals (Godfrid et al., 1991). Since water normally has a pH of 7, coal is highly effective as a water purifier. Below follows two case studies concerning biochar as a water treatment method.

Werner et al. (2018) performed a study of the effectiveness of biochar to be used as a purifier of wastewater with the goal to reduce loads of pathogens. The author notes that a positive bonus-effect of this water treatment method is that the biochar can later be used as a fertilizer since it will be enriched with nutrients after the purification process (**figure 8**, Werner et al., (2018)). They found that untreated biochar was just as effective as a regular sand filter. A normal sand filter can reduce phosphate by 91%, nitrate by 22%, and Escherichia coli (e-coli) by 2.6 log units.

In a study by Palansooriya et al. (2019) alternative methods of water treatment are discussed. They say that due to drawbacks (formation of disinfection by-products such as chlorite, haloacetic acids, and more) in common water treatment methods such as biofiltration, ozonation, and membrane filtration, biochar is an efficient and economical alternative. It efficiently removes microbial contaminants, heavy metals, pharmaceutical products, inorganic contaminants, endocrine disrupting chemicals, and volatile organic compounds.

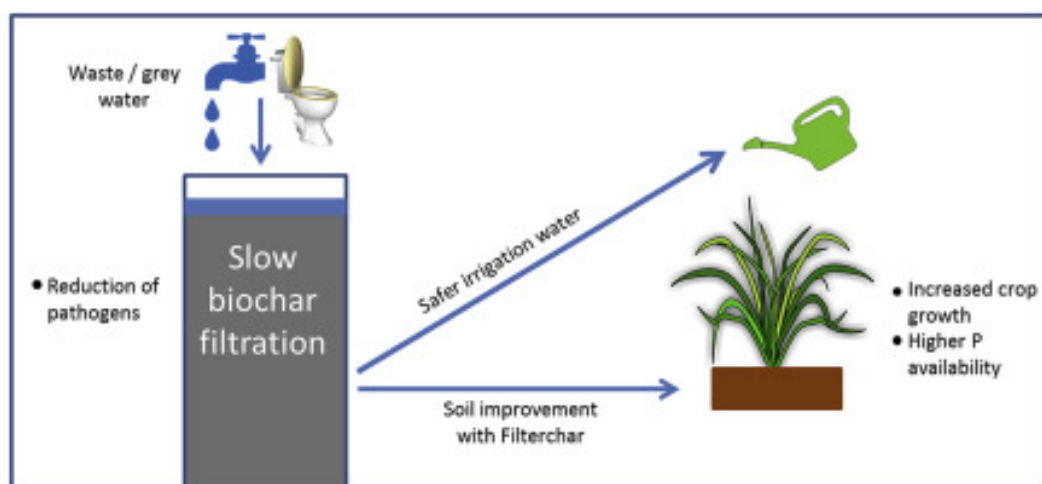


Figure 8 (Werner et al, 2018): Usage of biochar as a water purifier, and later used as soil improver in agriculture.

The collected results from these studies support the idea that biochar is perfectly suitable for increasing soil health through increased pH-levels and microbial activity, increase crop growth rate through fertilization, increase nutrient uptake in vegetation, to be used as a filter to purify water, and most importantly: work as a carbon capture solution.

3.2.4 Bio-oil and biogas

When treating biomass through pyrolysis two products are produced aside from biochar: biogas and bio-oil. Depending on temperature the amount of each substance varies. At slow pyrolysis mostly biochar and biogas will be produced while at fast pyrolysis mostly bio-oil will be produced, but also some biochar and biogas. Flash pyrolysis produces an abundance of bio-oil with only a small amount of biochar and biogas (Panchasara & Ashwath, 2021), see **table 1**.

