Exploring future potentials for biochar in Gothenburg

An evaluation of the potential to utilize locally available feedstocks for sustainable biochar production

Master's thesis in Master Programme Industrial Ecology

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Abstract

Gothenburg city has adopted a vision of becoming an environmentally sustainable city by 2030, with a climate footprint close to zero. One of the planned actions to reach this vision is to build a pyrolysis plant for garden waste, which will provide biochar for urban plantations and contribute with negative emissions and surplus heat to the district heating system. This thesis aimed at exploring future potentials for sustainable biochar production in Gothenburg, based on locally sourced feedstocks beyond garden waste.

The thesis was divided into three steps, based on the backcasting from principles methodology that was used as an overall framework in this study. The three steps included: defining guiding principles for a sustainable biochar production, mapping biomass flows in current systems and evaluating feedstocks to find leverage points for future biochar production. The methods applied within the steps were literature study, top-down approaches for waste flow identification, surveys, semi-structured interviews and multi-criteria analysis (MCA).

Six different feedstock flows were analysed: garden waste, untreated wood waste, agricultural plant residues (APR), sewage sludge, food waste and horse manure. The sustainability evaluation conducted in the MCA covered criteria for each feedstock's certification potential, biochar production potential, negative emissions potential, present utilization of biomass, cost per climate benefit, cost compared with alternative, collection infrastructure and pretreatment requirements.

The results show an aggregated annual potential of approximately 240 000 tonnes of locally sourced feedstock, with the ability to produce around 41 000 tonnes of biochar and generate 114 000 tonnes of negative CO_2-equivalents. Untreated wood waste was identified as the feedstock with the highest overall score in the MCA, followed by garden waste and APR. Horse manure performed slightly better than sewage sludge and food waste, which received the lowest scores.

Finally, discussions and recommendations for each feedstock was provided, where discussions around the results and uncertainties are provided to give stakeholders a good knowledge-base for future sustainable biochar production in Gothenburg.

Keywords: Biochar, Feedstock, Gothenburg, Backcasting

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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

APR	Agricultural plant residues
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CCU	Carbon capture utilization
CDR	Carbon Dioxide Removal
CHP-plant	Combined heat and power plant
CO_2-eqv	Carbon dioxide equivalents
DAC	Direct air capture
EBC	Europeen Biochar Certificate
EU	European Union
EU ETS	European Union Emissions Trading System
EWC-stat	European Waste Classification for Statistics
GHG-emissions	Greenhouse gas emissions
GMHP	The municipalities of Gothenburg, Mölndal, Härryda and Partille
IBI Standards	International Biochar Initiative Standards
IPCC	Intergovernmental Panel on Climate Change
MCA	Multi-Criteria Analysis
MSW	Municipal solid waste
NACE	Statistical Classification of Economic Activities in the European Community nomenclature
PAH	Polycyclic aromatic hydrocarbon
PFAS	Per- and Polyfluorinated Substances
WF	Waste Factor
WWTP	Wastewater treatment plant

Contents

1

Introduction

Imagine a technology that can mitigate climate change by capturing carbon from the atmosphere and store it safely in the ground. Imagine that agricultural soils used for storing this carbon receive increasing yields through enhanced ability to maintain water and nutrients. Imagine that the technology can run on biogenic sources defined as waste in other sectors. Imagine that the technology doesn't require any additional energy, but instead produces an energy surplus that can be utilized in a district heating system. And finally, imagine that this technology is not a fancy futuristic vision by a tech start-up, but actually a technology that have been known for hundreds of years.

The technology described above is the production of biochar through pyrolysis (E. Azzi, 2021) (Bates, 2010). The advantages of biochar production might almost seem too good to be true, but the question remains on how the technology might fit into today's society.

Biochar is a porous charcoal-like substance, made from burning organic material in an oxygen deficient environment (Spears, 2018). It is most often made through pyrolysis and has the ability to generate net negative emissions since the organic material used in the production can be considered climate neutral, yet can store carbon in terrestrial form for thousands of years when applied in soil. Biochar has also gained recognition for its potential to mitigate soil degradation. Research and field studies have begun demonstrating beneficial properties such as increased soil water-holding capacity, conservation of fertilizers, adsorption abilities, filter media for water drainage and carbon sequestration (Fuchs et al., 2014). Energy production synergies, coupled to biochar production, and their economical and environmental implications have also attracted interest from researchers and public agencies. The biochar industry is further being investigated for its contribution to economic growth, climate mitigation, and waste management. However, the diverse properties of the biochar create uncertainty in its implementation to utilize the potentials in symbiosis.

In Sweden, there´s been a growing interest in biochar technology in recent years after Stockholm Exergi built Sweden's first pilot plant for biochar production in 2017 and received a lot of publicity (Stockholm Exergi, 2021). In Gothenburg, the first biochar production facility is planned to be built in 2024 and like the pilot plant in Stockholm it will be using garden residues like branches, sticks and twigs as a feedstock (M. Eriksson, personal communication, February 15, 2023). This biochar production plant is one of the actions in the city's plan to transition to an environmentally sustainable city by 2030, with a climate footprint close to zero (Göteborg Stad, 2021).

According to Gothenburg's energy plan, the planned biochar production plant has the potential of annually achieving negative emissions between 4 500-8 500 tonnes of CO_2-equivalents (CO_2-eqv) (Göteborg Stad, 2022). This can be compared with the total amount of greenhouse gas (GHG)-emissions generated in Gothenburg, amounting to approximately 2.4 million tonnes of CO_2-eqv (Göteborg Stad, 2021) (SCB, 2022). Considering that carbon dioxide removal (CDR) is included in all the Intergovernmental Panel on Climate Change's (IPCC's) pathways that succeeds in limiting global warming to 1.5°C, it's valuable to explore the potential of all CDR-technologies that can contribute in limiting global warming (IPCC, 2022). Exploring future potentials for biochar can thus provide an important piece of the puzzle for the City of Gothenburg in their transition to an environmental sustainable city by 2030.

1.1 Aim and Research Question

This thesis aims to explore future potentials for sustainable biochar production in Gothenburg, utilizing locally sourced feedstocks from the Gothenburg region and contributing to the city's sustainability targets.

The research question is stated as:
What is the potential for locally sourced feedstocks for biochar production in Gothenburg and how might the potential be utilized in a sustainable way?

The research question is answered by addressing the three specific objectives:

- Define important aspects of sustainability for biochar production.
- Map out biomass flows within the Gothenburg region that might be utilized for biochar production.
- Evaluate identified feedstocks based on a set of predefined criteria coupled to the sustainability aspects.

1.2 Approach

In order to build a foundation to help answer the research question, the study will be divided according to the three specific objectives. The framework of this thesis will then be inspired by the backcasting methodology, as a lens through which a sustainability transition is viewed, by aligning the three specific objectives with the first three steps of the backcasting methodology as described in Chapter 3. In contrast to forecasting, where future predictions are based on the progress of current paths, backcasting starts by defining a desirable future and explore paths to reach that future (Holmén, 2020).

Apart from backcasting, other methods applied to answer the research question and address the objectives within the framework of the thesis are presented below:

Step 1 will include a literature study to define important aspects of sustainability for biochar production. The literature study will be conducted in accordance with the method described in Chapter 3.2.

Step 2 will map out biomass flows within the Gothenburg region that might be utilized for biochar production. The identification of biomass flows will be based on the literature study, described in Chapter 3.2. The selected biomass flows will then be mapped and quantified using the methods: Top-down approach for waste intensity per sector, Complementary top-down approach, Surveys and Semi-structured interviews, described in Chapter 3.3, in order to display the current systems.

Step 3 will evaluate the identified feedstocks based on a set of predefined criteria coupled to the sustainability aspects. To evaluate each feedstock on equal terms, the method multi-criteria analysis (MCA) including weighting will be used, described in Chapter 3.4.

1.3 System boundaries

Biochar can have different characteristics depending on e.g., the type of biomass, temperature of process and application area. Due to the diversity of the char, biochar can often be defined in various ways. However, in this thesis the definition stated by the European Biochar Certificate (EBC) will be used. Since the thesis aims to explore future potentials for sustainable biochar production in Gothenburg, only currently present biomass flows considered as waste from other processes according to EBC were considered. Hence, the potential of dedicated feedstocks solely produced for the purpose of producing biochar were not investigated within the scope of this thesis.

To limit the thesis, focusing on the Gothenburg region, a geographical system boundary of a 20 km radius from Gothenburg city centre will be considered in the report. The geographical system boundary was selected, based on literature reviews of optimal distances between biomass production and processing, in order to evaluate the identified biomass fractions on equal terms (Labriet, 2013) (Simon Berg & Dimitris Athanassiadis, 2018) (Kurowska et al., 2021). Since only waste biomass flows, generated in the vicinity of Gothenburg city, were considered and longer transport of biomass types with low energy density and high water content are rarely feasible, the 20 km radius was selected to depict the biochar production potential in the Gothenburg region (Institute for Energy and Transport, 2015). Further, in order to be able to utilize regional data from municipalities within the geographical system boundary, the 20 km radius was translated to account for the four municipalities of Gothenburg, Mölndal, Härryda and Partille (GMHP).

2

Background

This chapter covers background information around technical aspects of the biochar technology, regulatory aspects and certification possibilities applicable to biochar and how the biochar technology can be connected to the sustainability transition in Gothenburg.

2.1 The element cycles

Elemental cycling is a term used to describe the transport and transformation of chemicals within and among ecosystems (Ågren & Bosatta, 1998). The elements considered, refers to elements in the periodic table which is required by all life and hence element cycles link the living (biotic) and non-living (abiotic) parts of the ecosystems (Weathers et al., 2012). Apart from carbon, which is the building blocks of life and thereby defines the organic system, nutrient cycles are important parts of the element cycling since they are vital for living organisms. To achieve a transparent view of the element cycles, the carbon, nitrogen and phosphorus cycles were considered since the three elements are critical to life in ecosystems and therefore critical for biomass growth. However, although each of the three elements cycles are specifically presented for individual elements, one should note that none of the selected element cycles are isolated but interact with multiple elements and cycles in larger systems.

2.1.1 The carbon cycle

The element cycle of carbon is important to consider for biomass growth since it is the major building block for all life and the second most abundant element in organisms by mass (Weathers et al., 2012). Most of the carbon on Earth is stored in rocks, but much is also stored in the atmosphere, oceans, soil, living organisms and fossil fuels (Riebeek, 2011). The mediums where the carbon accumulates is called reservoirs, and it is the exchanges between these reservoirs which make up the carbon-cycle. The chemical forms of carbon in the cycle can vary among physical states including gas, solid, liquid or redox states. While studying the element cycling of carbon, the cycle is often divided into two categories: the fast and slow domain, described in more detail in Sections 2.1.1.1 and 2.1.1.2.

Over the last decade, human manipulation of the carbon-cycle have had an enormous impact on the balance between the fast and slow domain of the cycle (National Oceanic and Atmospheric Administration, 2019). The extensive use of fossil fuels, land use change and utilization of limestone to produce concrete, transfers large amounts of CO_2 to the atmosphere and hence heavily enhances the accumulation of carbon in the slow domain. As a result of the carbon accumulation in the atmosphere, enhancing the greenhouse effect on Earth, the ocean absorbs larger amounts of carbon, leading to ocean acidification and deterioration of the natural carbon-cycle.

In efforts to limit the human manipulation of the carbon-cycle and to combat climate change, bio-based alternatives have been suggested as a possible substitute to offset the use of fossil fuels (Hao et al., 2021). Biomass absorbs CO_2 from the atmosphere when growing, using photosynthesis to store carbon, and releases the CO_2 back into the atmosphere through decomposition, respiration and human activities (Turgeon & Morse, 2022). Hence, using bio-based material, carbon can be utilized yet retained within the slow domain and is thereby in many cases considered to be climate neutral (Berndes et al., 2016). An overview depiction of the difference between the cyclic biomass carbon flow (green arrows) with biochar production and utilization (blue arrows generating a carbon neutral or carbon negative system) and the linear fossil carbon flow (grey arrows), are depicted below in Figure 2.1.

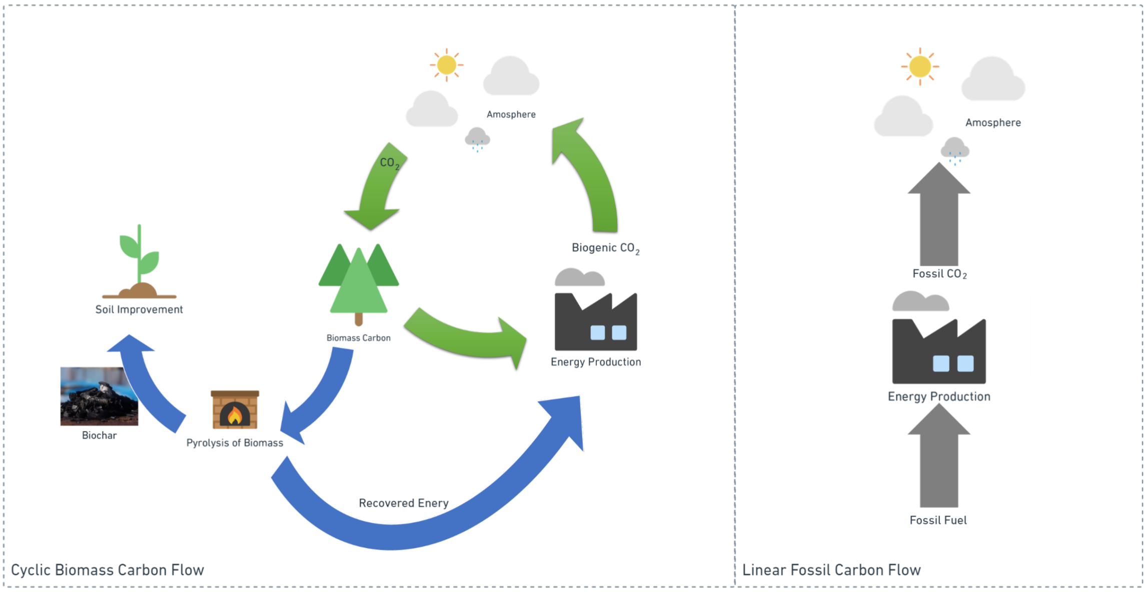


Figure 2.1: Overview depiction of the cyclic biomass carbon flow, with biochar production and utilization, and the linear fossil carbon flow.

2.1.1.1 The slow carbon-cycle

The slow domain of the carbon-cycle operates over time frames of 100-200 million years where the carbon moves between atmosphere, soil, ocean and rocks via chemical reactions and spontaneous movements in the Earth's crust (Riebeek, 2011). To give a short description of the slow domain of the carbon-cycle, starting with the atmosphere, the carbon reacts with water to form carbonic acid (Lerman, 2009). Rain then transports the dissolved carbon to the surface of the earth and the acid reacts with crystalline rocks. Over time, the acid slowly reacts with the rock in a process called chemical weathering, where metal ions are released from the rock structure and dissolves in the water phase. In the water phase the positively charged calcium ions are to a large degree balanced by negatively charged bicarbonate ions and are slowly transported to the ocean with the watercourse (Riebeek, 2011).

Once the water reaches the ocean, organisms utilize the calcium and carbonate to form calcium carbonate, via calcification, in a shell-building process (Riebeek, 2011). As the organisms die, the shells sink and accumulates at the bottom of the ocean. Under large pressure, shells and sediment are then slowly cemented together at the bottom of the ocean and turn to rock.

It is estimated that the oceans account for about 80% of the carbon stored in rock formation, and that the remaining 20% are formed in a similar process on land (Riebeek, 2011). The fraction formed on land mainly consists of organic carbon, which accumulates in layers of mud. Over time, the organic carbon is then compressed under high heat and pressure to form both rock formations and pockets of fossil fuels, like coal, oil or natural gas. By spontaneous movements in the Earth´s crust, the carbon-containing rocks melt under extreme pressure and heat and are once again released into the atmosphere in form of volcanic eruptions and tectonic processes (Lerman, 2009).

The slow carbon-cycle hence regulates the balance between the carbon reservoirs in atmosphere, ocean and land over very long periods of time (Riebeek, 2011). Although the slow carbon-cycle in general operates over millions of years, the ocean reservoir contains some faster components. Based on the partial pressure between the air and water, CO_2 ventilates in and out of the water under steady conditions (Weathers et al., 2012).

2.1.1.2 The fast carbon-cycle

The fast domain of the carbon-cycle operates over much shorter time frames and is often measured in a lifespan (Riebeek, 2011). In contrast to the slow carbon-cycle, accounting for carbon flows in atmosphere, ocean and land, the fast carbon-cycle mainly consists of carbon movement in organisms.

Considering the atmosphere as the starting point, plants and phytoplankton absorbs CO_2 from the atmosphere via photosynthesis to sugar derivatives (Weathers et al., 2012) (Riebeek, 2011). Once the organisms have formed the sugar derivatives, there are four different respiratory pathways which the carbon can take before once again ending up in the atmosphere. In the first pathways, the organisms break down the sugar in order to grow and retain energy itself. For the second pathway, the organism is consumed by animals as part of the food chain to grow and retain energy. The third alternative pathway is decaying, where organisms would be consumed by bacteria after dying, and the last and final pathway where fire might incinerate the organisms, releasing the carbon back into the atmosphere.

The fast carbon-cycle depends to a large extent on the photosynthesis and respiration balance of plant life (Riebeek, 2011). Since the northern hemisphere contains far more land area than the southern, the seasonal changes in the northern hemisphere have larger impact on the carbon fluctuations in the atmosphere (Copernicus, 2019). Hence, during the winter season decaying causes respiration which increases the amount of carbon in the atmosphere and during the spring, when plants grow via photosynthesis, the carbon amount in the atmosphere decreases.

2.1.2 The nitrogen cycle

Nitrogen is one of the major essential elements for life and often limits primary production in many biospheres of the planet, especially in saltwater ecosystems and temperate forests (Weathers et al., 2012). The nitrogen-cycle contains a complex and interesting series of biological transformations and is a system which is highly manipulated from human intervention. Since nitrogen often limits primary production, reactive nitrogen derived from fossil fuel combustion is often added to enhance the yields from crop production. However, the manipulation generates an excess of nitrogen in the system which leaches into the surrounding ecosystem, leading to cascade effects causing problems with air and water in the ecosystem.

Nitrogen can in general be divided into two categories on Earth, where the majority is molecular nitrogen in the atmosphere, consisting of about 79% of the stable aggregate, and the biologically reactive nitrogen including nitrate, ammonium and organic nitrogen aggregates (Takai, 2019). Nitrogen is the only element, essential for primary production, which is not a component of the common rocks that makes up the Earth‘s crust. Hence, although nitrogen is abundant in the atmosphere, primary production is often limited by the conversion of molecular nitrogen into its reactive soluble forms.

Traditionally, the nitrogen-cycle was divided into three dominating processes: nitrification, denitrification and dinitrogen fixation (Weathers et al., 2012) (Stein & Klotz, 2016). However, as the understanding of the complexity of the nitrogen-cycle has broadened, the cycle is now considered to consist of five potential nitrogen transformation flows: ammonification, nitrification, denitrification, anammox and nitrate-nitrate interconversion.

As mentioned, human manipulation of the nitrogen-cycle is substantial but there are processes and techniques which has the potential to mitigate the leching element cycle and contribute regenerating the natural nitrogen balance (Clough & Condron, 2010). Research indicates that biochar has the potential to mitigate nitrogen leaching in soil while creating beneficial soil structure to help restore the natural nitrogen production.

2.1.3 The phosphorus cycle

Phosphorus is an important component in DNA, RNA and formation of cell membrane, which is essential for all organisms (Jahnke, 1992) (Weathers et al., 2012).

Much like nitrogen, the availability of phosphorous often limits primary production and therefore has a large impact on the carbon uptake in terrestrial ecosystems. However, in contrast to nitrogen which has an abundant atmospheric reservoir, phosphorous mainly occurs in solid or liquid form and in small quantities (G. M. Filippelli, 2009). Since phosphorous are rarely found as gaseous aggregates, the atmospheric reservoir generally plays a minor role in the cycle. Instead, natural availability of phosphorous is strictly limited by the rate of release from soil weathering, both affecting the primary production on land and in water. Although the phosphorous-cycle operates relatively quickly through animals and plants, the cycling in rock and soil is one of the slowest element cycles on Earth as it operates over time ranges of about 500 million years.

Human manipulation of the phosphorous-cycle has been substantial over the last 150 years, most significantly through agricultural activities (G. M. Filippelli, 2009). As human activities started to influence the phosphorous-cycle long before the scientific interest in the element cycle appeared, pre-anthropogenic phosphorous equilibrium levels can only be estimated. Today, the phosphorous-cycle is dominated by human activities, where phosphorous aggregates are mined and transported all around the world in form of fertilizers, animal feeds and detergents, leading to a redistribution of the phosphorous reservoirs (Jahnke, 1992) (Weathers et al., 2012). The overextended use in contrast to the long turnover time has resulted in an accumulation of aquatic phosphorous, due to leaching of terrestrial phosphorous aggregates. It is estimated that the natural load of aquatic phosphorous in marine ecosystems has doubled due to increased use of fertilizers, soil loss, deforestation and sewage sources causing eutrophication (G. Filippelli, 2008) (Weathers et al., 2012).

A promising role of biochar in relation to the phosphorous-cycle could be to facilitate the re-circulation of phosphorous from waste flows into agriculture, or slowing down the leaching of phosphorous from soil aggregates. Especially animal manure and sewage sources has been investigated as potential opportunities to retain the phosphorous where biochar could offer a solution to sanitize the material before application, without sacrificing the retention potential (G. Filippelli, 2008).

2.2 Definition of biochar

The designated term biochar is a modern classification of a material which has been widely utilized in a range of applications for hundreds of years, and has recently been recognized as a potential tool to reduce the effects of soil degradation and climate change experienced in today's society (Fransson et al., 2020). Biochar bares many similarities to ordinary charcoal produced from wood but has a higher potential acting as a carbon-sink and as a mean to improve soil quality (Hagemann et al., 2018). To give a short description of what biochar actually is, one could conclude that biochar is carbonized biomass containing stable carbon which does not chemically react with its surrounding environment (Fransson et al., 2020). Although, this short definition of biochar is a bit vague, there are other more transparent and specific definitions on what should be considered as biochar. However, one should note that the definitions stated by different certification systems might differ slightly, further described in Section 2.3.2. In Europe, the most commonly applied definition of biochar, and hence the definition used throughout this study, is that developed by Ithaka Institute and included in the European certification system for biochar, EBC. The definition expressed in the EBC framework states that (Carbon Standards International, 2023):

"Biochar is a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C-sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation."

As described in the definition, only charcoal produced from pyrolysis is considered biochar (Fransson et al., 2020). Hence, charcoal produced from other carbonization processes like hydrothermal carbonization and torrefaction are not regarded as biochar, although there has been debates regarding the exclusion of alternative processing methods. However, the definition do not exclude any biomass feedstock materials, as long as the raw material is considered to be residual products or sustainably produced.

2.2.1 History

The first known evidence of human enhancement of soil quality through the addition of biochar is from thousands of years ago in the Amazon region of Brazil (Schmidt, 2014). This dark soil is called "Terra Preta", which is Portuguese for "black soil", and part of the initial interest in the black soil was the pottery and other traces of human activities found in the soil. Based on the findings from the remains of the indigenous population, researchers has been able to be date the soil manipulation back to ancient human civilizations somewhere around 400 BC (Fransson et al., 2020). The Terra Preta soil is highly fertile compared to the expected soil type in this kind of tropical landscape, but it's debated however if the soil was enhanced intentionally or not (Biochar.co.uk, 2023). Regardless if the process of soil enhancement were intentional or not, the biochar is thought to have been formed when the indigenous population cleared the rainforest for agricultural purposes (Fransson et al., 2020). Similar to the practices used today, the forests were burnt down under low-intensity in a controlled environment to achieve a carbonized soil to cultivate in.

The pyrolysis technology, heating biomass with low oxygen supply, has also been used for hundreds of years to produce charcoal as a fuel for cooking, heating and metal production (Fuchs et al., 2014). A common and simple method of producing charcoal is through firing a wood pile and covering it with turf or soil to block air from reaching the burning pile of wood. The first implementations of the technology, are thought to have been using simple campfires to produce the charcoal. Thereafter, the technology evolved through implementations of different types of kilns which improved yields and decreased the health risks of the process by adding chimneys.

2.2.2 Applications

The diverse potential applications for the biochar itself are many, with even more applications considering the generated by-products produced during the biochar production process (Bridgwater & Grassi, 2012). Even though the soil enhancing and climate change mitigating effects are often highlighted as the most promising benefits gained from biochar, the utilization potential reaches beyond soil integration (Söderqvist et al., 2021) (Kumar & Bhattacharya, 2018). Although many of the alternative application areas are in early stages of evaluating the possibility to utilize biochar, researchers are investigating the potential to integrate the product in new organic systems like building, farming, clothing and electronics (Schmidt & Wilson, 2014). Beyond the properties as a physical material, biochar can also demonstrate several cascading effects which can be used to optimize and recycle current material, nutrient and energy flows.

The vast variation of applications for the biochar are enabled by the properties of the carbon matrix which can bind and hold water, air, metals and organic chemicals (Schmidt & Wilson, 2014). The carbon matrix also gives the biochar its porous physical structure which can provide habitat for microorganisms. Therefore, biochar has recently been investigated as an additive to boost other biological treatments. Since biochar has beneficial properties to enhance conditions for microorganisms, the effects of utilizing biochar in processes such as biogas production could increase the process productivity.

Although it is recognized that biochar has many different beneficial properties, perhaps the most essential property is its ability to sequester carbon, generating negative emissions and acting as a CDR-technology, when applied in soil. However, some researchers point out that the biggest drawback with application of biochar directly in soil, with the purpose of carbon sequestration, is the cost (Schmidt & Wilson, 2014). Hence, cascading applications has been suggested as a possibility to decrease the total system cost for the biochar before finally being applied in soil. It is however important to point out that there are applications, such as utilizing biochar as an adsorbent to clean up metal and chemical contaminants, which could render the biochar unsuitable for soil application.

To summarize the potential applications, some of the most promising implementations of biochar is to use it as soil amendment in agricultural farming, as a cascading product in animal farming, as a building material in the construction sector or to use it as a filter material (Schmidt & Wilson, 2014) (Gerlach & Schmidt, 2014). However, the composition of the biochar itself can differ depending on the feedstock used and processing conditions, rendering the biochar more or less suitable for certain applications. In the following sections, some of the most promising applications of biochar will be described.

2.2.2.1 Soil amendment in agricultural farming

The perhaps most proven utilization potential for biochar is to use it as a soil conditioner, where applying untreated biochar to poor soils have shown to display positive effects on soil fertility while acting as a carbon-sink (Schmidt & Wilson, 2014). The positive effects, derived from the char structure and composition, includes improving soil characteristics such as aeration of the soil, increased nutrient availability due to the raised pH in the soils and higher capacity to retain water in the soil. Although biochar acts as a soil conditioner over long periods of time, the untreated char's ability to adsorb nutrients could decrease crop yields in the short to medium-term. However, in order to decrease the adsorption effects, the biochar can be activated before application. One way to activate the biochar is to co-compost the biochar with biomass, loading it with nutrients before the application. Beyond the characteristics of the biochar, effects of applying biochar in soil depends to large extent on the soil type and its properties, but in average it is estimated that biochar increase (78%), decreases (16%) or showcases no effect on the yields in different soil types (Purakayastha et al., 2019) (Jay et al., 2015).

2.2.2.2 Cascading product in animal farming

An early adaptation of the modern applications for biochar has been to utilize it in animal farming. In contrast to soil applications, the effects of utilizing biochar in animal farming can be observed within a few days reducing the smell through applications such as feeding, litter or slurry treatment (Schmidt & Wilson, 2014). By utilizing biochar as a cascading product in animal farming, the biochar value can be maximised prior to being used as a final long-term carbon storage in soils (Osman et al., 2022). Within animal farming, the biochar could be used to small extent as co-feeding by combining the biochar with ordinary animal feed. Field studies have shown that utilizing biochar as co-feeding, can have positive effects on growth, gut microbiota, enteric methane production, egg yield and endotoxin mitigation in several different farming animals. Beyond integration in feed, biochar can be used in animal farming as a litter amendment and for wastewater treatment. Adding the biochar directly to litter or wastewater improves the sanitation by adsorbing contaminants and integrates the beneficial properties of the biochar into the waste fractions.

2.2.2.3 Building material in the construction sector

Another promising application for biochar is the materials potential contribution in the construction sector. Due to the high and still growing carbon footprint of the construction sector, many actors look to reduction solutions to limit their carbon footprint. Biochar possesses several properties suitable for reduction solutions such as low thermal conductivity, ability to absorb and hold water, high chemical stability and low flammability (Osman et al., 2022) (Schmidt & Wilson, 2014). Within the construction sector, biochar could be used in applications as an additive in cement, inclusion in materials such as asphalt or sustainable bricks and used in composites for a variation of applications (Osman et al., 2022). Much like the other alternative applications discussed, biochar in construction acts like a carbon-sink during the lifetime of the built structure. However, the accounting of these carbon-sinks have been discussed since the lifetime of different structures varies significantly. It is also important to note that at the end-of-life of the structure, the material could be recycled which indicates a possibility to reuse the biochar as a cascading product.

2.2.2.4 Utilization as a filter material

The absorption and adsorption properties of the biochar can as mentioned be utilized in several application areas to filter out contaminants. Due to the physiochemical adsorption properties of biochar, the material has been linked to applications such as clean up metal or chemical contaminants in contaminated soil, acting as a barrier to reduce leaching, wastewater treatment, utilized in exhaust filters or in active carbon filters (Osman et al., 2022) (Schmidt & Wilson, 2014). Studies have indicated that the adsorption mechanisms, mainly the physical adsorption, could be a reversible process which would allow cascading use of the biochar (Osman et al., 2022). However, regardless if the adsorption is reversible or not, secure management of the adsorbed pollutants must be assured. Therefore the solutions to incinerate the contaminated biochar, store the contaminated biochar in a controlled environment (landfill) or regenerate the biochar could all present viable options. Although one should recognize that incineration would require advanced and costly purification equipment, storage of biochar in landfills would have to be thoroughly controlled to inhibit leaching and regeneration could potentially effect the carbon-sink potential of the biochar.

2.2.3 Pyrolysis

The most common process used for biochar production is pyrolysis and the equipment implementation can be as simple as an ordinary campfire or as complex and technical as a modern biorefinery or incineration plant (International Biochar Initiative, 2022). Pyrolysis is a process where thermochemical decomposition of biomass under anaerobic conditions is used to produce valuable gaseous, liquid and solid components (Iwuozor et al., 2022). The components are formed via chemical reaction processes, such as fragmentation and cross-linking, during the thermal treatment. For the pyrolysis of biomass, the solid fraction consists of biochar, the liquid fraction of bio-oil and the gaseous fraction of synthesis gas. Since the process is a thermochemical conversion, using heat to degrade the biomass, energy can also be recovered from the production system.

However, it is important to note that pyrolysis is only one of the options for thermochemical conversion where a material input is degraded using thermal heat processing. For thermochemical processing of biomass, there are four main thermochemical methods for conversion: Pyrolysis, Liquefaction, Gasification and Combustion (Bridgwater & Grassi, 2012). Although all the methods are used for biomass utilization, it is vital to note that the processes technologies generate different primary products. According to the EBC even gasification can, under specific circumstances where the process is optimized for biochar production, be regarded as equal to pyrolysis and certified under EBC (Carbon Standards International, 2023).

