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Biochar usefulness in achieving goals of carbon farming and sustainable agricultural systems

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Abstract. This paper presents an overview of the literature research on the benefits of biocarbon (biochar) as an important part of sustainable agriculture and carbon farming. The main objective was to familiarise the reader with the literature findings on the effects of biocarbon application on the environment, soil, soil organic mater, soil microorganisms, and impact on crop yields. On the basis of the research presented, it can be concluded that the incorporation of biocarbon into the soil generally has a positive effect on soil fertility, but that proper application is required (mainly its application together with fertilization). The quality, properties, and agricultural usefulness of the biochar depend on the raw material that has been subjected to the pyrolysis process, as well as the temperature and time of. The findings of the paper are based on the literature review on the subject.

Keywords: biochar, sustainable agriculture, soil organic matter, carbon farming

INTRODUCTION

Climate change has a major impact on agriculture, with varying effects on production patterns, crop yields, and post-harvest characteristics. The negative impact on crop productivity can affect food security and livelihoods in different regions (Khakimov et al., 2020). Extreme weather events, such as droughts and floods, limit the ability of farmers to effectively adapt to and mitigate the effects of climate change, thereby increasing the risk of yield losses (Nikitin et al., 2022). To mitigate these negative impacts, it is essential to develop adaptation strategies to address the challenges posed by climate change in agriculture. These strategies include the adoption of climate-smart agricultural practices, changes in crops and varieties, improved water management strategies, and adapted plant nutrition and protection practices, with the aim of increasing food productivity, building resilience in agricultural systems, and reducing greenhouse gas (GHG) emissions (Mussa et al., 2015; Jolánkai et al., 2019). Climate change affects agriculture through higher temperatures, changes in precipitation, and increased atmospheric CO_2 concentrations. This can directly affect crop growth rates and affect the productivity of plants and animals. On the other hand, greenhouse gas emissions from agriculture, particularly methane and nitrous oxide, contribute significantly to global emissions. Nitrate leaching and ammonia volatilisation can reduce agricultural GHG emissions (Sinha et al., 2018). Farmers will need to adapt to the significant impacts of climate change on agriculture while taking into account the sector's contribution to greenhouse gas emissions and carbon storage in soils. Policymakers should design policies that address climate change issues in agriculture, taking into account the relative costs of different actions to reduce greenhouse gas emissions. Agricultural practices can influence the microclimate and macroclimate, which can affect the global climate. Agriculture accounts for a significant amount of greenhouse gas emissions, mainly methane and nitrous oxide. Land-use change in agriculture can also alter the albedo of the Earth's surface, which affects the absorption of solar energy (Kang, Banga, 2013; Mehraj et al., 2022). The fundamental factors that directly affect yields are habitat, weather and climatic conditions (Guo et al., 2008; Szwejkowski et al., 2008). It is estimated that the negative effects of high temperature, salinity, drought, and stress from the use of crop protection products can contribute to yield losses of up to 30% (McKeown et al., 2006; Sowa, Linkiewicz, 2007). To increase food production, breeding efforts are underway worldwide to produce higher-yielding crop varieties. Agrotechnical advances promote more efficient use of nutrients (Ladha et al., 2005; Anioł, 2010). Moreover, agricultural intensification leads to losses of organic matter of soil, which should be compensated by applications of manure or other natural or organic fertilis-