Bio-oil, also called pyrolysis-oil, or bio-crude, is a synthetic source of energy that can be used as fuel in boilers and engines to produce energy and heat. Bio-oil has a high amount of oxygen compared to crude oil but can however be treated. The oxygen can be reduced, and bio-oil could be used as a more environmentally friendly alternative to petroleum. Biogas, syngas (synthetic gas) is the other product produced when treating biomass through pyrolysis. Syngas can be used as a fuel, a source of hydrogen, and be used in the production of methanol. These two alternative sources of energy are considered “green energy” (Pandey et al., (2019); Abanades et al., (2022)), despite emitting greenhouse gases when oxidated through combustion. The difference between bio-oil and biogas vs natural gas and crude oil is that the latter is a fossil fuel. When used they all above present a threat to the climate crisis as they increase the atmospheres concentration of greenhouse gases. Fossil fuels, contrary to bio-fuels, are not renewable. When bio-oil or biogas is combusted greenhouse gases are emitted, but these gases do not originate from rocks as they have been bound as biomatter through photosynthesis from atmospheric CO₂. Thus, biogas and bio-oil produced through the pyrolysis of organic matter do not further increase atmospheric concentrations of greenhouse gases (Wilkie, 2019).

3.3 Negative effects of biochar

As seen in the sections above, biochar provides many useful features for crop growth, soil health by increased microbe activity and a balanced pH, water treatment, and maybe most importantly as a carbon capturing solution. Most studies on biochar and its application have been done in the last two decades, with a few exceptions from before the year 2000. As this is a relatively “new” area some scientists are concerned regarding eventual side effects and hazards. Below are some common concerns about biochar’s ability to aid in the climate crisis by removing greenhouse gases from the atmosphere.

Sundberg (2014) and Lehmann (2007) both found positive effects on atmospheric greenhouse concentrations (N₂O, CO₂, CH₄, CO) when implementing the biochar cycle as a carbon capturing solution, and used as a fertilizer to further increase the carbon capturing. But some would argue that the area of biochar is not fully studied and needs to be tested further. Xiang et al., (2021) tells us that there is support for the application of biochar as a fertilizer could have a negative effect on greenhouse gas emissions by increasing the N₂O emissions, which would further increase the climate crisis. When used as a fertilizer biochar could influence the microorganism activity, and due to this increase the emission of N₂O in soil. The nitrogen dynamics is shown to be affected by alternation, soil pH, and type of biochar (Lin et al., 2017; Xiang et al., 2021). The right type of biochar needs to be added to the appropriate soil. A study showed that a straw-derived biochar had a negative impact on soil pH due to its high nitrogen content. The growth rate of ammonia-oxidizing bacteria increased, and thus enhanced the rate of nitrification, this leading to an increase of N₂O emissions (Lin et al., 2017).

Another study shows that there is a positive connection between biochar ash concentrations (i.e., amount of potassium, sodium, phosphorus, and other) and N₂O emissions, where the salt rich concentration of biochar ash affects the soil N₂O emissions due to the caused “salting out effect” i.e., the process where classes of molecules varying in charge, size, and surface area are separated from the water through reducing their solubility. When salt is added to a mixture the salt and the molecules compete with the binding of water, and the solubility decrease (Henicke & Kaupenjohann, 1999). Biochar originated from different types of biomasses may have varying effects on soil pH, and soil microbe-balance, depending on the mineral concentration in the soil. How N₂O is affected by the different types of biochar requires more research (Nui et al., 2018). Xu et al. (2020) found that different biochar can have very different effects on soil, and one type of biochar lowered the N₂O emissions to roughly 51% from 90%, when another type of biochar enhanced the soil emission of N₂O, which has a global warming potential 265 times that of CO₂.

All these studies above give cause for further investigation on biochar and its uses. However, note that none of the articles above have mentioned the use of charged/loaded biochar (enhanced with nutrients before used as a fertilizer), but have only used non-charged biochar. When uncharged biochar is used as a fertilizer, it may adsorb the surrounding nutrients, leaving less for the vegetation which could damage the crops (Agegnehu et al., 2017)

3.4 Economical sustainability

As showed in previous chapters, the production and use of biochar comes with several positive effects, but is it economically justifiable? How does the cost of biochar use stand against conventional methods in energy production, fertilization, water treatment, and waste management? The economic viability of biochar, and its production through pyrolysis, is mostly dependent on the production of feedstock (biomass), carbon offset, and pyrolysis.