The temperature range for the pyrolysis process can differ depending on both the properties of the biomass feedstock used for the application and the desired characteristics and volumes of each generated product fraction. However, generally pyrolysis is performed in the range of 300-900°C, although there are exceptions where it could be favourable to increase or decrease the temperature further (Fuchs et al., 2014) (Iwuozor et al., 2022) (Jha et al., 2022) (Rahimi et al., 2022) (Bridgwater & Grassi, 2012). However, temperature is not the only regulating parameter for biochar yield since other processing conditions, such as residence time, heating rate and pressure, regulates the generated yield from the process (Iwuozor et al., 2022). It is further important to note that determining factors like the intended application of the biochar and the reactor design could generate further trade-off mechanisms affecting the potential yield of the process. Depending on the processing conditions (temperature, residence time, heating rate and pressure), the pyrolysis process is often classified as slow, intermediate or fast/flash pyrolysis as depicted in Figure 2.2 (Lee et al., 2019). Based on the scope of this report, indicated by the green boxes, slow pyrolysis were considered to be the main pyrolysis process and biochar the main desired product from the pyrolysis system.

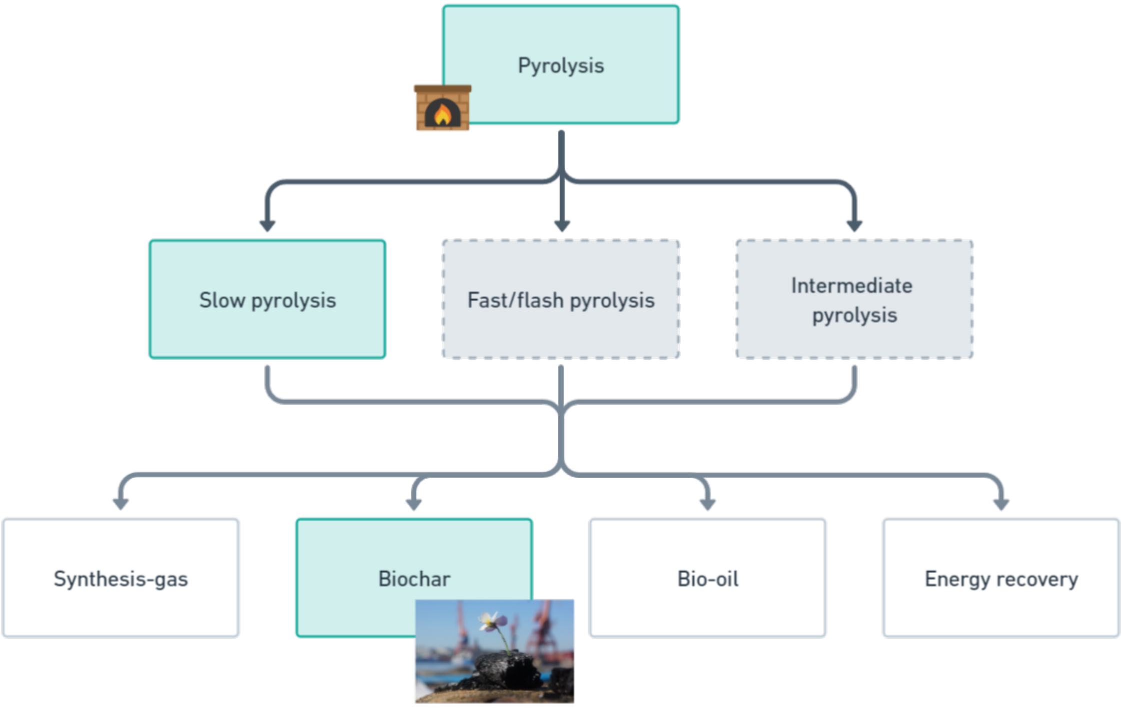


Figure 2.2: An overview of the pyrolysis processing alternatives and its generated product fractions.

2.2.3.1 Slow pyrolysis

What characterizes the process conditions for slow pyrolysis is essentially an oxygen free environment, low heating rates, low temperatures and long residence time (Fuchs et al., 2014). In a slow pyrolysis application, biomass is slowly heated up to the maximum set treatment temperature and has a long residence time inside the furnace to enhance char and gas formation. Due to the long residence time both primary and secondary reactions occurs in the furnace, allowing larger char yields as the secondary reactions are stimulated (Amalina, Razak, et al., 2022). Since the process is most commonly used to maximize the char yield, slow pyrolysis is sometimes also referred to as carbonization (Bridgwater & Grassi, 2012). Depending on the selected maximum temperature and feedstock characteristics, i.e particle size or moisture content in the feedstock, the residence time can fluctuate from minutes to several days (Fuchs et al., 2014).

As the biomass is slowly charred in the furnace, lighter fractions are continuously degraded and converted into vapours (Fuchs et al., 2014). In modern applications for pyrolysis plants, the vapours are often cleaned from contaminants and utilized as a co-product. The vapours consist of a water-phase, originating from the moisture content in the biomass feedstock and can include acids and sugar derivatives, and an oil-phase which stems from the lighter biomass fractions and can include phenol compounds. The vapour can hence be condensed and utilized, but in smaller applications the vapour is sometimes released to the atmosphere directly as flue gas. To minimize the vapour water-phase and enhance thermodynamic properties, pyrolysis requires relative dry biomass feedstocks and in general the moisture content is recommended to be less than 30% (Amalina, Razak, et al., 2022). In theory, the moisture content of the input material could exceed 30% but would require external energy input and longer residence time in order to vaporize the water content during the process.

As slow pyrolysis conditions favour char formation, it is estimated that about 25 - 35 mass% of the original feedstock and about 50% of the original carbon can be recovered in the produced charcoal (Amalina, Razak, et al., 2022) (Fuchs et al., 2014). On the other hand, if the biomass feedstock is not allowed to be completely charred in the furnace, but is only partially carbonized during the residence time, the char yield will be higher and the process would then be referred to as torrefaction (Bridgwater & Grassi, 2012). However, since the feedstock is not completely charred in such process the fraction will contain high levels of volatile compounds which could be problematic for feedstocks containing potential contaminants.

2.2.3.2 Intermediate pyrolysis

In contrast to slow pyrolysis, the intermediate pyrolysis has much quicker reactions and the residence time can span from seconds to minutes (Amalina, Razak, et al., 2022). The temperature range is often held at similar ranges as in slow pyrolysis, but the heating rate is considerably higher. Since the residence time is shorter and the heating rate is higher in intermediate pyrolysis, secondary reactions are less prevalent and hence prevents the formation of high molecular weight aggregates. Thereby, the intermediate approach prevents formation of higher molecular weight aggregates and the produced char fraction will be less stable and might develop less favourable properties for certain applications. For example, much like in slow pyrolysis, intermediate pyrolysis can produce a fairly pure charcoal fraction but the O/C ratio from intermediate processes often exceeds the 0,4 O/C ratio limit established by the EBC for defining biochar.

2.2.3.3 Fast/Flash pyrolysis

Fast/flash pyrolysis is most often used for maximizing the yield of bio-oil, hence the charcoal fraction is most commonly seen as a by-product (Fuchs et al., 2014). Fast pyrolysis is often characterized by short residence time, high temperatures and high heating rates. In fast applications, the biomass is often very finely granulated in order to enhance the active area during the thermal treatment to rapidly release the vapours from the material. The vapours are then quickly removed for condensation to prevent secondary reactions from occurring in the furnace and thereby maximize the yield of the liquid fraction. Since the charcoal fraction from fast pyrolysis are considered a by-product and most often not suitable to be classed as biochar, the charcoal is combusted in many such applications in order to stimulate that high energy demand of high temperature furnace.

2.2.3.4 Pyrolysis plants

There are several models of pyrolizers used for biomass conversion depending on what pyrolysis application is to be used (Amalina, Razak, et al., 2022). Since slow pyrolysis is considered to be the most common approach to maximize the biochar yield, mainly slow pyrolysis plants will be considered as alternatives in this study.

For slow pyrolysis fixed bed, drum, rotary kilns and screw/auger reactors are the most common implementations for biomass conversion (Rahimi et al., 2022). The choice of reactor can depend on the intended application of the plant but also process conditions and feedstocks, although most of the pyrolysis plants available today are tailor made to optimize the intended system. As for example, the rotary kiln offers a less complex system for biochar production suitable for smaller batch-production scale applications. Choosing a rotary kiln offers advantages such as no need for carrier gas to remove ash and vapours, flexibility in terms of feedstock and a simple system to retain control over the residence time for the solid product. However, the system also incorporates several disadvantages such as up-scaling restrains for larger implementations and inefficient heat transfer for utilization of heat surplus. In contrast to the rotary kiln, a fixed bed reactor also offers simple operation/construction, steady temperature control and feedstock flexibility. However, it has a long residence time for the solid fraction, offers low ash movement hence mixing it with the solid fraction, up-scaling restrains and challenges separating the char from the fixed bed material.

For biochar production there are many trade-off mechanisms to consider in order to optimize the system and therefore, many pyrolysis plants are tailor made to fit the intended application (Paulsson, 2020). Although many pyrolysis plants are tailor made to some extent, there are options for pyrolysis plant packages on the market. In Sweden, the currently active biochar production plants, that are not special built, are delivered from the retailers Pyreg, Biomacon, Earth Systems and Veto (Wahlberg Roslund, 2022). The retailers offers different systems, adapted to a broad variety of feedstocks, where some are more adapted to small scale implementations and some for larger depending on the desired production capacity. Depicted in Figure 2.3 is a real life example of a farm scale pyrolysis plant situated in Sweden. The pyrolysis plant is owned by the company ETC and has been equipped with an accumulation tank and a steam turbine, in order to recover surplus energy from the process in form of heat and electricity.

Figure 2.3: Picture of a pyrolysis plant package, delivered by Biomacon, for farm scale applications.

2.2.4 Feedstocks

Charcoal can be made from any carbon source, regardless if it is fossil or renewable materials (Hagemann et al., 2018). However, based on the requirements stated by the EBC, the product should mainly be made from sustainably produced biomass or biomass waste material (International Biochar Initiative, 2022). The advantage of utilizing biomass waste materials is to avoid creating competition for land use, which might interfere with other land use options, such as food production. Some of the most commonly applied biomass types for biochar production is lignocellulosic biomass, mainly due to the material's renewable properties, high availability and processing simplicity with regard to contaminants (Amalina, Syukor Abd Razak, et al., 2022). Lignocellulosic biomass primarily originates from agriculture and forestry and the most essential components are cellulose, hemicellulose and lignin.

In general, biogenic feedstocks can be split into two categories: wood-based and non-wood-based feedstocks (Tye, 2022). Wood-based biomass are often characterized by low moisture content, high calorific value and low ash content. Non-wood-based feedstocks, on the other hand, often have high moisture content, high ash content and low calorific value. Although there is a large range of biomass waste materials which could potentially be appropriate for biochar production, it is important to consider all aspects of the feedstock supplies (International Biochar Initiative, 2022). Biochar production offers an alternative treatment of the biomass feedstock which could mitigate the pollution cycle generated from current waste management techniques (Lehmann & Joseph, 2009). However, one should also note that there are toxins, such as heavy metals, which are not necessarily removed during the process and hence must be regulated via feedstock selection. Availability of the feedstock is further important to consider since the availability for some feedstocks varies both from year to year and/or within years.

Depending on the composition of the biochar, the application of the product could have a variation of impacts on the element cycles (Lehmann & Joseph, 2009) (International Biochar Initiative, 2022). Dependent on the chosen feedstock and processing conditions, the amount of carbon, nitrogen and phosphorus vary in the biochar. Hence, although some feedstocks generate biochar with lower carbon content, the char could still contain nutrient elements valuable to recycle.

From an economical perspective it is also often favourable to utilize locally available feedstocks to minimize system costs coupled to collection, transport and storage (International Biochar Initiative, 2022) (Lehmann & Joseph, 2009). Feedstocks which are considered residue products are, in many cases, more economically beneficial since costs related to production of the feedstock are excluded. At the same time, some of the residue feedstocks may include the possibility for companies to charge waste generating actors a fee for handling the waste, creating an additional income. For the transportation perspective, minimized transports are preferable since long transports could diminish economical and environmental benefits. Longer transports could also increase the need to pre-treat the biomass before transportation. Pre-treatments could then include needs to dry or densify, by for example chipping or pelleting, the biomass to facilitate the transportation conditions. However, one should note that if the biomass is dried before transport, symbiosis effects, from utilizing surplus energy obtained from the pyrolysis, to dry the feedstock might be lost.

2.3 Regulations and certifications

This chapter covers a selection of European Union (EU) regulations which might affect the biochar industry and gives an overview of available certification systems, including guidelines and requirements, regulating the production and application of biochar. The chapter further includes current uncertainties and perspectives on certification systems on national level.

2.3.1 European Union regulations

The EU regulations described below cover some essential parts of the European Green Deal, which is an effort to transform the EU into a modern, resource-efficient and competitive economy (European Commission, 2023c). Even if the regulations not specifically target biochar technology, the utilization of biomass in a sustainable way is a common denominator.

2.3.1.1 European Union Taxonomy

The EU taxonomy, EU regulation 2020/852, is a framework designed to facilitate sustainable investments by defining which economic activities that are considered sustainable (European Parliament, 2020). The purpose is to harmonize the criteria for sustainability in the EU in order to:

"Remove barriers to the functioning of the internal market with regard to raising funds for sustainability projects, and to prevent the future emergence of barriers to such projects".

Biochar production is so far not specifically mentioned in the EU taxonomy, while carbon capture utilization (CCU) and carbon capture and storage (CCS) are technologies specifically listed below the headline “Substantial contribution to climate change mitigation”.

2.3.1.2 Renewable Energy Directive

The Renewable Energy Directive addresses the development of renewable energy across all EU countries and sectors (European Parliament, 2018). Biochar is not explicitly mentioned in the directive, but indirectly linked to the regulation through its need for biomass. At the same time accelerating the rollout of renewable energy, the supply of biomass is a key factor in the directive to ensure the sustainability of bio-based energy. The carbon accounting rules of bio-based energy are a complex issue which has been debated and criticised by e.g., the European Academies’ Science Advisory Council for not considering emissions from land use change and biomass combustion (European Academies’ Science Advisory Council, 2019).

The directive was introduced in 2009, revised in 2018, and is now about to be revised again since an agreement was reached in March 2023 to reinforce the directive to accelerate the rollout of renewable energy (European Commission, 2023d). The agreement aims to strengthen the sustainability criteria of bio-energy by lowering the threshold for which installations that should apply the criteria, and by ensuring that biomass is not sourced where it can have a large impact on biodiversity and carbon stocks. Additionally, the agreement states that cascading use have to be applied in order to use woody biomass according to its highest economic and environmental added value.

2.3.1.3 European Union Emissions Trading System

The EU Emission Trading System (ETS) is a cap and trade system for reducing emissions of GHG from actors covered by the system. At the moment, the system covers around 40% of the total GHG-emission in the EU and includes CO_2 emissions from electricity and heat generation, energy-intensive industry sectors and aviation within the European Economic Area (European Commission, 2023b).

Even though the focus in ETS is set on emissions from fossil sources, the system is connected to the Renewable Energy Directive regarding emissions from biomass.

Biomass fuels that meet the applicable sustainability criteria in the Renewable Energy Directive can be considered zero-rated. After January 2023, the requirements considering which biomass emissions that are allowed to be considered zero-rated have become stricter (European Commission, 2022b).

2.3.1.4 European Union certification framework for carbon removals

In November 2022 the EU Commission proposed a suggestion for a certification framework for carbon removals (European Commission, 2022a). The main objectives of this framework are to ensure the quality of carbon removals and to establish a certification system to avoid greenwashing. At the moment, the proposal lacks detailed descriptions of which carbon storing methods that will be included, and biochar is not mentioned in the proposed text.

2.3.2 Guidelines and certification systems

For certification of biochar there are two major international guidelines used, which includes voluntary certification systems: the EBC and the International Biochar Initiative Standards (IBI Standards). Both are established guidelines for certification used on the market. However, the EBC framework is better suited to the surrounding European requirements and regulatory frameworks (Hellmann et al., 2022). As for instance, the EBC further includes a Swedish implementation appendix, integrating requirements and regulatory frameworks which are specific to Sweden. Hence, EBC is the most commonly used certification system in Europe and will be regarded as most relevant in this study. The IBI standards, on the other hand, are used globally outside of the EU and could be relevant in terms of trade. One should further note that there are alternative certification systems which are less established, present on both local and international levels. Two of these worth noting are the KRAV certification, applicable i Sweden, and the EU Ecolabel (Fransson et al., 2020). In the absence of an overall accepted certification system, there are several certification systems under development on different diffusion scales.

Looking at the certification systems for EBC and IBI, they are quite similar in many ways although they are built on two different approaches. The main difference is that the IBI standards are aimed towards the product only, while EBC accounts for regulations covering both the product, the biochar itself, and the processing approach (Slattery, 2015).

2.3.2.1 European Biochar Certificate

The approach, which the certification system apply, can be coupled to the definition used to describe what can be regarded as biochar. As mentioned in Section 2.2, the EBC defines biochar as (Carbon Standards International, 2023):

"Biochar is a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C-sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation."

As suggested in the definition, both the product and the procedure are considered in the system. According to the EBC definition, pyrolysis is specifically mentioned as the only approved processing method to produce biochar although gasification has later on been added to the guidelines considered as equal to pyrolysis under certain conditions.

The EBC certification system is continuously updated to account for new feedstock alternatives and intended applications (Carbon Standards International, 2023). In order to account for the broad application potential of biochar, the "EBC Guidelines: for a sustainable production of biochar" has introduced several certification classes, where EBC-BasicMaterials is the latest addition added in 2022. The EBC-BasicMaterials, was introduced as a fundamental certification class with the intention that all future and present certification classes should at least meet the requirements of EBC-BasicMaterials and hence also meet the requirements of the EU registration, evaluation, authorisation and restriction of chemicals (EU-REACH) regulation. As of today, there are seven certification classes added in the "EBC Guidelines: for a sustainable production of biochar" (Carbon Standards International, 2023). These certification classes are also listed in Table 2.1 below.

Table 2.1: List of the seven EBC certification classes.

Certification class:	**Short description:**
EBC - Feed	Meets all requirements of the EU feed regulation.
EBC - FeedPlus	Meets all EU and EFTA (European free trade association) regulations and requirements for animal feeding and agricultural soil application.
EBC - Agro	Meets all requirements of the EU fertilizer product regulation.
EBC - AgroOrganic	Meets all requirements of the EU fertilizer product regulation and the requirements of the EU commission regulation on organic products.
EBC - Urban	For use in urban soils (urban trees), for soil remediation, for producing ornamental plants and tree nurseries, not for food and feed production.
EBC - ConsumerMaterial	For products with direct skin or food contact (plastics), not allowed for medical and health products or food.
EBC - BasicMaterial	Possible applications mainly in building materials, aims for further diversification, depending on industry demand.

The certification classification aims to adjust the enclosed limit values and controlled parameters in accordance with the requirements and safety regulations of different applications (Carbon Standards International, 2023). The classification does not account for the quality of the biochar, but simply distinguishes if the biochar is admissible or not for a specific form of application. When buying and selling certified biochar there are also regulations regarding the classification of the biochar. When the biochar is sold to end-consumers, the finished product can only be classified for one certification class and hence one intended use. However, for biochar trade between businesses, the biochar can have multiple certification classes but must be labeled for one specific applicable certification class before it reaches the end-consumer.

For production of biochar according to the seven published certification classes, above in Table 2.1, there are several enclosed limit values and controlled parameters (Carbon Standards International, 2023). Looking at the feedstock, there are several requirements listed in the EBC guidelines, indicating which feedstocks are acceptable to use for sustainable biochar production. For the feedstock itself the EBC has published a "Positive list of permissible biomasses for the production of biochar" (Carbon Standards International & European Biochar Certificate, 2023). The list indicates which feedstocks are considered acceptable to use either as a pure feedstock or as combination mixes. However, it is worth noting that the list is continuously updated, just like the EBC guidelines, and there are other requirements for the feedstock regulating parameters such as toxic contaminants, fossil contaminant fractions of the feedstock or additives.

Similar to the requirements for the biomass feedstock, there are several requirements for the pyrolysis processing, specifying regulations for fluctuations regarding e.g., temperature, changes in feedstock composition or storage after production (Carbon Standards International, 2023). All requirements follows a batch system, where batch certifications are issued to ensure a consistent product. To further make sure that the product produced is consistent in quality, several limiting parameters are analysed in EBC certified laboratories. All analyses tested to ensure the quality are depicted in Table 2.2 below.

Table 2.2: Limiting parameters tested on the produced biochar product for EBC-certification to ensure quality limits.

EBC -Certification Class		EBC-FeedPlus	EBC-Feed	EBC-AgroOrganic	EBC-Agro	EBC-Urban	EBC-ConsumerMaterials	EBC-BasicMaterials
Elemental analysis	Declaration of Ctot, Corg, H, N, O, S, ash							
	H / Corg	< 0.4		< 0.7				
Physical parameters	Water content, dry matter (as received and @ < 3mm particle size), bulk density (DM), WHC, pH, salt content, electrical conductivity of the solid biochar							
TGA	Needs to be presented for the first production batch of a pyroylsis unit							
Nutrients	Declaration of N, P, K, Mg, Ca, Fe							
Heavy metals	Pb	10 g t^{-1} (88%DM)	10 g t^{-1} (88%DM)	45 g t^{-1} DM	120 g t^{-1} DM	120 g t^{-1} DM	120 g t^{-1} DM	*declaration, no limit values for certification*
	Cd	0.8 g t^{-1} (88% DM)	0.8 g t^{-1} (88% DM)	0.7 g t^{-1} DM	1,5 g t^{-1} DM	1,5 g t^{-1} DM	1,5 g t^{-1} DM	
	Cu	70 g t^{-1}DM	70 g t^{-1}DM	70 g t^{-1}DM	100 g t^{-1} DM	100 g t^{-1} DM	100 g t^{-1} DM	
	Ni	25 g t^{-1} DM	25 g t^{-1} DM	25 g t^{-1} DM	50 g t^{-1} DM	50 g t^{-1} DM	50 g t^{-1} DM	
	Hg	0.1 g t^{-1} (88% DM)	0.1 g t^{-1} (88% DM)	0.4 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM	
	Zn	200 g t^{-1} DM	200 g t^{-1} DM	200 g t^{-1} DM	400 g t^{-1} DM	400 g t^{-1} DM	400 g t^{-1} DM	
	Cr	70 g t^{-1} DM	70 g t^{-1} DM	70 g t^{-1} DM	90 g t^{-1} DM	90 g t^{-1} DM	90 g t^{-1} DM	
	As	2 g t^{-1} (88% DM)	2 g t^{-1} (88% DM)	13 g t^{-1} DM	13 g t^{-1} DM	13 g t^{-1} DM	13 g t^{-1} DM	
Organic contaminents	16 EPA PAH	6±2.4 g t^{-1} DM	CSI-declaration	6±2.4 g t^{-1} DM	6.0+2.4 g t^{-1} DM	CSI-declaration	CSI-declaration	CSI-declaration
	8 EFSA PAH	1.0 g t^{-1} DM						4 g t^{-1} DM
	benzo[*e*]pyrene benzo[*j*]fluoranthene	< 1.0 g t^{-1} DM for each of both substances						
	PCB, PCDD/F	See chapter 10		Once per pyrolysis unit for the first production batch. For PCB: 0.2 mg kg^{-1} DM, for PCDD/F: 20 ng kg^{-1} (I-TEQ OMS), respectively				

* medical and health care products are not included

Apart from classification for intended use, all the EBC certification classes are applicable for complementary carbon-sink certification (Carbon Standards International, 2023). The concept of accounting EBC certified biochar as a carbon-sink can be concluded in three fundamental steps: Removal of CO_2 from the atmosphere, processing the carbon into a stable biochar form and ensure safe long-term storage (Schmidt et al., 2021). This principle is regarded to apply for all certification classes where biochar is directly integrated in soil or indirectly integrated via alternative applications e.g as animal feed or slurry management. The EBC further recognizes biochar utilization in construction materials as a potential short- or long-term carbon-sink. However, in comparison to soil applications of the biochar, carbon-sinks generated from integration in construction materials mainly depends on the persistence of the construction material itself. In other words, the sequestrated carbon are thought to be released back into the atmosphere only when the material containing biochar is disposed of, causing the carbon-sink to loose its value.

For the different applications, EBC offers carbon-sink certifications where the amount of actual stored carbon are expected to fluctuate over time as parts of the biochar degrades (Schmidt et al., 2021). In order to account for the partial degradation, EBC uses annual depletion rates where carbon leakage is subtracted from the certified stored carbon. This accounting system differs from the IPCC's, suggesting that only the proportion of permanent stored carbon (carbon which remains in the soil for over 100 years) should be regarded as a carbon-sink (IPCC, 2019). The EBC recognizes the IPCC's suggestion as a possible accounting system but point out that such an approach diminishes and underestimates the short-term carbon-sink potential.

2.3.2.2 International Biochar Initiative standards

The IBI standards, are as mentioned quite similar to the EBC guidelines but have some fundamental differences. For instance, the IBI standards define biochar as (International Biochar Initiative, 2015):

"Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment."

As indicated from the definition, pyrolysis is not mentioned as the specific method for producing biochar. Instead thermochemical conversion in an oxygen-limited environment are mentioned, creating a interpretative opening for alternative processing methods.

Much like the EBC guidelines, IBI includes certification requirements to ensure the creation of a stable and safe carbon-sink potential while prohibiting the use of environmentally toxic raw material (Fransson et al., 2020). Enclosed limit values and controlled parameters, are also used in order to ensure a consistent quality of the product itself. However, in contrast to the EBC guidelines, the IBI standards are very clear in describing that the framework relates to the physiochemical properties of the produced biochar product only (International Biochar Initiative, 2015). Hence the guidelines do not consider specific feedstocks or production methods. Nor do they consider the sustainability limitations or GHG-emission mitigation potentials of the product.

One thing that makes the IBI standard stand out from other certification systems is that it includes requirements for positive properties when the product is applied in soil, such as total surface area and available nutritional contents (International Biochar Initiative, 2015) (Fransson et al., 2020). These beneficial properties are analyzed in the same way as the limitations set by the EBC guidelines, but are not mandatory for all certifications. The positive properties analyzed are further used to provide aid for researchers, linking specific functions and properties of the biochar to soil and crop impacts (International Biochar Initiative, 2015).

The IBI standards are seen as a global certification system, but are in the same way as EBC not fully developed and widely accepted yet. Hence, requests for IBI certification is only possible in USA and Canada at the moment but the system is continuously expanding (Fransson et al., 2020).

2.3.2.3 Alternative certifications systems guidelines

Apart from the two major established certification systems, the EBC and the IBI standards, there are less established certification systems and guidelines under development. Since EBC is the most established voluntary guideline and certification system in Europe, many of the producers choose to apply it. However, due to the novelty of the biochar technology, much of the EBC branches are situated in central Europe and it can therefore be costly for small scale producers to certify their biochar (Söderqvist et al., 2021). Thus, many of the biochar producers put their hopes in cost effective local developing implementations, connecting the certification system to local regulation surrounding production and application of the biochar.

One such alternative certification system applied in Sweden is the KRAV certification, regulating organic production in Sweden (Paulsson, 2020). The KRAV certification has its foundation i European regulations and includes both a list of permissible materials for biochar production and limit values for the biochar product itself (KRAV, 2023). Biochar was added in the KRAV certification system after being included as permissible in the updated version of EU regulations on fertilizers, soil conditioners and nutrients for organic farming in 2019 (Ekologiska Lantbrukarnas kansli, 2023) (Official Journal of the European Union, 2019).

Another certification, relevant for production and application of biochar, is the EU Ecolabel (Paulsson, 2020) (Quintero et al., 2015). The EU Ecolabel is an official voluntary European Union label, established in 1992, and is recognized world wide (European Commission, 2023e). The label means to ensure that awarded products and services meet high environmental standards throughout their entire life cycle, by independent verification. Much like other certifications, the EU Ecolabel aims to offer eco-friendly alternatives to conventional products and helps guide consumers in making informed choices, contributing in the green transition. For the Swedish context, the EU Ecolabel is administrated by the Swedish branch certification called Svanen. The Svanen certification mainly regulates contaminants and limit values for the biochar.

In some cases, there are also already established certification systems which regulates problematic waste flows in society. One example of these systems is the REVAQ-certification in Sweden, regulating sustainable recycling of plant nutrition and waste management of toxic compounds in sewage sludge (Svenskt Vatten, 2023). Although the REVAQ-certification mainly focuses on returning sanitized sewage sludge to agricultural soils in form of biofertilizers, there has been a push to extend the regulations to include treatment using pyrolysis and incineration of the sludge (Pär Dalhielm & Anders Finnson, 2023) (Stockholm Vatten och Avfall, 2018). In the EU, the question regarding if sanitized sewage sludge should be allowed to be spread on agricultural soils has been controversial and many countries have introduced a ban on such activities. Instead, pyrolysis and incineration has been introduced as alternative ways to recycle the nutrients back to agricultural soils but as of yet Sweden is still considering whether a similar ban should be introduced.

In Chapter 2.3.2.1, the possibility to certify a biochar carbon-sink through EBC was described. There are complementary business platforms available for trading the negative emissions from a carbon-sink such as biochar, where Puro Earth is one example (Puro Earth, 2023). Puro has developed a standard for how to measure and verify carbon removal from the atmosphere, turning the negative emissions into carbon credits abbreviated CORC (CO2 Removal Certificate). These carbon credits can be purchased by companies who wishes to offset their emissions of GHGs through the use of this voluntary carbon market.

2.3.3 The Swedish perspective on guidelines and certification systems

To facilitate the use and control of biochar in Sweden a reference group, connected to the project ”Rest till Bäst”, has conducted a Swedish appendix for the EBC certification (Paulsson, 2020). The appendix adjusts the limit values on heavy metal content to align with Swedish regulations for specific applications, in order to make it easier for Swedish producers to adopt the EBC system. However, even though the EBC certification is the most commonly used biochar certification system in Sweden, there are only 10 registered EBC certified producers, transformers and sellers in Sweden currently (European Biochar Certificate, 2023). In a market investigation, conducted in connection to the Swedish-Danish project “Greater Bio”, indications of some of the most essential barriers for EBC certification were identified (Söderqvist et al., 2021). The market investigation highlighted the cost of certification and the lack of available biochar on the Swedish market as essential barriers for the biochar market development.

For Swedish producers, the implementation of the EBC certification could result in trade-off mechanisms including both benefits and drawbacks. In previously conducted feasibility studies, eight driving effects contributing with benefits and drawbacks from EBC certification were identified (Hellmann et al., 2022). The identified possible beneficial effects of certification were: increased market conditions and demand, the enabling of carbon-sink trade, quality assurance, increased competitiveness, increased knowledge and continuous improvement from production controls. The drawbacks, on the other hand, were mainly identified as the cost from heavy administration and the time-consuming commitment required to certify the product.

