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White paper
SkyClean Biochar

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Table of contents

1 Introduction

1.1 Background

The purpose of this white paper is to provide an overview of various aspects of biochar produced by Stiesdal SkyClean.

Biochar refers to carbon-based materials produced by heating organic matter at high temperatures under low-oxygen conditions - a process known as pyrolysis.

Dry plant material typically consists of approximately 50% carbon, which the plant absorbs from the atmosphere as CO_2 during its lifetime. This percentage remains consistent whether the residue is purely plant-based or originates from animal husbandry or the food industry.

During the pyrolysis process, approximately half of the carbon in the residue is transformed into biochar, while the other half is converted into pyrolysis gas.

The resulting biochar is a stable material that decomposes very slowly, which means that the one half of the carbon that becomes biochar is therefore effectively removed from the atmosphere.

The remaining carbon, not converted into biochar, exits the pyrolysis process as gas and oil. The gas can be used as a fuel source for heat production and industrial applications, while the oil can be refined into fuel for the transportation sector.

SkyClean's pyrolysis process builds on many years of research at the Technical University of Denmark (DTU), aiming to produce biochar of a quality suitable for application on cultivated arable land.

Figure 1: SkyClean biochar applied to a maize field for photographic purposes. In practice, the biochar is intended to be spread before sowing and then incorporated into the soil through ploughing or harrowing.

2 Overview of the chapters of the white paper

2.1 Scope of the white paper

This white paper explores biochar and its production using SkyClean technology. It examines the characteristics of biochar, its integration into agricultural practices, and its role in carbon sequestration. Additionally, it addresses key topics such as relevant legislation, certification standards, environmental safety considerations, and the potential for generating CO_2e credits.

This document does not describe the technical specifics of the SkyClean pyrolysis process, or the energy production enabled by SkyClean technology.

The chapters of this white paper are designed to be read independently, which means that some information may be repeated across chapters.

As pyrolysis is a rapidly evolving field in Denmark, this white paper serves as a dynamic document. It will be updated and republished regularly to reflect the latest knowledge on relevant legislation, standards, and the impacts of pyrolysis and biochar.

2.2 Sections of the white paper

Section 3 of this white paper discusses the types of biomass that can be utilized in the SkyClean process, along with how the choice of biomass affects the production and quality of the resulting biochar. The type and quality of the biomass are crucial not only during the preparation phase but also throughout the pyrolysis process. Moreover, the properties of the biomass significantly influence the carbon and nutrient content of the biochar, which in turn determines its potential applications.

Section 4 of this white paper describes the transportation of biochar from the SkyClean plant to the field and its application in agricultural settings. It examines various storage options, such as field stacks, and the recommended methods for covering biochar. We also discuss handling techniques, including the use of standard agricultural equipment and spreaders. Importantly, biochar is not classified as hazardous material for transportation purposes. The section explores biochar's ability to redistribute phosphorus in the soil, recommended application rates for fields, its potential for mixing with slurry, and observations from testing different spreading techniques.

Section 5 explores the positive effects of biochar and its benefits for agricultural practices. Biochar enhances soil health by supporting balanced pH levels, retaining water and nutrients, and potentially improving soil structure. These properties make it valuable for mitigating drought effects and improving water availability, which can significantly enhance agricultural production and crop yields. Additionally, we examine how biochar influences soil phosphorus and potassium content and its contribution to stabilizing carbon in the soil.

Section 6 focuses on the environmental aspects of biochar. It references standards that ensure compliance with regulations regarding xenobiotic substances, including polycyclic aromatic hydrocarbons (PAHs), dioxins, furans, dioxin-like PCBs, and heavy metals.

Section 7 investigates the stability and climate impact of biochar. The stability of biochar is determined by various factors, including the type and quality of biomass used in the pyrolysis process, the temperature of the pyrolysis, and the duration of biomass processing. Higher pyrolysis temperatures are particularly significant, as they enhance the stability of the carbon in biochar. This is due to the formation of carbon dust at higher temperatures, which decomposes very slowly in natural environments.

Section 8 provides an overview of biochar-related legislation in Denmark and the EU. While EU regulations are more clearly defined, Denmark is still working toward establishing comprehensive rules and standards for biochar use. Stiesdal SkyClean collaborates with authorities and organizations to help shape regulations that support the integration of biochar into standard agricultural practices.

Section 9 discusses the certification options for biochar through the European Biochar Certification (EBC). EBC certification is a voluntary European standard focused on the production of environmentally safe biochar. According to the EBC website: "The EBC was developed to limit the risks of biochar usages to the best of our scientific knowledge and to help the users and producers of biochar to prevent or at least to reduce any hazard for the health and for the environment while producing and using biochar." It also includes a "C-sink" certificate that reflects the climate impact of biochar production and transportation. To achieve this certification, companies must complete technical audits, conduct sample analyses, and participate in annual inspections.

Section 10 explains the climate credit system for biochar. Biochar primarily consists of stable carbon, making it an effective tool for carbon sequestration. The pyrolysis process used to produce biochar removes more CO_2 from the atmosphere than it emits during production and transportation, classifying biochar as a carbon-negative product. Even when accounting for CO_2 emissions from the combustion of pyrolysis gas or fuels derived from it, biochar remains a carbon-negative solution.

2.3 Other applications of biochar

This white paper emphasizes the application of biochar in agriculture. This focus is driven by the fact that the types of biomass available in Denmark contain essential nutrients that enrich the soil when returned to fields in the form of biochar. Furthermore, under current carbon accounting frameworks and legislation, the net storage of CO_2 from biochar can only be credited to the national greenhouse gas inventory when it is applied to agricultural land.

In scenarios where nutrient recycling is not a priority or where national carbon accounting is not a focus, biochar can also be utilized in other industries, such as a component in concrete or as a raw material for producing industrial products.

3 Biomass

3.1 SkyClean can convert a wide range of materials into biochar and fuel

SkyClean is capable of utilizing nearly any type of organic material as input (see Figure 2). The range of suitable biomass types includes residual materials from agriculture and forestry, waste from food production and urban areas, algae, and more. This versatility makes the SkyClean technology applicable beyond Denmark as well.

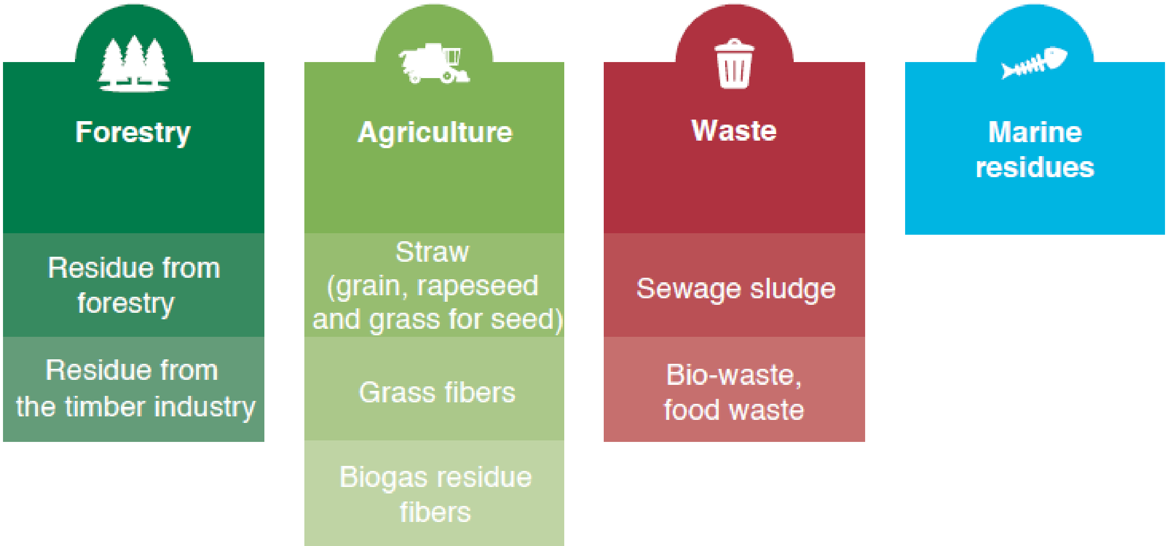

Figure 1: Examples of biomass suitable for pyrolysis in the SkyClean technology.

Wood chips, nutshells, and other hard biomass types can typically be pyrolyzed without pre-treatment. However, straw, manure, and other agricultural biomass usually require pelletizing before undergoing pyrolysis with SkyClean technology. Pelletizing compresses the biomass into hard, pea-sized pellets. Without pelletizing, a significant portion of the biomass turns into dust during pyrolysis. While this does not affect the biochar's climate benefits, it complicates its handling.

Biomass with high moisture content, such as biogas fibers, requires both drying and pelletizing before use in the pyrolysis process. The drying method employed depends on the specific type of biomass.

When agricultural biomass is used as input in the production of biochar, most of its nutrients are preserved in the final product, binding to the biochar. These nutrients are returned to the soil when the biochar is applied to fields. Recirculated phosphorus is particularly valuable, given the global scarcity of phosphorus reserves. Essential nutrients such as phosphorus, potassium, and magnesium are retained in the biochar, while nitrogen and, to a lesser extent, sulfur are incorporated into the pyrolysis gas and do not return to the soil. The nutrient composition of the biochar depends on the nutrient profile of the biomass used in pyrolysis.

Denmark currently has a significant, underutilized supply of biomass, primarily from agricultural sources, with the potential for substantial growth. According to researchers from Aarhus University, as detailed in *Knowledge Synthesis on Biochar in Danish Agriculture* (Elsgaard et al., 2022), approximately 6.6 million tons of dry biomass could be available by 2030 under current agricultural practices. Of this, around 2 million tons are projected for bioenergy production. The synthesis also examines scenarios where biomass potential could range between 9.5 and 14.6 million tons of dry matter by 2030. Thus, even after accounting for competing biomass uses, the potential for biomass pyrolysis remains substantial.

3.2 Carbon uptake

The type of biomass used for pyrolysis influences both the amount of carbon stored in the resulting biochar and the energy produced. However, regardless of the biomass type, the overall distribution of the climate impact remains largely consistent. Approximately two-thirds of the climate benefit stems from carbon storage in the biochar, while the remaining one-third comes from the displacement of fossil fuels. This distribution is relatively uniform, whether straw or biogas residual fibers are used, as illustrated in Table 1.