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ers (sources of organic carbon), including straw and crop residues (Maćkowiak, 1998). The basic indicator of the soil quality, fertility and health is the content of organic matter. According to studies, a significant part of world's agricultural land has lost up to 75% of its organic carbon compared to natural soils that have not been cultivated and fertilised with artificial fertilisers. Conservation agriculture has been identified as a promising way to mitigate the effects of climate change in agriculture by reducing greenhouse gas emissions and promoting sustainable land management practices (Karki, Gyawaly, 2021). The integration of bioenergy and food production systems is also needed to reduce the negative impact of agriculture on climate (Smith, Olesen, 2010). In recent years, products and substances which, when introduced into the soil environment, have a beneficial effect on soil structure and fertility have also gained in popularity. An alternative to increasing the amount of organic matter can be the introduction of carbonised biomass (known as biocarbon or biochar) into the soil environment. A positive or at least neutral soil organic matter balance is crucial for sustainable farm management, as soil carbon content is one of the main drivers of soil health, which defines the ability of the soil to provide ecosystem services that underpin sustainable agriculture (Kuś, Krasowicz, 2001). Biocarbon derived from organic sources through pyrolysis has been identified as a potential soil amendment for carbon sequestration, contributing to long-term climate change mitigation (Wyzińska, Smreczak, 2019). The use of biocarbon in agriculture has shown promising results in improving crop productivity, soil health, and carbon sequestration, thus providing a sustainable solution for agricultural practices (Wyzińska, Smreczak, 2019; Czekała et al., 2022). The use of biocarbon has been promoted as part of climate change initiatives, such as the Kyoto Protocol and Reducing Emissions from Deforestation and Forest Degradation (REDD+), highlighting the importance of biocarbon in addressing climate change challenges (Dimobe et al., 2018).

THE CHALLENGES

Climate change is probably the most important challenge for agriculture today. It is leading to shifts in precipitation patterns, more frequent extreme weather events and negative impacts on crop growth and quality (Keutgen, 2023). The growing world population and the need to feed it will require a 70% increase in agricultural production, while agricultural activities are already impacting planetary boundaries, is another challenge for global agriculture (Grimblatt, 2021). Chemical fertilisers are widely used to bridge the gap between food production and consumption, but can harm the environment and human health (Rehmaan et al., 2022). Widespread use of chemical fertilisers has led to ecosystems and climate degradation, highlighting the need for alternative approaches. Improved fertiliser use efficiency (FUE) has been proposed to achieve economic yields and a safer environment, contributing to more sustainable agricultural systems (Aziz et al., 2015).

The Food and Agriculture Organization of the United Nations defines sustainable development as the use and conservation of natural resources and the orientation of technologies and institutions in such way that the satisfaction of human needs can be achieved and maintained for present and future generations (Wilkin, 2003). The main objectives of agricultural sustainable development are the conservation of soil, water, and natural resources, the use and conservation of plant and animal genetic resources, the protection of the environment, and the use of appropriate technologies that make agriculture economically viable and socially acceptable in the long term. Sustainable agriculture is a key to extensification of modern, intensive production with high levels of chemical plant protection products input and excessive use of heavy machinery (Kutkowska, 2007). Alternative, more environmentally friendly agricultural systems (organic, sustainable and integrated farming systems) are designed to balance the use of the biological potential of plants with soil conservation (Robertson, Harwood, 2001). A sustainable farming system mainly involves the rational use of natural resources, aimed at reducing the negative impact of farming practices on the environment, often by preventing the loss of soil organic matter. Biocarbon in sustainable agriculture can be used in a number of applications, including soil improvement, carbon sequestration and the development of environmentally friendly materials. It has been identified as a sustainable filler for composite materials, offering reduced environmental impact and a lower carbon footprint (Chang et al., 2020). Biocarbon can help with restoration of heavy metal-contaminated soils through biosorption, providing an effective and sustainable method of soil remediation (Rana et al., 2021; Shell et al., 2021). Agricultural applications of biocarbon are mostly associated with its ability to improve soil fertility and mitigate climate change through carbon sequestration (Haider et al., 2020).

Reaching a neutral or positive balance of organic matter in the soil is currently a challenge. Soil organic matter (SOM) is lost from agricultural soils due to several factors. Land use change is one of such factors. Shift from natural, native vegetation to modern, intensive agricultural practices increases the mineralization rate of SOM, leading to a decrease in soil carbon (C) levels (Chen et al., 2022). High crop residue inputs do not necessarily result in significant increases in SOM levels, as factors such as soil physical properties, residue quality, decomposition of native SOM, and partitioning of residue C can affect SOM stabilisation (Brichi et al., 2023). Crops residues, deposited in soil after harvest, decompose rapidly due to microorganism activity (Sapek, 2010). Understanding the effects of land use change, organic residue management, and anthropogenic activities is crucial to mitigate SOM loss and promote sustainable agricultural practices. The main organic component of SOM is humus (humic acids, humin and mineral-organic compounds). Humus is mainly composed of elements such as carbon (about 60%), oxygen (30%), nitrogen (about 10%), phosphorus and sulphur (about 1% each) and trace elements.