Although many of the biochar related actors in Sweden recognizes the need for a certification system like EBC, there is still an uncertainty regarding how such a system will be integrated to align with the development of Swedish regulations (Paulsson, 2020). Adaptations to include the biochar technology has been developed for a few of the current widely adopted certification systems in Sweden such as KRAV or Svanen. However, many actors call for a broader adopted Swedish certification of biochar, anchored in the development of Swedish regulations.

2.4 Sustainability transition in Gothenburg

The City of Gothenburg has established a new environmental and climate program which was published in 2021 with the ambition of transitioning to an environmentally sustainable city by 2030 (Göteborg Stad, 2021). In connection to the completion of the new environmental and climate program, Gothenburg became one of the first nine Swedish cities to sign the Climate City Contract coupled to the strategic innovation program Viable Cities (Viable Cities, 2020). These nine Swedish cities were also the first cities in Europe to sign the Climate City Contract, thus becoming the forerunners in urban climate transition.

Figure 2.4: Hand holding biochar in the City of Gothenburg.

2.4.1 Objective and goals for 2030

The overarching objective of the programme is to *"transition the city to an environmentally sustainable city by 2030"* (Göteborg Stad, 2021). This is defined in the Environment and Climate Programme as follows:

"Gothenburg will become one of the world's most progressive cities when it comes to preventing and addressing environmental and climate problems. Our children and future generations should not be burdened with problems that we can solve ourselves. Nor should humans, animals and nature in other countries be negatively affected by our way of living."

Within the program, there are three environmental goals for nature, climate and people respectively. These goals are in turn divided into sub-goals and all goals are assigned indicators that can be used in the follow-up.

The environmental goal for the climate is formulated as: *"Gothenburg's climate footprint is close to zero"* (Göteborg Stad, 2021). Although the focus is on reducing emissions, the programme also states that the city still needs to work towards facilitating and deploying carbon capture technologies. A specific chapter in the energy plan is devoted to carbon capture technologies which covers both CCS from existing point sources and biochar (Göteborg Stad, 2022).

BECCS receives the main attention in the energy plan with a stated potential of 320 000-400 000 tonnes CO_2-eqv of annual negative emissions, which can be compared with a stated potential of 4 500-8 500 tonnes CO_2-eqv of annual negative emissions for biochar (Göteborg Stad, 2022). The estimated potential from biochar is connected to the deployment of a biochar production facility for garden residues in Gothenburg.

2.4.2 Planned facility for biochar

The energy plan for the City of Gothenburg states that the local waste management company Renova AB, in collaboration with central actors "Kretslopp- och Vattennämnden" and the energy company Göteborg Energi AB, shall start a project to produce biochar with the possibility of utilizing surplus heat in the city's district heating system (Göteborg Stad, 2022). The facility is planned to be established in Tagene, in the north part of Gothenburg, and the targeted biomass feedstock will consist of locally generated garden waste. Renova is planning to bring the biochar plant into operation in September 2024, at the latest (M. Eriksson, personal communication, February 15, 2023).

For the biochar itself, Renova AB recognized the city's garden management department ("Stadsmiljöförvaltningen" in Swedish) as one of the major actors interested in utilizing the biochar in the city gardens for soil amendment (Detterfelt et al., 2019).

Using garden waste as a feedstock for biochar production is an effective way to utilize a waste stream which otherwise can be hard to handle. In 2017, Renova AB handled 6 300 tonnes of garden waste, which was incinerated in Renova's waste-to-energy plant in Sävenäs in Gothenburg (Detterfelt et al., 2019). Using this waste stream in a biochar plant would lead to 4 900 tonnes of negative CO_2-emissions, 6 GWh of surplus heat and 1 500 tonnes of produced biochar. There might be an increase of garden waste handled by Renova in the future, since some of Renova's owner municipalities today handle their garden waste through other actors. The planned facility for biochar will have the capacity of generating 6 000 tonnes of CO_2 annually, which is equivalent to the emissions from 700 inhabitants of Gothenburg (Göteborg Energi, 2023).

There has been a growing interest in recent years in biochar production. One contribution to the diffusion of the technology is the investment support these biochar plants can receive from the national subsidy scheme called "the Climate Leap initiative" ("Klimatklivet" in Swedish). The Climate Leap initiative provides aid for investments that decrease GHG-emissions. Since the start in 2015 up until the end of 2022 the Climate Leap initiative has supported around 30 investments in biochar technology with a total amount of around 233 Million SEK, which corresponds to around 50% of the investment costs on average (Naturvårdsverket, 2022). Renova has been approved investment support for their planned facility for biochar production.

3

Methods & Application

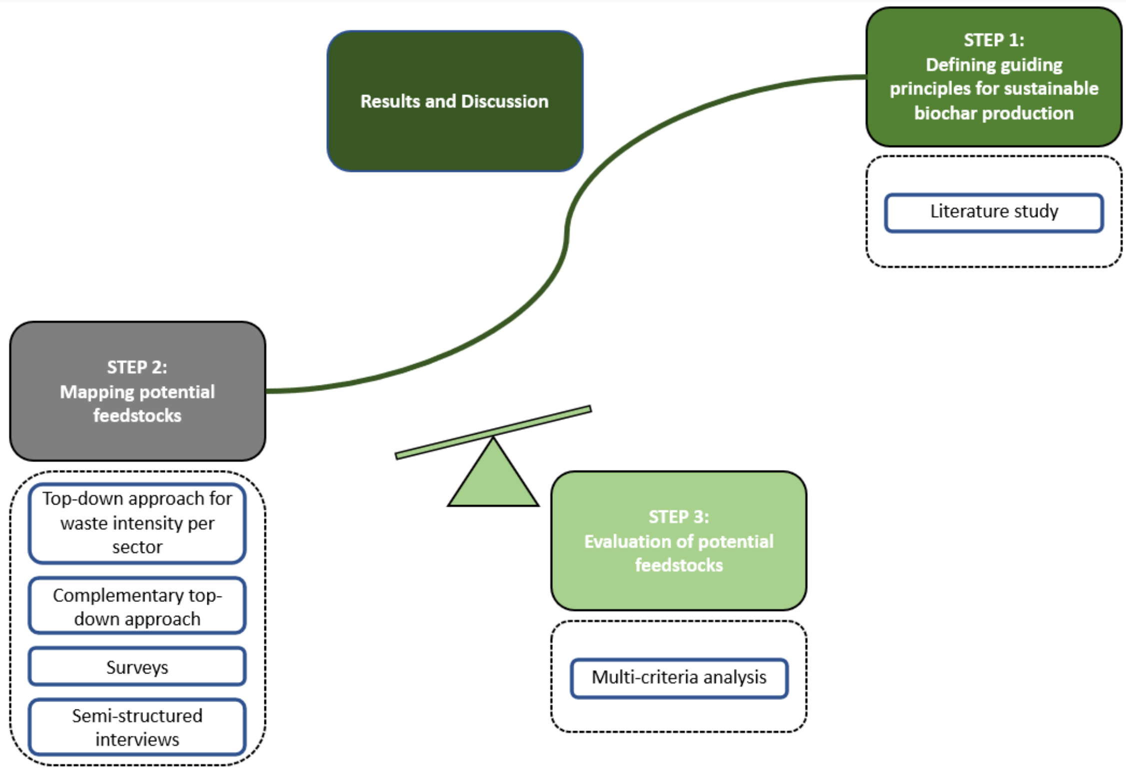


Figure 3.1: Schematic illustration of method

This chapter covers the methods used in this thesis and their application, describing each method in detail and how it was applied in order to contribute towards the aim of the thesis. An overview of the method is illustrated in Figure 3.1, aligning with the analogy of the backcasting methodology.

3.1 Backcasting

Backcasting was first developed as an alternative method in energy planning, which was previously mostly conducted using forecasting methods (Robinson, 1982). A key difference between forecasting and backcasting is that forecasting presumes development to continue in the same trajectory as recent development, while backcasting, on the other hand, acknowledges the possibility of various futures depending on feasibility and human choices (Robinson, 1988) (Robinson, 1990). Because of this, backcasting starts with the desired future situation and then moves to the present situation to explore which actions are needed to happen in order to reach that future situation.

Nowadays, backcasting is commonly used to guide complex processes related to sustainability and transformation (Holmén, 2020). Since biochar is often considered as a novel technology, containing a complex system of diverse actors with different perspectives on the priority of biomass utilization, backcasting is a suitable method to explore its technological potential. The benefits of backcasting is related to the open-ended approach of the methodology which invites actors to participate in exploring and adapting means for reaching the desired future state by navigating the landscape in an uncertain system. In the context of this thesis, a specific approach to backcasting is used which is called backcasting from principles, which was first developed by Holmberg (Holmberg, 1998) and Holmberg and Robèrt (Holmberg & Robert, 2000). This approach is explained in the following four steps as outlined by Holmén (2020), which is also presented visually in figure 3.2.

1. *Formulate guiding principles for a sustainable and desirable future*
2. *Analyse some present situation or system in relation to the principles to illuminate gaps and challenges*
3. *Identify leverage point interventions with the potential to bridge the gaps*
4. *Strategically experiment with leverage point interventions*

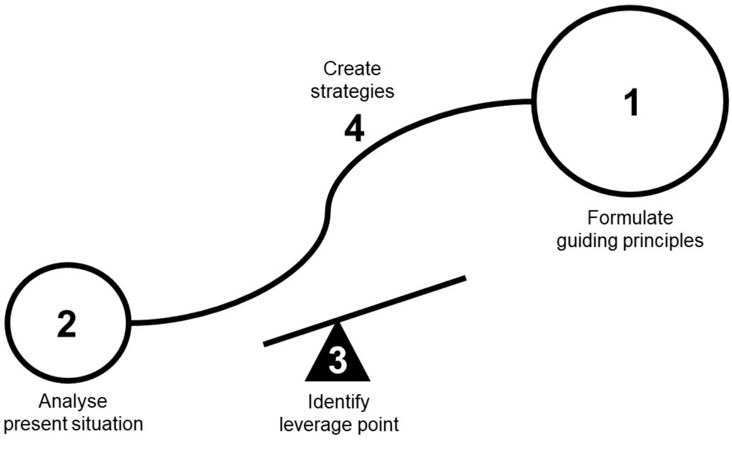


Figure 3.2: Overview of the primary steps applied in a backcasting from principles methodology.

The sections below describe how the overall approach in this thesis has been linked to the methodology of backcasting from principles, while specific methods used within each step of the backcasting methodology is further explained in Sections 3.2-3.4 below. An overview of how backcasting from principles has been applied in this thesis can be seen in Figure 3.3.

In the context of exploring feedstocks for future sustainable biochar production in Gothenburg, the process started by defining guiding principles covering important aspects of sustainability to depict a future desirable scenario.

Step two consisted of analysing the present situation to display the gap between the desired future and the present. In the case of this thesis topic, the identification and mapping of present biomass flows was conducted in this step.

The third step of the backcasting approach is about finding leverage points which can facilitate the transition from the present situation to the desired future. Specifically for this case, step three included the evaluation of feedstocks according to criteria derived from the guiding principles defined in the first step. Thus, the outcome of step three was to conclude which feedstocks that might be utilized in biochar production in a sustainable way within Gothenburg.

The fourth step is about transforming the identified promising feedstocks into concrete actions by suggesting implementation strategies. The backcasting methodology emphasises the process of transformative social learning, which preferably would include the participation of multiple affected actors in a co-creation process of exploring feasible strategies for implementation. Since no specific actors were engaged in this phase of the backcasting process, relevant parts of step four has only been included as a part of the recommendations in Chapter 6.1.

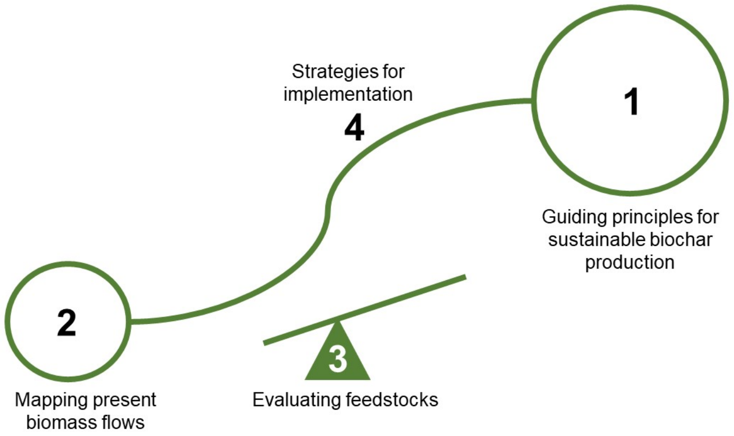


Figure 3.3: Overview of how the backcasting from principles methodology was applied in this thesis.

3.2 Step 1 - Defining guiding principles for sustainable biochar production

Aligning with the backcasting methodology, the first step started with an overview perspective of which guiding principles that are desirable for a future sustainable production of biochar. Therefore, a literature study described in Section 3.2.1 below, was conducted to determine essential guiding principles which defines sustainable biochar production in this study.

3.2.1 Literature study

A literature study was conducted to explore guiding principles which might be important to include when connecting biochar production in Gothenburg to sustainable development.

Sustainable development is often described to include three dimensions to meet human needs: ecological, social and economic. Holmén (2020) visualises a lighthouse model for sustainability, where the ecological dimension represents the foundation of the lighthouse, and the social and economic dimensions represents the vertical supporting structures essential for the stability of the lighthouse. While the conceptual framework of a sustainability lighthouse can be suitable when approaching many broad sustainability challenges, the guiding principles in this thesis need to be applicable to the scope of exploring potential feedstocks for biochar production. Therefore, the book "Decision-Making for Biomass-Based Production Chains" was used, which describes sustainability issues in biomass-based production chains with four pillars (Yilmaz Balaman, 2018):

- Environmental sustainability
- Social sustainability
- Economic sustainability
- Technical sustainability

These four pillars were set as a starting point in the literature study, exploring guiding principles for sustainable biochar production.

Literature was obtained from databases such as Scopus, Google and Google Scholar, as well as actors working in the field of biochar, both from academia and other professional areas. Several feasibility studies on biochar (listed in Section 4.1.1) for different Swedish cities were analysed in order to display important aspects of each sustainability pillar. Literature describing the certification requirements for EBC (explained in Section 2.3.2.1) were also included in this step, as well as documents covering the plans for Gothenburg's transformation to an environmentally sustainable city.

3.3 Step 2 - Mapping potential feedstocks

Based on potentially available biomass feedstocks mentioned in the literature study and in communication with actors, an extensive list of possible feedstocks was created to get an overview of the waste streams generated in the region. Since the exploration aimed to pinpoint the potential of current waste flows within the system boundary, no qualitative or quantitative restrains were considered while listing the feedstocks. Through the methods used further in step 2, the most promising feedstocks were then mapped in order to explore the current waste management system and display the annual biomass availability.

3.3.1 Top-down approach for waste intensity per sector

The top-down approach for waste intensity per sector introduces a method to identify industrial symbiosis opportunities using statistical datasets (Patricio et al., 2020). Derived from the circular economy concept of industrial symbiosis, where an output from one company can be utilized as an input by another company, the method aims to quantitatively estimate waste generation by implementing a top-down approach.

In contrast to implementing a bottom-up approach, using interviews, workshops and surveys which can be costly and time consuming, the top-down approach is based on available statistics of waste streams for each industrial sector (Patricio et al., 2020). The top-down approach also avoids challenges regarding company confidentiality since the waste flows are estimated based on available statistics. Patricio et al. (2020) used the method to explore and estimate the potential of biogas production in West Sweden by identifying waste streams suitable for biogas production and bio-based industries within the selected geographical area. Since biogas and biochar production both utilizes biomass as feedstock, the method was deemed suitable to estimate the potential for biochar production in the Gothenburg region. The method is based on the relationship between amounts of waste generated and number of employees, which according to Patricio et al. (2020) has been confirmed for each sector with statistical tests.

The method starts by defining desired waste categories based on the standard waste nomenclature for the EU called European Waste Classification for Statistics (EWC-stat) (Patricio et al., 2020). Industrial sectors are then selected based on their quantities of the desired waste categories. The classification of industrial sectors uses the Statistical Classification of Economic Activities in the European Community nomenclature (abbreviated NACE).

The next step is to calculate the waste intensity of each sector by relating the national amounts of each waste type generated within a sector to the total number of employees within the same sector (Patricio et al., 2020). This can be conducted by using statistics on a national level and generates the Waste Factor (WF), as depicted in Equation 3.1. Finally, to implement WF to the defined geographical area, statistics for total number of employees within a specific sector in the targeted area are used, according to Equation 3.2.

$$WF_{jkz} = \frac{W_{jkz}}{E_{jkz}} \tag{3.1}$$

WF = Waste factor (tonnes/employee)
W = Amount of waste produced (tonnes)
E = Number of employees/inhabitants
j = Waste type
k = Industrial sector
z = Country

$$WF_{jkz} \times E_{rk} = W_{jrk} \tag{3.2}$$

WF = Waste factor (tonnes/employee)
W = Amount of waste produced (tonnes)
E = Number of employees/inhabitants
j = Waste type
k = Industrial sector
z = Country
r = Region

When this method was applied in the thesis, waste statistics for Sweden was collected from Eurostat for each industrial sector. The following waste categories possible for biochar production were selected:

- Vegetal waste
- Animal and mixed food waste
- Wood waste
- Animal faeces, urine and manure

Number of employees within each sector was retrieved from the databases of Statistics Sweden for Gothenburg city and three adjacent municipalities (Mölndal, Härryda and Partille), located within the system boundary of this thesis. The Gothenburg area's share of the national waste flows was then mapped according to the share of a sector's employees working within the area according to Table 3.1.

Table 3.1: The share of employees working within each sector in the Gothenburg region, based on Swedish statistics regarding employed 15-74 years by region, sex and industrial classification (SCB, 2022).

	Sector	**Employees Sweden 2020**	**Employees GMHP [2]**	**Share of employees**
A[1]	Agriculture, forestry and fishing	73 209	573	0.78%
B+C[1]	Mining and quarrying + Manufacturing	541 371	51 829	9.57%
D+E[1]	Electricity, gas, steam and air conditioning supply + water supply, sewerage, waste management and remediation activities	53 341	3 668	6.88%
F[1]	Construction	353 550	25 587	7.24%
G-U[1]	Services	3 882 997	347 074	8.94%
For the household sector, population numbers are used instead of employees				
HH	Households	10 379 295[3]	730 715[3]	7.04%

[1] Letter representing each sector according to NACE Rev. 2.

[2] GMHP = Gothenburg, Mölndal, Härryda, Partille.

[3] Population by 31th of December 2020 (SCB, 2022).

In the end, it was concluded that the mapping of most feedstock flows were able to be calculated with higher accuracy using other methods described below. However, for the estimation of wood waste, this method was found to be the most suitable tool.

Also, food producing companies with a high probability of generating a lot of "Vegetal waste" were identified through this method and afterwards targeted with surveys described in section 3.3.3.

3.3.2 Complementary top-down approach

In some cases, the mapping of feedstock flows were possible to conduct without using the specific approach described in section 3.3.1. This was the case for food waste and sewage sludge where there is only one major actor for each feedstock responsible for the collection within the city. These two feedstocks could be mapped using statistics on the flows retrieved directly from the actors.

For agricultural plant residues (APR), the method described in section 3.3.1 was problematic since the relationship between employees and waste generation was not as established as for other sectors. Companies within the agricultural sector sometimes consists of a single farmer without employees, and still generate large quantities of waste. The estimation of APR was instead conducted through statistics for each cereal crop regarding cropland area and average yield collected from the Swedish Board of Agriculture.

From the mapping of "Animal faeces, urine and manure" using the method described in section 3.3.1, it was revealed that the largest flow is generated within the agricultural sector, thus a similar situation as for APR arises. To avoid uncertainties involved in coupling the waste generation to the number of employees in the sector, focus was instead set on horse riding schools since these facilities often are located close to cities and might not always have the possibility to circulate the flow in the local area as might be the case for an agricultural farm growing plants. Statistics on number of horses in riding schools in the Gothenburg area, as well as average number on annual manure production from a horse, were used to estimate the total flow of this feedstock.

3.3.3 Surveys

While the top-down approaches described in sections 3.3.1 and 3.3.2 gave estimated numbers on the annual feedstock flows, surveys were used to enhance the collection of qualitative information such as present handling of the flows. Surveys were sent through e-mail to the following actors:

- Food producers, to map current flows of food waste.
- Recycling companies, to map current flows of untreated wood waste.
- Riding schools, to map current flows of horse manure.

3.3.4 Semi-structured interviews

Interview methods can roughly be divided into three types: structured, semi-structured and unstructured (Van Teijlingen, 2014). The method chosen for this thesis, semi-structured interviews, means that questions are prepared in advance of the interview while the order of questions can be decided during the interview depending on the direction the interview takes. The goal of the semi-structured interviews in this thesis was to allow a space for discussions around aspects that hadn't been anticipated in advance, to highlight important qualitative aspects of the feedstocks explored.

3.4 Step 3 - Evaluating potential feedstocks

The evaluation of the potential feedstocks was based on the guiding principles, defining sustainable biochar production for this study. From the identified guiding principles, specific criteria were then formulated to represent important aspects of sustainable use. To guide the evaluation in a systematically manner, a MCA method was used. Within the MCA, a survey was conducted to collect expert opinions of the relative importance of the different criteria.

3.4.1 Multi-Criteria Analysis

Multi-criteria decision analysis (MCDA) or multi-criteria decision making (MCDM) is a term used broadly to describe situations where multiple and conflicting criteria affects a decision (Scott et al., 2012). Rather than guiding a clearly defined stakeholder in a specific decision, this thesis provides a foundation for decision making, thus the term used in this report is MCA. Scott et al. (2012) provides a review of different methods within the field of MCDM which are suitable for bioenergy systems. From the categorisation depicted by Scott et al. (2012), the "Optimisation of problems with few alternatives" as well as the "Mainly qualitative study methods" were deemed most suitable for the evaluation of feedstocks for biochar production.

Out of the papers reviewed by Scott et al. (2012), an article by Buchholz et al. (2007) was chosen as the main inspiration for the MCA performed in this thesis, since it emphasizes a systems approach which has similarities with the backcasting methodology applied in this thesis (Scott et al., 2012) (Buchholz et al., 2007). Buchholz et al. (2007) compares the systems approach with the reductionist approach in science, where systems is divided and studied in isolation. The systems approach, on the other hand, acknowledges that *"The whole is greater than the sum of its parts"* (Aristotle), and that the approach is especially applicable for a holistic and evolving concept like sustainability. The simplification of complex systems is conducted through the concentration on certain common principles without losing a holistic overview of the system. This summarizes the application for the evaluation performed in this report, breaking down the guiding principles based on the sustainability dimensions into a set of criteria which were chosen to provide a simplified, but yet correct, overview picture of the feedstocks evaluated.

A weighting system was further included in the MCA to compensate for the fact that all criteria were not assessed as equally important in the evaluation. To decide upon the importance of each criteria, a survey was sent through e-mail to actors and experts that had been previously contacted during the thesis to collect their views on the relative importance of respective criteria. The survey was sent to representatives from organizations within the academia, the City of Gothenburg, the waste management sector, the biochar industry, the construction sector and the consultancy sector for transparency.

3.4.1.1 Quantitative basis for MCA

Out of the evaluated nine criteria, four were evaluated through quantitative analyses derived from calculations for each feedstock. The waste flows identified in step 2 were used as a starting point in Table 3.2 and 3.3 to calculate the potentials for biochar, surplus heat and negative emissions. Two of those parameters, the potential annual amounts of biochar produced and negative emissions, were used as separate evaluation criteria while all three aspects were included as input parameters for the economic calculations presented in Table 3.6 and 3.7.

Since both sewage sludge and food waste were recognized to possess several inert potential flows, considering utilization before and after biological treatment of the feedstocks, Table 3.4 and 3.5 display the calculations used to quantify the complementary waste flows which were identified in step 2. For sewage sludge, the theoretical flow of sludge biomass before anaerobic digestion was quantified. For the food waste fraction, the calculations showcase the estimated remaining quantified mass of digestate following the anaerobic digestion process.

Table 3.6 and 3.7 provide the basis for the quantitative economic criteria called Cost per climate benefit and Calculated price compared with cost of alternative. Due to lack of references for biochar production from certain feedstocks and uncertainties regarding market prices, some general estimates and assumptions were made to reach comparable results for all feedstocks. Income and costs are presented per tonne produced biochar in order to facilitate comparison between the feedstocks.

Overall, the planned biochar plant for garden waste in Gothenburg was used as a reference for all costs except the drying costs, which were calculated separately to account for the diverse feedstock alternatives. Operational costs were based on Renova's feasibility study from 2019, where some costs were estimated to be halved of removed in cases where characteristics of the feedstock diverged from the reference (Detterfelt et al., 2019). According to collected information from actors in close contact with the field of biochar, investment costs for biochar plants have increased substantially in recent years. Therefore, a 50% increase has been added in the evaluation to the investment costs presented in Renova's feasibility study to compensate for the rising prices. The investment costs were scaled according to the fractions of dry mass for each feedstock and a 10 year write-off period was applied. No investment subsidies, like the Climate Leap initiative were assumed.

Investment and operational costs for drying were applied to the feedstocks with moisture contents exceeding 60%, that were assumed to require extensive drying. Costs for drying were based on 179 SEK/tonne feedstock, which was calculated from a specific dryer case presented in an article by Turek et al. covering extensive drying of sewage sludge (Turek et al., 2018). Values per feedstock were converted to SEK/tonne biochar in the tables.

Table 3.2: Quantitative values for garden waste, untreated wood waste, agricultural plant residues (APR) and horse manure used in the multi-criteria analysis (MCA).

	Garden waste	**Untreated wood waste**	**APR**	**Horse manure**
Pyrolysis temperature (°C)	450	700	450	500
Mass (tonnes)	5 670	116 829	1 791	4 723
Moisture content (%)	35[1]	20[2]	15[3]	64[4]
Dry mass (tonnes)	3 686	93 463	1 522	1 700
C content (% of DM)	50[5]	50[5]	43[6]	52[4]
C content (tonnes)	1 843	46 732	655	884
Conversion rate (% of DM)	41[7]	29[1]	34[11]	33[8]
Heating potential (MWh)	6 000[9]	152 345[10]	2 481[10]	2 771[10]
Biochar potential (tonnes)	1 500[9]	27 104	512	561
C content of biochar (%)	90[9]	93[1]	67[11]	67[8]
Negative CO_2-eqv (tonnes)	4 950[9]	92 426	1 251	1 378

[1] (Lundvall & Hellsten, 2020)

[2] (Swedish wood, 2023)

[3] (McCartney et al., 2006)

[4] (Hemlin & Lalangas, 2018)

[5] (Lamlom & Savidge, 2003)

[6] (Li et al., 2023)

[7] This value has been calculated through backtracking from the biochar potential stated in Renova's feasibility study for garden waste (Detterfelt et al., 2019)

[8] (Tsai et al., 2015)

[9] (Detterfelt et al., 2019)

[10] The garden waste conversion factor from dry mass to heating potential was used to calculate the heating potential for the other three feedstocks.

[11] (Cheng et al., 2018)

Table 3.3: Quantitative values for sewage sludge and food waste used in the multi-criteria analysis (MCA).

	Sewage sludge digestate	**Sewage sludge**	**Food waste (all)**	**Food waste reject**	**Food waste digestate**
Pyrolysis temperature (°C)	700	700	500	500	500
Mass (tonnes)	54 124	62 237[5]	50 000	15 000	22 090[10]
Moisture content (%)	70[1]	70[1]	70[8]	60[8]	80[8]
Dry mass (tonnes)	17 092[2]	18 671	15 000	6 000	4 418
C content (% of DM)	36[3]	54[6]	46.1[9]	46.1[9]	42.6[10]
C content (tonnes)	6153	10 078[5]	6 915	2 766	1 882[10]
Conversion rate (% of DM)	48[4]	44.4[7]	32.3[9]	32.3[9]	42.5[9]
Heating potential (MWh)	0	0	0	0	0
Biochar potential (tonnes)	8 204	8 290	4 845	1 938	1 878
C content of biochar (%)	18[4]	24.5[7]	71.3[9]	71.3[9]	35.3[9]
Negative CO_2-eqv (tonnes)	5 415	7 447	12 666	5 067	2 430

[1] (Gryaab AB, 2021)

[2] 5% food waste is added to the fraction to enhance biogas production (Gryaab AB, 2021) (D. Lorick, personal communication, February 24, 2023).

[3] (D. Lorick, personal communication, February 24, 2023)

[4] (Wongrod et al., 2022)

[5] From Table 3.4

[6] Calculated value. Corresponds well with values from literature (Rorat et al., 2019)

[7] (Gopinath et al., 2021)

[8] (Samuelsson, 2011)

[9] (Opatokun et al., 2016)

[10] From Table 3.5

Table 3.4: Calculations of estimated mass of sewage sludge before anaerobic digestion and without the 5% food waste which is normally added in the anaerobic digestion process.

Parameter	**Value**
C content in sewage sludge digestate	6 153 tonnes[1]
C content share to biogas	42%[2]
C content share to digestate	58%[2]
CH_4 share of biogas	75%[2]
CO_2 share of biogas	25%[2]
C content without added food waste	5 845[3]
Total C content before anaerobic digestion	10 078[4]
C content in biogas	4 233[5]
Mass of sewage sludge before anaerobic digestion	62 237[6]

[1] From Table 3.3
[2] (Van Phamn et al., 2020)
[3] 6 153 x 0.95 = 5 845
[4] 5845 / 0,58 = 10 078
[5] 10 078 - 5 845 = 4 233
[6] 54 124 + 4 233 x (0,75 x (16/12) + 0,25 x (44/12)) = 62 237
Molar mass of C=12, CH_4=16, CO_2=44 g/mol

Table 3.5: Calculations of estimated mass of food waste digestate based on the annual amount of slurry produced in Gothenburg.

Parameter	**Value**
Mass input to anaerobic digestion	35 000
Moisture content	80%[1]
Dry mass	7 000
C content of dry mass	46.1%[2]
C content of dry mass	3 227 tonnes
C content share to biogas	42%[3]
C content share to digestate	58%[3]
CH_4 share of biogas	75%[3]
CO_2 share of biogas	25%[3]
C content of biogas	1 345 tonnes[4]
Mass of biogas	2 582 tonnes[5]
C content of digestate	1 882 tonnes[6]
Digestate dry mass	4 418 tonnes[7]
C content of digestate	42.6%[8]
Digestate mass	22 090 tonnes[9]

[1] (Samuelsson, 2011)

[2] (Opatokun et al., 2016)

[3] (Van Phamn et al., 2020)

[4] 3 227 x 0.42 = 1 345

[5] 1 345 x (0.75 x (16/12) + 0.25 x (44/12)) = 2 582
Molar mass of C=12, CH_4=16, CO_2=44 g/mol

[6] 3 227 x 0.52 = 1 882

[7] 7 000 - 2 582 = 4 418

[8] 1 882 / 4 418 = 42.6

[9] 4 418 / 0.2 = 22 090

Table 3.6: Overview of economic values for garden waste, untreated wood waste, agricultural plant residues (APR) and horse manure used in the multi-criteria analysis (MCA).