Production per ton of biomass input	**Straw**	**Biogas fibers**
Biomass [tons of dry matter]	1,00	1,00
Biochar production [tons CO_2e]	0,70	0,75
Displacement of fossil fuels [tons CO_2e]	0,45	0,30
Methane emissions avoided [tons of CO_2e]	-	0,10
Stored and displaced CO2e [tons CO_2e]	**1,15**	**1,15**

Table 1: Average energy flows in SkyClean scenario with straw and biogas residue fibers.

The SkyClean process converts approximately half of the carbon in the biomass into biochar, while the remainder is transformed into pyrolysis gas, which can be utilized for high-temperature heat or condensed into bio-oil. The energy distribution of a 20 MW SkyClean plant is illustrated in the diagram in Figure 3.

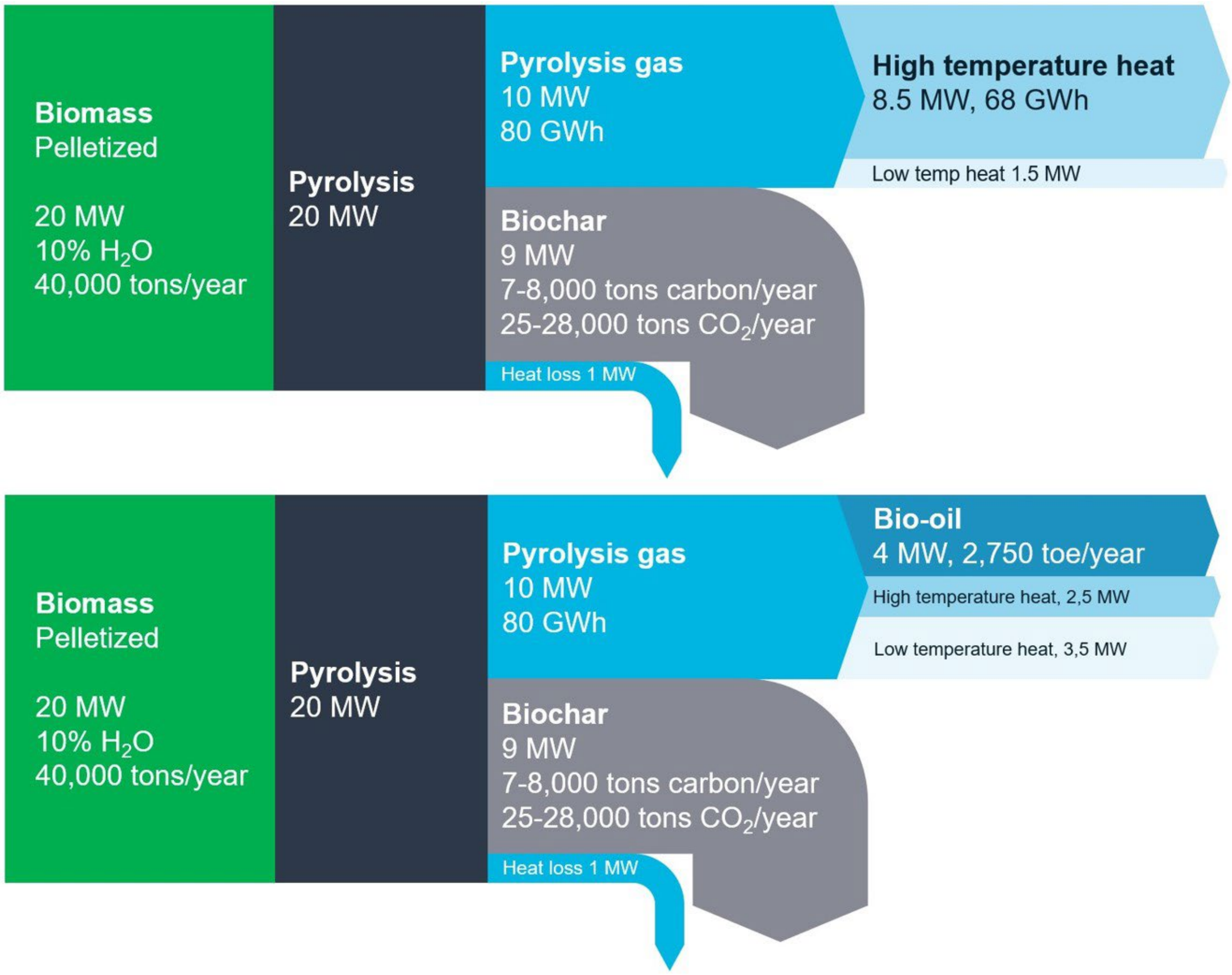

Figure 2: Sankey diagram with energy distribution with and without condensation of bio-oil for a 20 MW SkyClean plant.

The pyrolysis process in a SkyClean facility demonstrates high energy efficiency, requiring only about 5% of the energy content of the biomass input to operate, as illustrated in Figure 3. The remaining energy content is retained in the biochar and pyrolysis gas.

The overall energy balance varies based on the moisture content of the biomass. When processing wet biomass, a portion of the excess heat generated during pyrolysis is used to dry the biomass in a pressurized steam dryer. A significant amount of the heat used for drying is recovered and can often replace fossil energy sources, such as natural gas.

4 The journey of biochar from the SkyClean plant to storage in the field

4.1 Biochar handling

A SkyClean plant processing residual fibers from biogas as biomass produces approximately 19.000 tons of biochar annually, with a water content of 30%. This volume equates to around 25.000 cubic meters of biochar, necessitating regular transportation from the SkyClean facility to storage sites, ideally close to the areas where it will be applied.

Biochar is classified as processed manure and can therefore be stored in stacks directly on the field. If a stack remains in place for more than a week, it must be covered with a waterproof cover. Temporary storage options include farm facilities or locations such as agricultural supply stores, although minimizing the number of times the biochar is handled is preferable.

Biochar can also be stored in big bags, although this incurs an additional cost of approximately 50–100 DKK per ton.

Loose biochar is typically managed on farms using standard equipment such as skid steer loaders, backhoes, or wheel loaders. It can be spread using common agricultural machinery, including lime spreaders, fertilizer spreaders, slurry tankers, or manure spreaders. When loading biochar stored in field stacks, care must be taken to avoid introducing soil or stones into the spreading equipment.

Biochar does not require special precautions during transportation, as it is not classified as hazardous material.

Application rates range from 500 kg to 10 tons per hectare, depending on the intended use and nutrient content of the biochar.

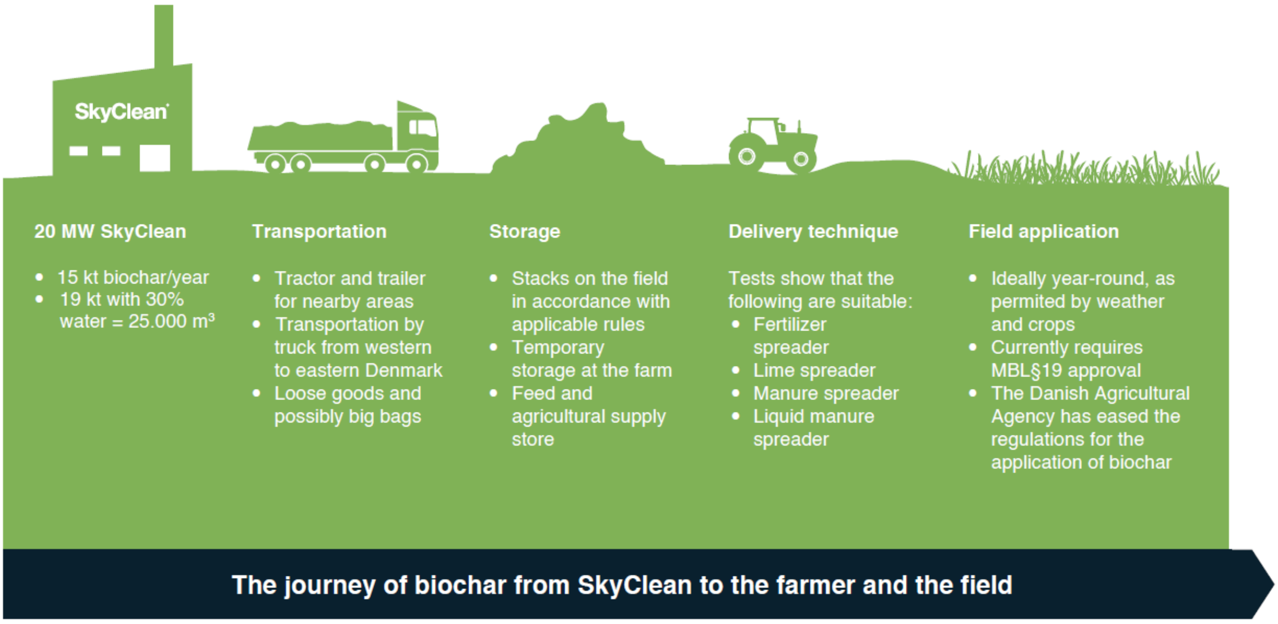

Figure 3: The journey of biochar from the SkyClean plant to storage in the field.

4.2 Nutrients

Biochar contains essential nutrients, including phosphorus and potassium. Phosphorus, a vital nutrient for crop growth, can be redistributed using biochar to address regional imbalances - for example, transferring surplus phosphorus from Western Denmark to regions in Eastern Denmark where deficits exist.

Stiesdal SkyClean has assessed the economic feasibility of transporting biochar from Vrå in Vendsyssel to Eastern Denmark. For long-distance transport to be cost-effective, the phosphorus content of the biochar must exceed 4%, as not all phosphorus in biochar is immediately bioavailable to crops. Biochar derived from biogas residue fibers typically contains 2–4% phosphorus, making transport from Vendsyssel to Eastern Denmark marginally viable. The financial feasibility improves if the biogas plant is situated further south in Jutland, reducing transportation distances.

If the phosphorus content of the biochar is below 4%, transportation between Western and Eastern Denmark can still be economically viable under specific conditions, such as high market prices for phosphorus. For example, biochar with 2% phosphorus content requires a market value of DKK 16 per kilogram of phosphorus to cover transportation costs. Including the potassium content improves the economics further to an extent that biochar with 3% phosphorus can be transported profitably at a phosphorus market price as low as DKK 7 per kilogram.

4.3 Application of biochar

Biochar in pellet form is well-suited for distribution on fields using standard farming machinery such as lime spreaders, fertilizer spreaders, manure spreaders, and slurry spreaders. To ensure pellets withstand handling without breaking, they must be sufficiently durable to resist pressure. Strong pellets also ensure even spreading as well as minimizing dust generation, with the moisture content in the biochar further helping to reduce dust levels.