Back in 2011 Meyer et al. did a literature review concerning climate, economic and technical aspects of biochar production and its uses. They reviewed studies of gasification, flash carbonisation, hydrothermal carbonization, and most of all, pyrolysis. When producing biochar through pyrolysis the cost is estimated to be 51 USD (530 SEK) per tonne when produced from yard waste. Meyer (2011) compared biochar and charcoal production costs and found biochar to be the more economical one, since one tonne of produced charcoal costs 386 USD (4.013 SEK). This makes one tonne biochar 87% cheaper than one tonne of retort charcoal. The Greenhouse Gas Protocol (GHG) is a global standard used by companies and organizations to become more efficient and prosperous while measuring and managing their greenhouse gas emissions. CO₂e equal the amount of emitted carbon dioxide a product corresponds to. The carbon footprint of charcoal production is as high as 220kg CO₂e per tonne (Norgate et al., n.d), which is higher than the production of biochar. The Greenhouse Gas Protocol of biochar systems found atmospheric effects between -1054kg CO₂e, and +123kg CO₂e per tonne biomass feedstock.

South Asia and sub-Saharan Africa are hotspots for economic growth through industrialisation. They both play a major part in the 1.6 billion tonnes emitted globally every year from waste management (Nair et al., 2020). In urban areas, in Asia and Africa the organic waste is rapidly increasing and puts pressure on waste treatment. These areas are also expected to double their waste by the year 2050. Water treatment is also affected by this increasing waste management

as well as the soil becomes more and more degraded as well, and in need of fertilization (Nair et al., 2020). When looking at the economic growth rate, and the environmental pollution that accompanies it, it is obvious that a sustainable waste treatment is essential for a healthy future. If the biochar-cycle would be implemented, not only would it have a positive effect on the climate, but if organic waste were to be treated through pyrolysis, the resulting product would also have the potential to increase soil health and later increase crop yield. Additionally, new alternatives of waste-water treatment and new energy sources such as biogas and bio-oil would become available. However, centralised water treatment systems are most often considered the most cost effective as they are built in areas with high population where the consumer lives near the treatment plant. But in areas with few inhabitants there is rarely any local water treater, and the water is instead pumped over long distances. This is however not economically sustainable since it is difficult and expensive. The implementation of biochar-use in water treatment in these smaller communities is both economical and simple. The filter (**figure 10**, Dalahmeh, 2016) operates with gravity, it does not require pumping, and can be constructed by local materials (Holsett et al., 2018). As written earlier, biochar (especially biochar from agricultural waste) is a low-cost method for water treatment and is efficient in removing organic and inorganic pollutants as well as heavy metals (**figure 11**, Khiari et al., 2020).

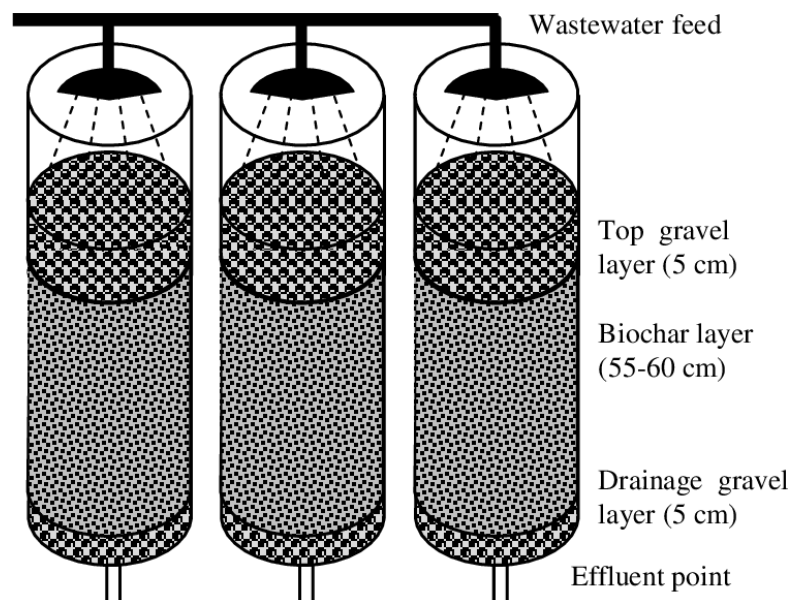


Figure 10, (Dalahmeh, 2016): Biochar filtration system. Contaminated water is added at the top and is filtered through gravel and biochar.

The director of biochar research at the University of Colorado, Josh Kearns, is producing biochar in the villages along the border of Thailand and Burma to provide safe drinking water for the inhabitants. In rural areas in Indonesia biochar has been used as a waste management system, and tested as a fertilizer and as a heating agent for cooking. Thanks to the increased vegetational growth rate, and the reduced amount of indoor air pollutants, biochar has shown to both improve health as well as an increased income of 173 USD (1786 SEK) per household annually (Sparrevik et al., 2014).