	Garden waste	**Untreated wood waste**	**APR**	**Horse manure**
Income				
Biochar (SEK/tonne)	5 500[1]	5 500[1]	5 500[1]	4 000[2]
Heat (500 SEK/MWh presented per tonne BC)[3]	1 988	2 810	2 426	2 470
Carbon-sink (1000 SEK/CO_2-eqv presented per tonne BC)[3]	3 300	3 410	2 446	2 457
Costs				
Investment (SEK/tonne BC)	-4 503	-6 366	-5 495	-5 594
Drying (SEK/tonne BC)	0	0	0	-1 507
Pretreatment (SEK/tonne BC)	-840	-840	-840	-420
Personnel (SEK/tonne BC)	-332	-332	-332	-332
Electricity & water (SEK/tonne BC)	-667	-667	-667	-667
Handling of residues (SEK/tonne BC)	-63	-63	-63	0
Other operational costs (SEK/tonne BC)	-420	-420	-420	-420
Maintenance & reinvestments (SEK/tonne BC)	-1 283	-1 283	-1 283	-1 283
Total profit or cost (SEK/tonne feedstock)	**714**	**406**	**363**	**-154**
Cost per climate benefit (SEK/tonne CO_2-eqv)	**-188**	**-487**	**-480**	**-1 528**

[1] (Söderqvist et al., 2021)

[2] Assuming EBC classification classes as a reference for the quality of the biochar, hence the price on the market. Assuming a price between biochar produced from Sewage sludge and biochar produced from Wood waste.

[3] Table 3.2 state potentials for heat surplus, negative emissions and biochar production. The price of purchasing district heating was 675 SEK/MWh in Gothenburg 2022, but a lower price was assumed for selling surplus heat to the system (Göteborg Energi, 2022). Prices for carbon removal exceeded 1000 SEK/tonne CO_2-eqv in 2022 (Puro Earth, 2022).

Table 3.7: Overview of economic values for sewage sludge and food waste used in the multi-criteria analysis (MCA).

	Sewage sludge digestate	**Sewage sludge**	**Food waste (all)**	**Food waste reject**	**Food waste digestate**
Income					
Biochar (SEK/tonne)	1 500[1]	3 000[2]	3 000[2]	3 000[2]	1 500[1]
Heat (500 SEK/MWh presented per tonne BC)[3]	0	0	0	0	0
Carbon-sink (1000 SEK/CO_2-eqv presented per tonne BC)[3]	660	898	2 614	2 614	1 294
Costs					
Investment (SEK/tonne BC)	-3 846	-4 158	-5 716	-5 716	-6 882
Drying (SEK/tonne BC)	-1 181	-1 344	-1 847	-1 385	-3 336
Pretreatment (SEK/tonne BC)	-420	-420	-840	-840	-420
Personnel (SEK/tonne BC)	-332	-332	-332	-332	-332
Electricity & water (SEK/tonne BC)	-667	-667	-667	-667	-667
Handling of residues (SEK/tonne BC)	0	0	-63	-63	0
Other operational costs (SEK/tonne BC)	-420	-420	-420	-420	-420
Maintenance & reinvestments (SEK/tonne BC)	-1 283	-1 283	-1 283	-1 283	-1 283
Total profit or cost (SEK/tonne feedstock)	**-908**	**-629**	**-538**	**-658**	**-566**
Cost per climate benefit (SEK/tonne CO_2-eqv)	**-10 074**	**-6 260**	**-3 124**	**-2 948**	**-9 148**

[1] (Olovsson & Saarela, 2022)

[2] (Söderqvist et al., 2021)

[3] Table 3.3 state potentials for heat surplus, negative emissions and biochar production. The price of purchasing district heating was 675 SEK/MWh in Gothenburg 2022, but a lower price was assumed for selling surplus heat to the system (Göteborg Energi, 2022). Prices for carbon removal exceeded 1000 SEK/tonne CO_2-eqv in 2022 (Puro Earth, 2022).

4

Results

In this chapter the results from all three steps will be presented. The results will showcase the definition of guiding principles, the identification and mapping of feedstocks and the evaluation in relation to the criteria derived from the defined aspects of sustainable biochar production.

4.1 Step 1 - Defining guiding principles for sustainable biochar production

Following the methodology of backcasting from principles, the outlining of guiding principles for the definition of sustainable biochar production was made in Step 1. Later on, the guiding principles will be further developed into criteria for the evaluation performed in step 3.

The four sustainability pillars from Yilmaz Balaman (2018) were concretized to provide guidance according to the descriptions under respective headline below, generating the guiding principles. Out of the four pillars identified, the three dimensions of environmental, economic and technical sustainability were prioritized in order to limit the scope of the study.

4.1.1 Environmental sustainability

The environmental dimension was deemed as one of the most important perspectives in the scope of this thesis, while at the same time also difficult to evaluate. Fortunately, the EBC-certification system has defined a series of sustainability requirements, incorporated in the certification, related to the environmental perspective, and was therefore chosen as a baseline for defining environmental sustainability.

EBC has been acknowledged as an important benchmark in all feasibility studies analysed in this thesis (Detterfelt et al., 2019) (Ek & Gustafsson, 2020) (Hellmann et al., 2022) (Lundvall & Hellsten, 2020). Therefore, the first guiding principle for feedstocks suitable for sustainable biochar production was that the produced biochar can be EBC-certified. Further on, the certification requirements was complemented with additional environmental sustainability aspects described below, to cover aspects relevant in the local context of Gothenburg.

The guiding principles related to environmental sustainability were connected to Gothenburg's vision of becoming an environmentally sustainable city by 2030. Relating to the city's climate targets, achieving negative emissions through biochar is clearly connected, but alignment with other sustainability targets was also highlighted as an important guiding principle. Hence, other beneficial properties of the produced biochar, beyond negative emissions, were regarded. However, it's crucial to maintain a holistic view on these issues since there might be other solutions available outside the biochar technology that provide even better results coupled to the sustainability targets.

4.1.2 Social sustainability

Yilmaz Balaman (2018) associates this sustainability pillar with aspects such as job creation, contribution to the rural development, social and cultural acceptability and food and energy security. Even though these aspects can be influenced by the implementation of biochar production in Gothenburg, the social sustainability aspects were not considered in this report due to time constrains. However, it is vital to recognize that the social sustainability could potentially be equally important for the technological system development of biochar. Hence, the social sustainability pillar remains, in this report, as a general guiding principle to facilitate its importance. Encountered aspects related to the social dimension in the following steps of this thesis will therefore be expressed in the report but not further evaluated.

4.1.3 Economic sustainability

For actors considering to invest in pyrolysis equipment for biochar production, the economic aspects are essential. Considering that modern biochar production is a novel technology, there are great uncertainties associated with both incomes and costs. Collecting information on economical prerequisites for biochar in general, as well as for each feedstock specifically, was acknowledged as important pieces to cover in order to evaluate cost-effectiveness and profitability in step 3. Competitiveness is also one aspect raised by Yilmaz Balaman (2018), which was considered relevant to include since there might be several options for how to utilize biomass feedstocks in Gothenburg.

Coupled to the competitiveness and comparison with other solutions, present utilization of biomass flows in Gothenburg was included in the definition of guiding principles for sustainable biochar production. To indicate opportunities where biochar production might be preferable to the current practices for each feedstock, a value pyramid, indicating cascading and value retention from a bioeconomic prospective, was used as a reference point. The value pyramid, depicted in Figure 4.1, pictures examples of biomass applications in categories, showing high value applications in the top of the pyramid and lower value applications in the lower parts of the pyramid (Andersen et al., 2022). The broader base of the pyramid and the smaller top represents the volume, which is usually larger for lower value applications. The main products of biochar production are a combination of the material product (biochar) and the surplus energy (heat and electricity) potentially generated from the pyrolysis process. This pyramid has been used as an indicator to evaluate the potential to increase value retention of the present utilization for each feedstock.

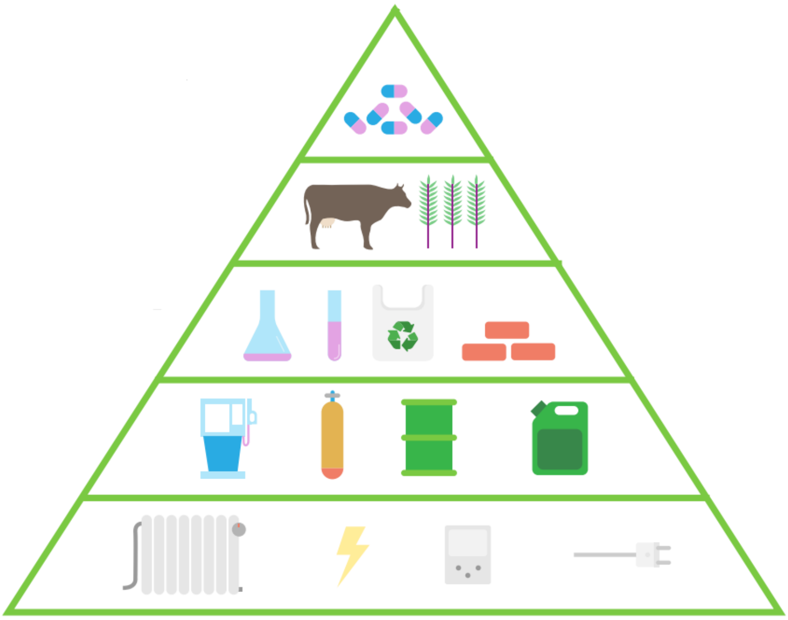


Figure 4.1: The value pyramid of the bio-based economy, displaying high value applications in the top of the pyramid and lower value applications in the lower parts of the pyramid (Andersen et al., 2022).

4.1.4 Technical sustainability

As with the economic perspective, the immature technology might also affect the technical sustainability in various ways. Yilmaz Balaman (2018) mentions factors such as reliability, efficiency and productivity. In the context of technical sustainability of biochar production, the need for pretreatments like storage, drying and sorting is included among the guiding principles related to this dimension. Also, the aspect of collection infrastructure for each feedstock was viewed as one guiding principle to consider.

4.1.5 Summary of guiding principles

The four pillars of sustainability depicted in Figure 4.2 were used as guiding principles in the exploration of suitable feedstocks for biochar production in Gothenburg.

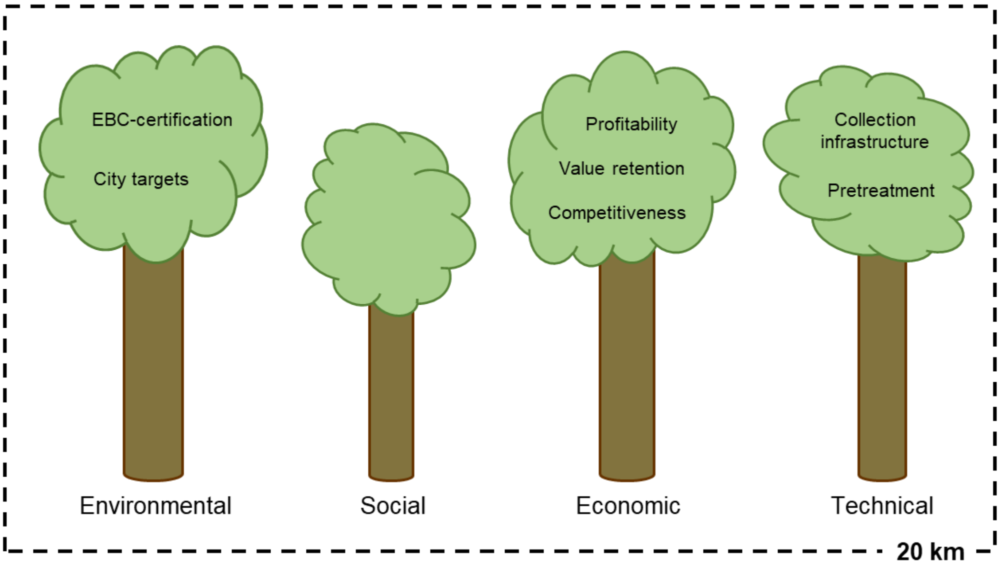


Figure 4.2: The four pillars of sustainability, enclosed by the system boundary applied in this thesis of 20 km. The figure also summarizes examples on relevant factors within each pillar.

The geographical system boundary of this thesis has been set to a maximum of 20 km from Gothenburg city centre, accounting for the GMHP municipalities. The guiding principles, derived from the sustainability pillars, were evaluated with regards to the established system boundary as illustrated in Figure 4.2.

4.2 Step 2 - Mapping potential feedstocks

The mapping of potential feedstocks began with exploring the current system of bio-based waste flows generated in the Gothenburg region.

Once identified, the bio-based waste flows were summarized in Table 4.1. In order to perform an in-depth analysis of the most promising waste streams, by limiting the number of feedstocks chosen for further evaluation, 7 of the 13 identified fractions were chosen. Compost material, invasive plant species, meat residues from butchers, blue biomass, forest management residues and press cakes from bio-refineries were excluded from this study. The exclusion was based on evaluations from previously conducted feasibility studies considering bio-based materials in Swedish urban areas and interviews with actors, indicating which feedstocks were thought to be more promising for the biochar production implementation. (Fransson et al., 2020) (Hellmann et al., 2022)(Lundvall & Hellsten, 2020) (Andersen et al., 2022). However, even though these fractions were excluded from being evaluated further, the identification process indicates that they could have inherent utilization potential relevant for the Gothenburg region.

Table 4.1: List of identified bio-based waste streams with utilization potential for biochar production in an urban setting.

Potential feedstocks	**Chosen for further evaluation**
Garden waste	✓
Untreated wood waste	✓
Compost material	⊘
Invasive plant species	⊘
Sewage sludge	✓
Horse manure	✓
Meat residues from butchers	⊘
Agricultural plant residues	✓
Blue biomass	⊘
Digestate from anaerobic digestion	✓
Forest Management	⊘
Press cakes from bio-refineries	⊘
Food waste	✓

The bio-based waste flow identification resulted in six major waste flows considered for further evaluation: garden waste, untreated wood waste, sewage sludge, animal manure, APR and food waste. The digestate fraction from anaerobic digestion was not considered to be an individual waste fraction, instead it was integrated as partial flows within the value chains of the selected six biomass waste flows. Hence the digestate fractions were included in the biomass value chains where anaerobic digestion was identified to occur with regards to today's waste management.

Once the six potential biomass feedstocks had been selected, each of the generated waste flows were mapped with regards to the fraction's current waste management and utilization. The mapping was designed to display an overview of the system from the actor generating the waste to the end-product, specific for waste management activities in the Gothenburg region. When conducting the mapping, only the most essential waste streams and actors were identified and included using literature, surveys, semi-structured interviews with actors and top-down approaches for waste intensity per sector. Once the current systems had been mapped, the internal fractions with a deemed potential for pyrolysis processing were quantified.

4.2.1 Garden waste

The local waste management company Renova conducted a feasibility study in 2019 exploring the prerequisites for biochar production of garden waste in Gothenburg (Detterfelt et al., 2019). In order to evaluate the current status of the project, an interview was held with Renova where it became clear that the plan is to build a pyrolysis plant for garden waste in 2024 (M. Eriksson, personal communication, February 15, 2023). Because of this, garden waste was not explored in detail in this thesis, but used as a reference in the exploration of other biomass flows. In the feasibility study by Renova, a waste flow of 6300 tonnes of garden waste collected per year was considered. This was also assumed to be the largest accumulation of garden waste within the city. Out of the 6300 tonnes, about 10% of the total mass has to be removed in the sorting process due to impurities. Hence, after the sorting, 5670 tonnes wood chip from garden waste was retrieved as potential pyrolysis feedstock.

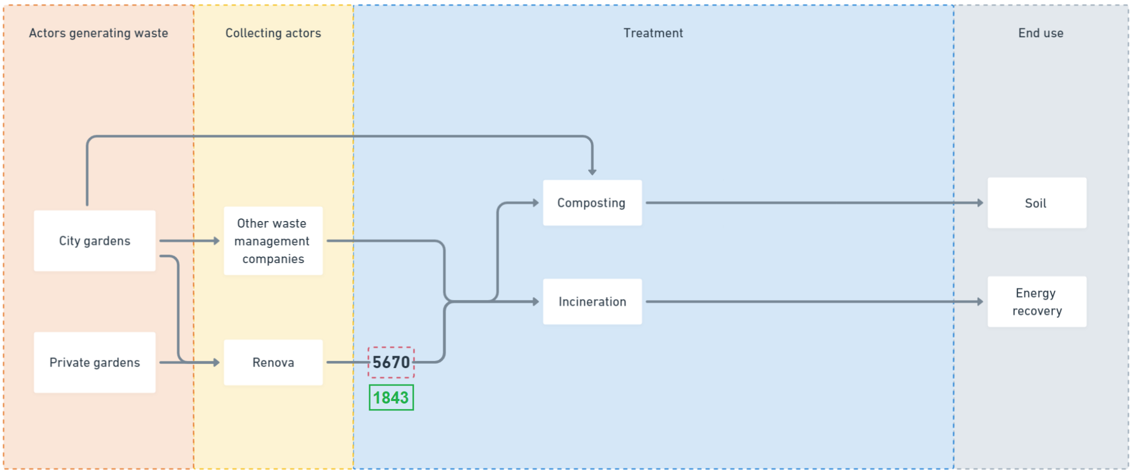


Figure 4.3: Overview mapping of identified garden waste flows in the Gothenburg region, amounting to 5670 tonnes/year of wood chip from garden waste. The corresponding carbon flow is highlighted in green, measured in tonnes/year.

Figure 4.3 showcases an overview mapping of the current flows of garden waste within the city, based on personal communication with Renova. Garden waste from private gardens and a majority of the city gardens are collected by Renova. However, garden waste from some city gardens, such as churchyards and "Botaniska Trädgården" (a big city garden), are not included in Renova's waste flow and were therefore not further explored in the scope of this thesis. It was assumed that these flows are collected by other waste management companies or utilized within the garden. Regardless of the collecting actor, two main treatment methods were identified, composting and incineration for energy recovery together with other municipal waste. From the identified flows in the mapping, 5670 tonnes of garden waste biomass was considered for further evaluation.

4.2.2 Agricultural plant residues

The potential to utilize APR as a feedstock for biochar production is often investigated in research of small scale farm implementations (E. S. Azzi et al., 2021) (Zhang et al., 2021). However, APR from nearby agricultural lands could also be utilized as a potential feedstock for large scale biochar production in a city setting. Considering the system boundary of a 20 km radius from the Gothenburg city centre, the four municipalities of GMHP were investigated. In order to quantify the potential APR in the four municipalities, data on the total amount of cereal cropland area and yield for cereal crops in the Västra Götaland region were collected from the Swedish Board of Agriculture (Jordbruksverket, 2022) (Jordbruksverket, 2021). The total estimated waste flow of APR were then calculated in accordance to Table 4.2, amounting to 1791 tonnes.

Table 4.2: Estimation of agricultural plant residues (APR) in the GMHP region, based on statistics from the Swedish Board of Agriculture if no other reference is stated. Values on yield/ha and straw/grain ratio are stated as the average values for the combination of cereal types cultivated in the GMHP region.

Parameter	**Value**	**Reference**
Cereal cropland area Gothenburg	502 ha	Average 2018-2022
Cereal cropland area Mölndal	23 ha	Average 2018-2022
Cereal cropland area Härryda	69 ha	Average 2018-2022
Cereal cropland area Partille	29 ha	Average 2018-2022
Total cereal cropland area	**623 ha**	Calculated
Yield for cereal crops in Västra Götaland region	4612 kg/ha	Average 2018-2021
Yield grain in GMHP/year[1]	2873 tonnes	Calculated
Straw/grain ratio	0.62	(McCartney et al., 2006)
Estimated straw in GMHP/year[1]	1791 tonnes	Calculated

[1] GMHP = Gothenburg, Mölndal, Härryda, Partille.

To get an overview of the availability potential of APR in relation to a more agriculture intensive municipality, the total cereal cropland area of the GMHP municipalities was compared with the municipality of Vara. Even though the total land area of Vara is smaller, the cereal cropland area is 25 086 ha (Jordbruksverket, 2022). Fourty times the size of the cereal croplands within the scope of this thesis.

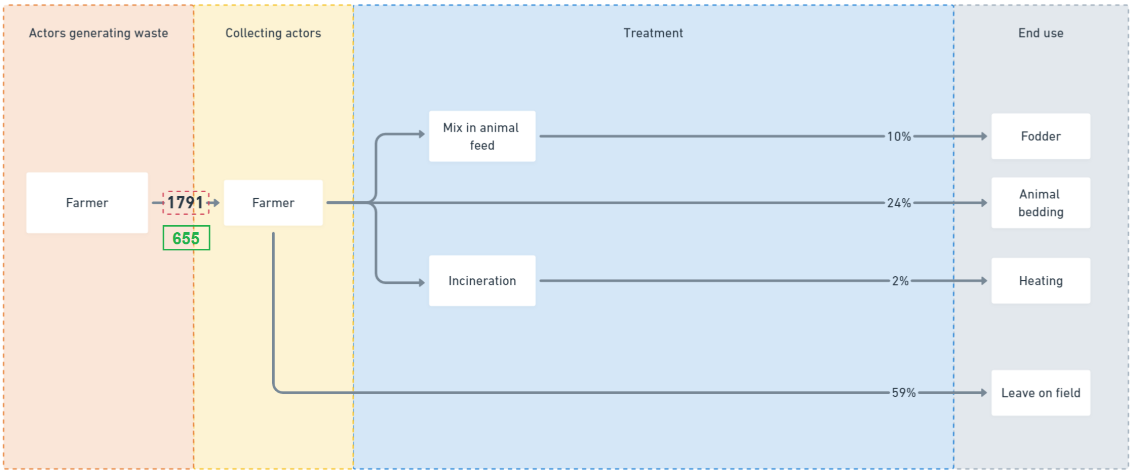


Figure 4.4: Overview mapping of identified agricultural plant residues (APR) flows in the GMHP region, amounting to 1791 tonnes/year. The percentage share of applications for APR were based on statistics from SCB on straw from cereals in Västra Götaland (SCB, 2013). The corresponding carbon flow is highlighted in green, measured in tonnes/year.

Figure 4.4 represents an overview mapping of the current APR waste flows in the Gothenburg region. The main actors generating and being responsible for the potential collection of the biomass were identified as the farmers, cultivating the crops. Although it is important to note that the farmer does not always collect the APR, but instead leaves the APR on the fields, recycling nutrients and acting as protective layer to counteract soil erosion. In the cases where the farmer collects the APR, several possible areas of application were identified. Some of the APR is utilized as animal bedding, mixed in animal feed or incinerated for heat production, often utilized on the farm itself.

4.2.3 Untreated wood waste

Wood waste was initially included as one of the first materials in the positive list of permissible biomasses from EBC, which makes it approved as a feedstock for biochar production. However, wood waste containing glue, paint, wood preservatives, PVC content and/or heavy metal enrichment is only approved for lower certification classes, such as construction material (Carbon Standards International & European Biochar Certificate, 2023). Hence, only untreated wood waste were considered in this study.

The top-down approach explained in section 3.3.1 was used to estimate the waste flows within each industrial sector in the Gothenburg region, as depicted in Table 4.3.

Table 4.3: Estimated annual waste flows of untreated wood waste. The flows for each sector are based on the country's reported numbers to the EU for 2020 (Eurostat, 2020). The flows for GMHP are based on the share of employees calculated in Table 3.1.

Sector[1]	**Untreated Wood Waste Sweden**	**Untreated Wood Waste GMHP**[2]
B+C[1]	190 375	18 226
D+E[1]	336 608	23 147
F[1]	571 282	41 345
G-U[1]	32 946	2 945
Households	484 516	34 111

[1] Letter representing each sector according to NACE Rev. 2.

[2] GMHP = Gothenburg, Mölndal, Härryda, Partille.

As seen in Figure 4.5, the sectors identified to generate the most wood waste were "Construction" and "Households". Due to aggregated numbers of employees for B+C and D+E, the waste flows were aggregated as well. However, the statistics from Eurostat revealed that sector C (manufacturing) was responsible for more than 99% of generated waste for B+C, and sector E (water supply: sewerage, waste management and remediation activities) was responsible for more than 99% of generated waste for D+E (Eurostat, 2020). In Figure 4.6 below, the term "Waste management companies" was used to describe sector D+E and the term "Manufacturing" was used to describe sector B+C.

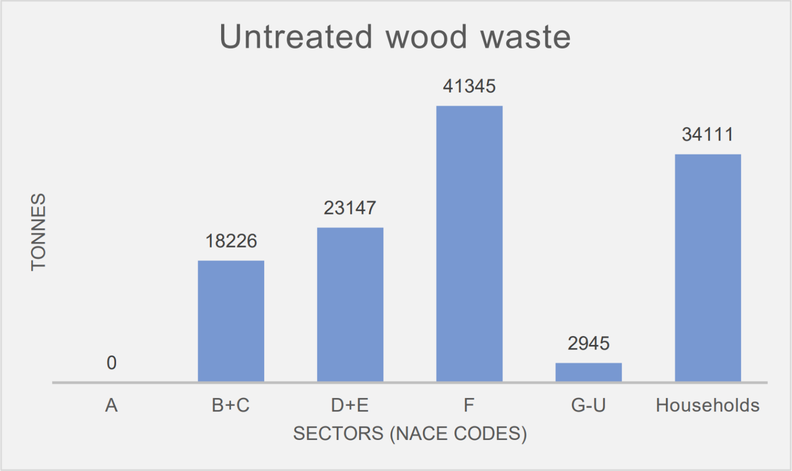


Figure 4.5: Results of annual Untreated wood waste in the GMHP region using a top-down estimation method.

The central collection of wood waste within the city amounted to approximately 12 000 tonnes per year according to the feasibility study by Renova (Detterfelt et al., 2019). To map other flows of untreated wood waste within the waste management sector a survey was sent to 3 other waste management companies with activities in the Gothenburg region. Through answers from 2 of those companies it was established that the main fraction of untreated wood waste was cut into wood chips and sold to biomass combined heat and power plants (CHP-plants) for energy production, which also matches the description in Renova's feasibility study. The aggregated numbers from the three identified actors within waste management generated approximately 19 000 tonnes. Another aspect highlighted by the survey responses was that a lot of the untreated wood waste ended up with the fraction of treated wood waste due to insufficient sorting, since it was collected as "Mixed wood waste".

Untreated wood waste from households was considered to be included in the central collection of waste within the city and was thus not further mapped in detail. To avoid the risk of double counting, only the waste flows reported to Eurostat was included in Figure 4.6 below, thus not covering in detail how reported waste statistics are divided between each sector when the value chain involves actors from multiple sectors.

The construction sector was considered to include some large companies producing high volumes of wood waste and therefore were recognized to have great possibilities of utilizing wood waste in biochar production. To cover qualitative aspects of biochar in the construction sector an interview was set up with the construction company Skanska who have invested in a mobile pyrolysis plant, and is planning to scale up with more pyrolysis plants in the future (M. Asplund, personal communication, February 27, 2023). Their biochar production is currently located in Skellefteå in northern Sweden, where they are constructing a new industrial site. Tree stumps and leftover wood waste from the construction site is used as a feedstock for the pyrolysis plant, which is built in steel containers and is loaded with batches of feedstock in large metal baskets. The main benefit with the biochar production from Skanska's perspective is to achieve negative carbon emissions, even though they also see the potential of creating circular material flows by reusing the material in e.g., dikes for cleaning water or as part of construction material in buildings. Surplus heat from the process is currently used to dry the feedstock, but the utilization of this potential might be expanded in the future.

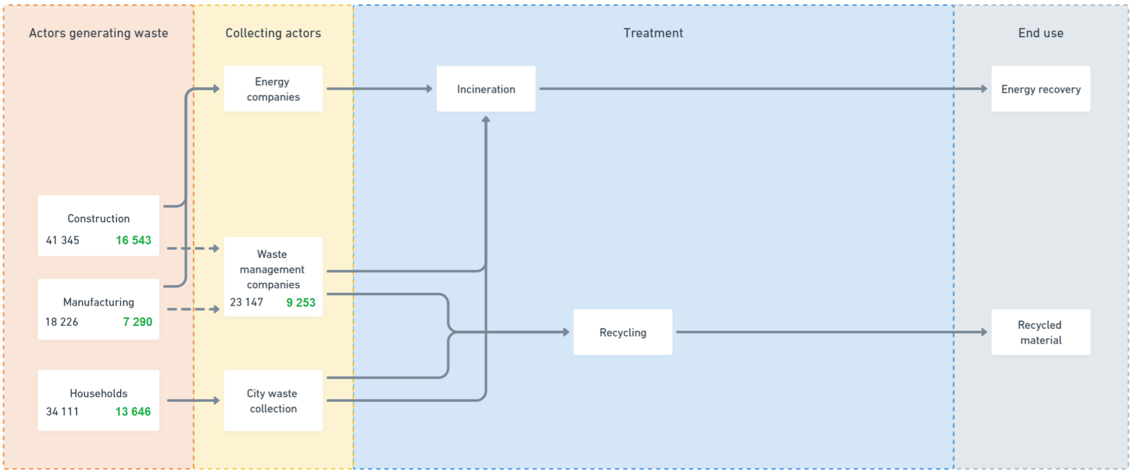


Figure 4.6: Overview mapping of identified untreated wood waste flows in the GMHP region based on the top-down approach described in section 3.3.1, amounting to 116 829 tonnes/year. The corresponding carbon flows is highlighted in green, measured in tonnes/year.

The mapping displayed in Figure 4.6 includes dashed arrows where flows probably exists but weren't possible to quantify. From surveys and interviews it was concluded that the main application of wood waste was identified as a substrate for energy production in biomass CHP-plants. However, some actors also communicate that they strive to recycle wood waste into new materials, but this flow is expected to currently only cover a minor part of the total waste flow of untreated wood waste.

4.2.4 Food waste

Food waste consists of two different waste categories reported in Eurostat, the statistical office of the European Union. These two categories are "Vegetal waste" and "Animal and mixed food waste". The top-down approach explained in section 3.3.1 was used to estimate the waste flows within each industrial sector in the Gothenburg region, which is displayed in Table 4.4.

Table 4.4: Estimated annual waste flows of "Vegetal waste" and "Animal and mixed food waste" (in tonnes). The flows for each sector in Sweden are based on the country's reported numbers to the European Union for 2020 (Eurostat, 2020). The flows for GMHP are based on the share of employees calculated in Table 3.1.

Sector[1]	**Vegetal waste Sweden**	**Vegetal waste GMHP**[2]	**Animal and mixed food waste Sweden**	**Animal and mixed food waste GMHP**[2]
A[1]	42 709	334	28 486	223
B+C[1]	159 096	15 231	179 945	17 227
D+E[1]	3 714	255	6 774	466
F[1]	1 370	99	1 522	110
G-U[1]	280 360	25 059	113 587	10 153
Households	439 728	30 957	336 818	23 712

[1] Letter representing each sector according to NACE Rev. 2.

[2] GMHP = Gothenburg, Mölndal, Härryda, Partille.

As seen in Figure 4.7 and 4.8, the sector generating the most food waste is the household sector. The service sector (represented by letters G-U) is the second largest source of "Vegetal waste" and the third largest source of "Animal and mixed food waste". The manufacturing industry is also a sector with substantial flows of food waste. More precisely, it is the food producers who generate 99% of the waste streams in sector B+C according to the detailed statistics of Eurostat (Eurostat, 2020).