Preliminary tests with lime and fertilizer spreaders indicate that biochar can be spread over widths of up to 24 meters, with a variation of 6–8%. This level of variation is acceptable for typical agricultural use. Crushed pellets can still be applied using a lime spreader, but this may result in a less uniform spreading pattern and increased dust levels unless a specialized spreader equipped with an auger boom is used.

With standard fertilizer spreaders, the maximum application rate is approximately 1 ton per hectare. For higher application rates, multiple passes or the use of two spreaders - one mounted at the front and the other at the rear of the tractor - may be required.

Tests with standard manure spreaders have achieved spreading widths of up to 8 meters, with a variation of 15%, which is acceptable for this type of equipment. Additionally, Samson Agro A/S has developed a more advanced centrifugal spreader, capable of achieving wider spreading widths up to 18 meters with less than 15% variation.

Spreading biochar mixed with slurry has also been tested. The mixing ratio should not exceed 1:15 by weight to avoid overloading the distribution pump and to ensure the dry matter content of the slurry remains manageable.

Limited tests have been conducted using biochar as a placement fertilizer with an air seeder. However, the biochar's moisture content and the presence of crumbs or dust created challenges, making this method unsuitable in its current form. Application during seeding is therefore unlikely to be a practical method for delivering large quantities of biochar.

5 Properties of biochar in the soil

5.1 Fundamental features

Biochar is an alkaline, porous material with numerous small pores that create a large internal surface area. This unique structure allows biochar to effectively regulate soil acidity (pH), enhance the soil's water retention and transmission capacity (hydraulic conductivity), and increase its ability to attract and retain positively charged ions (cation exchange capacity).

Additionally, biochar serves as a growth medium for beneficial microorganisms, such as fungi and bacteria, while also contributing essential nutrients to the soil.

For farmers, biochar provides a range of benefits, summarized below and explored in detail later:

- Reduced lime requirement, leading to lower CO_2 emissions associated with liming.
- Improved soil structure, enhancing water availability for crops.
- Increased drought resilience.
- Healthier soil microbiome, supporting better root development.
- Reduced nitrogen leaching and lower nitrous oxide (N_2O) emissions into the environment.
- Slow-release nutrient storage, providing a sustained supply of nutrients.
- Enhanced growing conditions, with the potential to increase crop yields.

Ongoing research and development projects continue to explore and quantify the effects of biochar in agricultural soils, offering deeper insights into its benefits and value.

5.2 Valuation of the use of biochar in agriculture

The properties and benefits of biochar vary significantly depending on the type of biomass used in its production and the specific conditions of the soil where it is applied.

Stiesdal SkyClean has developed several scenarios to evaluate the direct value of biochar as a fertilizer and its potential to enhance soil quality.

As shown in Figure 5, the primary benefit of biochar in agriculture lies in its value as a fertilizer. While improvements in soil quality from biochar typically accumulate over several years, these effects are expected to be less significant in Danish agriculture, where soils are already of high quality and achieve strong yields. Biochar is estimated to have a value of approximately DKK 500 per ton, though this figure can vary significantly based on the biomass used to produce it and its nutrient composition.

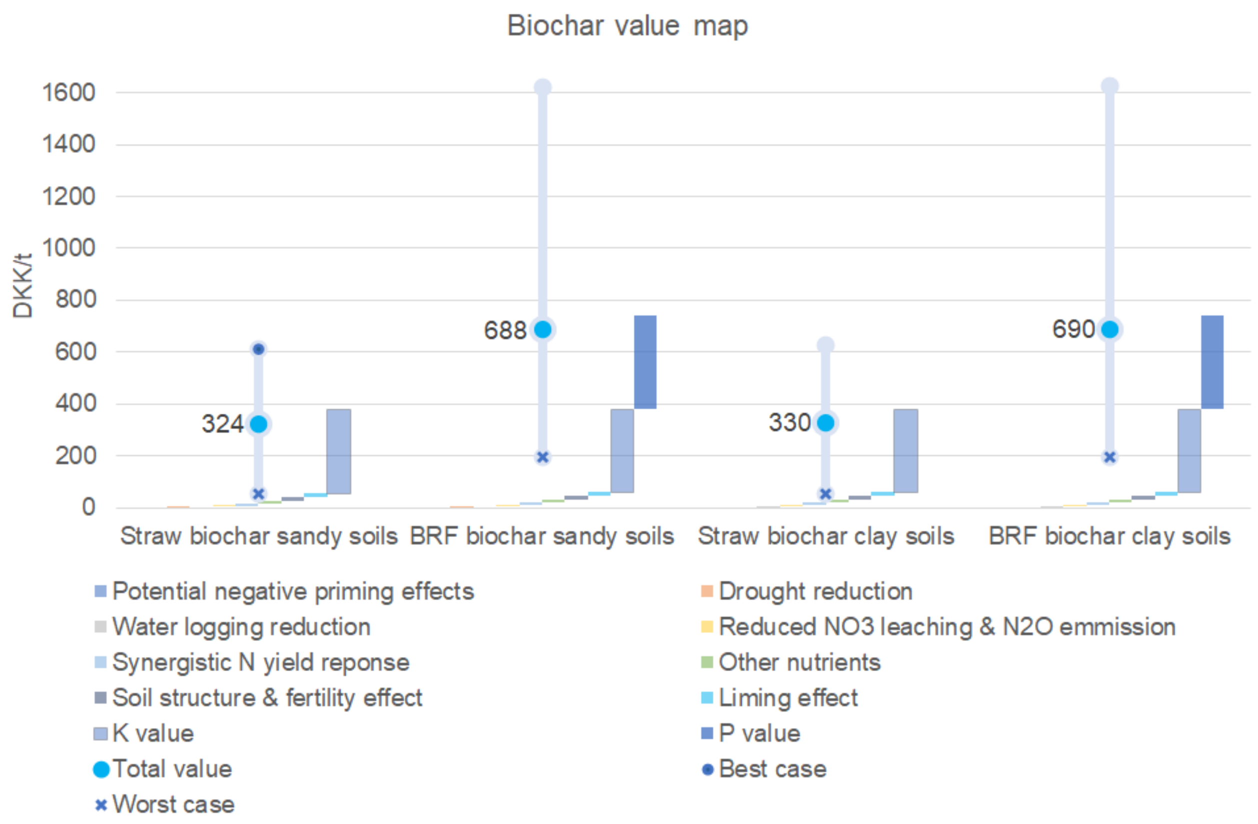

Figure 5: Overview of the value that biochar produced from straw or biogas residue fiber (BRF) can provide across different soil types. The target point to the right of the monetary value represents the baseline scenario, while the surrounding bars depict results from various alternative scenarios. These scenarios consider varying levels of nutrient value and nutrient availability to crops. The step diagram illustrates the fundamental value components and their individual assessments for each soil and biochar type within the baseline scenario.

5.3 Liming effect

Biochar is an alkaline material, typically with a pH value of around 10 when produced from straw or biogas residue fibers. The exact pH value varies depending on the type of biomass used. However, it is important to note that biochar's alkalinity is relatively weak, and it cannot replace agricultural lime. Nevertheless, biochar helps maintain the soil's natural pH balance.

A study by Nissen et al. (2021) found that between 4 and 33 tons of biochar per hectare were required to increase soil pH by 0.1 units, depending on the biochar type. By comparison, achieving the same pH increase typically requires only 0.5 to 1.0 tons of lime per hectare, indicating that significantly larger quantities of biochar are needed to produce comparable effects on soil pH.

5.4 Soil structure and water holding capacity with biochar

Biochar's high porosity allows it to absorb and retain water exceptionally well, often holding an amount exceeding its own weight and, in some cases, several times its weight. This ability stems from the preservation of the plant material's structural features - such as capillaries and channels - during the biochar production process. Figure 6 shows an electron microscopic image of straw-derived biochar, highlighting these structural characteristics.

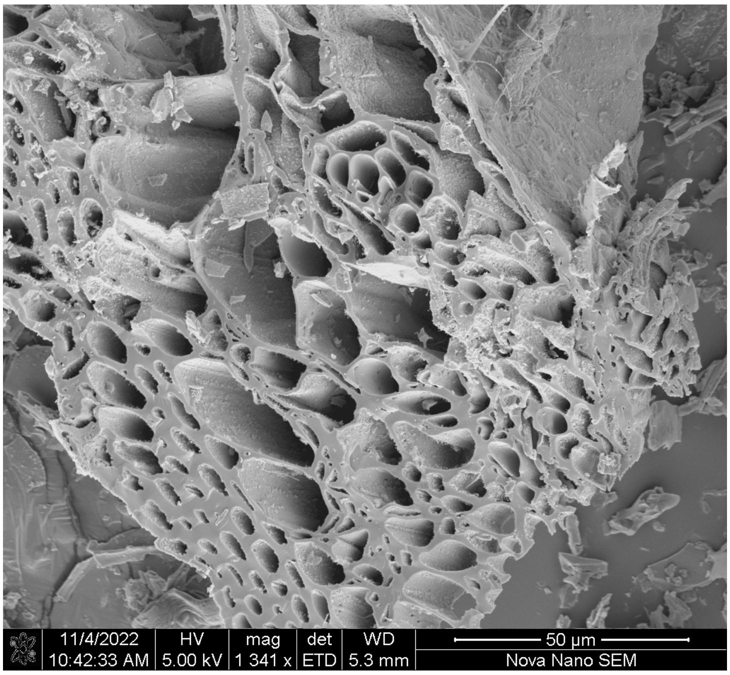

Figure 4: Electron microscopic image of finely shredded straw-based biochar showing that the pore structure of the plant material is retained in the biochar. This structure helps provide a high water-holding capacity. © Charlotte Skjold Qvist Christensen, AU.

Biochar can enhance the availability of plant-accessible water in soil, increasing it by approximately 5% in sandy soil and by 2% in clay soils when applied at a rate equivalent to 1% of the soil volume. The plough layer, approximately 20 cm deep, contains roughly 3.000 tons of soil per hectare. Thus, applying 1% biochar corresponds to 30 tons per hectare.

When finely ground to a particle size of less than 0.1 mm and applied to sandy soils, biochar can fill coarse pores, improving the soil's capillary effect and increasing its water-holding capacity. A study conducted by the University of Copenhagen on coarse sandy soils showed that adding 4% biochar increased the soil's water content from approximately 14% to 19% by late April, with this improvement sustained until June. However, achieving a 4% concentration requires applying relatively large quantities of biochar.