Carbon farming is an approach to land management that aims to sequester carbon in soils and plants, thereby reducing greenhouse gas emissions. It involves implementing environmentally friendly strategies such as biochar application, agroforestry, and agro-ecological management to increase carbon storage and reduce emissions (Sharma et al., 2021; Leifeld, 2023; Nogués et al., 2023). By incorporating practices that promote carbon farming, such as soil amendment with biochar and integration of trees and crops with livestock, it is possible to increase carbon sequestration and reduce greenhouse gas emissions from agricultural systems (Sharma et al., 2021). Carbon farming has the potential to improve soil health, increase soil water-holding capacity, and benefit pollinator communities, thereby contributing to more sustainable food production and increased resilience of agricultural systems in the face of climate change (Sardiñas et al., 2022).

Biocarbon (biochar) is an excellent source of organic matter. It can solve a number of the agricultural challenges we face today, such as the overuse of synthetic fertilisers in agriculture which often leads to nutrient run-off to waterways. The chemical composition of biochar varies depending on the type of biomass used to produce it, but also on the time and temperature used during the carbonization process. It can contain 9–90% carbon, 1–34% water, 0–40% volatiles and 0.5–5% micro- and macronutrients (Wilkin, 2010). The effectiveness of the carbonisation process in terms of carbon content in final product, varies for different substrates used for carbonisation. This is due to their chemical composition, including moisture content (Gładki, 2017). Some examples of carbon content in biochar obtained from different substrates are given in Figure 1. Biocarbon is also resistant to microbial decomposition and can persist in soils for hundreds of years (IBI, 2015). Biocarbon is a solid renewable fuel produced from all types of biomass (mainly energy crops, forestry waste, municipal waste, roadside trees and shrubs, agricultural production residues such as straw but also sewage sludge, organic waste, manure, etc.) (Sanchez et al., 2009; Kwapinski et al., 2010; Ibarrola et al., 2012; Song, Guo, 2012). It is obtained by pyrolysis of biomass in an oxygen-free environment (Lehmann, 2007; Bis, 2012). The result of carbonisation is a black, fine-grained substance with a highly porous structure (Sohi et al., 2009).