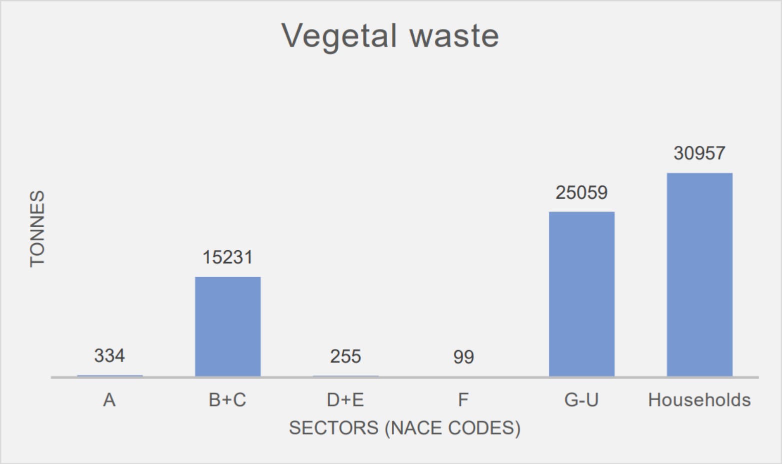


Figure 4.7: Results of annual "Vegetal waste" in the GMHP region using a top-down estimation method.

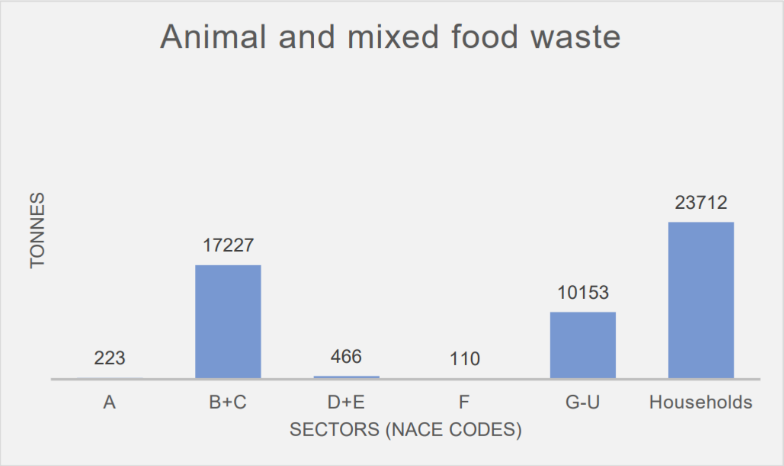


Figure 4.8: Results of annual "Animal and mixed food waste" in the GMHP region using a top-down estimation method.

The central collection of food waste within the city, managed by Renova, amounts to approximately 50 000 tonnes per year (Göteborg Stad, 2022). Compared with the numbers from the top-down approach, this flow was considered the most significant waste flow to utilize as a potential feedstock in this thesis.

However, the food waste generated by food producers was also further analyzed through surveys and interviews. A survey was sent to 7 of the largest food producers in the Gothenburg area inquiring amounts of food waste and current utilization methods. Through answers from the 3 responding companies and a phone call with one of the companies, it was established that waste management of food waste fractions from food producers were more diversified than that for households. The communication indicated that parts of the fractions were handled in the same manner as household food waste, but that other parts were utilized in alternative treatments like production of animal feed and biogas production outside the geographical system boundary of this study.

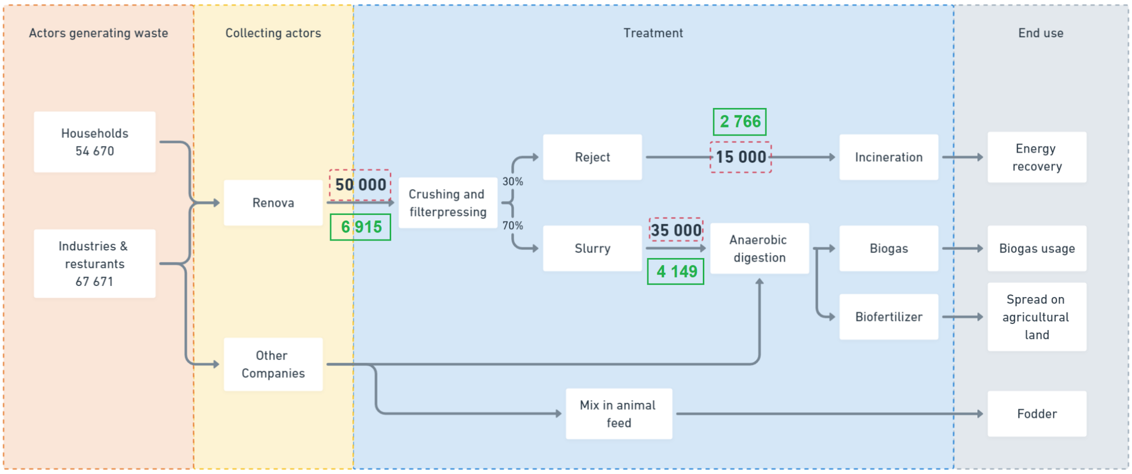


Figure 4.9: Overview mapping of identified food waste flows in the Gothenburg region based on the top-down approach described in section 3.3.1. Three different fractions for pyrolysis processing were identified amounting to 50 000, 35 000 and 15 000 tonnes/year of food waste. The corresponding carbon flows is highlighted in green, measured in tonnes/year.

The overview mapping of the current food waste flow in the Gothenburg region, presented in Figure 4.9 above, showcase households, industries and restaurants as the identified main actors generating the waste. From interviews and surveys, Renova was identified as the main collecting actor of the food waste and therefore only the fraction collected by Renova was considered available as a potential feedstock. Although, only Renova's fraction was considered, interviews with industry actors indicated that there were other companies collecting some fractions of the total generated waste but these fractions were only recognized and not included in the scope of this study.

Once collected, the food waste is pretreated in Renova's waste management facility in Marieholm. In the pretreatment process, the food waste is crushed and then sorted using a filter press (L. Detterfelt, personal communication, February 15, 2023). During the sorting process the food waste is divided into two separate fractions. The largest separated fraction, the slurry, contains finely crushed and pressed food waste mixed with water. The smaller reject fraction contains larger pieces of food waste, wrongly sorted inorganic impurities and fossil components such as plastics. Once sorted, the reject fraction is sent for incineration together with municipal solid waste (MSW) in a CHP-plant in order to recover the energy from the material. The slurry, on the other hand, is transported to a external biogas plant for production of biogas and digestate, used as biofertilizer. During the interviews with Renova, the company mentioned that feasibility studies on building a biogas production plant in connection to the facility in Marieholm had been conducted. However, after long consideration it was determined that external processing were both more environmentally and economically viable due to established biogas grid connections and shorter transport distances in order to utilize the produced biofertilizer on agricultural land.

Summarizing the overview mapping of the current food waste flow in the Gothenburg area, three partial flows were identified as potential feedstocks for further evaluation. The largest fraction consists of all food waste collected by Renova and amounts to 50 000 tonnes of mixed food waste. The second largest waste flow to be investigated is the digestate fraction, the slurry after anaerobic digestion, amounting to 35 000 tonnes input before anaerobic digestion. The last fraction considered for further evaluation was the reject fraction, amounting to 15 000 tonnes of larger pieces of food waste mixed with inorganic impurities and fossil components (L. Detterfelt, personal communication, February 15, 2023). Through personal communication it was further reviled that previously conducted component analyses of the reject fraction indicated that the levels of fossil components could prove problematic for the certification possibilities. However, since the content of fossil components did not exceeded the limit values for certification in all cases, the fraction was still considered for further evaluation.

4.2.5 Horse manure

Animal manure is reported in the waste category "Animal faeces, urine and manure" in Eurostat. Using the top-down approach, explained in section 3.3.1, the total amount of animal manure generated in the Gothenburg region was estimated for each corresponding sector, which is displayed in Table 4.5.

Table 4.5: Estimated annual waste flows of "Animal faeces, urine and manure" (in tonnes). The flows for each sector are based on the country's reported numbers to the European Union for 2020 (Eurostat, 2020). The flows for GMHP are based on the share of employees calculated in Table 3.1.

Sector[1]	**Animal Faeces, urine and manure Sweden**	**Animal Faeces, urine and manure GMHP[2]**
A[1]	924 180	7 233
B+C[1]	66 267	6 344
G-U[1]	714	64

[1] Letter representing each sector according to NACE Rev. 2.
[2] GMHP = Gothenburg, Mölndal, Härryda, Partille.

Based on the result from the top-down approach calculations, seen in Figure 4.10, "Agriculture, forestry and fishing" and "Mining and quarrying" + "Manufacturing" were identified as main sectors generating the waste. However, this approach is not the most suitable method for quantifying this category of waste since the large manufacturing industry in the Gothenburg region heavily impacts the estimated amounts in the GMHP region, thus indicating a higher amount than what is reasonable. Additionally, for the agricultural sector, much of the waste generated originates from individual private farmers, able to utilize the animal manure as biofertilizer on their own or nearby agricultural land. With regards to local established utilization of the animal manure, horse manure was instead chosen for further investigation. Although horse manure could similarly be utilized as biofertilizers on agricultural soil, it is reported that many of the horses in Sweden are located close to urban areas. In 2016, it was estimated that about 76% of all horses and about 71% of the facilities for horse keeping in Sweden were located in, or in the vicinity of urban areas, indicating that the fraction could be more beneficial for alternative utilization (Enhäll, 2017). From interview and survey communication with central actors, the cost and labour coupled to waste management of horse manure was highlighted as a potential to explore alternative management systems. In order to estimate the amount of horse manure generated in urban areas in the Gothenburg region, riding schools was targeted as the main actors generating the waste. Hence, the potential of the animal manure fraction was chosen to be represented by the collected data on horse manure, implementing a complementary top-down approach to estimate the waste flow from riding schools.

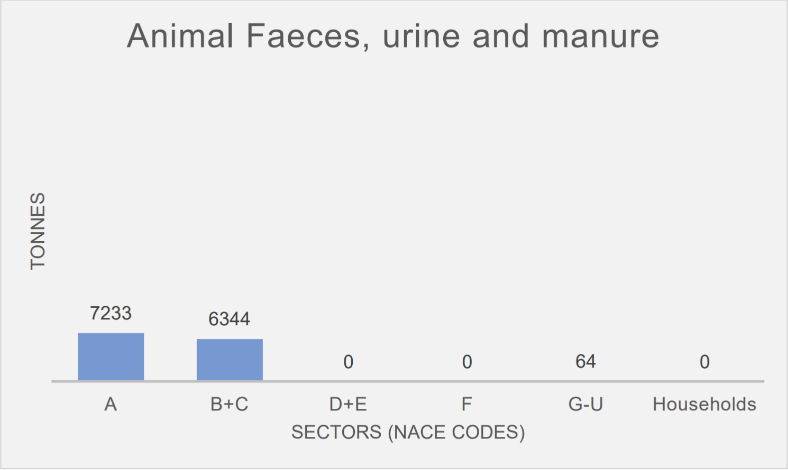


Figure 4.10: Results of annual "Animal faeces, urine and manure" in the GMHP region using a top-down estimation method.

According to a report by the City of Gothenburg covering knowledge about the riding sport in the city, there are 532 horses in the riding school facilities (Ekdahl, 2019). In order to relate the amount of horses to the generated waste, it is first important to distinguish the difference between pure horse manure and horse manure mixed with bedding material. In this study, if nothing else is stated, the horse manure fraction will be defined to include both horse manure and animal bedding material since this is the case for most reported data regarding the generated waste fractions. Therefore, an estimation of the annual generation of horse manure was made based on the identified number of horses in the Gothenburg region, see Table 4.6.

Table 4.6: Estimation of annual horse manure production from riding schools in the Gothenburg region.

Parameter	Value
Number of horses	532
Assuming share of ponies	1/3[1]
Assuming pony size of full-size horse	2/3
Number of full-size horse equivalents	472.3
Annual manure per horse	10 tonnes[2]
Annual horse manure	4723 tonnes

[1] Estimated based on information presented on riding schools' websites.

[2] (Brännström & Guldbrand, 2016)

To gain a transparent overview of the waste management system for horse manure, surveys were sent to 8 riding schools in the Gothenburg region regarding their current waste management systems. 3 riding schools responded with information on their amounts of annual stable waste, which bedding materials that are used, how the waste is handled today and which costs that are associated with current waste management practices. The response indicated that in cases where the horse manure is not possible to spread on the actor's own land, the waste is usually collected by farmers or horse feed suppliers for a fee of between 191-383 SEK/tonne horse manure.

- Riding school A: 191-255 SEK/tonne
- Riding school B: 192-339 SEK/tonne
- Riding school C: 340-383 SEK/tonne

The surveys further indicated that the choice of bedding materials varies a lot between the respondents. Peat mix, wood shavings, sawdust pellets and straw were used in different combinations. Finally, the amounts of horse manure per horse reported by the riding schools were found to correspond well with a general estimation of 8-10 tonnes stable waste annually per horse found in literature (Brännström & Guldbrand, 2016).

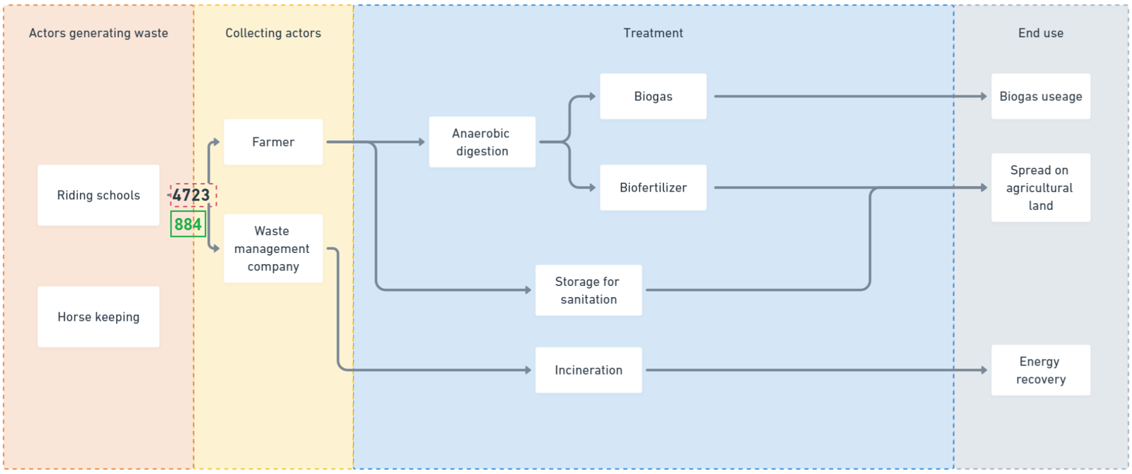


Figure 4.11: Overview mapping of identified horse manure flows in the Gothenburg region, amounting to 4723 tonnes/year. The corresponding carbon flow is highlighted in green, measured in tonnes/year.

Looking at the overview mapping of the current horse manure waste flow in the Gothenburg region, depicted in Figure 4.11, one can see that riding schools was identified as the main actor generating the waste. However, while only considering the waste generated from riding schools, one should note that horse-keeping beyond riding schools is recognized to be another actor generating potential horse manure but were deemed insignificant in comparison to riding schools within the system boundary.

The mapping identified farmers and waste management companies as the most significant collecting actors, payed by the riding schools for waste management services. Once collected, the mapping identified three current waste treatment alternatives established in the Gothenburg region. Some of the horse manure was incinerated with MSW in a CHP, in order to recover the energy. While some fractions were managed locally via biogas-production, to produce biogas and biofertilizer, and storage for sanitation generating biofertilizer.

Summarizing the results from the mapping, the horse manure generated from riding schools was identified as a potential feedstock, amounting to 4723 tonnes. Comparing this amount with the estimated value derived from the top-down approach, 13 641 tonnes, horse manure from riding schools accounted for about 35% of the total animal manure in the Gothenburg region. The result indicates that there is potential to utilize more of the animal manure in the Gothenburg region. However, only horse manure was accounted for since the top-down approach estimated per employee was deemed unsuitable for the agricultural and manufacturing sector.

4.2.6 Sewage sludge

In Sweden, the most common utilization option for sewage sludge is to spread the sludge on agricultural soil in order to recycle the nutrient phosphorous. However, it has been debated for a long time if sewage sludge should be allowed to be spread on soil, as it is thought to be connected to posing climate and health risks (Holmgren et al., 2020) (Naturskyddsföreningen, 2021) (Svenskt Vatten, 2021). Currently Swedish regulations do not prohibit the use of sludge on agricultural soils but since several countries in Europe have recently established such bans, actors are exploring alternative waste management techniques in order to retain the nutrients recycling. In response to the exploration for alternative processing methods, incineration and pyrolysis has been highlighted as two viable alternatives.

For the Gothenburg region, the local wastewater treatment plant (WWTP) is in charge of handling all the waste connected to the sewage system and was therefore considered the main actor in the system. Hence, the mapping was conducted based on reported values and interview communication with the company Gryaab (Gryaab AB, 2021).

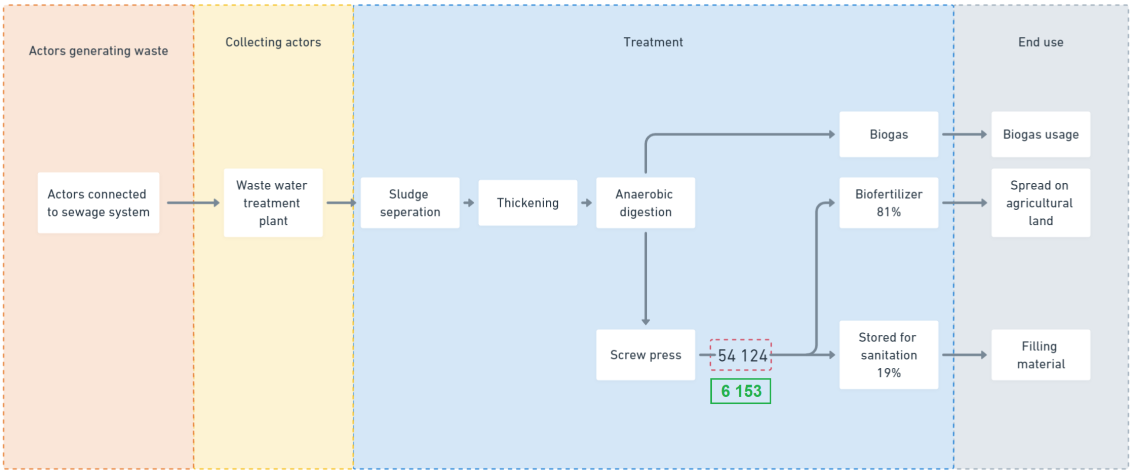


Figure 4.12: Overview mapping of identified sewage sludge flows in the Gothenburg region, amounting to 54 124 tonnes/year of sewage sludge digestate. The corresponding carbon flow is highlighted in green, measured in tonnes/year.

In Figure 4.12 an overview mapping of the current sewage sludge waste flow in the Gothenburg region is depicted. From the mapping, actors connected to the sewage system were identified as the main actor generating the waste. The sewage sludge, mixed with the sewage wastewater, is then collected by the WWTP.

At the WWTP larger pieces of impurities, the reject fraction, is filtered out and sorted before being sent to incineration for energy recovery (Gryaab AB, 2023). Similarly to the food waste fraction, options to utilize the reject fraction generated from the WWTP was explored. However, due to the low content of organic material in the reject fraction indicated from personal communication, it was deemed unsuitable for biochar production and was not included in the study. Once filtered, the sludge and water is partly separated in a floating tank via sedimentation. The sludge is then gradually separated during the biological treatment of the wastewater. The separated sludge fraction is thereafter thickened, reducing the moisture content of the sludge from about 98% to 94%, before being used for biogas production. From the biogas production, the produced gas is sent for upgrading. However, the process also produces digestate, meaning remaining solid/liquid sewage sludge fraction, which is further dried using a screw press. The screw press lowers the moisture content in the digestate from about 94% to 70% and once dried, the digestate is either be spread on agricultural land as biofertilizer or used as filling material. The distribution of how much of the sludge which can be utilized as fertilizer and filling material depends on the content of contaminants in the sludge, determined from the REVAQ-certification standard. Based on interviews with Gryaab, it was revealed that the distribution between fertilizer and filling material for 2021 was 81% and 19% respectively but that the distribution differs from year to year.

Summarizing the overview mapping for sewage sludge, the total annual waste flow of generated sludge reported by Gryaab was chosen for further evaluation, amounting to 54 124 tonnes (Gryaab AB, 2021). In order to display trade-off effects in the current established system, both cases of sludge with and without biogas production were considered. Hence, the fraction of sewage sludge before anaerobic digestion was recognized and identified as a possible feedstock but was not quantified at this stage due to data availability.

4.2.7 Overview of mapping

Table 4.7 provides a summary of all identified feedstocks from the mapping conducted in step 2. These flows were then used as input parameters in the evaluation performed in step 3.

Table 4.7: Summary of all identified feedstock flows in the mapping.

Feedstock	**Mass**[1]	**Carbon**[1]
Garden waste	5 670	1 843
APR[2]	1 791	655
Untreated wood waste	116 829	46 732
Food waste	50 000	6 915
Horse manure	4 723	884
Sewage sludge	54 124	6 153

[1] Presented in tonnes/year
[2] Agricultural plant residues

4.3 Step 3 - Evaluating potential feedstocks

In order to evaluate and compare each of the identified potential feedstocks, a MCA was conducted. By recognizing that the biochar technology is a complex system, the MCA aimed to mediate a simplification of the system by evaluating certain common principles while still maintaining a holistic approach. Hence, to evaluate the identified feedstocks on equal terms, criteria and indicators were derived from the guiding principles defined in Section 4.1. Summarizing the identified guiding principles, three pillars of sustainability were considered during the evaluation: Environmental sustainability, Economic sustainability and Technical sustainability. Based on personal communication with actors in the Gothenburg region and information gathered from literature, specific criteria and indicators were selected to represent each of the three considered pillars of sustainability.

To account for the aspects of environmental sustainability, three criteria (individually described in Section 4.3.1) were selected to represent the broad concept of environmental sustainability in the evaluation:

- Certification potential according to EBC
- Negative emissions potential (tonnes CO_2-eqv)
- Biochar production potential (tonnes)

Looking at the aspects of economic sustainability, three criteria (individually described in section 4.3.2) were chosen to reflect the economical perspectives vital to consider for each feedstock in the evaluation:

- Potential to increase value retention in current system
- Cost per climate benefit (SEK/tonne negative CO_2-eqv)
- Calculated price compared with cost of alternative (SEK/tonne feedstock)

In order to account for the aspects of technical sustainability, three criteria (individually described in Section 4.3.3) were selected to indicate the technical difficulties coupled to the utilization of each fraction in the evaluation:

- Collection of feedstock
- Drying (feedstock moisture content in %)
- Pretreatment (storing, sorting and chipping)

Once the criteria for the MCA had been selected, the feedstocks were individually evaluated based on the results of the previously conducted two steps and information gathered on each respective feedstock. To evaluate the performance, the feedstocks were given a score between 1 (lowest) to 5 (highest), corresponding to colors as depicted in Figure 4.13, for each of the criteria.

Figure 4.13: Scoring system used in the multi-criteria analysis (MCA) with corresponding colors applied for each criteria from 1 (lowest score) to 5 (highest score).

Although all aspects regarded in the MCA are important for the development of biochar in the Gothenburg region, different criteria might still have varying importance for the overall sustainability of the system. Hence, in order to account for the importance of each criteria, a weighting system was integrated into the MCA.

A survey was sent to 18 professionals working within, or in close contact with, the field of biochar technology. The persons were asked to assign each criteria a percentage of importance which made all 9 criteria add up to a total sum of 100%. The 8 people responding the survey represented organisations within the academia, the City of Gothenburg, the waste management sector and the biochar industry. The average grading from the responding persons were distributed between the criteria according to Table 4.8.

Table 4.8: Weighting applied in the multi-criteria analysis (MCA) based on the average graded importance of each criteria derived from survey respondents.

Sustainability pillar	Criteria	Weighting
Environmental	Certification potential (EBC)	**18%**
	Negative emissions potential (tonne CO_2-eqv)	**22%**
	Biochar production potential (tonnes)	**8%**
Economical	Potential to increase value retention in current system	**11%**
	Cost per climate benefit (SEK/tonne negative CO_2-eqv)	**13%**
	Calculated price compared with cost of alternative (SEK/tonne feedstock)	**9%**
Technical	Collection of feedstock	**5%**
	Drying requirements (feedstock moisture content in %)	**6%**
	Pretreatment requirement (storing, sorting, size adjustment)	**8%**

When the score system had been established, the feedstocks were given a score between 1-5 for each criteria and was multiplied with the weighting percentage. The equation used to calculate the average score of each individual feedstock can be seen in Equation 4.1 where X is the 1-5 scoring for each criteria and Y is the weighting factor (in percent) for each criteria i:

$$\sum(Xi * Yi) = Average\ score \tag{4.1}$$

Hence, an average total score between 1-5 was calculated for each feedstock to evaluate the overall performance. The summarized results can be seen in Figure 4.27.

4.3.1 Environmental sustainability

In this section the criteria chosen to represent the environmental sustainability of each identified biomass feedstock will be explained and evaluated from an environmental perspective.

4.3.1.1 Certification potential EBC

One of the most essential criteria for evaluating feedstocks is the potential to certify the produced biochar according to the EBC. Used as a benchmark for what is considered as an environmentally sustainable production and usage of biochar, aligning with EU policies and regulation, EBC is the most widely accepted certification system i Europe. Since the certification covers a broad perspective on environmental sustainability, throughout the whole production chain, while still integrating both economic and technical aspects, it was regarded as one of the important criteria covered in the MCA. In order to determine potentials for each feedstock to be certified, the EBC's published "Positive list of permissible biomasses for the production of biochar" was used (Carbon Standards International & European Biochar Certificate, 2023) as a reference. To grade the criteria, the feedstocks were given a score according to the interval depicted in Table 4.9, reflecting the purity and application potential for the produced biochar. While grading, a score of five was considered for materials approved for all certification classes and the grading one was considered for materials not approved for any of the certification classes.

Table 4.9: The scoring interval used to grade EBC certification potential in the multi-criteria analysis (MCA), based on which different certification classes biochar derived from each feedstock is permissible for.

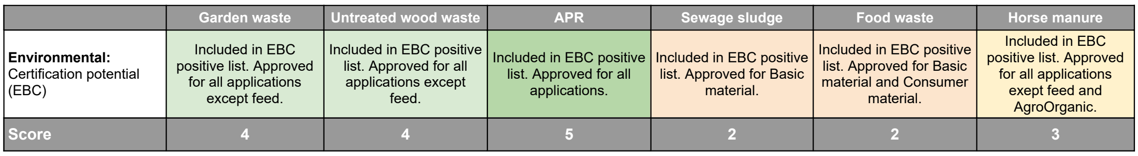
Score:	Defined intervals:
5	Permissible for all EBC certification classes
4	Permissible for: EBC-BasicMaterials EBC-ConsumerMaterial EBC-Urban EBC-Agro EBC-AgroOrganic
3	Permissible for: EBC-BasicMaterials EBC-ConsumerMaterial EBC-Urban EBC-Agro
2	Permissible for: EBC-BasicMaterial
1	Not permissible for any of the EBC certification classes

Looking at the grading for certification potential, depicted in Table 4.10, one can see that all the identified substrates are permissible for at least one certification class (Carbon Standards International & European Biochar Certificate, 2023). APR received the highest grading since the feedstock fulfill the requirement of all certification classes. Both wood-based biomass feedstocks, garden waste and untreated wood waste, are permissible for all certification classes except EBC-Feed and EBC-FeedPlus. In contrast to the more established feedstocks, food waste is only approved for EBC-BasicMaterials and EBC-ConsumerMaterials. Apart from modest certification potential, some fractions of the food waste might contain plastic contaminants which in larger quantities prohibits the certification potential. The remaining two substrates, sewage sludge and horse manure, were added to the EBC list of permissible biomasses in April 2023. According to the updated version of the permissible biomass list, horse manure is approved for all certification classes except EBC-Feed, EBC-FeedPlus and EBC-AgroOrganic. Sewage sludge, on the other hand, is only permissible for EBC-BasicMaterial and was thereby graded lowest accompanied by food waste.

Beyond the list of permissible biomasses, the updated EBC guidelines of April 2023 further included an extended Danish annex (Carbon Standards International, 2023). The Danish annex stated that an exception has been made for EBC-BasicMaterial classified biochar to be permissible in agricultural uses considering that requirements from specific Danish policies and regulations are met, levels of Polycyclic aromatic hydrocarbons (PAHs) in the biochar are compliant with EBC-Agro and that the biochar is labeled as specified in the annex.

The exception includes biochar derived from sewage sludge, digestates and food waste which could strengthen the demand for these types of biochar on the Danish market. Although, no such regulation is yet established in Sweden, the Danish initiative might create future incentives to develop a similar approach in Sweden or create opportunities for Swedish actors to enter the Danish market.

Table 4.10: Results for the criteria "certification potential" for each feedstock evaluated in the multi-criteria analysis (MCA). The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Environmental: Certification potential (EBC)	Included in EBC positive list. Approved for all applications except feed.	Included in EBC positive list. Approved for all applications except feed.	Included in EBC positive list. Approved for all applications.	Included in EBC positive list. Approved for Basic material.	Included in EBC positive list. Approved for Basic material and Consumer material.	Included in EBC positive list. Approved for all applications exept feed and AgroOrganic.
Score	4	4	5	2	2	3

4.3.1.2 Negative emission potential

One of the core environmental aspects to consider while evaluating a CDR-technology such as biochar is the negative emissions potential. The negative emissions potential, describes the yearly potential for each substrate to sequester carbon in terrestrial form. The potential was derived from considering the estimated biochar production potential and the theoretical carbon content in each type of biochar, giving a value of the total generated negative emissions depicted in Figure 4.14 measured in CO_2-eqv. However, the negative emission potential should not be confused with the total net-negative emissions generated from the process where probable emissions throughout the value chain are subtracted from the negative emission potential.

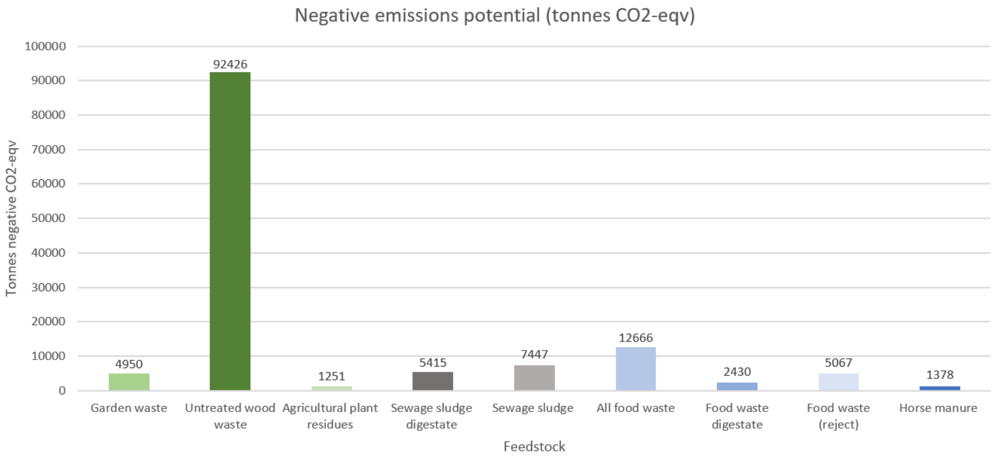


Figure 4.14: Overview of the calculated negative emission potential (tonnes CO_2-eqv) of each feedstock based on the fractions identified during the mapping in step 2.