Improved water retention also helps reduce nitrate leaching by keeping nitrates in the soil for longer periods.

In addition to water retention, biochar enhances the soil's hydraulic conductivity, improving drainage and benefiting waterlogged soils. Enhanced water conductivity facilitates better air exchange and oxygen availability in the soil. This is particularly important for reducing emissions of nitrous oxide (N_2O), a potent greenhouse gas primarily produced under anaerobic (oxygen-deficient) conditions. By promoting oxygen availability, biochar mitigates anaerobic conditions, thereby reducing N_2O emissions. International studies have reported reductions in N_2O emissions of up to 38% following biochar application.

Furthermore, increased water conductivity promotes root development and supports the soil microbiome, including beneficial mycorrhizal fungi.

5.5 Nutrient contribution from biochar

Biochar typically releases nutrients into the soil and interacts with existing nutrients by adsorbing them onto its surface.

Similar to clay particles, biochar carries a negative charge, allowing it to bind positively charged nutrient ions. These ions are gradually released into the soil as needed by plants, improving nutrient availability over time.

Biochar primarily contains phosphorus, potassium, and small amounts of magnesium, sulfur, and micronutrients. For example:

- Biochar derived from biogas residue fibers generally contains 2-4% phosphorus and 3-5% potassium.
- Biochar produced from straw contains less than 1% phosphorus but a comparable potassium content to that of biochar from biogas residue fibers.
- Other nutrients, such as magnesium and sulfur, are present in trace amounts, typically less than 1%.

Additionally, biochar contains 1–2% nitrogen, which is tightly bound within its structure and not readily available for plant uptake.

Some highlighted nutrient availability studies:

- Danish studies found that the dry matter yields of lupine and wheat fertilized with biochar were comparable to those achieved using traditional fertilizers (Kristensen, 2020).
- Another study reported a phosphorus extraction rate from biochar of 34–49% over 16 weeks, nearly matching the 52% recovery rate observed with conventional fertilizers (Li et al., 2017).
- An English study revealed that 5–25% of the phosphorus added through fertilizer was recovered by crops within the same year (Poulton & Johnston, 2019). These findings suggest that the immediate plant-available phosphorus content in fertilizers is not the sole determinant of their effectiveness.

The general perception is that maximizing plant-available phosphorus in fertilizers is crucial, especially given the regulatory phosphorus ceilings imposed on individual farms. In conventional agriculture, the availability of phosphorus in biochar can be enhanced through acid treatment. In organic farming, fermenting biochar with compost has been shown to achieve similar results.

Stiesdal SkyClean conducted a pot experiment using biochar derived from biogas residue fibers to evaluate its fertilizing properties. The results of this experiment are presented in Figure 7.

Figure 5 Demonstration trials carried out by Stiesdal SkyClean in 2023 with spring barley grown in vermiculite.

1. *Without fertilizer*
2. *Fertilized with N & P in mineral fertilizers*
3. *Fertilized with N & K in mineral fertilizers*
4. *Fertilized with N in mineral fertilizer & biochar*
5. *Fertilized with N in mineral fertilizer & biochar treated with 10% sulfuric acid*
6. *Fertilized with N, P & K in mineral fertilizers.*

The fertilizer application rates were tailored to meet the crop's nutrient requirements: 150 kg of nitrogen (N) per hectare, 20 kg of phosphorus (P) per hectare, and 50 kg of potassium (K) per hectare. A blend of micronutrients was also added to all six pots. The pots were maintained in a greenhouse during the initial four weeks, and the accompanying photograph was taken eight weeks post-sowing.

5.6 The soil's carbon balance with biochar

Biochar primarily consists of carbon, with the remainder being ash. Biochar derived from biogas residue fibers typically contains 50-65% carbon, while straw-based biochar has a carbon content of 75-80%. The carbon in biochar is highly stable, enabling it to significantly increase soil carbon levels beyond what can be achieved with organic matter alone. From a climate perspective, biochar offers the advantage of sequestering carbon derived from atmospheric CO_2 for extended periods.

However, biochar cannot fully replace the incorporation of organic biomass into the soil. Decomposing organic material is essential for sustaining soil organisms that are critical to maintaining soil fertility. As a result, farming systems must strike a balance: part of the crop residues should be incorporated into the soil to support microbial life, while the remainder undergoes pyrolysis and is returned to the field as biochar. Contributions from roots, stems, harvest losses, and potential cover crops help sustain a readily decomposable supply of organic material and carbon in the soil.

International studies have reported yield improvements of up to 15% with the use of biochar, likely due to overall enhancements in crop growth conditions. However, similar results have not yet been observed in Danish studies, which lack data on long-term impacts. Danish soils are generally well-fertilized, structurally sound, and maintain normal pH levels, potentially reducing the extent of crop growth improvements observed elsewhere.

5.7 Precautions for the use of biochar

When applying very large quantities of biochar to soil, negative effects may occur, such as excessive adsorption of nutrients. This can lead to a reduction in soil organic matter, potentially resulting in CO_2 emissions. However, studies involving applications of up to 50 tons of biochar per hectare have not demonstrated harmful effects. As a precaution, current recommendations limit biochar application to 5-10 tons per hectare until further research and practical experience provide more comprehensive guidance.

The phosphorus content of biochar may also impose limitations on application rates due to regulatory phosphorus caps. These caps typically allow for approximately 30 kg of phosphorus per hectare, corresponding to 0.5-10 tons of biochar per hectare, depending on its phosphorus concentration. However, since the phosphorus cap is applied at the farm level, there is flexibility to distribute biochar across fields to optimize crop yield potential.

Biochar offers the unique ability to increase soil carbon levels beyond what is achievable with other biomass sources. When materials such as straw, crop residue, manure, or digested biomass are incorporated into soil over multiple years, an equilibrium is eventually reached, representing the upper limit of organic matter and carbon that the soil can retain. In contrast, biochar applications allow soil carbon levels to surpass this natural equilibrium, enabling greater long-term carbon storage in the soil.

6 Biochar and environmental safety

6.1 Generally

The pyrolysis process in a SkyClean plant is built on a pyrolysis technology developed over more than two decades of research at the Technical University of Denmark (DTU). This research has focused on the safe application of pyrolysis technology in agriculture and the potential of biochar as a climate solution. Continuous monitoring of the biochar for undesirable substances is ensured through certification.

6.2 Polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are tar-like substances formed during combustion and pyrolysis processes. Their formation is influenced by factors such as the type of biomass, the heating rate, the residence time in the reactor, and the pyrolysis temperature.

Although the formation of PAHs cannot be entirely eliminated, steps can be taken to prevent their deposition on biochar. This is achieved by avoiding the condensation of pyrolysis gases on the biochar's surface. The pyrolysis process developed by DTU is specifically designed to produce PAH-free biochar.

The SkyClean process incorporates built-in safety features to minimize the risk of tar condensation on the biochar surface. These measures include maintaining sufficiently high temperatures at points where the biochar interacts with pyrolysis gases, which prevents PAH condensation, and implementing a gas-flushing system to remove residual gases before the biochar exits the system.

Given the potential health risks associated with PAHs, their levels are regulated at both the EU and national levels. The relevant limit values are provided in Table 2.

	Limit	**Limit value origin**
16 EPA PAHs	< 6 µg/g DM	EBC Agro based on EU fertilizer regulation
8 EFSA PAHs	< 1 µg/g DM	EBC Agro based on EU EFSA
Benzo[e]pyrene Benzo[j]fluoranthene	< 1 µg/g DM per substance	EBC Agro based on EU REACH
11 PAH Compounds	< 3 µg/g DM	Danish Legislation on the use of waste for agricultural purposes.

Table 2: Limit values and origin of limit values for PAH compounds in biochar dry matter (DM) within the EBC Agro category.

Analyses of biochar from SkyClean in Skive show that all limit values have been complied with, as illustrated in Figure 8.

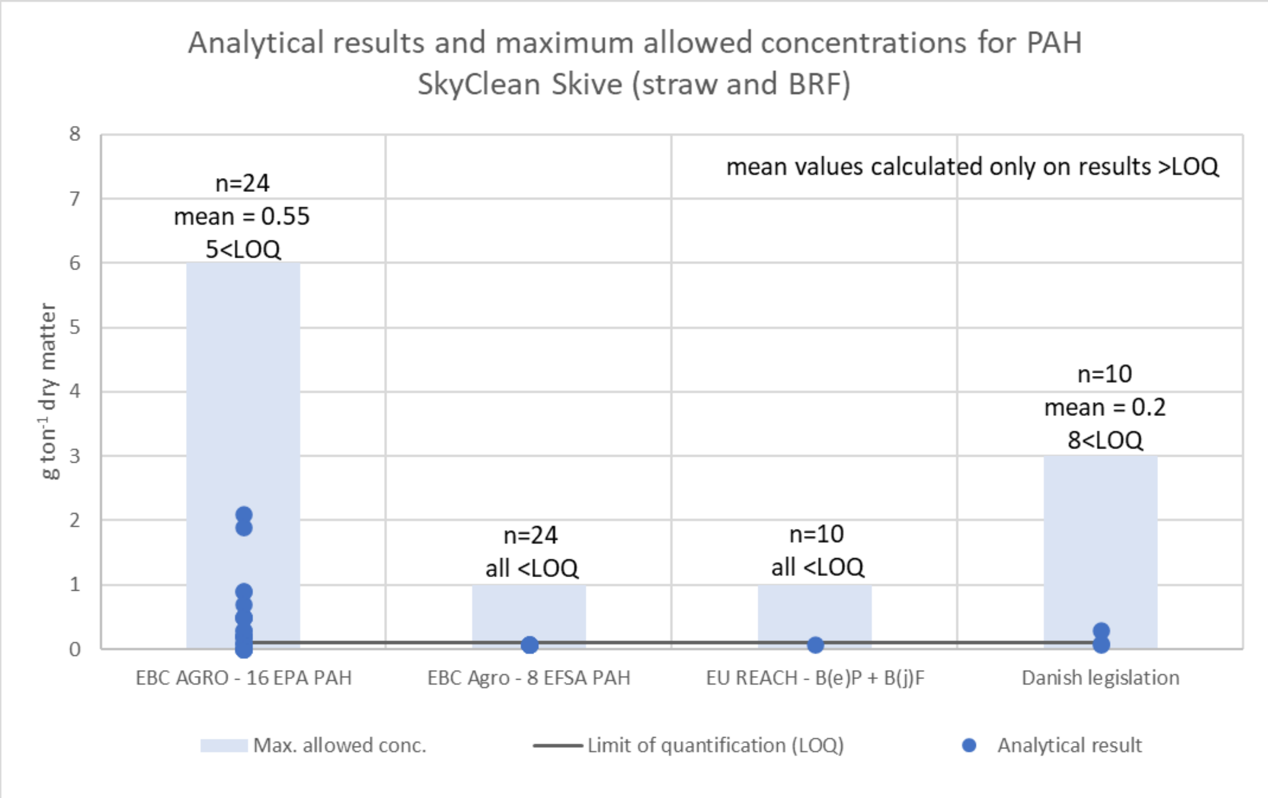

Figure 6: Analysis results from biochar produced at SkyClean plant in Skive. Limit values from EBC Agro, EU REACH and the Waste to Soil Executive Order.