Figure 11, (Khiari et al., 2020): Contaminated water before (inflow) and after (outflow) being processed through a biochar filter.

Roberts et al., did a review 2009 of the economic potential of biochar production and its uses. They found that the ones with the highest economical profitability are farms with high yard waste, as they can re-use the biochar after pyrolysis to further increase their crop yield. The transport cost of biomass such as lumber or agricultural waste is simply too high for the biochar pyrolysis-systems to be economically profitable, which is why the most economical usage of biochar is local use (i.e., farms and local waste management).

A study done in Massachusetts, USA, found that the sustainable biomass supply of the state could support up to 71 facilities specializing in biochar, biogas, and bio-oil production. These facilities would be able to produce in total 142 MW of electricity, giving jobs to roughly 700 people. These facilities would replace a small amount of energy production in the state, they lower the use of distillate fuel oils, and finally lower the greenhouse emissions of the state of Massachusetts. The author concludes by writing that the energy contribution of these facilities is less important. In the long run the most important thing about implementing the biochar-cycle is the contribution to not only Massachusetts, but the world's agriculture, as the climate change facing this over-populated world requires sustainable sources of food (Timmons et al., 2017).

3.5 Biochar in Sweden

The most common soil-type found in Sweden is podzol, which covers roughly 70% of the Swedish land. The Swedish land area is covered by 68% forest (SCB, 2022), a majority being coniferous forest. The podzol soil-type is acidic partly due to the degradation of the vegetation above such as spruce and pine needles, and partly from the felsic bedrock of granite and gneiss. As already stated, Cornelissen's study in 2018 showed that adding biochar to an acidic soil helped balance the pH to a more favourable condition for vegetational growth. Rizhiya et al. performed an experiment in 2016 where biochar along with clover residues was added to podzols to measure the effects on fertilization. Not only did they find that biochar increased the water holding capacity of the soil, but also a higher nitrate content was measured and due to the high-water content, the conditions of denitrification were poor. The soil with biochar showed higher fertility than the compared medium fertile soil. They found that N₂O emissions were significantly reduced, however no reduction in CO₂ emission was observed.

Biochar has been receiving more awareness in recent years as private organizations (Biokol Sverige) as well as the Swedish Environmental Protection Agency (Naturvårdsverket) has seen its potential. In Sweden there is now 26 pyrolytic facilities, which is more than Norway's (nine) and Denmark's (six) combined. Most of them are located around the Stockholm region and in Skåne. However, only a few of them produce biochar for commercial use, and none of them produce the amount needed to cover the steel production market of Sweden. The production sites sell an amount suitable for private farms and gardens. The Swedish Government of Energy (Energimyndigheten) gave in June 2022 twelve million SEK to research on if biochar production can support the steel and iron industry of Sweden on an industrial scale. The steel industry is responsible for 12% of Sweden's annual GHG emissions (globally 7-9%), and the major reason for this is the usage of fossil carbon. David Pallarés, professor at Chalmers University says that the usage of biochar instead of fossil carbon is a great step in the right direction, since it is both cost effective and would reduce the GHG emissions of Sweden (Malmberg, 2022).

The Swedish government aspires for Sweden's heating sector to be fossil free by the year 2030, and climate positive (sequester more carbon than emitted) by the year 2045. To reach this goal the government aims to use bio-waste as a mean of carbon sequestration, and for the district heating to have produced a carbon sink of 5 million tons from biowaste in the form of biochar (Energimyndigheten, 2021).

4. Discussion

The main purpose of this review has been to analyse if biochar is a sustainable method to reduce carbon dioxide from the atmosphere, and to keep it reduced for thousands of years. Based on the studies reviewed in this study, biochar is praised to be a highly efficient mean for carbon sequestration with a potential of sequestering up to 1.8 Pg CO₂ annually without disturbing eco-systems or disorganize food security (Wang et al., 2016). The buried carbon is fixed in solid form for thousands of years unless burned (Schmidt et al., 2002). The motivational key for biochar use may lie in the highly positive effect it has on agriculture as a mean of fertilization, as well as the use of the renewable energy sources found as a by-product of pyrolysis process: bio-oil and biogas.