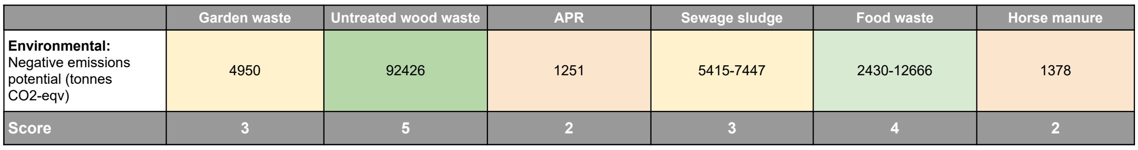
In order to evaluate the feedstocks based on negative emission potential, the substrates were graded in relation to the garden waste reference flow. The intervals used to score each feedstock in comparison to the garden waste reference flow based on the negative emission potential can be seen in Table 4.11.

Table 4.11: The scoring interval used to grade negative emission potential and biochar production potential in the multi-criteria analysis (MCA), in relation to the garden waste reference flow.

Score:	Defined intervals:
5	>300%
4	150 - 300%
3	50 - 150%
2	25 - 50%
1	<25%

The garden waste reference flow was thereby given the grading three as a base line for the negative emission potential, depicted in Table 4.12. As indicated from the results, the negative emission potential mainly regarded the relation between quantitative availability and carbon content in the produced biochar. Looking at the results for the high quantitative available feedstocks: untreated woods waste, food waste and sewage sludge, the potential differed based on the carbon content of the biochars. Untreated wood waste displayed the highest potential out of all the feedstocks with a negative emission potential of 92 426 tonnes CO_2-eqv, and was given the highest score. Since the potentials of food waste and sewage sludge were presented in ranges, depending on the internal fraction considered, the average potentials were assumed during the grading. Thereby food waste was graded slightly below the potential of untreated wood waste, showcasing a relatively high potential, and sewage sludge received a similar scoring as the reference flow. The low quantitative available feedstocks: APR and horse manure, both received lower grading accounting for merely 1251 tonnes CO_2-eqv and 1378 tonnes CO_2-eqv respectively.

Table 4.12: Results for the criteria "negative emissions potential" for each feedstock evaluated in the multi-criteria analysis (MCA). The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Environmental: Negative emissions potential (tonnes CO2-eqv)	4950	92426	1251	5415-7447	2430-12666	1378
Score	3	5	2	3	4	2

4.3.1.3 Biochar production potential

The biochar production potential is an indicator which describes the relation between local availability of dry matter, identified and quantified in Section 4.2, and the theoretical conversion rate for each feedstock. The indicator estimates the total amount of biochar product which each feedstock is capable of generating per year, if the entire identified biomass flow was to be pyrolized, as depicted in Figure 4.15. The amount of produced biochar influences both the total environmental benefits of applying the biochar and the economic potential. In this criteria, the biochar production potential was used as a simplified parameter to estimate the environmental benefits achieved during application, beyond carbon sequestration, considering effects from for example structural properties. When estimating the environmental benefits, it is vital to note that the composition differs between the biochars. Hence, depending on the composition, the biochars could generate different environmentally beneficial properties. Under the prerequisite that larger amounts of biochar produced and applied are preferable, the feedstocks were thereby graded in relation to the biochar production potential of the garden waste reference flow. To score the feedstocks in comparison to the garden waste reference flow, the same percentage based interval was used to estimate the biochar production potential as for negative emission potential, depicted in Figure 4.11.

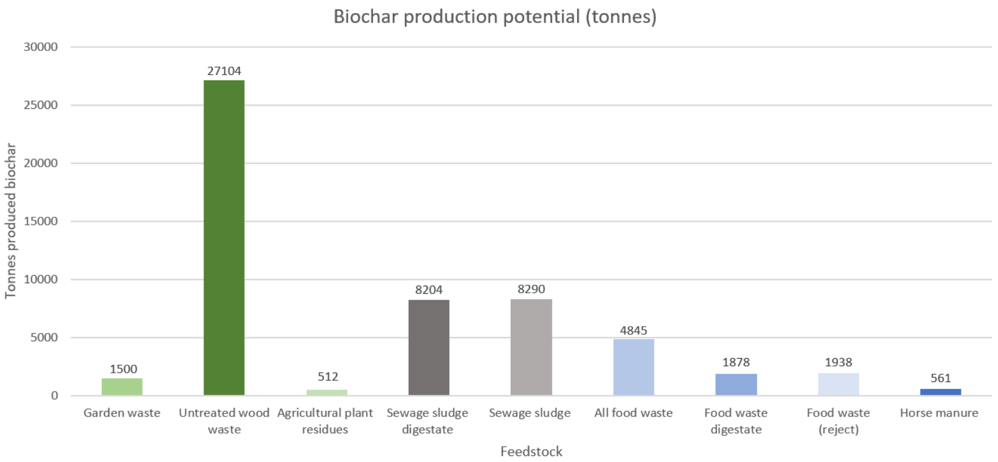


Figure 4.15: Overview of the calculated biochar production potential (in tonnes) of each feedstock, based on the fractions identified during the mapping in step 2.

Taking a look at the results from the grading of estimated biochar production potential, depicted in Table 4.13, the largest potentials were represented by untreated wood waste, sewage sludge and food waste. Although all three feedstock offers large potential, the characteristics of each biochar are quite different as indicated in Table 3.2 and 3.3. Since the potentials of food waste and sewage sludge were presented in ranges, depending on the internal fraction considered, the average potentials were assumed during the grading. The lowest graded feedstocks were APR and horse manure, which both offered relatively small potentials in the Gothenburg region. However, although the potentials of both APR and horse manure were relatively small, the substrates could be used as supplementary feedstocks in co-pyrolysis.

Table 4.13: Results for the criteria "biochar production potential" for each feedstock evaluated in the multi-criteria analysis (MCA). The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.

	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Environmental: Biochar production potential (tonnes)	1500	27104	512	8204-8290	1878-4845	561
Score	3	5	2	5	4	2

4.3.2 Economic sustainability

In this section the criteria chosen to represent the economic sustainability of each identified biomass feedstock will be explained and evaluated from an economic perspective.

4.3.2.1 Potential to increase value retention in current system

Considering the economic dimension of sustainability, it is important to account for the established systems and indications of development within them. As the EU has recognized the potential in bio-based material, committing to support the shift of the European economy towards a greater and more sustainable use of renewable resources, the competition for bio-based material has increased drastically (European Commission, 2023a). As part of the EU initiative to strive towards a bio-economy, cascading use of bio-based materials has been recognized as an important strategy to achieve efficient utilization (European Commission, 2021). The aim of cascading is to use biomass for the highest value application possible, where the different levels of values are often presented as a pyramid (Delahaye & Tunn, 2022). Presumed that cascading use is vital for a stable increase in sustainable utilization of bio-based material, opportunities to increase the value retention in the current system of each feedstock were explored. With regards to the value pyramid, the alternative treatments identified in the current systems were graded according to the application value of each generated product. Hence, each feedstock was graded based on the corresponding levels in the value pyramid, according to the scoring interval depicted in Table 4.14, where lower applications resulted in a higher grading and higher applications in lower grading to reflect the potential to increase value retention in the system by applying biochar production (Andersen et al., 2022).

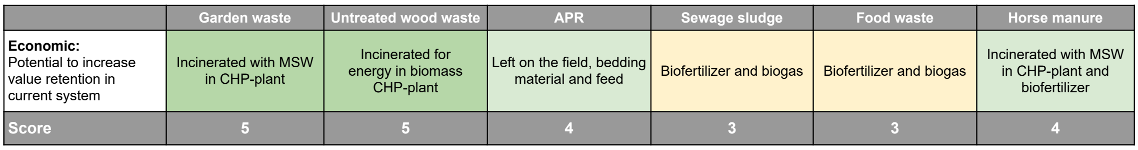
Table 4.14: The scoring interval used in the multi-criteria analysis (MCA) to grade the potential to increase value retention in current system. The criteria is based on the value pyramid from the field of circular economy, where a low-value utilization of a feedstock in current system result in a high score.

Score:	Defined intervals:
5	Energy recovery
4	Recovery in form of fuels
3	Recovery in form of chemicals and materials
2	Recovery in forms of food and feed
1	Recovery in form medicine and health promoting products

The results from the grading, depicted in Table 4.15, indicated a large potential to retain value in the garden waste and untreated wood waste fractions. Since the majority of both waste flows are incinerated in CHP-plants to recover energy, there is an opportunity to retain value in the material. Thereby, garden waste and wood waste were graded highest due to the low value application implemented in the current system. Graded slightly lower than the wood-based biomasses, are the APR and horse manure. Although some of the APR as left on the fields and some of the horse manure as incinerated, indicating a high potential to retain value, both systems also included high value applications such as feed, bedding material and biofertilizer production. Thereby both APR and animal manure were considered to have a lower potential than the wood-based biomasses and received a lower scoring. Food waste and sewage sludge were both systems which generated biogas and biofertilizers.

Therefore both sewage sludge and food waste were given a scoring of three, based on the hierarchy in the value pyramid where biofertilizers were considered as a material/chemical.

Table 4.15: Results for the criteria "potential to increase value retention in current system" for each feedstock evaluated in the multi-criteria analysis (MCA). The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Economic: Potential to increase value retention in current system	Incinerated with MSW in CHP-plant	Incinerated for energy in biomass CHP-plant	Left on the field, bedding material and feed	Biofertilizer and biogas	Biofertilizer and biogas	Incinerated with MSW in CHP-plant and biofertilizer
Score	5	5	4	3	3	4

4.3.2.2 Cost per climate benefit (SEK/tonne negative CO_2-eqv)

The relation between environmental and economic sustainability is complex where the economic interpretation of the environment has developed since the 1960's to account for environmental and resource economics, and later on ecological economics (Gómez-Baggethun et al., 2010). To relate the environmental benefits to the economical perspective of a technology, cost per climate benefit is often used as an indicator to develop cost-efficient strategies for climate change mitigation. The indicator can be compared to carbon pricing which is an instrument that expresses the external costs of GHG-emissions (The World Bank Group, 2023). Therefore, cost per climate benefit, measured in SEK/tonne negative CO_2-eqv, was calculated considering the estimated cost of a pyrolysis plant per negative emission potential of each feedstock, depicted in Figure 4.16. For the evaluation of the cost per climate benefit, the grading was based on a voluntary carbon removal price currently estimated to approximately 1000 SEK/tonne CO_2-eqv (Puro Earth, 2022). The feedstocks were then given a score according to the interval depicted in Table 4.16.

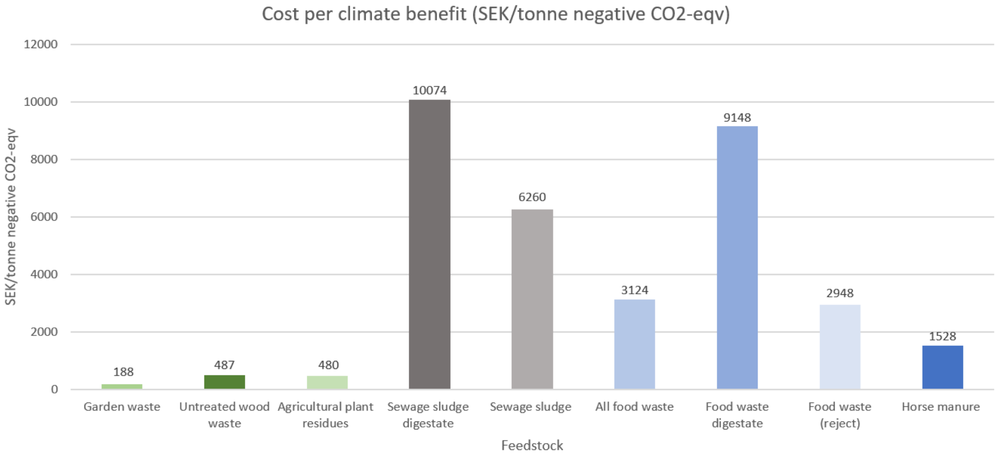


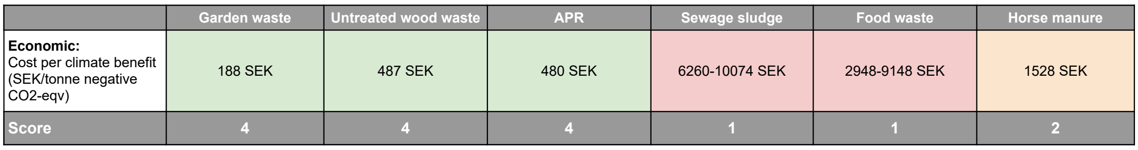
Figure 4.16: Overview of cost per climate benefit (in SEK/tonne negative CO_2-eqv) of each evaluated feedstock.

Table 4.16: The scoring interval used in the multi-criteria analysis (MCA) to grade the cost per climate benefit.

Score:	Defined intervals:
5	<0 (SEK/tonne negative CO_2-eqv)
4	0 - 500 (SEK/tonne negative CO_2-eqv)
3	500 - 1500 (SEK/tonne negative CO_2-eqv)
2	1500 - 3000 (SEK/tonne negative CO_2-eqv)
1	>3000 (SEK/tonne negative CO_2-eqv)

The results of the cost per climate benefit aspect can be seen in Table 4.17, showcasing that garden waste, untreated wood waste and APR were the currently most cost-efficient alternatives to sequester carbon. The evaluation further showed that horse manure was in the vicinity of being cost competitive, based on the current carbon removal price. The two lowest graded feedstocks were food waste and sewage sludge indicated to be relatively costly alternatives.

Table 4.17: Results for the criteria "cost per climate benefit" for each feedstock evaluated in the multi-criteria analysis (MCA), expressed as a cost in Swedish crowns per tonne negative CO_2-eqv. The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Economic: Cost per climate benefit (SEK/tonne negative CO2-eqv)	188 SEK	487 SEK	480 SEK	6260-10074 SEK	2948-9148 SEK	1528 SEK
Score	4	4	4	1	1	2

4.3.2.3 Calculated price compared with cost of alternative

The implementation of the biochar technology relies to a large extent on the existing infrastructure and the current utilization of the biomass flows. By estimating the economical feasibility of biochar production in comparison to the current utilization, the technique can be deemed favourable or unfavourable from an economic perspective.

To indicate the competitiveness of the biochar technology, the total profit or cost (from Table 3.6 and 3.7) was calculated by considering income from all three parameters (biochar, heat and carbon-sink) and costs for investments and operations, as depicted in Figure 4.17 . This price was converted to SEK/tonne feedstock and resulted in either positive or negative numbers depending on the feedstock characteristics. Hence, positive numbers represents the profit an actor can make by producing biochar out of one tonne feedstock. The profit for each feedstock was then compared with the profit generated by the dominant current utilization of that particular feedstock. In the case of untreated wood waste, the profit of making biochar of the substrate was compared with the price applicable when an actor sell wood chips to a biomass CHP-plant. The same procedure was applied to feedstocks generating a cost per feedstock, since these costs were able to be compared with the total costs of the current handling of the specific waste fraction. For the case of APR left on the fields, the cost was assumed to be zero.

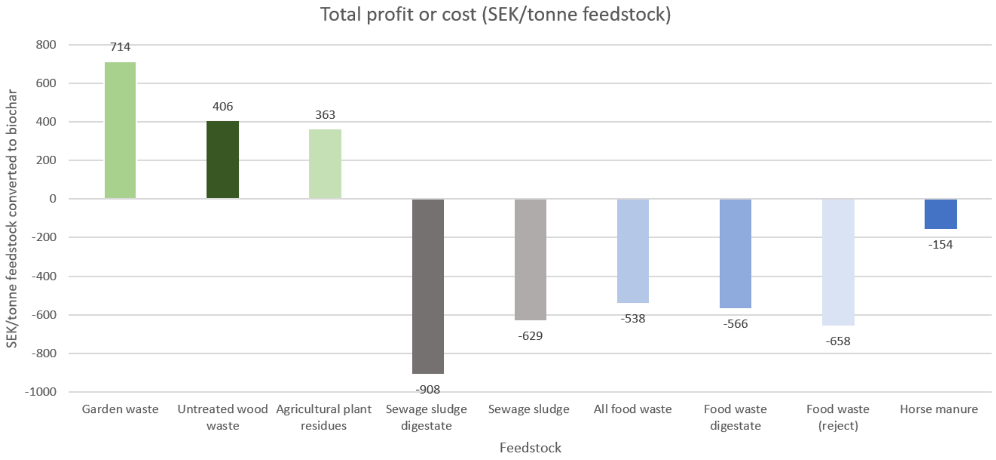


Figure 4.17: Overview of the total profit or cost (in SEK/tonne feedstock) of each evaluated substrate.

Unlike the criteria "Potential to increase value retention in current system", no cascading effects were accounted for in this criteria but only the economical price of the alternative treatment. While evaluating the substrates, the grading was conducted in relation to the current price of handling for each individual feedstock, displayed in Table 4.18. Since the identified waste flows of sewage sludge and food waste contains multiple fractions, one fraction each was chosen for the evaluation of this criteria.

For sewage sludge, the fraction following anaerobic digestion was chosen since it represents the current situation where an external company is paid to handle the sanitation process of the digestate. For the food waste, the fraction "All food waste" was chosen. The comparable cost in the current system was calculated using both the share of reject (30%) and the share of slurry (70%). Updated prices on slurry from food waste was difficult to collect and since both positive and negative prices occurred in the literature analyzed, the price of slurry was assumed to be zero (Fagerström, 2011) (Wennerberg, 2016). The cost of incinerating the reject fraction was obtained through the waste fees charged by waste management companies, which in this calculation was rounded to 1000 SEK/tonne (SYSAV, 2020). Weighting the share of slurry and reject results in an average cost of 300 SEK/tonne.

While grading the calculated price compared with cost of alternative, each feedstock was scored according to the interval depicted in Table 4.19.

Table 4.18: List of prices (per tonne) for the handling of each feedstock in current system. Negative numbers are the prices a holder of the feedstock must pay another part to handle the waste and positive numbers are the prices a holder of the feedstock can receive when selling the feedstock.

Feedstock	Present handling	Price
Garden waste	Renova currently charges a fee to handle garden waste from their customers	-309 SEK[1]
Untreated wood waste	Sold to biomass CHP-plants	292 SEK[2]
APR[5]	59% of APR is left on the fields	0 SEK
Sewage sludge	Gryaab pays an external company for handling the sewage sludge digestate	-500 SEK[3]
Food waste	Assuming the fraction "All food waste" where 70% is turned into a slurry for biogas production and 30% is incinerated as reject	-300 SEK
Horse manure	Riding schools pay external companies to collect their horse manure	-268 SEK[4]

[1] (Detterfelt et al., 2019)

[2] Calculating with 2 MWh/tonne wood chips. Using statistics from the Swedish Energy Agency for prices on recycled wood waste the fourth quarter of 2022 (Energimyndigheten, 2022)

[3] Estimated price includes storage and transportation (D. Lorick, personal communication, April 18, 2023)

[4] Average fee paid by the riding schools responding the survey conducted in step 2

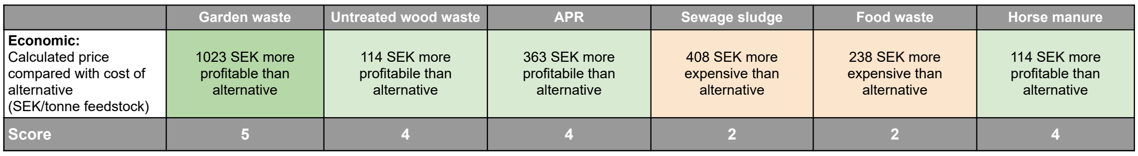
[5] Agricultural plant residues

Table 4.19: The scoring interval used in the multi-criteria analysis (MCA) to grade the calculated price of producing biochar of a feedstock compared with the price of current handling. The price of current handling is subtracted from the profit/cost calculated for biochar production, which results in the comparison price graded according the the intervals in the table.

Score:	Defined intervals:
5	>500 (SEK)
4	50 -500 (SEK)
3	(-50) - 50 (SEK)
2	(-500) - (-50) (SEK)
1	<(-500) (SEK)

The grading for Calculated price compared with cost of alternative can be seen in Table 4.20. Looking at the results one can see that for some of the feedstocks, the biochar production implementation is profitable compared to the current alternative while for others it is more expensive. The results indicated that biochar production of untreated wood waste, garden waste, APR and horse manure might be more profitable than the current utilization of the feedstock. However, for food waste and sewage sludge the process was seemingly more expensive than the current utilization.

Table 4.20: Results for the criteria "calculated price compared with cost of alternative" for each feedstock evaluated in the multi-criteria analysis (MCA). The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Economic: Calculated price compared with cost of alternative (SEK/tonne feedstock)	1023 SEK more profitable than alternative	114 SEK more profitabile than alternative	363 SEK more profitabile than alternative	408 SEK more expensive than alternative	238 SEK more expensive than alternative	114 SEK more profitable than alternative
Score	**5**	**4**	**4**	**2**	**2**	**4**

4.3.3 Technical sustainability

In this section the criteria chosen to represent the technical sustainability of each identified biomass feedstock will be explained and evaluated from a technical perspective.

4.3.3.1 Collection of feedstock

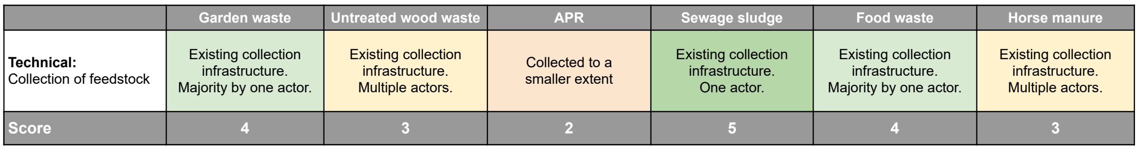
The development of biochar technology from a new feedstock can be facilitated if the feedstock is already collected. If collection also is centralized through one actor, the probability increases of finding an actor with a sufficiently large flow of feedstock to supply a biochar plant. To evaluate the collection of feedstocks, the grading was based on both the current collection infrastructure and the diversity of collecting actors identified during the mapping in step 2. The grading of this criteria was conducted from the perspective of an actor in possession of a large feedstock flow. From this perspective, centralization through one actor was assumed to be preferable since the identified feedstock flows are then located at the same place, and therefore each feedstock was scored according to the interval depicted in Table 4.21. However, one should note that such is not always the case since centralization through one actor could also be interpreted as a possible vulnerability in the supply system, relying on one single actor.

Table 4.21: The scoring interval used to grade the collection of feedstocks in current system, based on the prerequisite that centralized collection through one actor is desirable.

Score:	Defined intervals:
5	Collected by one actor
4	Majority collected by one actor
3	Collected by multiple actors
2	Collected to an extent
1	Not collected at all

In Table 4.22 the grading for the collection of feedstock criteria was summarized, corresponding to the current established collection system for each waste fraction. The results from the mapping conducted in step 2 indicated that a majority of APR were left on the fields after harvest, which for this criteria resulted in the lowest score out of all feedstocks. Both untreated wood waste and horse manure received a scoring of three since the fractions are collected by multiple actors. Garden waste and food waste received scores of four since the majority of the biomass was collected by one actor, while sewage sludge received the highest scoring since only one collecting actor could be identified.

Table 4.22: Results for the criteria "collection of feedstock" based on the existing infrastructure for each feedstock evaluated in the multi-criteria analysis (MCA). The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Technical: Collection of feedstock	Existing collection infrastructure. Majority by one actor.	Existing collection infrastructure. Multiple actors.	Collected to a smaller extent	Existing collection infrastructure. One actor.	Existing collection infrastructure. Majority by one actor.	Existing collection infrastructure. Multiple actors.
Score	4	3	2	5	4	3

4.3.3.2 Drying requirements

Another technical aspect to make the pyrolysis process work is the limitation of the moisture content in the feedstock. For functional purposes, the feedstock used in the pyrolysis process must be relatively dry, preferably below 20% moisture content (Xiong et al., 2013) (Lundvall & Hellsten, 2020). In cases where the moisture content is higher, worse operating conditions might be experienced and the vaporized moisture content could prohibit complete combustion of the pyrolysis gases contributing to the processing emissions. Depending on the characteristics of the pyrolysis gases released, synthesis gas and vaporized bio-oil, the climate benefits generated from the biochar production could potentially even be outweighed by the released emissions. Hence, if the moisture content is too high, it is necessary to dry the feedstock before pyrolysis which results in consequences for the logistics in the production chain. Moreover, a complex production chain impacts cost for investments and operations, and therefore it is good to be aware that the criteria to some extent also overlaps with the economic parameters. To evaluate the drying requirements, each feedstock were scored based on their moisture content, described in Table 3.2 and 3.3, according to the scoring interval depicted in Table 4.23.

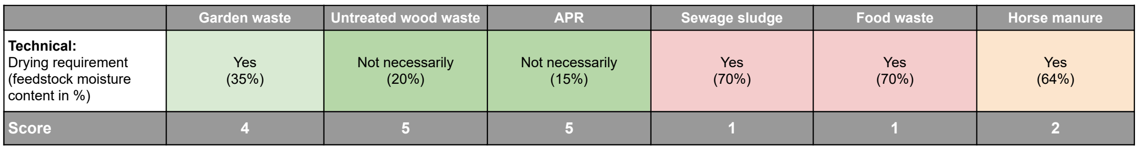
Table 4.23: The scoring interval used in the multi-criteria analysis (MCA) to grade the drying requirements.

Score:	Defined intervals:
5	<21% moisture content
4	21-35% moisture content
3	36-50% moisture content
2	50-65% moisture content
1	>65% moisture content

In Table 4.24 the grading according to the moisture content of each substrate depicts the large differences in drying requirements between the explored feedstocks. Untreated wood waste and APR received high scores since they were assumed to not require any drying. However, there can be circumstances when these feedstocks needs drying due to e.g., unsatisfactory storing conditions. Garden waste was considered to need some drying but due to the relatively low moisture content, surplus heat from the pyrolysis process or natural sun-drying were assumed to be sufficient drying methods. The other three feedstocks are wet and thus require drying before pyrolysis.

Three separate fractions of food waste with different moisture content were considered in the mapping conducted in step 2. The 70% moisture content in this criteria represents the fraction "All food waste".

Table 4.24: Results of the criteria "drying requirements" based on the moisture content of each feedstock. The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Technical: Drying requirement (feedstock moisture content in %)	Yes (35%)	Not necessarily (20%)	Not necessarily (15%)	Yes (70%)	Yes (70%)	Yes (64%)
Score	4	5	5	1	1	2

4.3.3.3 Pretreatment requirements (storing, sorting and size adjustment)

Since availability, contamination content and physical size of the different feedstock alternatives can differ, it is important to consider all pretreatment requirements for each individual feedstock. In order to get an overview of the pretreatments necessary for each feedstock: storing, sorting and size adjustment were considered. Depending on the pretreatment requirements, additional investments might be necessary to ensure a homogeneous and stable input for the process. Additional investments could have large effect on several dimensions of the overall feasibility of the system. Hence, the need for additional pretreatment could deteriorate the feasibility of utilizing the feedstock for biochar production. In order to evaluate the pretreatment requirements, each feedstock was given a score according to the interval depicted i Table 4.25 based on the quantity of pretreatements considered necessary.

Table 4.25: The scoring interval used in the multi-criteria analysis (MCA) to grade the pretreatment requirements.

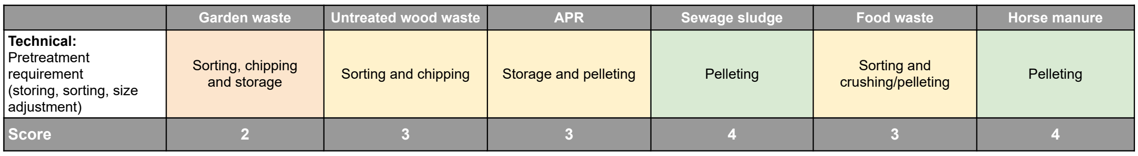
Score:	Defined intervals:
5	No pretreatment needed
4	One pretreatment needed
3	Two pretreatments needed
2	Three pretreatments needed
1	More than three pretreatments needed

The grading of pretreatment requirements for the substrates can be seen in Table 4.26, where one can note that almost all feedstocks need some form of pretreatment. Considering the need for storage, both garden waste and APR were recognized as possibly problematic due to the seasonal changes in biomass availability. Since both APR and garden waste have relatively low availability during the winter season, storage will be necessary if the biochar production plant is to be continuously running all year around.

In terms of sorting, both garden waste and untreated wood waste need to be sorted in order to filter out possible contaminants such as stones, soil or nails. Apart from untreated wood waste and garden waste, food waste was also considered to need additional sorting depending on what fraction of the food waste were to be utilized. In order to fulfill the requirements of EBC, stating that plastic contamination must in total not exceed 10%, especially the reject fraction might need additional sorting.

Beyond storing and sorting, all wood-based biomass were considered to need additional chipping to ensure a homogeneous size of the input. Since the pyrolysis process aims to fully carbonize the biomass, a homogeneous size on the input material make it easier to maintain stable processing conditions. In a similar fashion: APR, sewage sludge and horse manure were considered to possibly need pelleting to adjust the size of the material and to reduce dusting as the material is dried. Once again the food waste was specifically considered and depending on the utilized fraction: crushing or pelleting might be necessary.

Table 4.26: Results of the criteria "pretreatment requirements" for each feedstock in the multi-criteria analysis (MCA), with regards to storing, sorting and size adjustment. The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.



	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Technical: Pretreatment requirement (storing, sorting, size adjustment)	Sorting, chipping and storage	Sorting and chipping	Storage and pelleting	Pelleting	Sorting and crushing/pelleting	Pelleting
Score	2	3	3	4	3	4

4.3.4 Overview of MCA

Table 4.27: Overview of the results from the multi-criteria analysis (MCA), evaluating feedstocks for biochar production in the Gothenburg region with regards to environmental, economic and technical sustainability. The color of the boxes represent the score from 1 to 5 according to Figure 4.13. APR = agricultural plant residues.