6.3 Dioxins, furans and dioxin-like PCBs

Dioxins and furans are chemical compounds formed during the combustion of organic matter. The formation of dioxins, however, specifically requires the presence of chlorine during the combustion process.

Dioxin-like polychlorinated biphenyls (PCBs), once commonly used in building materials, have been phased out. Some PCB compounds exhibit toxicological effects similar to those of dioxins and are therefore classified within the dioxin group.

These substances are known to pose risks to human health and are regulated in food products in Denmark. However, there are currently no specific Danish regulations governing dioxins, furans, or dioxin-like substances in biochar for agricultural use.

The voluntary European Biochar Certificate (EBC) has established limits for these compounds, based on environmental protection standards from Germany and Switzerland. Biochar produced through the SkyClean process consistently meets these standards, as outlined in Table 3.

	EBC Agro limit	**SkyClean straw biochar**	**SkyClean BRF biochar**
Dioxins and furans I-TEQ (NATO/CCMS) upper-bound ng/kg TS	20	0,892	0,944
PCB Total 6 ndl PCBs (upper-bound) µg/kg DM	200	0,828	0,428

Table 3: Limit values from EBC for dioxins and furans and associated analytical values for biochar from SkyClean Skive.

6.4 Heavy metals

As plants grow, they absorb heavy metals from their environment, incorporating them into their biomass. During pyrolysis, most of the heavy metals present in the biomass remain in the biochar. Consequently, biochar can contain heavy metals if the original biomass used for pyrolysis is contaminated. Sources of heavy metals may include plant materials used in livestock feed or alloys in equipment and structures processing the biomass, such as barn fittings (Kofoed & Kjellerup, 1984).

While pyrolysis does not create new heavy metals, it can concentrate existing ones due to loss of feedstock mass during the pyrolysis process where part of the biomass is converted into gas.

Heavy metals are a diverse group of elements, with some posing significant health risks and others serving as essential trace elements, required in small amounts for optimal plant and animal growth.

The heavy metal content in biochar is regulated both nationally and at the EU level. The European Biochar Certificate (EBC) has established limit values for heavy metals in alignment with the EU Fertilizer Regulation.

In Denmark, environmental protection regulations governing the spreading of biochar are outlined in the Danish Legislation on the use of waste for agricultural purposes. This regulation ensures the recycling of nutrient-rich waste fractions for agricultural purposes while safeguarding the environment, humans, plants, and animals.

The Danish Legislation assesses heavy metal content either per unit of dry matter (DM) or per unit of phosphorus (TP), depending on the biochar's primary use. For straw-based biochar, where the focus is on dry matter, the applicable limits are based on dry matter. For biochar derived from biogas residue fibers, used primarily as a phosphorus fertilizer, the phosphorus-based limits apply, as specified in the Danish Environmental Protection Agency Guideline No. 9473.

Both types of biochar meet the specified limits under the EBC Agro category and the Danish Legislation on the use of waste for agricultural purposes, as illustrated in Table 4.

Heavy metals		EBC Agro limit value	Danish legislation	SkyClean straw biochar	SkyClean BRF biochar
Arsenic	mg/kg DM	13	-	*	1,8
Lead	mg/kg DM	120	120	*	
Pb/P	mg/kg TP	-	10000		96
Cadmium	mg/kg DM	1,5	0,8	*	
CD/P	mg/kg TP	-	100		*
Copper	mg/kg DM	100	1000	6	70
Nickel	mg/kg DM	50	30	*	
Ni/P	mg/kg TP	-	2500		2150
Mercury	mg/kg DM	1	0,8	*	
Hg/P	mg/kg TP	-	200		*
Zinc	mg/kg DM	400	4000	49	260
Chromium	mg/kg DM	90	100	2	16

Table 4: Limit values for heavy metals and analysis results for biochar produced at SkyClean Skive. An asterisk (*) indicates that the analysis, or a portion of the analysis used to calculate the ratio, is below the detection limit. Grey-shaded cells denote limit values that are not applicable to the specific biochar type; refer to the accompanying text for further explanation.

6.5 PFAS

Per- and polyfluoroalkyl substances (PFAS) are a large group of fluorinated compounds known to pose various health risks. Over the past decades, these substances have been widely used in applications such as firefighting foams, water-repellent agents, and food packaging materials. PFAS have become a growing concern due to their increasing detection in the environment and the recent tightening of regulatory limits.

Any presence of PFAS in biomass used for pyrolysis will largely depend on the origin of the material. Biomass sources closely linked to human activities, such as waste products, are more likely to contain PFAS. Research suggests that PFAS compounds decompose at the high temperatures achieved during pyrolysis. Stiesdal SkyClean has not conducted any PFAS related tests.

At present, no certification standards or regulations specify limit values for PFAS content in biochar. This regulatory gap underscores the need for further research and the potential development of future guidelines to address PFAS in biochar applications.

7 Stability and climate effect

7.1 Stability of biochar

Biochar is a method of capturing and storing CO_2 by converting a portion of the organic carbon in biomass into stable carbon compounds through pyrolysis. This process results in a net reduction of atmospheric CO_2, as the carbon sequestered in biochar is effectively removed from the active carbon cycle for extended periods.

Modeling studies suggest that pyrolyzing straw and biogas residue fibers, rather than incorporating them into the soil via ploughing, significantly increases the proportion of carbon retained after 100 years - from approximately 5% and 10%, respectively, to around 85% (Jensen et al., 2022). However, direct comparisons between pyrolysis and ploughing must consider differences in carbon retention. While pyrolysis converts roughly half of the biomass carbon into biochar, releasing the remaining carbon as climate-neutral pyrolysis gas, ploughing adds the entire carbon content of the biomass directly into the soil.

Recent research into the stability of biochar equates its carbon storage potential with that of geological storage technologies, such as DACCS (Direct Air Carbon Capture and Storage), BECCS (Bioenergy with Carbon Capture and Storage), and enhanced weathering. Enhanced weathering involves accelerating natural geological processes to facilitate the reaction of minerals with CO_2, converting it into stable carbon.

The stability of biochar is influenced by several factors:

- Pyrolysis temperature and residence time: The thermal treatment that biomass undergoes during pyrolysis is largely determined by the pyrolysis temperature, residence time in the reactor, and biomass characteristics such as moisture content and particle size. These parameters collectively play a critical role in the efficiency of carbon conversion and stabilization in the resulting biochar.

- $H:C_{org}$ ratio: The $H:C_{org}$ ratio, which represents the ratio of hydrogen (H) to organic carbon (C_{org}) in biochar, is an indicator of the degree of carbon restructuring during pyrolysis. A low $H:C_{org}$ ratio suggests extensive thermal conversion, with hydrogen being released as water vapor, resulting in a more stable biochar with a condensed carbon structure. Conversely, a high $H:C_{org}$ ratio indicates less restructuring, often linked to the presence of volatile compounds, leading to less stable biochar that is more prone to degradation over time. Biochar with a low $H:C_{org}$ ratio is preferred for long-term carbon storage due to its enhanced stability and prolonged sequestration potential.

- Soil temperature: The degradation of biochar is driven by microbial activity, which is influenced by soil temperature. Higher soil temperatures increase microbial activity, potentially accelerating the breakdown of biochar's degradable components. Therefore, soil temperature is a key factor in determining the long-term stability of biochar in the soil.

The carbon in biochar originates from atmospheric CO_2 absorbed by plants during growth. This absorbed CO_2 is stored in the plant as various organic compounds, from simple sugars to complex structural carbon compounds. During pyrolysis, approximately half of the carbon in the biomass is released as pyrolysis gas, while the other half is retained in the biochar.

The composition of carbon compounds in biochar varies based on the input biomass. For example, biochar derived from straw typically contains about 75-80% carbon, while biochar from biogas residue fibers contains approximately 50-65% carbon.

The pyrolysis process restructures the carbon in biomass, enhancing its stability. This transformation results in biochar containing a higher proportion of carbon compounds resistant to microbial decomposition compared to the original organic material. By disrupting the natural decomposition cycle of organic matter, pyrolysis enables long-term carbon storage in biochar. However, not all carbon in biochar is equally stable. Some of it consists of hydrocarbons, which are more biodegradable and have an average soil residence time of about 50 years (Schmidt et al., 2022). See Figure 9 for an illustration of this process.

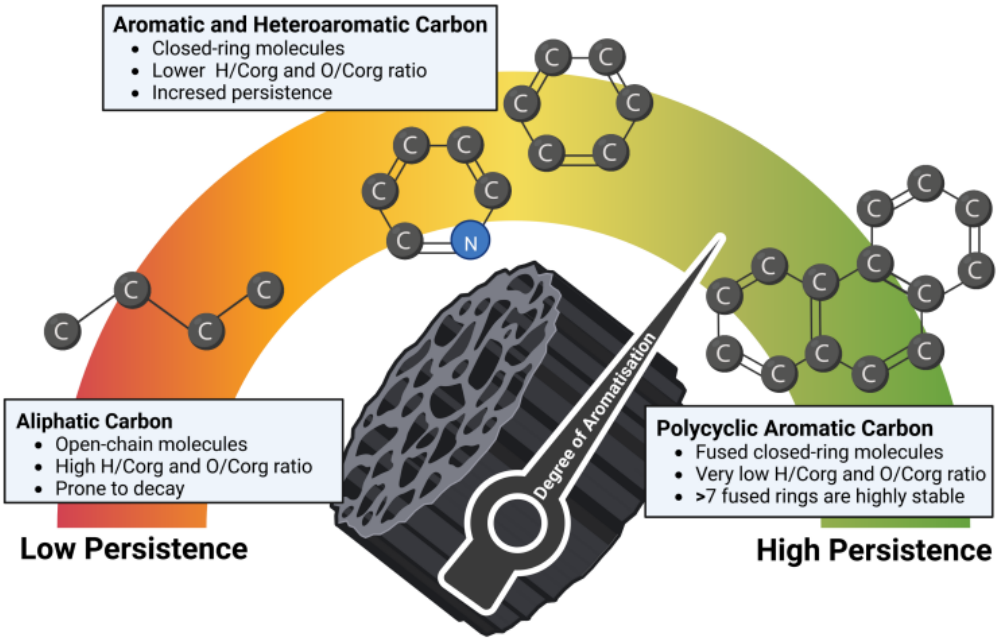

Figure 7: The stability of carbon in biochar and its connection to the restructuring of the carbon pools during pyrolysis. The higher the temperature used in the pyrolysis unit, the higher the formation of polycyclic aromatic carbon. The figure is from Schmidt et al 2022.