By processing biomass, especially yard waste, through slow pyrolysis, the resulting char is seen to be a great deal cheaper compared to buying the same amount of charcoal (51\$ and 386\$ respectively for 1 tonne of char) (Meyer et al., 2011). Biochar becomes even more profitable if later used as a fertilizer. The most profitable use of biochar seems to be locally, by farmers who can re-use the biochar on site as a fertilizer at a later stage. Based on the review performed by Roberts et al. (2009) it does not seem to be profitable for companies to buy biomass from afar due to the expensive transport costs to the site of pyrolysis. The same goes for biochar as a water treater, pumping water over long distances is expensive, but to use biochar as a water treater in smaller communities is both economic and simple. Rural areas would benefit if the pyrolysis system were to be implemented as a way to dispose of organic waste, not only as a method of waste management, but as a way of increasing crop yield as well as an energy source in the form of bio-oil and biogas. The combined result from the analysed studies clearly shows that biochar is both a highly effective and economically sustainable mean for carbon

sequestration, mainly as a mean for waste management due to the high lifespan of biochar in soil ($>10^3$ years).

If implemented in Sweden, as well as globally, a drastic reduction of emissions would be seen, and in the long run, up to 130Gt of CO₂ before the beginning of the next century (Woolf et al., 2010). However, the use of biochar will not alone stop the climate changes and help reaching the goal of a global mean temperature of $<1.5-2^{\circ}\text{C}$, but together with other negative emission technology systems (NETs) it might play a powerful role. Due to its many ways and cheap and simple methods biochar can contribute to our urban society, as well as in rural areas, it is expected to be seen more in the near future, not only in Sweden, but also other countries all over the world.

It is important not to dismiss other greenhouse gases when talking about emissions. Is it actual worth mixing biochar with soil to sequester carbon and reduce CO₂ when other gases might increase due to this? There seems to be concern about the increased emission of nitrous oxide (N₂O), and nitrous oxide has a global warming potential (GWP) 265 times higher than CO₂ (Xu et al., 2020). However, these types of biochar were not charged/loaded with nutrients before being used, and uncharged biochar could have other negative effects other than raised emissions of N₂O, as it could also damage the vegetation (Agegnehu et al., 2017). The effect of biochar in uncertain/different soil types must undergo further studies if it is to be used on a global scale. If it were to be used for 1) increase CCS, 2) prevent N₂O emission, 3) increase crop yield, it should be in tested soils, preferably in the rhizosphere where it was highly effective (Chew et al., 2020). Two examples are cambisol or the common podzol of Sweden and large parts of the northern hemisphere. Lastly, it seems that to prevent crop damage and soil emissions, then biochar should be charged/loaded with nutrients from manure, rock dust or other sources of minerals and nutrients.

The unanimous findings from the analysed studies give further credibility to their results. Most of the studies I have used, as well as the majority of other studies I read during my research, are very positive about the use of biochar as a method of carbon capture storage, a fertilizer, and as an agent of clean water. Although, even if they agree that biochar increases crop yield, their conclusions could vary a great deal regarding the fertilization potential of biochar, from just 7.3% (Zhang et al., 2011) to an astounding 179.6% (Bai et al., 2022). Only a few studies I have found during my research has argues against the use of biochar, where most of them also provide several positive effects in various fields. Of the reviewed studies found in this study 48 argues for, and 9 argues against (**table 3**).