Criteria	Garden waste	Untreated wood waste	APR	Sewage sludge	Food waste	Horse manure
Environmental: Certification potential (EBC)	Included in EBC positive list. Approved for all applications except feed.	Included in EBC positive list. Approved for all applications except feed.	Included in EBC positive list. Approved for all applications.	Included in EBC positive list. Approved for Basic material.	Included in EBC positive list. Approved for Basic material and Consumer material.	Included in EBC positive list. Approved for all applications exept feed and AgroOrganic.
Environmental: Negative emissions potential (tonnes CO2-eqv)	4950	92426	1251	5415-7447	2430-12666	1378
Environmental: Biochar production potential (tonnes)	1500	27104	512	8204-8290	1878-4845	561
Economic: Potential to increase value retention in current system	Incinerated with MSW in CHP-plant	Incinerated for energy in biomass CHP-plant	Left on the field, bedding material and feed	Biofertilizer and biogas	Biofertilizer and biogas	Incinerated with MSW in CHP-plant and biofertilizer
Economic: Cost per climate benefit (SEK/tonne negative CO2-eqv)	188 SEK	487 SEK	480 SEK	6260-10074 SEK	2948-9148 SEK	1528 SEK
Economic: Calculated price compared with cost of alternative (SEK/tonne feedstock)	1023 SEK more profitable than alternative	114 SEK more profitabile than alternative	363 SEK more profitabile than alternative	408 SEK more expensive than alternative	238 SEK more expensive than alternative	114 SEK more profitable than alternative
Technical: Collection of feedstock	Existing collection infrastructure. Majority by one actor.	Existing collection infrastructure. Multiple actors.	Collected to a smaller extent	Existing collection infrastructure. One actor.	Existing collection infrastructure. Majority by one actor.	Existing collection infrastructure. Multiple actors.
Technical: Drying requirement (feedstock moisture content in %)	Yes (35%)	Not necessarily (20%)	Not necessarily (15%)	Yes (70%)	Yes (70%)	Yes (64%)
Technical: Pretreatment requirement (storing, sorting, size adjustment)	Sorting, chipping and storage	Sorting and chipping	Storage and pelleting	Pelleting	Sorting and crushing/pelleting	Pelleting
Avg weighted score	**3.74**	**4.34**	**3.46**	**2.69**	**2.7**	**2.79**

The summarized result of the MCA can be seen in Table 4.27, with the average weighted score visible at the bottom line and depicted in Figure 4.18. Untreated wood waste received the highest total score with 4 or 5 in all criteria except the collection of feedstock and pretreatment requirements, where it scored 3. The feedstock is superior to the other feedstocks when considering the total available mass, which is directly linked to the potential of producing biochar and generating negative emissions.

Garden waste received the second highest total score and was strongest in the aspect of profitability. Another benefit with this feedstock is that it is not well utilized in current system, since a majority of the biomass is incinerated together with MSW. One drawback with garden waste is the requirements on sorting, chipping, storing and drying.

APR is a common feedstock in biochar production and scored high in many aspects. However, in the context of a city, the availability of feedstock is the limiting factor which affects the scaling potential of biochar production and negative emissions.

Horse manure, sewage sludge and food waste are found at lower total scores in the summarized result. The strengths with sewage sludge and food waste are the large amounts of raw material available with few actors, while the negative aspects are associated with the substrates' high moisture content and lower EBC-cerfitication classes which affects the profitability. Horse manure on the other hand, received a better total score than sewage sludge and food waste but is affected by low amounts of available feedstock.

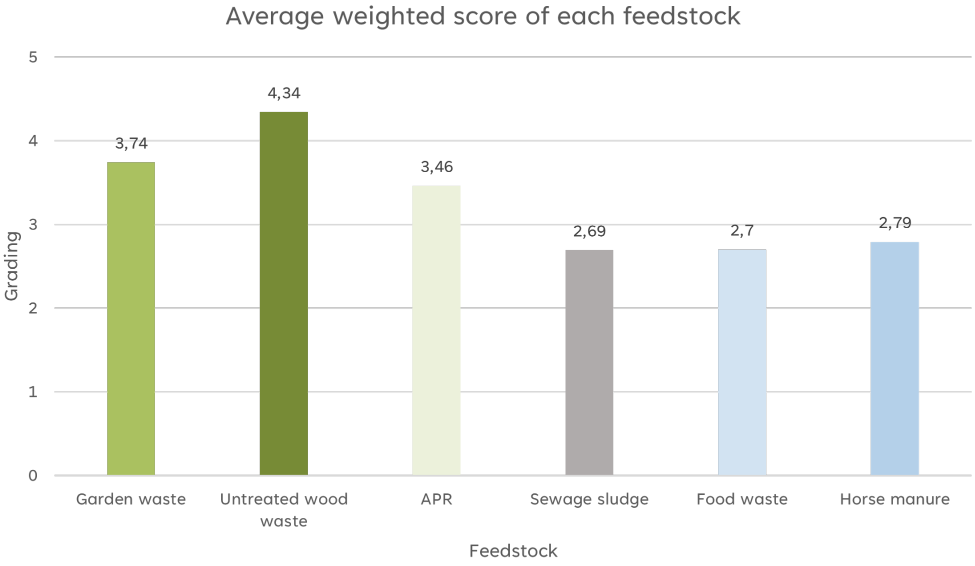


Figure 4.18: Summary of the average weighted score of each evaluated feedstock for biochar production in Gothenburg concluded in the multi-criteria analysis (MCA). The evaluation was based on nine criteria representing environmental, economic and technical sustainability aspects and were graded between 1 and 5. APR = agricultural plant residues.

5

Discussion

The aim of this thesis was to explore future potentials for sustainable biochar production in Gothenburg, utilizing locally sourced feedstocks from the Gothenburg region and contributing to the city's sustainability targets. The aim indicated that the entry point of this thesis was to view an upscaled biochar technology in Gothenburg as desirable, contributing to the city's sustainability targets. Therefore, in Section 5.1 the discussion is oriented around particular aspects of the results and limitations of this thesis. Section 5.2 provides a discussion around the biochar technology in the broader perspective by comparing biochar technology with other CDR-technologies.

5.1 Discussion of results and limitations

Aiming at fulfilling the aim of this thesis and answering the research question, three objectives were formulated that each was assigned a dedicated step in the structure of this report. The approach for addressing the first objective, "Define important aspects of sustainability for biochar", was to identify relevant criteria coupled to the four sustainability pillars: Environmental, Social, Economic and Technical. The perspectives on the sustainability aspects that were collected from the actors during interviews showed a great diversity in terms of which aspects of sustainability each actor highlighted. This was also clearly revealed by the diverse survey responses that were collected for the weighting system applied in the evaluation phase. Despite the fact that perspectives from different business sectors were collected, one should be aware of the fact that the limited selection of people providing their opinions on the sustainability aspects of the biochar technology has an impact on the results of the thesis. The social sustainability should also be considered in any future studies on upscaled biochar production in Gothenburg, that was not possible to include in this report due to time constrains.

For the second objective, "Map out biomass flows within the Gothenburg region that might be utilized for biochar production", only the largest identified fractions were considered. Based on results generated from the implementation of the Top-down approach for waste intensity per sector, indications showcased a gap between the estimated amount of waste produced and the identified biomass availability derived from actor communication. Although the difference in identified biomass availability is partly coupled to the uncertainty of the method, it further indicates that the mapping might not be entirely complete. Apart from the biomass flows evaluated in this study, some additional flows were discussed without being included in the mapping. Among these, blue biomass is one substrate which could have a potential in coastal cities like Gothenburg, where amounts of sea weed washed ashore might be utilized for biochar production. There might also be additional benefits with blue biomass in eutrophicated water bodies that might be benefited by having nutrient rich sea weed or reed removed from the area. Another feedstock discussed with the possibility of providing additional benefits is invasive plant species, which in today's handling is associated with expensive waste management procedures to avoid the spreading of the plants. Several stakeholders have in interviews mentioned the idea of growing hemp dedicated for biochar production. However, since the scope of this thesis is limited to waste fractions, hemp was not further considered.

When considering the flows of sewage sludge and food waste, several sub-flows were considered. The largest potential for biochar is to consider the entire flows, without anaerobic digestion. However, since the systems currently are designed to produce biogas, which also provides a higher overall energy efficiency in the system, a more feasible first step might be to consider the fractions of digestate following anaerobic digestion. In terms of increased utilization potential, the reject fraction of food waste was early in the process identified as a low-hanging fruit due to the quite large amount of biomass being incinerated when sorted out together with plastics and other impurities. However, when estimating the share of impurities in the reject, it is expected to approach the 10% limit of the lower EBC-certification class applicable for basic material. The latest version of the EBC-guidelines opens up for the certification of deliberately mixed feedstock containing fossil carbon which might enable a solution involving mixing the reject fraction with another substrate not containing fossil carbon. On the other hand, it was assumed that the reject fraction of food waste in Gothenburg might decrease since other Swedish cities report 10% reject fractions compared to the 30% reject fraction in Gothenburg (SEVAB, 2019). Hence, a smaller reject fraction will contain an even larger share of fossil carbon which might hinder this solution.

The third objective in this thesis was to "Evaluate identified feedstocks based on a set of predefined criteria coupled to the sustainability aspects". In the quantitative evaluation, single values was used, instead of intervals, to estimate values for e.g., carbon content, moisture content, biochar potential and negative emissions potential. This can be viewed as a limitation in this thesis, but it's also important to highlight the possibilities associated with this flexibility of deliberately adjusting parameters in the biochar production process to prioritize different aspects. Processing conditions (temperature, residence time, heating rate and pressure) are parameters that affects the carbon content and yield of the biochar. However, to determine the characteristics of the different types of biochar, in this report, only pyrolysis temperature was considered although all processing conditions were recognized to have an effect on the biochar characteristics. The results of the evaluation should therefore be seen as flexible estimations that can be affected by user preferences.

Another area providing factors for user preferences are the technical aspects of how the biochar production system should be implemented. The estimated potentials calculated in the evaluation phase do not consider specific prerequisites such as the location within the city, transportation, size of pyrolysis equipment and drying logistics, even if a general categorisation of pretreatment prerequisites and collection system is included in the evaluation of each feedstock. One aspect highlighted in interviews with stakeholders was the importance of a uniform operation throughout the year to maximize the utilisation and economic performance. Difficulties in utilizing the surplus heat in the summertime and handling irregular flows of feedstock throughout the year are two key parts in this aspect which needs to be addressed. Maximizing drying during summertime is one possibility to enhance the efficiency of the system. Related to a uniform operation is also pretreatments of the feedstock which can facilitate a smooth operation and minimize downtime for repair and maintenance. Specifically the risk of dust explosions have been highlighted in interviews as one concrete reason for pelleting a feedstock before pyrolysis. Also, a larger size of pyrolysis equipment is reported to increase the risk of dust explosions. Other technical aspects to consider in a specific case of implementing a biochar production facility is related to the placement in the city, as the supply of extinguishing water for accidents, water purification, transports, synergy potential with other industries and connection to district heating system.

Besides the potential increased risk of dust explosions mentioned above, the main advantage of a large scale biochar production is naturally that economies of scale can provide better conditions for profitability. The economic evaluation in this thesis was based on the planned facility for biochar made from garden waste, with an linear scaling applied for different feedstocks. It can however be reasonable to assume that a larger amount of available feedstock can lead to decreasing costs per tonne biochar produced. Additionally, investment support from the Climate Leap initiative has not been included in this evaluation and could improve the economical prerequisites even more. Another limitation is that the costs of biochar production from different feedstocks likely will be more diversified than what has been depicted in this thesis. Biochar made of sewage sludge is one example of this, where the investment cost estimated by a contacted stakeholder was substantially higher per tonne feedstock than the cost used in the evaluation. The higher estimate on investment cost however, was based on a small testbed example and was therefore deemed not representative for the larger utilization evaluated in this thesis.

Apart from the diversification of costs for biochar made of different feedstocks, it is also reasonably to assume a diversification in market prices for biochar generated from different feedstocks reflecting the varying characteristics. Diversified prices have been applied in the evaluation, but considering the small market for biochar in Sweden, including a large share of imported biochar, market prices are sensitive and might quickly be affected by factors such as the expansion of biochar production in Sweden and other countries, development of regulations and certification systems, competitiveness of other utilization of biomass and development of biochar applications. One stakeholder estimated that prices of biochar in Sweden could decrease with up to 50%, depending on the effect that new installations of biochar production facilities could have on the market.

5.2 Uncertainties of the biochar technology

Looking at the biochar technology from a broader perspective, the perception of the technology as a whole is still very fragmented. The fragmented perception was further displayed by the weighting survey conducted in step 3 of the thesis, where survey responses indicated that many actors tend to focus on one of the three dimensions of sustainability covered in this report. Although the diversity of generated products from biochar production is often highlighted as a strength, there are indications, from surveys and interviews in the study, showcasing an uncertainty regarding how the fragmented perceptions might fit into a common symbiotic solution.

There are certification systems which aim to build a common framework for the technology, but there are still practical and theoretical uncertainties coupled to the implementation of the technology. Since the overall benefits generated from the biochar are highly dependent on the application, EBC has tried to implement certification classes to ensure certain areas of use. However, although the inclusion of certification classes aims to reflect the quality and property variations in different types of biochar, the practical response from the implementation is still too novel to evaluate. Some actors have expressed concerns regarding how the differences in quality and propriety of the biochar will practically be reflected on the market.

Although the certification classes specifies the intended application, the system has previously only been considered from a cradle to gate approach. The cradle to gate approach meant that certified producers had to label the biochar product according to indented application, but there was no regulatory control checking whether the biochar was actually applied or not. For the applications of biochar in soil, the carbon-sink is generated when the biochar is applied whereas previously the producer could account the benefits of the potentially generated carbon-sink once the product had been sold. In response to the cradle to gate approach, EBC have started to investigate how a cradle to grave approach could be facilitated instead. The cradle to grave approach would imply that the carbon-sink could only be accounted for once the biochar has been applied according to the intended application. However, there are still uncertainties regarding how the final application could be assured and to whom the carbon-sink should be assigned. Many view the biochar technology as a mean to mitigate climate change but as experienced by the early adaptations, biochar and the potentially generated carbon-sink are two very different products. The question of whom the carbon-sink belongs to are more simple for adaptations where there is only one actor both producing and applying the char. In cases where the producer and user are two different actors on the other hand, several constellations can be explored. As of today, there are no standards for whom the carbon-sink should belong to but is assigned according to the agreement between producer and user. Thereby, in cases where the carbon-sink is considered a desired product for the producer, the price of the biochar might be lower. While in cases where the carbon-sink is assigned to the user, the price of the biochar might be higher.

In terms of the carbon-sink generated from the biochar, there are as of yet no accounting for the benefits generated for other element cycles such as for nitrogen or phosphorus. At the same time, the environmental requirements are continuously extend. For future certification requirements, regulations covering per- and polyfluorinated substances (PFAS), PAH and microplastics are projected to become more relevant as the EU environmental requirements becomes more extensive. Especially for soil application, regulations covering PFAS are becoming more relevant and Denmark has already introduced benchmark requirements to regulate PFAS contamination, although no such requirements has been introduced in Sweden as of yet.

As covered in the report, the main process for producing biochar is pyrolysis which is a thermochemical process. As a thermochemical process, biochar production is often coupled to the potential to produce surplus heat which could be used in a district heating system or be converted to electricity. In the past, the biochar itself was often considered as an energy carrier which could be used as fuel to retain energy. However, in recent years, the definition of biochar has diverted from the concept of utilizing biochar as an energy carrier, emphasizing the difference between biochar and the energy oriented counterpart biocarbon. Hence, even though biochar was mainly accounted for in this thesis, utilizing the biochar as biocarbon is an alternative which could generate offset effects, avoiding emissions from fossil fuels, although the use of biocarbon would not generate a carbon-sink.

The energy aspect of biochar has been especially important in recent years as the world has experienced an energy crisis while the electrification of society is becoming more essential. The ability to produce surplus energy aligns with several of the city's environmental targets, focusing on electrification of the transport sector while maintaining the city's growing total energy demand. It is estimated that about 30% of the city's total energy consumption from district heating is currently supplied from the oil refineries located in the Gothenburg area. However, Gothenburg city has expressed a desire to find a viable alternative solution to decrease its reliance on fossil fuels and is therefore keen to look for bio-based options. The biochar technology could contribute with an offset effect on the local district heating system but many are sceptical towards its competitiveness in comparison to incineration regarding energy production. In a similar fashion, trends are showing an increased interest in biogas as an alternative to fossil fuels in the heavy transport sector. Both bio-based energy and biogas are products which often shares the same potential feedstocks as biochar production. Hence, depending on future development within these sectors, uncertainties regarding the competition could act as a barrier for the development of the biochar technology.

Another aspect to consider for the future development of the biochar technology is where it should be applied and by whom. Although this report has mainly discussed the implementation of a biochar production plant in a city setting, the technology is available at different scales. In theory it could be implemented by farmers, municipalities, cities, industrial companies or even by private persons. Most of the biochar production plants built today are either small scale farm implementations or larger public projects. There are however examples where industries have adopted the technology, mainly as a mean to offset the use of fossil fuels and reduce their overall climate footprint. One such industry is the construction sector where biochar has been recognized as an opportunistic solution to reduce the climate footprint. In many regards, the availability of biomass and localization of users are often a limiting factor for where a biochar production plant is feasible to build. Some producing companies have therefore explored the possibility of building mobile biochar production plants, which could add flexibility to the system and reduce the risks coupled to locational uncertainties.

Apart from investors, there are many indications suggesting novelty among the pyrolysis plant producers. There is a wide range of producers in the business but many of the producers only have a handful of built reference plants which are proven to work. From the interviews conducted during the thesis, some actors expressed the perspective that many of the producers gives the impression of being start-up companies while others mainly highlighted the long delivery time as problematic. Derived from personal communication, producers delivery time could currently be up to two years due to recent increases in steel prices and shortage of components which could prove problematic for a fast changing market adding to the uncertainties surrounding the technology. An alternative to newly produced pyrolysis plants could therefore be to retrofit existing plants, by rebuilding them to fit the intended application. Retrofitting has recently been highlighted as a viable alternative to reduce the investment cost and reduce the delivery time. Another option could further be to install a smaller pyrolysis plant and run it parallel to a larger biomass CHP plant, as done in some Swedish implementations. The biochar production plant could then be utilized during the summer when energy demand is lower to produce both energy and biochar. However, such implementation are mainly viable for homogeneous feedstocks and the discontinuous use of the pyrolysis plant could have negative effect on technical and economical aspects.

Since the climate benefit generated from the biochar technology is often highlighted as one of the most essential properties, comparison with other CDR-technologies are further relevant. There are several potential CDR processing technologies which could contribute towards the mitigation of climate change such as: CCS, direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS). Accompanied by biochar, CCS is specifically mentioned in Gothenburg's energy plan investigating the potential to implement the CCS technology in the Gothenburg area.

To give a short comparison between biochar and BECSS, it is recognized that both technologies have the potential to generate negative emissions. Derived from the generated CDR potential stated in Gothenburg's energy plan the biochar and BECCS potential were estimated to be between 4500-8500 and 320 000-400 000 tonnes of annual negative emissions respectively. Although the negative emission potential for biochar, identified and estimated in this report amounting to about 114 000 tonnes CO_2-eqv, is considerably higher, BECCS is still estimated to generate a higher negative emission potential. The difference in negative emission potential could however be explained since BECCS is considered to capture all biogenic CO_2 emissions from a specific point source, while biochar are considered to emit about 50% of the carbon input from combustion of synthesis gas and bio-oil. In response, actors often highlight that technologies like CCS and DAC, in terms of carbon storage, often are thermodynamically inferior to biochar since they focus on storing the whole CO_2 molecule while biochar mainly stores carbon atoms.

Besides the negative emission potential, actors are often keen to highlight that biochar is a production technology, generating several desirable products, whereas CCS technologies are an extension for emission reduction of already established infrastructure. Regarding energy production, biochar is often depicted as an alternative generating smaller amounts of energy compared to the energy oriented incineration with CCS combination. However, energy consumption and processing conditions necessary to implement CCS in combination with incineration, deteriorating the energy output, is not always accounted for. Neither is the drawbacks connected to infrastructure and transportation of the captured CO_2 required for a functional CCS system. Therefore biochar might still prove beneficial offering a more flexible storing system.

Considering all CDR-technologies, novelty is a common denominator adding to the list of uncertainties. As indicated from the study, biochar has a large potential to contribute with several beneficial properties, but the uncertainties coupled to the technology still induces hesitation. Due to the novelty of all CDR-technologies, it is hard to determine an optimal solution. Meanwhile the uncertainties coupled to the time perspective remains, as many points out a need for development and immediate action.

6

Conclusion

This thesis aimed to explore future potentials for sustainable biochar production in Gothenburg, and thus contribute to the city's sustainability targets. The aim was addressed by mapping locally scoured feedstocks and evaluation their potential from a sustainability perspective.

From the mapping of feedstocks, the identified amounts of the locally sourced feedstocks garden waste, untreated wood waste, APR, sewage sludge, food waste and horse manure resulted in a maximum potential of approximately 240 000 tonnes/year. If all identified feedstocks were to be pyrolized, the annual biochar production would reach approximately 41 000 tonnes, generate around 114 000 tonnes of negative CO_2-eqv/year and provide approximately 164 GWh of surplus heat. In relation to the planned biochar plant for garden waste in Gothenburg, with the feedstock capacity of 10 000 tonnes/year, it is apparent that there is a large potential for enhanced biochar production from utilizing additional waste flows within the city region.

The largest fraction identified in the mapping of feedstocks was untreated wood waste, which stood for almost half of the total identified available biomass amounting to approximately 117 000 tonnes/year. Apart from untreated wood waste, the mapping further displayed sewage sludge and food waste as two large biomass flows, amounting to approximately 62 000 and 50 000 tonnes/year respectively. APR and horse manure represented the smallest fractions in the mapping, amounting to 1791 and 4723 tonnes/year respectively.

The MCA was conducted to account for both quantitative and qualitative criteria coupled to the aspects on environmental, economical and technical sustainability. The evaluation estimated the feedstocks' performance in biochar production, which were weighted in accordance to survey responses from stakeholders and experts in the business. Based on the MCA results, untreated wood waste was appointed a clear winner with an average weighted score of 4.34 out of 5 possible. Untreated wood waste is a relatively pure and homogeneous substrate, resulting in a highly applicable feedstock with a high potential for achieving a sustainable biochar production in the Gothenburg region. The reference flow, garden waste, and APR both received a slightly lower average weighted scoring of 3.74 and 3.46 respectively. In contrast to the more established feedstocks, the alternative feedstocks sewage sludge, food waste and horse manure, received lower scoring. Horse manure was awarded an average weighted score of 2.79 despite its relatively low grading for the two highest weighted criteria, negative emissions potential and certification possibility. Meanwhile, sewage sludge and food waste received a scoring of 2.69 and 2.7 respectively, characterized by high moisture contents, low certification possibilities and high costs.

Although the results indicate the potential of each feedstock in the Gothenburg region, the open-ended conclusion may still provide a knowledge-base with multiple possible pathways for the development of biochar production. Relating back to the backcasting methodology applied in this thesis, the last step of the methodology represents the transformation of identified leverage points into concrete actions for implementation strategies. Even if some strategies are suggested in Section 6.1 below, strategies developed by multiple collaborating stakeholders could potentially increase the probability of finding solutions aligned with the actors' own perspectives on sustainability and lead to an industrial symbiosis with multiple common benefits.

6.1 Recommendations

Based on the generated results from the mapping and the MCA evaluation of feedstocks, untreated wood waste presented the largest utilization potential for sustainable biochar production in the Gothenburg area. Therefore, untreated wood waste from locally sourced waste flows could present an opportunity as a bulk substrate for future enhanced sustainable production of biochar. However, from the mapping, the main current application for the substrate was identified as incineration with energy recovery. Depending on the development of biogenic energy production demand in the city, an increased demand could effect the availability. Hence the recommendation, based on the results from this study, is to allocate a fraction of the total identified untreated wood waste for biochar production, to be utilized as a bulk substrate with a potential for co-pyrolysis. With regards to the uncertainty coupled to the development of the energy production demand from biomass CHP-plants, co-pyrolysis could present a flexible option for fluctuations in availability. The implementation of running a biochar plant parallel to a biomass CHP-plant, utilizing untreated wood waste, was also regarded as a possibly viable alternative but could entail technical difficulties if the pyrolysis plant is not used continuously.

Besides untreated wood waste, garden waste was identified as a possible bulk substrate for sustainable biochar production in the Gothenburg region. As a wood-based biomass feedstock, garden waste was recognized to share some of the benefit properties of the untreated wood waste. Although the study was conducted to display the potential of each feedstock in the Gothenburg region, which entails that mass availability has a large influence over the overall potential, APR were recognized to have a relatively large potential for sustainable biochar production. Since the APR presented a low identified availability, it was instead considered as a possible co-pyrolysis substrate. The recommendations is therefore to utilize the APR as a supplementary feedstock to be co-pyrolyzed with the bulk substrates of either garden waste or untreated wood waste. An implementation of co-pyrolysis of garden waste and APR could however possibly be problematic due to the seasonal availability of both feedstocks. The collection and alternative utilization of APR could also be potentially problematic, depending on the actors willingness to utilize the feedstock for alternative purposes since there is no guarantee that the biochar produced in an urban setting will be returned specifically to agricultural soil.

Another alternative for a supplementary feedstock for co-pyrolysis is horse manure. In contrast to APR, horse manure availability is not as seasonally dependent which could make it more suitable for co-pyrolysis with garden waste. Although horse manure received a lower scoring compared to APR, in this study, characteristics of the biochar itself could be improved by mixing the horse manure feedstock with bulk substrates. Horse manure also presents an opportunity as the current waste management system is perceived as expensive by many actors. The substrate offers less utilization options than APR in the Gothenburg region which enhances the chances of an alternative treatment process to be prevalent. Therefore the recommendations is to utilize the horse manure as a supplementary feedstock in co-pyrolysis, with the potential for co-pyrolysis with both garden waste and untreated wood waste.

Based on indications from the study estimations, food waste was perceived as a relatively expensive alternative. Although the substrate has the availability potential of being utilized as a bulk feedstock, it includes several drawbacks in comparison to the wood-based alternatives. The current utilization of the waste flow could further diminish the advantages of utilizing the feedstock for biochar production, as both biogas and biofertilizer are considered desirable products which could generate negative feedback effects if the food waste was used for alternative processing. Therefore, the recommendation is to mainly oversee the potential to utilize the reject fraction for biochar production. The reject fraction offers a substantial availability but due to the contamination content, the substrate might only be permissible as a supplementary feedstock.

Sewage sludge shared many of the food waste characteristics but also presented several opportunities for biochar production. Much like the food waste, biogas and biofertilizer are produced from the waste flow in the current system. However, in contrast to the food waste, biofertilizer produced from sewage sludge has been a debated topic where its use has been banned in some parts of Europe. It should further be noted that not all of the sludge are permissible for fertilizer production according to the REVAQ-certification limits. Hence, the recommendation is to utilize sewage sludge as a bulk substrate for biochar production with the purpose of sanitizing and retain value in the generated sludge. Although the treatment process is rather expensive, it might still be a viable alternative to incineration and further opportunities could arise if sewage sludge based biofertilizers were to be banned in the future. However, if such a ban was to be established in Sweden, it is recognized that the choice between alternative treatments might be highly influenced by the choices made in parts of Europe where such a ban has already been established.

Apart from feedstock choices, the report has discussed and explored options in terms of equipment and manufacturers. The identified quantitative availability of biomass feedstocks in the urban setting of the Gothenburg region were regarded as enough to power either many small pyrolysis plants or larger implementations. However, interviews with actors indicated that larger pyrolysis plant implementations could potentially be problematic both in terms of safety and technical viability. Some actors highlighted that there are few manufacturers which would commit to larger projects due to the lack of reference plants, financial capacity or technical expertise on such implementations. Therefore, the recommendation is to focus on more established small scale pyrolysis plants. Using multiple small scale pyrolysis plants could enable a larger flexibility in terms of feedstock choices and certification potential since each plant would be regarded as an individual system. One suggestion could then be to explore a solution where pyrolysis plants could be implemented in symbiosis in one area. Gathering the plants on one collective site could then potentially simplify the optimization of surrounding infrastructure such as having a collective extinguishing water source, connection to the district heating system, drop off/storage for the biomass feedstock and administration.

6.2 Recommendations for further studies

- The recommended solution to co-pyrolyze different feedstocks requires further studies in order to ensure a homogeneous mix of feedstocks and optimal processing conditions.

- The thesis has generally discussed and explored options for choices of manufacturers and equipment. However, an in-depth mapping of potential manufacturers and exploration of equipment choices, covering aspects such as scaling, market prices, delivery time and technical options, would need further considering.

- This thesis has collected information on available mass of feedstocks either through a few actors or through top-down estimations. For the planning and implementation of biochar production, additional bottom-up studies might be needed for each considered feedstock flow in order to map out all important actors within the current system.

- For element cycles, the C-cycle has been given the most attention in this thesis. However, further studies on the N-cycle and P-cycle might be needed if a new feedstock is considered for biochar production. This is especially important if sewage sludge and horse manure is to be considered for biochar production.

Bibliography

Ågren, G. I., & Bosatta, E. (1998, July 13). *Theoretical ecosystem ecology: Understanding element cycles*. Cambridge University Press.

Amalina, F., Razak, A. S. A., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications – a review. *Journal of Hazardous Materials Advances*, *7*, 100134. https://doi.org/10.1016/j.hazadv.2022.100134

Amalina, F., Syukor Abd Razak, A., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Advanced techniques in the production of biochar from lignocellulosic biomass and environmental applications. *Cleaner Materials*, *6*, 100137. https://doi.org/10.1016/j.clema.2022.100137

Andersen, C. H., Lerhard, K., Sandalgård Knudsen, L., & Hougaard Nielsen, S. (2022). *Greater bio - biomassa är en viktig pusselbit i den gröna cirkulära omställning*. Retrieved March 3, 2023, from https://www.gate21.dk/wp-content/uploads/2022/09/GreaterBio-SVENSK-final.pdf

Azzi, E. (2021). Biochar systems across scales in Sweden: An industrial ecology perspective (PhD dissertation, KTH Royal Institute of Technology). Retrieved February 3, 2023, from http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-303912

Azzi, E. S., Karltun, E., & Sundberg, C. (2021). Small-scale biochar production on swedish farms: A model for estimating potential, variability, and environmental performance. *Journal of Cleaner Production*, *280*, 124873. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124873

Bates, A. (2010). *The biochar solution - carbon farming and climate change*. New Society Publishers.

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., & Yeh, S. (2016, October 12). *Forest biomass, carbon neutrality and climate change mitigation* (From Science to Policy) [Series: From Science to Policy]. European Forest Institute. https://doi.org/10.36333/fs03

Biochar.co.uk. (2023). *Terra preta soils - the ancient soil that could help agriculture and the climate today*. Retrieved April 5, 2023, from https://biochar.co.uk/terra-preta/

Brännström, C., & Guldbrand, H. (2016). *Logistik och hantering av hästgödsel - en kartläggning av dagens logistiksystem för hästgödsel samt förbättringsförslag* *för framtida system*. Retrieved April 3, 2023, from https://hdl.handle.net/20.500.12380/239196

Bridgwater, A. V., & Grassi, G. (2012, December 6). *Biomass pyrolysis liquids upgrading and utilization* [Google-Books-ID: 0knzCAAAQBAJ]. Springer Science & Business Media.