In scientific literature, pyrolysis temperature and the $H:C_{org}$ ratio are commonly used as primary indicators of biochar stability:

- Pyrolysis temperature: During pyrolysis, biochar is subjected to heating. With careful process monitoring and sufficient residence time in the reactor, the biochar's temperature can be estimated with high precision. The pyrolysis temperature strongly influences the carbon structure and stability of the resulting biochar.

- $H:C_{org}$ ratio: The ratio of hydrogen (H) to organic carbon (C_{org}) reflects the degree of carbon stabilization. As the organic material undergoes heating and stabilization, a significant portion of the hydrogen is released, primarily as water vapor. This ratio, determined through analytical testing, serves as an indirect measure of the carbon biodegradability in biochar. Lower $H:C_{org}$ ratios indicate higher carbon stability and reduced susceptibility to microbial degradation.

Biochar stability is used to estimate the proportion of carbon that remains stored over a 100-year period, following guidelines from the United Nations Framework Convention on Climate Change (UNFCCC). The Intergovernmental Panel on Climate Change (IPCC) defines this as the "permanence factor" (F_{perm}), which quantifies the fraction of carbon applied as biochar that persists after 100 years. This factor is expressed as a percentage or fraction, providing a standardized measure of biochar's long-term carbon storage potential.

The stability of SkyClean biochar at average Danish soil temperature:

At a depth of 10 cm, the average annual soil temperature in Denmark is 9.8°C (AU Knowledge Synthesis). Test results indicate that the $H:C_{org}$ ratio of SkyClean biochar is 0.3 F_{perm}. Using the constants provided by Woolf et al. (2021), the permanence factor (F_{perm}) for 10°C soil is:

F_{perm} = 1.10 – 0.59 * 0.3 = 0.92.

This calculation suggests that 92% of the carbon in SkyClean biochar remains sequestered in the soil for at least 100 years under Danish soil temperature conditions.

The determination of the permanence factor (F_{perm}), as defined by the IPCC, is based on a meta-analysis of data concerning the degradation rates of biochar in soil. Only studies that report both the pyrolysis temperature and the $H:C_{org}$ ratio of the biochar are included in the analysis. Because the experiments were conducted at varying soil temperatures, and temperature significantly affects microbial turnover rates, all data were normalized to reflect a standard soil temperature of 14.9°C - the average global temperature for agricultural soils (IPCC, 2019; Woolf et al., 2021). For comparison, the IPCC (2019) uses a similar approach for calculating F_{perm} but employs a standard soil temperature of 20°C.

The meta-analysis demonstrates a strong correlation between F_{perm} and both the pyrolysis temperature and the $H:C_{org}$ ratio, as shown in Figure 10. However, some variability in the data is observed, which may be attributed to factors such as differences in biomass type, residence time, soil type, and other experimental conditions.

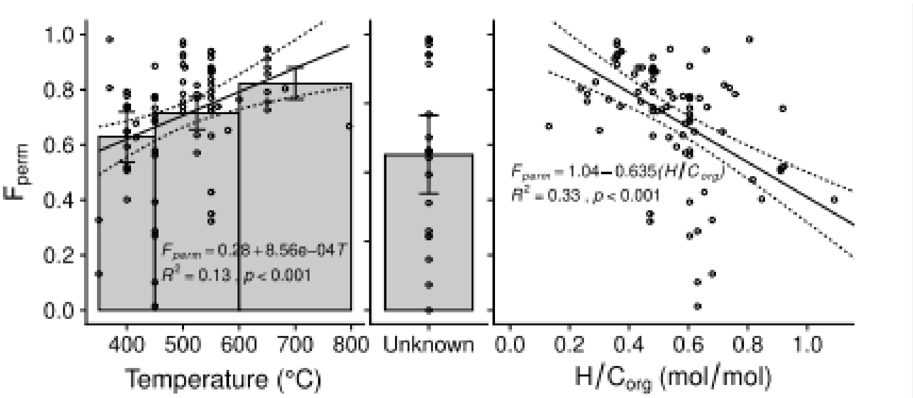

Figure 8: Correlation between carbon storage efficiency expressed as F_{perm} based on pyrolysis temperature and $H:C_{org}$ ratio. The figure is from Woolf et al (2021), a similar correlation is used by the IPCC (2019).

A portion of biochar undergoes microbial degradation in the soil, primarily driven by bacterial activity. Bacterial metabolic rates are highly temperature-dependent, with a general rule of thumb indicating that turnover rates double for every 10°C increase in soil temperature. The correlations presented by Woolf et al. (2021) incorporate this temperature effect, providing estimates of biochar turnover rates under varying soil temperature conditions.

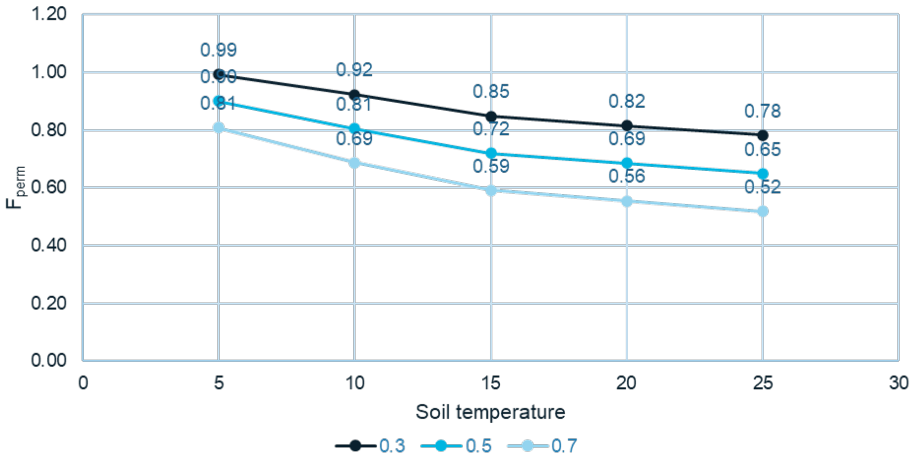

Figure 11: Illustration of the combined effects of the H:C_{org} ratio and soil temperature on biochar stability (F_{perm}). Each curve in the graph represents a specific H:C_{org} ratio (0.3, 0.5, and 0.7, respectively). The graph demonstrates that higher soil temperatures (x-axis) are associated with a lower proportion of biochar remaining in the soil after 100 years. Furthermore, biochar with a lower H:C_{org} ratio exhibits greater stability. The figure is based on data from Woolf et al. (2021) and Table 3.

7.2 New knowledge about the stability of biochar

Biochar contains various carbon pools and compounds, each with differing levels of stability. Some carbon compounds decompose rapidly, while others are highly resistant to degradation. Incubation experiments, typically conducted over short durations, tend to emphasize the turnover of rapidly metabolized carbon compounds. This can lead to an overestimation of the overall turnover rate, as the more stable carbon fractions are underrepresented in these studies.

Recent research provides a more nuanced understanding of biochar's carbon stability. For biochar with an H:C_{org} ratio below 0.4, the carbon pool can be divided into two categories: approximately 25% of the carbon is estimated to have a stability of 50-100 years in soil, while the remaining 75% is expected to remain stable for over 1000 years (Schmidt et al., 2022). See Figure 12 for an illustration of these carbon pools.

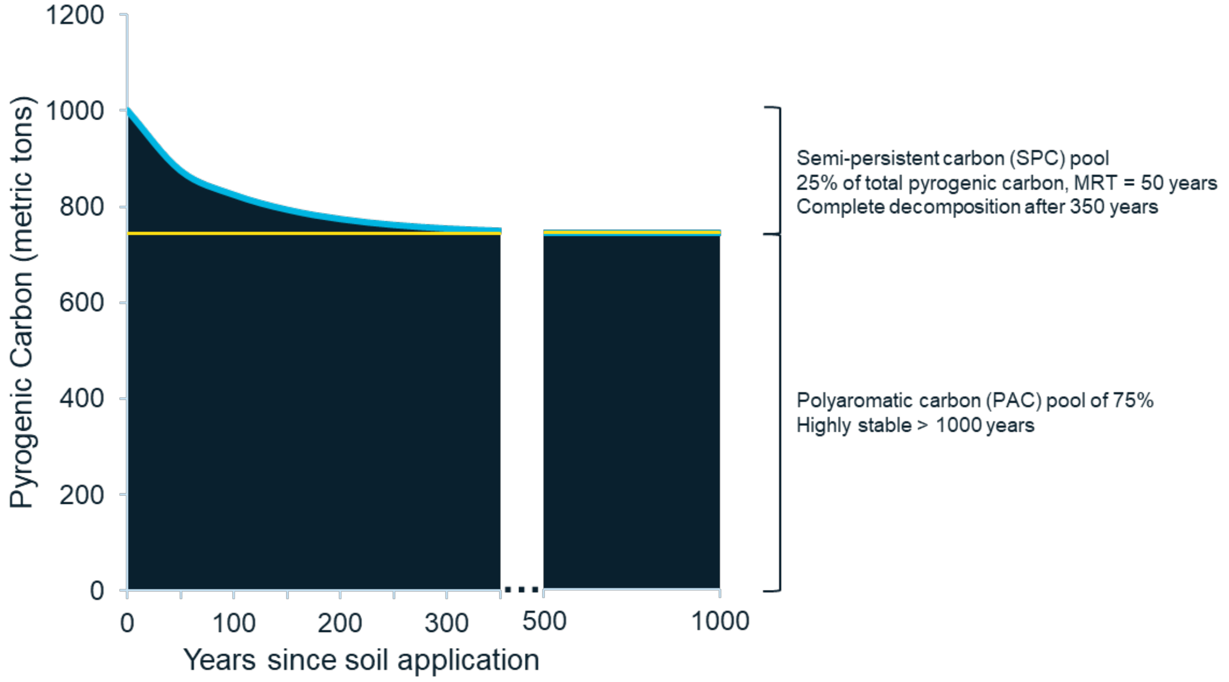

Figure 9: Carbon stability as described by Schmidt et al 2022, categorizing the carbon pool into a degradable fraction and a highly stable pool. The figure is from the article.