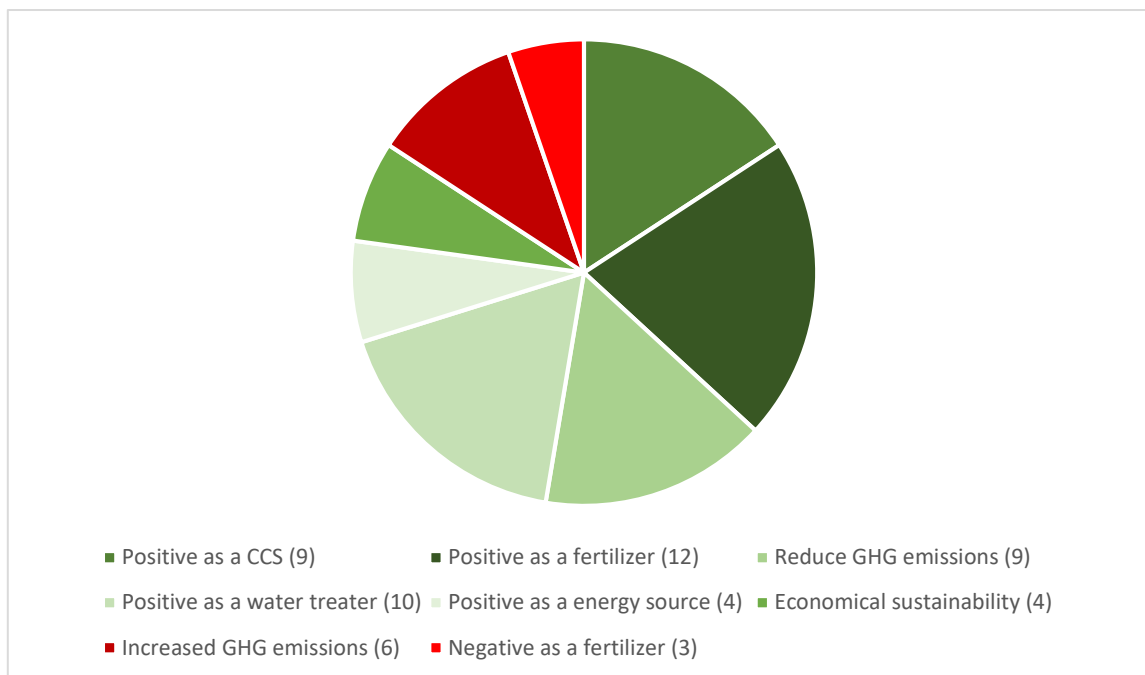


Table 3: The reviewed studies in this study arguing for (green) or against (red) the production and usage of biochar as a CCS, fertilizer, water treater, mean for reduce or increase emissions, energy source in the form of biogas and bio-oil, as well as economical sustainability.

4.1 Further studies

There is still some uncertainty about the effect of biochar in different soils depending on the mineral concentration of the soil. It is also not clear how biochar's with different biomass origins affects certain soil types, which is important to know to prevent negative impacts on soil pH, and increased ammonia-oxidating bacteria which enhances the nitrification rate (Lin et al., 2017).

The use of biochar as a water filtration system is highly praised and is being used in rural areas in Asia, and where the biochar can later be used as a fertilizer as it is charged/loaded after the purification of water (Werner et al., 2018). However, can biochar be too charged/loaded? Can the addition of biochar in soil in the long run have negative impacts on soil health and fertility when it is full of pathogens and heavy metals?

5. Conclusion

Biochar, this slow degraded fixation of carbon, puts the carbon cycle on hold as it captures atmospheric carbon and holds it for up to over 5000 years, unless oxidated either through combustion or respiration. Charged/loaded biochar has shown great potential when used as a fertilizer as it enhances both growth rate and nutrient uptake of crops, which further increase the capture of atmospheric carbon. It increases soil fertility by aiding microbial activity, balances pH in acidic environments, increases the water holding capacity in the soil, and

decreases the soil CO₂ emissions. The use of biochar in soil is well suited for not only Sweden, but the full northern hemisphere as it is highly effective as a fertilizer and water holder in for example podzol, which covers almost 5.000.000 square kilometres distributed in the countries above 30°N. The implement of biochar production as a waste management system has shown great potential in decreasing yearly emissions all over the world, but especially in Asia and Africa where the crop residue is high. When used as a water purifier biochar can successfully remove heavy metals, inorganic, pharmaceutical, and microbial pathogens. After being used as a water treater, the biochar can be further used in agricultural lands as a fertilizer. The two by-products formed through the pyrolysis of biomass, bio-oil and biogas, can be used as a carbon neutral energy source. However, through the denitrification process, it has been shown that biochar as a fertilizer could have a negative impact on soil emissions as it could increase nitrous oxide (N₂O), as well as have a negative impact on soil pH and potentially damage crops. Further, when uncharged/unloaded biochar is added to a nutrient-poor soil the CO₂ emissions could increase greatly due to increased microbial activity. Biochar has the potential to act as an effective method for carbon storage all over the world, but further studies in needed to evaluate the effects of biochar in different soils to prevent crop damage and N₂O emissions.

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