Buchholz, T. S., Volk, T. A., & Luzadis, V. A. (2007). A participatory systems approach to modeling social, economic, and ecological components of bioenergy. *Energy Policy*, *35*(12), 6084–6094. https://doi.org/https://doi.org/10.1016/j.enpol.2007.08.020

Carbon Standards International. (2023, April 5). *EBC (2012-2023) guidelines european biochar certificate: For a sustainable production of biochar* (Version 10.3E). Frick, Switzerland. https://www.european-biochar.org/en/ct/2-EBC-guidelines-documents

Carbon Standards International & European Biochar Certificate. (2023). *Positive list of permissible biomasses for the production of biochar version 10.3*. Retrieved April 24, 2023, from https://www.european-biochar.org/media/doc/2/positive-list_en_v10_3.pdf

Cheng, H., Jones, D. L., Hill, P., Bastami, M. S., & long Tu, C. (2018). Influence of biochar produced from different pyrolysis temperature on nutrient retention and leaching. *Archives of Agronomy and Soil Science*, *64*(6), 850–859. https://doi.org/10.1080/03650340.2017.1384545

Clough, T., & Condron, L. (2010). Biochar and the nitrogen cycle: Introduction. *Journal of environmental quality*, *39*, 1218–23. https://doi.org/10.2134/jeq2010.0204

Copernicus. (2019, May 28). *Carbon dioxide levels are rising: Is it really that simple? / copernicus*. Retrieved April 19, 2023, from https://atmosphere.copernicus.eu/carbon-dioxide-levels-are-rising-it-really-simple

Delahaye, R., & Tunn, V. (2022, August 4). *Monitoring the biobased economy from a macro-economic perspective: 4. indicators* [Statistics netherlands] [Last Modified: 2022-08-04T09:00:00+02:00]. Retrieved April 27, 2023, from https://www.cbs.nl/en-gb/longread/discussion-papers/2022/monitoring-the-biobased-economy-from-a-macro-economic-perspective/4-indicators

Detterfelt, L., Lindqvist, H., Dalek, D., Carlevi, M., & Zachrisson, J. (2019, June 20). *Förstudie biokol av ris i trädgårdsavfall från renovas ägarkommuner*.

Ek, L., & Gustafsson, M. (2020). Förstudie biokolproduktion SÅM gislaved, gnosjö, vaggeryd och värnamo kommun. *Version 2.0*. Retrieved February 13, 2023, from https://medborgare.vaggeryd.se/welcome-sv/namnder-styrelser/kommunstyrelsen-ks/mote-2021-03-10/agenda/forstudie-biokolproduktion-sam-20201216pdf?downloadMode=open

Ekdahl, A. (2019, May 28). *Ridsporten i göteborg - kunskapsunderlag*. Retrieved April 3, 2023, from https://goteborg.se/wps/wcm/connect/e0fb4797-0061-4c34-a84c-8465d6275e91/Ridsporten+i+G%5C%C3%5C%B6teborg+-+Kunskapsunderlag.pdf?MOD=AJPERES

Ekologiska Lantbrukarnas kansli. (2023). *Biokol godkänt i ekologisk och KRAV-certifierad odling*. Retrieved April 23, 2023, from https://www.ekolantbruk.se/nyheter/biokol-godkant-i-ekologisk-och-krav-certifierad-odling

Energimyndigheten. (2022). *Statistikdatabas*. Retrieved May 3, 2023, from https://pxexternal.energimyndigheten.se/pxweb/en/Tr%C3%A4dbr%C3%A4nsle%20och%20torvpriser/-/1_EN0307_1.px/table/tableViewLayout2/

Enhäll, J. (2017, February 22). *Hästar och anläggningar med häst 2016. resultat från intermittent undersökning*. Retrieved April 3, 2023, from https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2020-09-04-hastar-och-anlaggningar-med-hast-2016.-resultat-fran-intermittent-undersokning

European Academies' Science Advisory Council. (2019). Forest bioenergy, carbon capture and storage, and carbon dioxide removal: An update. *Forest Bioenergy, CCS, and CO2 removal, February 2019*. Retrieved April 17, 2023, from https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy_Feb_2019_FINAL.pdf

European Biochar Certificate. (2023). *EBC producer*. Retrieved April 23, 2023, from https://www.european-biochar.org/en/ct/9-EBC-Producer

European Commission. (2021, October 22). *Cascading use | knowledge for policy*. Retrieved April 27, 2023, from https://knowledge4policy.ec.europa.eu/glossary-item/cascading-use_en

European Commission. (2022a). Proposal for a regulation of the european parliament and of the council establishing a union certification framework for carbon removals. Retrieved April 17, 2023, from https://climate.ec.europa.eu/system/files/2022-11/Proposal_for_a_Regulation_establishing_a_Union_certification_framework_for_carbon_removals.pdf

European Commission. (2022b). Report from the commission to the european parliament and the council on the functioning of the european carbon market in 2021 pursuant to articles 10(5) and 21(2) of directive 2003/87/ec. Retrieved April 17, 2023, from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0516&from=EN

European Commission. (2023a). *Bio-based products*. Retrieved April 27, 2023, from https://single-market-economy.ec.europa.eu/sectors/biotechnology/bio-based-products_en

European Commission. (2023b). *Eu emissions trading system (eu ets)*. Retrieved April 17, 2023, from https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (2023c). *A european green deal*. Retrieved April 17, 2023, from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2023d). European green deal: Eu agrees stronger legislation to accelerate the rollout of renewable energy. *Press release, 2023-03-30*. Retrieved April 17, 2023, from https://ec.europa.eu/commission/presscorner/detail/en/ip_23_2061

European Commission. (2023e, April 20). *EU ecolabel - home*. Retrieved April 23, 2023, from https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home_en

European Parliament. (2018). Eu regulation 2018/2001. *Official Journal, L328*. Retrieved April 17, 2023, from https://eur-lex.europa.eu/legal-content/EN/

TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

European Parliament. (2020). Eu regulation 2020/852. *Official Journal*, *L198*. Retrieved April 17, 2023, from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=EN

Eurostat. (2020). *Eurostat statistics*. Retrieved March 31, 2023, from https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN__custom_4684461/default/table?lang=en

Fagerström, E. (2011). *Market research concerning raw materials for biogas production*. Retrieved May 3, 2023, from https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=4468136&fileOId=4469080

Filippelli, G. (2008). The global phosphorus cycle: Past, present, and future. *Elements*, *4*, 89–95. https://doi.org/10.2113/GSELEMENTS.4.2.89

Filippelli, G. M. (2009). Phosphorus cycle. In V. Gornitz (Ed.), *Encyclopedia of paleoclimatology and ancient environments* (pp. 780–783). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4411-3_186

Fransson, A.-M., Gustafsson, M., Malmberg, J., & Paulsson, M. (2020). Biokolhandboken - för användare. Retrieved February 13, 2023, from https://biokol.org/publikationer/pdf/biokolhandboken

Fuchs, M. R., Garcia-Perez, M., Small, P., & Flora, G. (2014). *Campfire lessons - breaking down the combustion process to understand biochar production, the biochar journal 2014, arbaz, switzerland*. Retrieved March 19, 2023, from https://www.biochar-journal.org/en/ct/47

Gerlach, A., & Schmidt, H. (2014, August 1). *The use of biochar in cattle farming* [The biochar journal 2014] [ISSN 2297-1114]. Retrieved April 22, 2023, from https://www.biochar-journal.org/en/ct/9

Gómez-Baggethun, E., de Groot, R., Lomas, P. L., & Montes, C. (2010). The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes. *Ecological Economics*, *69*(6), 1209–1218. https://doi.org/10.1016/j.ecolecon.2009.11.007

Gopinath, A., Divyapriya, G., Srivastava, V., Laiju, A., Nidheesh, P., & Kumar, M. S. (2021). Conversion of sewage sludge into biochar: A potential resource in water and wastewater treatment. *Environmental Research*, *194*, 110656. https://doi.org/https://doi.org/10.1016/j.envres.2020.110656

Göteborg Energi. (2022). *Så bestäms fjärrvärmepriset*. Retrieved May 4, 2023, from https://www.goteborgenergi.se/foretag/fjarrvarme/sa-bestams-fjarrvarmepriset#prisutveckling

Göteborg Energi. (2023). Gemensam klimatsatsning med biokolsanläggning. Retrieved February 3, 2023, from https://www.goteborgenergi.se/i-var-stad/artikelbank/renova-goteborg-energi-biokolsanlaggning

Göteborg Stad. (2021). Environment and climate programme for the city of gothenburg 2021-2030. Retrieved February 3, 2023, from https://goteborg.se/wps/wcm/connect/be800f8b-8c25-498e-80e8-b982d56ddc08/Environment+and+Climate+Programme+for+the+City+of+Gothenburg+2021-2030.pdf?MOD=AJPERES

Göteborg Stad. (2022). Göteborgs stads energiplan 2022-2030. Retrieved February 3, 2023, from https://www5.goteborg.se/prod/Stadsledningskontoret/LIS/Verksamhetshandbok/Forfattn.nsf/30944AE15043B0DDC1258845003CE158/%5C$File/C12574360024D6C7MSKDCEHF34.pdf?OpenElement

Gryaab AB. (2021). *Gryaab hållbarhetsredovisning.* Retrieved April 26, 2023, from https://www.gryaab.se/wp-content/uploads/2022/03/Gryaabs-hallbarhetsredovisning-2021.pdf

Gryaab AB. (2023). *Slambehandling* [Gryaab]. Retrieved May 7, 2023, from https://www.gryaab.se/vad-vi-gor/slam/slamhantering/

Hagemann, N., Spokas, K., Schmidt, H.-P., Kägi, R., Böhler, M. A., & Bucheli, T. D. (2018). Activated carbon, biochar and charcoal: Linkages and synergies across pyrogenic carbon's ABCs [Number: 2 Publisher: Multidisciplinary Digital Publishing Institute]. *Water*, *10*(2), 182. https://doi.org/10.3390/w10020182

Hao, H., Dai, L., Wang, K., Xu, J., & Liu, W. (2021). An updated framework for climate change impact assessment of bioenergy and an application in poplar biomass. *Applied Energy*, *299*, 117323. https://doi.org/10.1016/j.apenergy.2021.117323

Hellmann, J., Gustafsson, M., & Ek, L. (2022). Förstudie biokol. *Sveriges lantbruksuniversitet, SLU*, *Version 2.0.* Retrieved February 13, 2023, from https://internt.slu.se/globalassets/mw/stod-serv/miljo/forstudie_biokolproduktion_vid_slu_2022.pdf

Hemlin, H., & Lalangas, N. (2018, August 30). *Production of biochar through slow pyrolysis of biomass: Peat, straw, horse manure and sewage sludge.* Retrieved April 26, 2023, from http://www.diva-portal.org/smash/get/diva2:1295394/FULLTEXT01.pdf

Holmberg, J. (1998). Backcasting: A natural step in operationalising sustainable development. *Greener Management International*, *23*, 30–51. link.gale.com/apps/doc/A55308829/AONE?u=anon~57ce5930&sid=googleScholar&xid=f454aced

Holmberg, J., & Robert, K. .-. (2000). Backcasting — a framework for strategic planning. *International Journal of Sustainable Development & World Ecology*, *7*(4), 291–308. https://doi.org/10.1080/13504500009470049

Holmén, J. (2020). *Navigating Sustainability Transformations - Backcasting, transdisciplinarity and social learning* (Doctoral dissertation). Chalmers university of technology.

Holmgren, G., Larsson, F. K., Johansson, M. H., & Hammar, I. L. (2020). Hållbar slamhantering SOU 2020:3, 758. https://www.regeringen.se/contentassets/3d68880d2e6942f3a1dccb158e46beb7/hallbar-slamhantering-sou-20203/

Institute for Energy and Transport. (2015). *The JRC-EU-TIMES model: Bioenergy potentials for EU and neighbouring countries.* Publications Office of the European Union. Retrieved April 27, 2023, from https://data.europa.eu/doi/10.2790/39014

International Biochar Initiative. (2015, November 23). *Standardized product definition and product testing guidelines for biochar that is used in soil version 2.1* [International biochar initiative]. Retrieved February 16, 2023, from https://biocharinternational.org/standard-certification-training/biochar-standards/

International Biochar Initiative. (2022). *BIOCHAR PRODUCTION TECHNOLOGIES* [International biochar initiative]. Retrieved March 19, 2023, from https://biocharinternational.org/about-biochar/how-to-make-biochar/biochar-production-technologies/

IPCC. (2019). *Method for estimating the change in mineral soil organic carbon stocks from biochar amendments: Basis for future methodological development, in: 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories* (Volume 4: Agriculture, Forestry and Other Land Use). Retrieved February 14, 2023, from https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf

IPCC. (2022). Summary for policymakers. In *Global warming of 1.5°c: Ipcc special report on impacts of global warming of 1.5°c above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty* (pp. 1–24). Cambridge University Press. https://doi.org/10.1017/9781009157940.001

Iwuozor, K. O., Chizitere Emenike, E., Ighalo, J. O., Omoarukhe, F. O., Omuku, P. E., & George Adeniyi, A. (2022). A review on the thermochemical conversion of sugarcane bagasse into biochar. *Cleaner Materials*, *6*, 100162. https://doi.org/10.1016/j.clema.2022.100162

Jahnke, R. A. (1992, January 1). 14 the phosphorus cycle. In S. S. Butcher, R. J. Charlson, G. H. Orians, & G. V. Wolfe (Eds.), *International geophysics* (pp. 301–315). Academic Press. https://doi.org/10.1016/S0074-6142(08)62697-2

Jay, C. N., Fitzgerald, J. D., Hipps, N. A., & Atkinson, C. J. (2015). Why short-term biochar application has no yield benefits: Evidence from three field-grown crops [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/sum.12181]. *Soil Use and Management*, *31*(2), 241–250. https://doi.org/10.1111/sum.12181

Jha, S., Nanda, S., Acharya, B., & Dalai, A. K. (2022). A review of thermochemical conversion of waste biomass to biofuels [Number: 17 Publisher: Multidisciplinary Digital Publishing Institute]. *Energies*, *15*(17), 6352. https://doi.org/10.3390/en15176352

Jordbruksverket. (2021). *Statistikdatabasen*. Retrieved May 30, 2023, from https://statistik.sjv.se/PXWeb/sq/ef3fe205-bdf3-4d42-862b-7a6ccaa0b89b

Jordbruksverket. (2022). *Statistikdatabasen*. Retrieved May 30, 2023, from https://statistik.sjv.se/PXWeb/sq/855fc7fd-c160-4c3b-ba3c-332061a64c7b

KRAV. (2023). *4.8 gödselmedel och jordförbättringsmedel* [4.8.4 Tillåtna organiska gödsel- och jordförbättringsmedel]. Retrieved April 23, 2023, from https://regler.krav.se/unit/krav-article/54b649c5-a78e-4508-9973-a6b26b814c9f

Kumar, A., & Bhattacharya, T. (2018). Biochar and its application, 17. Retrieved April 22, 2023, from https://www.researchgate.net/publication/344138848_Biochar_and_its_Application

Kurowska, K., Marks-Bielska, R., Bielski, S., Aleknavičius, A., & Kowalczyk, C. (2021). Geographic information systems and the sustainable development of rural areas [Number: 1 Publisher: Multidisciplinary Digital Publishing Institute]. *Land*, *10*(1), 6. https://doi.org/10.3390/land10010006

Labriet, M. (2013, December). *Biomass production and logistics* [IEA-Energy Technology Network]. ENERGY TECHNOLOGY SYSTEM ANALYSIS PROGRAMME. Retrieved April 27, 2023, from https://iea-etsap.org/E-TechDS/PDF/P09_Biomass%5C%20prod&log_ML_Dec2013_GSOK.pdf

Lamlom, S., & Savidge, R. (2003). A reassessment of carbon content in wood: Variation within and between 41 north american species. *Biomass Bioenergy - BIOMASS BIOENERG*, *25*, 381–388. https://doi.org/10.1016/S0961-9534(03)00033-3

Lee, S. Y., Sankaran, R., Chew, K. W., Tan, C. H., Krishnamoorthy, R., Chu, D.-T., & Show, P.-L. (2019). Waste to bioenergy: A review on the recent conversion technologies. *BMC Energy*, *1*(1), 4. https://doi.org/10.1186/s42500-019-0004-7

Lehmann, J., & Joseph, S. (Eds.). (2009). *Biochar for environmental management: Science and technology* [OCLC: ocn259754287]. Earthscan. https://www.css.cornell.edu/faculty/lehmann/publ/First%5C%20proof%5C%2013-01-09.pdf

Lerman, A. (2009). Carbon cycle. In V. Gornitz (Ed.), *Encyclopedia of paleoclimatology and ancient environments* (pp. 107–118). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4411-3_28

Li, Y., Gupta, R., Zhang, Q., & You, S. (2023). Review of biochar production via crop residue pyrolysis: Development and perspectives. *Bioresource Technology*, *369*, 128423. https://doi.org/https://doi.org/10.1016/j.biortech.2022.128423

Lundvall, S., & Hellsten, C. (2020, April). *Biokol i jönköping – för naturen, klimatet och människorna – refarm linné*. Retrieved February 13, 2023, from https://refarmlinne.se/refarm-project/biokol-i-jonkoping-for-naturen-klimatet-och-manniskorna/

McCartney, D. H., Block, H. C., Dubeski, P. L., & Ohama, A. J. (2006). Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in western canada. *Canadian journal of animal science*, *86*(4), 443–455. https://doi.org/https://doi.org/10.4141/A05-092

National Oceanic and Atmospheric Administration. (2019, February 1). *Carbon cycle*. Retrieved April 21, 2023, from https://www.noaa.gov/education/resource-collections/climate/carbon-cycle

Naturskyddsföreningen. (2021, June 10). *Slam från ditt avlopp blir gödsel på åkern* [Naturskyddsföreningen] [© 2023 Naturskyddsföreningen]. Retrieved May 7, 2023, from https://www.naturskyddsforeningen.se/artiklar/slam-fran-ditt-avlopp-blir-godsel-pa-akern/

Naturvårdsverket. (2022, December 31). Resultat för klimatklivet. Retrieved February 24, 2023, from https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/klimatklivet/resultat-for-klimatklivet/

Official Journal of the European Union. (2019, December 18). *COMMISSION IMPLEMENTING REGULATION (EU) 2019/2164*. Retrieved April 23, 2023, from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R2164&from=EN

Olovsson, H., & Saarela, J. (2022, May 29). *Marknadsintroduktion förädlade rötrestprodukter*. Retrieved April 27, 2023, from https://biofuelregion.se/wp-content/uploads/2020/11/2022-Marknadsintroduktion-foradlade-rotrestprodukter.pdf

Opatokun, S. A., Kan, T., Al Shoaibi, A., Srinivasakannan, C., & Strezov, V. (2016). Characterization of food waste and its digestate as feedstock for thermochemical processing. *Energy & Fuels*, *30*(3), 1589–1597. https://doi.org/10.1021/acs.energyfuels.5b02183

Osman, A. I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R. A., Maksoud, M. I. A. A., Ajlan, A. A., Yousry, M., Saleem, Y., & Rooney, D. W. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: A review. *Environmental Chemistry Letters*, *20*(4), 2385–2485. https://doi.org/10.1007/s10311-022-01424-x

Pär Dalhielm & Anders Finnson. (2023, January 1). *REVAQ: Regler för certifieringssystemet*. Retrieved April 23, 2023, from https://www.svensktvatten.se/globalassets/avlopp-och-miljo/uppstromsarbete-och-kretslopp/revaq-certifiering/revaq-regler-2023-utgava-8.0-gul.pdf

Patricio, J., Kalmykova, Y., & Rosado, L. (2020). A method and databases for estimating detailed industrial waste generation at different scales – with application to biogas industry development. *Journal of Cleaner Production*, *246*, 118959. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.118959

Paulsson, M. (2020). *REST till BÄST: Sammanfattande slutrapport för projektet rest till bäst (steg 2)* [Co-authors: David Andersson (Ecoera), Jenny Bengtsson (Sustainable business hub), Sven-Olof Bernhoff (Skånefrö), Larsola Bromell (Malmö stad), Olivia Cintas (Rise), Kent Davidsson (Rise), Lotta Ek (Ecotopic), Johan Eriksson (Uppsala kommun), Ann-Mari Fransson (SLU), Mattias Gustafsson (Ecotopic), Johannes Hagström (Trelleborgs kommun), Ulrika Jönsson Belyazid (Belyazid consulting & communication), Jonatan Malmberg (Ecotopic), Lina Pettersson (Veg tech), Håkan Rosqvist (Sustainable business hub), Bengt Syrén (Bara mineraler), Gunnar Thelin (Ekobalans) och Mirja Ullvig (Trelleborgs kommun).]. Retrieved April 23, 2023, from https://www.ri.se/sites/default/files/2022-06/slutrapport%20RtB.pdf

Purakayastha, T. J., Bera, T., Bhaduri, D., Sarkar, B., Mandal, S., Wade, P., Kumari, S., Biswas, S., Menon, M., Pathak, H., & Tsang, D. C. W. (2019). A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security. *Chemosphere*, *227*, 345–365. https://doi.org/10.1016/j.chemosphere.2019.03.170

Puro Earth. (2022). *Corc carbon removal indexes*. Retrieved May 4, 2023, from https://puro.earth/carbon-removal-index-price/

Puro Earth. (2023). *About puro.earth*. Retrieved May 2, 2023, from https://puro.earth/about-us/

Quintero, R. R., Garbarino, E., Saveyn, H., & Wolf, O. (2015). *Revision of the EU ecolabel criteria for soil improvers and growing media* (ISSN 1831-9424 doi:10.2791/54696). Retrieved April 23, 2023, from file:///C:/Users/dougl/

Downloads/si%5C%20gm%5C%20eu%5C%20ecolabel%5C%20technical%5C%20report_june2015.pdf

Rahimi, Z., Anand, A., & Gautam, S. (2022). An overview on thermochemical conversion and potential evaluation of biofuels derived from agricultural wastes. *Energy Nexus*, *7*, 100125. https://doi.org/10.1016/j.nexus.2022.100125

Riebeek, H. (2011, June 16). *The carbon cycle*. Retrieved April 19, 2023, from https://earthobservatory.nasa.gov/features/CarbonCycle

Robinson, J. B. (1988). Unlearning and backcasting: Rethinking some of the questions we ask about the future [Special Issue Forecasting Social Change in Canada]. *Technological Forecasting and Social Change*, *33*(4), 325–338. https://doi.org/https://doi.org/10.1016/0040-1625(88)90029-7

Robinson, J. B. (1990). Futures under glass: A recipe for people who hate to predict. *Futures*, *22*(8), 820–842. https://doi.org/https://doi.org/10.1016/0016-3287(90)90018-D

Robinson, J. B. (1982). Backing into the future: On the methodological and institutional biases embedded in energy supply and demand forecasting. *Technological Forecasting and Social Change*, *21*(3), 229–240. https://doi.org/https://doi.org/10.1016/0040-1625(82)90052-X

Rorat, A., Courtois, P., Vandenbulcke, F., & Lemiere, S. (2019). Sanitary and environmental aspects of sewage sludge management. *Industrial and Municipal Sludge*, 155–180. https://doi.org/10.1016/B978-0-12-815907-1.00008-8

Samuelsson, G. (2011). *Matavfallets klimatpåverkan vid energiutvinning*. Retrieved April 27, 2023, from http://www.diva-portal.org/smash/get/diva2:461716/FULLTEXT01.pdf

SCB. (2013, June 26). *Cultivation measures in agriculture 2012*. Retrieved April 4, 2023, from https://www.scb.se/contentassets/5d965edd985b42e48a104f570464e23c/mi1001_2011b12_sm_mi30sm1302.pdf

SCB. (2022). *Statistikdatabasen*. Retrieved March 30, 2023, from https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/

Schmidt, H.-P. (2014). *Terra preta – model of a cultural technique, the biochar journal 2014, arbaz, switzerland*. Retrieved April 6, 2023, from https://www.biochar-journal.org/en/ct/4

Schmidt, H.-P., Kammann, C., & Hagemann, N. (2021). (EBC 2020) EBC-guidelines for the certification of biochar based carbon sinks. *Ithaka Institute, Arbaz, Switzerland, Version 2.1*. Retrieved February 10, 2023, from https://www.european-biochar.org/en/ct/139-C-sink-guidelines-documents

Schmidt, H.-P., & Wilson, K. (2014, May 12). *The 55 uses of biochar* [The biochar journal 2014] [ISSN 2297-1114]. Retrieved April 22, 2023, from https://www.biochar-journal.org/en/ct/2

Scott, J. A., Ho, W., & Dey, P. K. (2012). A review of multi-criteria decision-making methods for bioenergy systems [8th World Energy System Conference, WESC 2010]. *Energy*, *42*(1), 146–156. https://doi.org/https://doi.org/10.1016/j.energy.2012.03.074

SEVAB. (2019, January 24). *Så tar vi hand om ditt sorterade matavfall – från 2010 till nu*. Retrieved May 8, 2023, from https://www.sevab.com/privat/atervinning/sortera/sa-tar-vi-hand-om-ditt-sorterade-matavfall/

Simon Berg & Dimitris Athanassiadis. (2018, June). *Transportation costs from forest to industry*. Swedish University of Agricultural Sciences (SLU). https://biofuelregion.se/wp-content/uploads/2018/08/2018-No-15-Transportation-Costs.pdf

Slattery, R. (2015). Biochar - feedstock to ethicals. *Antaeus International Pty Ltd*. https://doi.org/10.13140/RG.2.1.4156.3369

Söderqvist, H., Norberg, V., & Turnstedt, L. (2021). *Marknaden för biokol i öresundsregionen*. Retrieved April 22, 2023, from https://2050.se/wp-content/uploads/2021/03/2050-Marknaden-for-biokol-i-Oresundsregionen.pdf

Spears, S. (2018, May 16). *What is biochar?* [Regeneration international]. Retrieved April 28, 2023, from https://regenerationinternational.org/2018/05/16/what-is-biochar/

Stein, L. Y., & Klotz, M. G. (2016). The nitrogen cycle. *Current Biology*, *26*(3), R94–R98. https://doi.org/10.1016/j.cub.2015.12.021

Stockholm Exergi. (2021). Biokolet - en kolsänka för det gröna hemmet. Retrieved February 3, 2023, from https://www.stockholmexergi.se/nyheter/biokolet-en-kolsanka-for-det-grona-hemmet/

Stockholm Vatten och Avfall. (2018). Slamstrategi för stockholm vatten och avfall. *Version 3*. https://www.stockholmvattenochavfall.se/globalassets/pdfer/riktlinjer/slamstrategi_med_bilagor.pdf

Svenskt Vatten. (2021, March 12). *Slamutredningen, vad händer nu?* [Svenskt Vatten]. Retrieved May 7, 2023, from https://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/kretslopp-och-uppstromsarbete/nationellt-natverk-for-fosfor-och-andra-avloppsresurser/fosfornyheter/slamutredningen---vad-hander-nu/

Svenskt Vatten. (2023, March 1). *Aktivt uppströmsarbete med revaq-certifiering* (Anders Finnson, Trans.) [Svenskt vatten]. Retrieved April 23, 2023, from https://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/kretslopp-och-uppstromsarbete/revaq-certifiering/

Swedish wood. (2023). *Moisture content*. Retrieved April 26, 2023, from https://www.swedishwood.com/wood-facts/about-wood/wood-and-moisture/

SYSAV. (2020). *Ändrade priser efter ny skatt på avfallsförbränning*. Retrieved May 3, 2023, from https://www.sysav.se/om-oss/pressrum/nyheter/nya-priser-pa-brannbart-avfall-fran-1-april-efter-inforande-av-forbranningsskatt-395493/

Takai, K. (2019). The nitrogen cycle: A large, fast, and mystifying cycle. *Microbes and Environments*, *34*(3), 223–225. https://doi.org/10.1264/jsme2.ME3403rh

The World Bank Group. (2023). *What is carbon pricing? | carbon pricing dashboard*. Retrieved April 27, 2023, from https://carbonpricingdashboard.worldbank.org/what-carbon-pricing

Tsai, W.-T., Huang, C.-N., Chen, H.-R., & Cheng, H.-Y. (2015). Pyrolytic conversion of horse manure into biochar and its thermochemical and physical properties. *Waste Biomass Valor*, *6*. https://doi.org/https://doi.org/10.1007/s12649-015-9376-1

Turek, V., Kilkovsky, B., Jegla, Z., & Stehlik, P. (2018). Proposed eu legislation to force changes in sewage sludge disposal: A case study. *Frontiers of Chemical*

Science and Engineering, *12*, 660–669. https://doi.org/10.1007/s11705-018-1773-0

Turgeon, A., & Morse, E. (2022, May 20). *Biomass energy.* Retrieved April 21, 2023, from https://education.nationalgeographic.org/resource/biomass-energy

Tye, M. (2022). *How feedstock choice impacts biochar production | onnu.* Retrieved April 16, 2023, from https://www.onnu.com/insights/how-feedstock-choice-impacts-biochar-production

Van Phamn, D., Takeshi, F., Hoang Minh, G., & Pham Phu, S. (2020). Comparison between single and two-stage anaerobic digestion of vegetable waste: Kinetics of methanogenesis and carbon flow. *Waste Biomass Valor*, *11*, 6095–6103. https://doi.org/10.1007/s12649-019-00861-0

Van Teijlingen, E. (2014, December 3). *Semi-structured interviews.* Retrieved March 28, 2023, from https://docplayer.net/20974698-Semi-structured-interviews.html

Viable Cities. (2020, December 11). Europe's first climate city contract signed in sweden today. Retrieved February 10, 2023, from https://en.viablecities.se/nytt/europas-frsta-klimatkontrakt-signerade-i-sverige-idag

Wahlberg Roslund, C. (2022, January 18). *Biomassa till energi och biokol -en effektivare råvaruanvändning med multifunktion för ett klimatsmart jordbruk* [CEWARO AB]. Retrieved March 19, 2023, from https://cewaro.se/biomassa-till-energi-och-biokol-en-effektivare-ravaruanvandning-med-multifunktion-for-ett-klimatsmart-jordbruk/

Weathers, K. C., Strayer, D. L., & Likens, G. E. (2012). *Fundamentals of ecosystem science* (Vol. 1). Academic Press. https://doi.org/10.1016/C2009-0-03622-8

Wennerberg, P. (2016, December 30). *Förstudie av biogasanläggning för samrötning av hästgödsel och matavfall i göteborgsregionen.* Agroväst. Retrieved May 3, 2023, from https://docplayer.se/106321638-Forstudie-av-biogasanlaggning-for-samrotning-av-hastgodsel-och-matavfall-i-goteborgsregionen.html?fbclid=IwAR3Y47J1X6Cz5riVSDiV1oWGuY07Zuaif7IDyU3vajAgl0Rdzt4OsP3h8vA

Wongrod, S., Guibaud, G., Simon, S., Lens, P. N. L., Huguenot, D., Pechaud, Y., & van Hullebusch, E. D. (2022). Biochar produced from organic waste digestate and its potential utilization for soil remediation: An overview. In A. Sinharoy & P. N. L. Lens (Eds.), *Renewable energy technologies for energy efficient sustainable development* (pp. 263–292). Springer International Publishing. https://doi.org/10.1007/978-3-030-87633-3_10

Xiong, S., Zhuo, J.-K., Zhang, B., & Yao, Q. (2013, May). *Effect of moisture content on the characterization of products from the pyrolysis of sewage sludge* [ResearchGate]. https://doi.org/10.1016/j.jaap.2013.05.003

Yilmaz Balaman, S. (2018). *Decision-making for biomass-based production chains: The basic concepts and methodologies.*

Zhang, Y., Wang, J., & Feng, Y. (2021). The effects of biochar addition on soil physicochemical properties: A review. *CATENA*, *202*, 105284. https://doi.org/10.1016/j.catena.2021.105284

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