Geological analysis methods for examining carbon composition have recently been applied to study the stability of biochar's carbon pool (Petersen et al., 2023; Sanei et al., 2024). Consistent with F_{perm} analyses, these studies indicate that higher pyrolysis temperatures and extended residence times promote greater aromatization within the carbon pool. Aromatization refers to the formation of aromatic carbon compounds, which are significantly more resistant to degradation.

Petersen et al. (2023) reports that biochar derived from wood, plant material, and fruit-based agricultural residues contains over 97% of its carbon pool in a geochemically stable form that is inaccessible to soil microorganisms. According to the study, this carbon would require combustion at temperatures ranging from 300°C to 850°C in an oxygen-rich environment to be broken down or transformed.

8 Legislation on biochar in Denmark and in the EU

8.1 National legislation

The regulatory framework for biochar use in Denmark remains uncertain. Currently, spreading biochar requires a permit under Section 19 of the Environmental Protection Act.

Stiesdal is advocating for biochar to be classified in two distinct ways:

- As a soil improver if it contains low levels of phosphorus and other nutrients.
- As an organic fertilizer if its phosphorus and nutrient content is higher.

Biochar differs from traditional organic fertilizers, such as livestock manure, which means some regulations need to be adapted. According to the guidelines for fertilization and nutrient management for the period August 1, 2023, to July 31, 2024, biochar is regulated under the rules for processed livestock manure or other processed organic fertilizers, depending on the input material used to produce the biochar. For instance, if livestock manure is used in a biogas plant, biochar produced via pyrolysis of biogas residue fibers will likely also be classified as processed livestock manure and therefore subject to livestock manure regulations.

Under the regulations governing livestock manure, processed livestock manure with a dry matter content of 26% or more can be stored in field stacks. Additionally, such manure must be covered with a tight-fitting, waterproof material immediately to prevent ammonia emissions. However, since biochar contains negligible amounts of nitrogen, the risk of ammonia emissions is minimal (Elsgaard et al., 2022).

The Danish Agricultural Agency updated the regulations for applying biochar under the new fertilizer application rules, effective from August 1, 2023. Biochar is now exempt from restrictions on application during closed periods and from rules requiring incorporation into the soil. This means that biochar can be spread year-round, provided it respects field and crop conditions and minimizes dust issues. Additionally, the agency has set the nitrogen efficiency of biochar at 0% in the fertilizer accounting system under the updated fertilization rules for the 2023/2024 planning period, which also came into effect on August 1, 2023.

8.2 Biochar in organic farming

Biochar intended for use in organic farming must be produced exclusively from plant-based materials, such as straw and wood, that are either unprocessed or processed only with products approved under organic farming regulations. As a result, organic farmers are prohibited from using biochar made from biogas residue fibers.

Although biochar does not need to be produced from organic biomass to be eligible for use in organic farming, its application must be included in the fertilizer plan, and a justification for its use must be documented in accordance with the Guidelines on Organic Agricultural Production. While the guidelines do not specify the exact content of such justifications, examples may include references to biochar's soil-improving properties or its liming effect.

8.3 EU rules – CE marking

Biochar produced through the pyrolysis of crop residues can currently be CE-marked as a fertilizer product under Component Material Category 14 of the EU Fertilizer Regulation (Regulation (EU) 2019/1009 of the European Parliament and Council, dated June 5, 2019).

A recent update to the EU fertilizer scheme has reclassified biogas residual fibers from waste to an organic fertilizer product. As a result, biochar derived from the pyrolysis of biogas residual fibers can now also be CE-marked as an organic fertilizer product.

While biochar does not require explicit approval as a fertilizer or soil improvement product under the EU Fertilizer Regulation, it must be formally reported and comply with the quality control standards outlined in Module D1 of the regulation. This mandates that biochar production is monitored through an ISO 9001-based quality control system, which is subject to external auditing by a third-party "conformity assessment body." This body is responsible for verifying production standards and conducting sample-based quality testing. Discussions are ongoing with potential external auditing and accreditation organizations to fulfill this role.

Limitations of CE marking:
- Strict tolerances for nutrient content must be maintained.
- Nitrogen (N) content must be declared.
- National regulations remain applicable; for example, CE-marked biochar still requires approval for spreading under Section 19 of the Danish Environmental Protection Act.

In Denmark, biochar can also be registered as a fertilizer and soil improvement product under the Fertilizer Order until further notice. While the national regulatory framework imposes less stringent requirements compared to CE marking, biochar that is not CE-marked cannot be traded across national borders.

8.4 EU REACH

REACH, which stands for Registration, Evaluation, Authorization, and Restriction of Chemicals, is a European Commission regulation designed to ensure the safety of approximately 100.000 chemical substances used within the EU, protecting both human health and the environment.

Under REACH, the registration of chemical substances is mandatory for chemicals manufactured or imported in quantities exceeding 1 ton per year within the EU. For biochar producers, REACH registration can be obtained as a sub-registration under the existing registration for charcoal. This process is facilitated through a Letter of Access (LoA), which grants permission to reference the technical dossier associated with the charcoal registration. The current cost for data access to the charcoal dossier is €25.700, with an additional processing fee of €25.000 for the application.

A REACH registration applies to a single legal entity. This allows a company operating multiple SkyClean facilities to consolidate all plants under one REACH registration, streamlining compliance and reducing administrative costs.

9 EBC certification of biochar

The European Biochar Certificate (EBC) is a voluntary standard for biochar producers, aimed at promoting the sustainable and safe production of biochar while ensuring its quality. Among its services, the EBC offers a C-sink certificate, which evaluates the climate footprint of biochar production from the sourcing of biomass to its departure from the pyrolysis plant. The certification process is verified by an independent third party.

The EBC standard includes various classifications based on the intended use of biochar. For biochar used as a fertilizer or soil improver in conventional agriculture, certification is provided under the EBC-Agro category.

EBC-Agro certification complies with all requirements of the EU Fertilizer Regulation (EU 2019/1009) and adheres to the limit values for potentially harmful substances outlined in the EU REACH Regulation. The EBC standard may also incorporate country-specific legislative requirements in annexes to address national regulations.

The EBC C-sink certificate assesses the climate impact of biochar production by considering:

- The carbon content of the biochar
- Transportation of biomass to the pyrolysis plant
- Energy consumption and greenhouse gas emissions during production

To account for the complete climate impact and qualify for climate credits associated with biochar storage in agricultural soils, emissions from transportation and spreading must also be deducted from the overall climate footprint.

10 Biochar and CO_2e credits

10.1 Carbon accounting

Biochar contains a significant proportion of highly stable carbon, making it an effective solution for long-term carbon storage. Furthermore, biochar is regarded as a carbon-negative climate measure, as its production and use result in the removal of more CO_2 from the atmosphere than is emitted during its production and transportation.

The carbon accounting framework for biochar quantifies the amount of carbon stored while factoring in emissions associated with its production, transportation, and application. This accounting encompasses three key metrics:

- Gross carbon storage potential
- Total CO_2e emissions from production
- Net carbon storage potential per ton of biochar

CO_2e

The production, transportation and delivery of goods and services generate a variety of greenhouse gases, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases differ in their impact on the climate, with the relative effects following the hierarchy: $CO_2 < CH_4 < N_2O$.

The CO_2e emissions of a good or service are calculated by summing the contributions of individual greenhouse gases, each converted to an equivalent amount of CO_2 per unit (kg, tons, km, etc.).

This carbon accounting determines the proportion of carbon effectively stored in biochar. The calculation is based on the total carbon content of the biochar, adjusted for CO_2e emissions generated during biomass production, biochar production, transportation, and application.

The carbon content of biochar is derived from analytical data and accounts for losses due to microbial turnover in the soil. These values are calculated using the methodology required for issuing a C-sink certificate (see Chapter 7 on Certification).

A C-sink certificate documents the carbon accounting of stored biochar and includes three key figures:

- Gross carbon storage potential expressed in tons of CO_2e
- Total CO_2e emissions from the production of biochar, expressed in tons of CO_2e and including emissions from biomass management
- The net carbon storage potential in tons of CO_2e per ton of biochar

The total carbon account, which forms the basis for calculating tradable CO_2e credits, also includes emissions that occur after the biochar leaves the pyrolysis plant. These emissions include the biochar's transportation, application, and the estimated amount of carbon remaining in the soil after 100 years.

10.2 CO_2e credits

The value of CO_2e credits is calculated based on the total carbon balance of biochar. This includes the potential CO_2e storage of the biochar, minus all emissions related to its production, transport, and application. The calculation can be summarized as:

CO_2e credit =
The total CO_2e storage potential of the biochar

Minus emissions from biomass production, such as cultivation, harvesting, and processing.
Minus emissions from the pyrolysis process.
Minus emissions from transporting the biochar.
Minus emissions from applying the biochar.
Minus emissions from the portion of carbon in the biochar that could eventually be released.
Minus a 10% safety margin for uncertainties.

Figure 13 provides an overview of how these factors are combined.

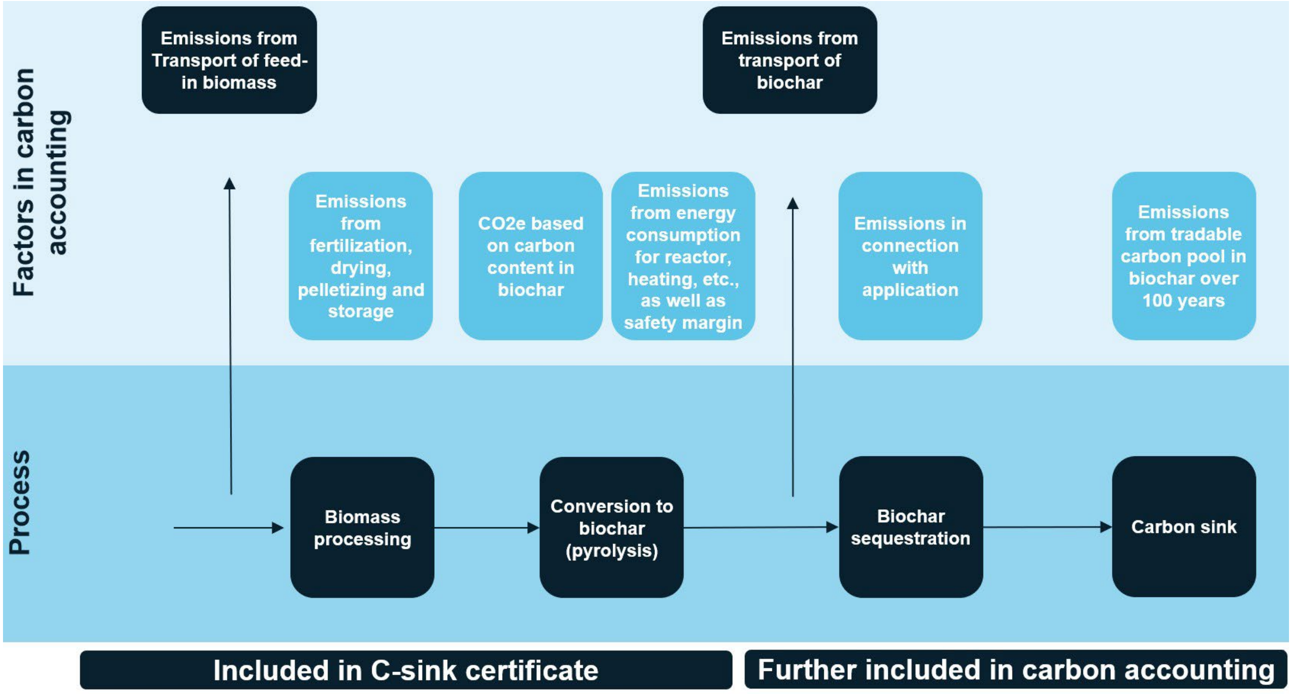

Figure 10: Overview of carbon accounting and associated processes and the factors included in the C-sink certificate and in the final carbon account.

10.3 Example C-sink certification from a 20 MW plant based on biogas residual fibers

When SkyClean operates in direct collaboration with a biogas plant, using biogas residual fibers as input biomass, it achieves a gross carbon removal of approximately 32.000 tons of CO_2e annually. After factoring in a 27% reduction due to emissions and soil turnover, the net carbon removal is estimated at 23.386 tons of CO_2e per year. Detailed calculations are presented in Table 5 and illustrated in Figure 14.

Carbon accounting	Amount [t CO_2e]
Gross carbon removals per year	31.981
Gross project emissions incl. reduction to permanence per year	8.595
Emissions: carbon removal ratio	0,269
Net carbon removals per year	23.386
Net carbon removal over the lifetime of the project (25 years)	584.642

Table 5: Carbon accounts for 20 MW SkyClean facility at a biogas plant

When biogas residue fibers are used as biomass (see Figure 14), the EBC certification standard classifies this as a residual product, meaning no CO_2e emissions are attributed to it. Furthermore, since the SkyClean plant is co-located with the biogas production facility, there are no transport-related emissions for the biomass. Drying of the biomass is carried out using climate-neutral energy from surplus heat generated during the pyrolysis process, and the energy required for pelletizing is sourced from renewable, climate-neutral energy.

The soil turnover rate in this example is based on the certification methodology established by the EBC, which assumes a fixed annual degradation rate of 0.3% over 100 years. This results in a total reduction of 26% in the amount of carbon eligible for conversion into CO_2e credits. However, recent research suggests that the metabolizable portion of the carbon pool in biochar is smaller than previously estimated, with the remaining fraction being highly stable (see Section 9.1).

Schmidt et al. (2022) estimate that 25% of the carbon in biochar is metabolizable and will fully decompose over 350 years, while the remaining 75% is expected to remain stable for more than 1000 years. It is anticipated that this new understanding will soon be integrated into the EBC methodology for determining CO_2e credit allocations.

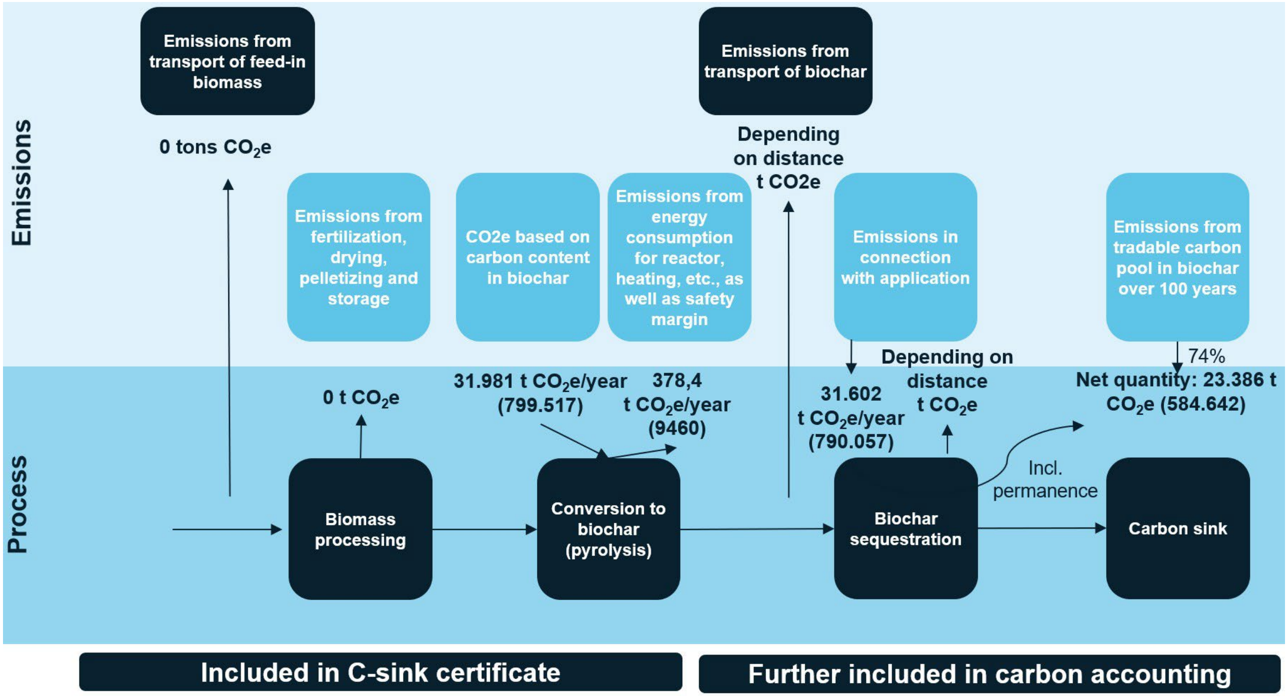

Figure 14: Overview of the carbon accounting for a 20 MW SkyClean plant integrated with a biogas facility, illustrating the annual contributions and the totals over a 25-year project lifespan (shown in brackets). This calculation does not include emissions associated with transporting biochar from the SkyClean facility to its final application site.

Over an estimated 25-year operational lifetime, a SkyClean plant has the potential to remove nearly 600.000 tons of CO_2e from the atmosphere on a net basis.

The net carbon removal represents the amount of carbon eligible for conversion into CO_2e credits. It is important to note that this figure does not capture the full climate impact of a SkyClean plant over its lifecycle. A significant portion of the climate benefits from biomass pyrolysis comes from the production of climate-neutral energy, which can replace fossil fuels. Additionally, stabilizing biologically active material in farm storage tanks reduces methane emissions, offering further climate benefits not reflected in this calculation.

Other factors excluded from this analysis include secondary soil effects, nitrogen losses, and the climate impacts associated with the construction, commissioning, and maintenance of the facility.

Preliminary studies on Danish biomass pyrolysis estimate an average climate benefit of approximately 1 ton of CO_2e per ton of dry matter processed. Furthermore, new methodologies and models are being developed to provide an even more comprehensive assessment of the climate and environmental impacts of Danish biomass pyrolysis, with results expected to be published in the coming years.

10.4 Sale of CO_2e credits

CO_2e credits, also known as CO_2 Removal Certificates (CORCs), represent quantified amounts of CO_2e removed from the atmosphere, measured in tons. These certificates are traded on specialized platforms that act as intermediaries between sellers and buyers. Sellers are organizations implementing climate measures, such as biochar production, who verify that the carbon has been permanently removed from the carbon cycle through its application and stabilization in storage. Buyers are typically organizations seeking to offset their own emissions by purchasing credits equivalent to their carbon footprint.

For carbon storage involving biochar, trading platforms require certification from standards such as the European Biochar Certificate (EBC) or equivalent systems. Certification ensures full traceability of the process and verifies the quality of the biochar, including compliance with regulatory limits.

The volume of CO_2e credits available for sale is determined through comprehensive carbon accounting, as detailed in Figure 13 and exemplified in Figure 14. This accounting includes emissions associated with transporting the biochar to its final storage location, converted into CO_2e. The entity responsible for biochar storage must confirm that the application has been completed, supported by documentation such as field plans or approvals under Section 19 of applicable environmental regulations. In the future, these verification steps may become automated.

CORCs can be traded after carbon storage is verified or as Pre-CORCs, which are issued before storage is completed. Pre-CORCs provide upfront capital for carbon-negative initiatives, enabling organizations to secure future negative emissions to meet carbon neutrality goals. Trading platforms issue publicly accessible certificates confirming the amount of carbon sequestered, ensuring transparency and accountability.

11 Other uses of biochar

This white paper focuses specifically on the application of biochar in the agricultural sector. This emphasis is driven by the significant nutrient content in the biomass types most commonly available in Denmark, which are prioritized for reintegration into the soil. In cases where nutrient recycling is less critical, biochar can also be utilized in other industries.

Biochar shares some properties with activated carbon, though to a lesser degree. It can be used in applications such as filtration and as an additive in animal feed without requiring further processing.

In the construction and materials industries, biochar is a versatile material. Its high porosity and humidity-regulating properties make it suitable for use as a filler in products like concrete and as an insulation material. In composite materials, biochar enhances UV resistance, thereby extending product lifespan.

The extent to which biochar acts as a carbon store depends on its application. The longevity of carbon sequestration is influenced by how the biochar is used and managed post-application. In some applications, microbial degradation is prevented, making the degradation rate irrelevant for carbon accounting.

Schmidt and Wilson (2014) provide a detailed overview of biochar application areas in their article. Additionally, *The European Biochar Industry Consortium* (EBI) summarizes these applications, as shown in Figure 15.

Figure 11: Areas of biochar application, as defined by EBI. The figure's source is https://www.biochar-industry.com/biochar/.

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