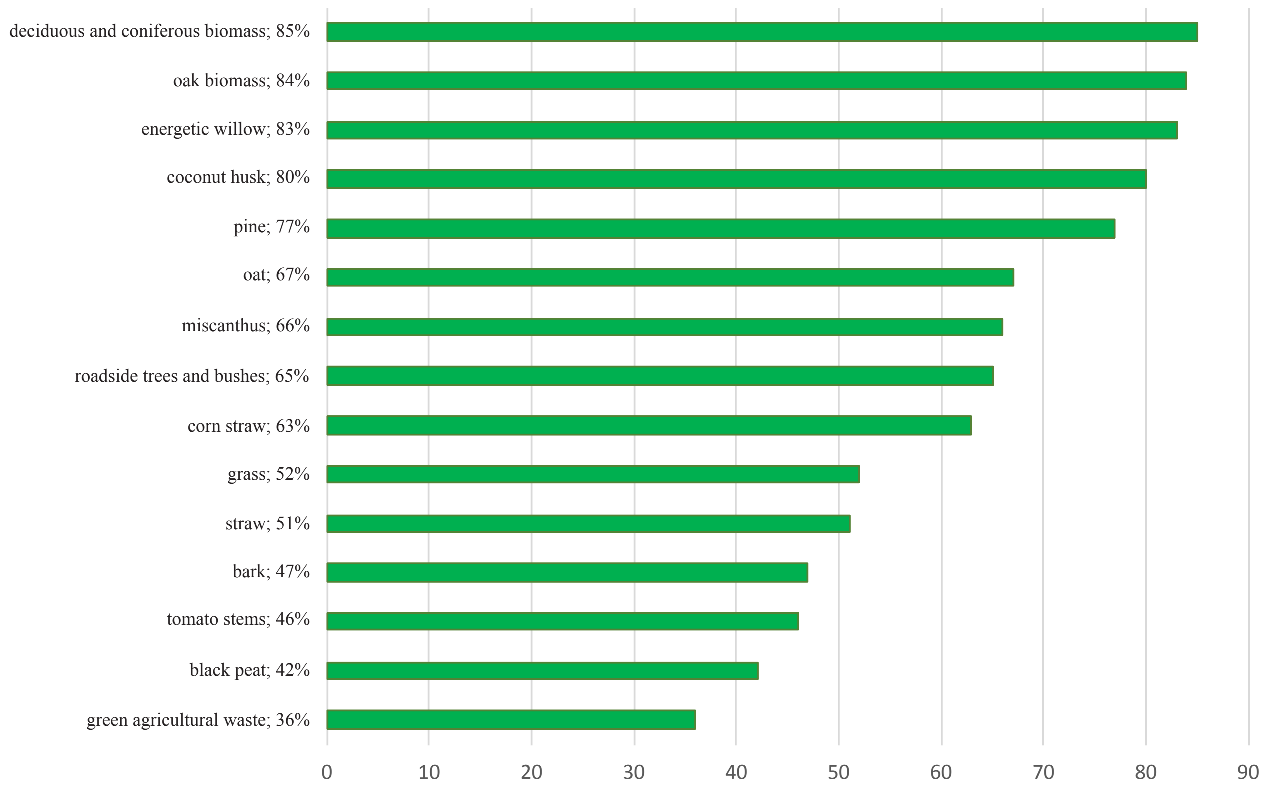

Figure 1. Percentage of carbon obtained from the carbonisation process in selected raw materials used in the production of biocarbon (Gładki, 2017).

BIOCHAR – PROPERTIES AND IMPORTANCE FOR AGRICULTURAL SOILS

The production and use of biocarbon for agricultural purposes dates back some 2000–2500 years. At that time, pre-Columbian tribes living in the Amazon basin began to use charred plant and animal residues (created by deliberate burning for agricultural purposes or by natural fires) to fertilise small areas. The addition of carbon to soil has created so called terra preta soils. Those soils, even after 2000 years, are still very fertile and rich in carbon. Biocarbon and its fertilising properties were used for soil cultivation in Europe on a limited scale (Olarieta et al., 2011). Since 1980s a renaissance of interest is visible in agricultural literature. Biocarbon is a solid renewable fuel produced by the thermal conversion of biomass (e.g. by heating wood chips) in the absence of oxygen at temperatures of 200–3000 ^{o}C (torrefaction process). The resulting substance has properties similar to charcoal (Lehmann, 2007; Jakubiak, Kordylewski, 2010; Bis, 2012; Jaworski, 2012). The substrate obtained has properties that increase the humus content of the soil, therefore improving soil fertility (impact on plant growth, crop yield potential and quality). Biocarbon is also characterised by its ability to retain water in the soil, increase the water-holding capacity and pH of soils, prevent leaching of nutrients and bind organic and inorganic pollutants (Lehmann, Joseph, 2009). The addition of biocarbon to soils can indirectly affect climate change by sequestering carbon dioxide and reducing N_2O and CH_4 emissions from soils. Biocarbon can address soil degradation problems by acting as a structuring material, and can also reduce nitrogen losses during composting (Igliński et al., 2009). The positive aspects of the use of biocarbon are highlighted by the work of Beesley et al. (2011) and Nigussie et al. (2012), who suggest that biocarbon can help improve soil fertility and productivity, and protect plants from diseases. Results from a study by Karhu et al. (2011) showed that the addition of biocarbon at 9 t ha^{-1} increased soil water holding capacity by 11%.

The results of biocarbon research are mostly based on experiments conducted under laboratory or pot conditions over relatively short periods of time, and therefore the full physio-chemical capabilities of biocarbon have not yet been satisfactorily recognised. By determining the physical, chemical and microbiological properties of soils, the impact of agricultural and non-agricultural activities on the soil environment can be monitored. Analysis of the state of soils in Poland shows that intensification of agricultural management (extensive use of chemical-based fertilisers and plant protection products) and mechanisation is not always positive for soil health. Soil humus is integral part of many biochemical processes in the soil. The high degree of chemisation and mismanagement of the soil environment often means that the soil carbon levels continue to drop in agricultural soils. This is a signal to look for alternative sources of substrates that can address the challenges associated with soil carbon loss. The addition of an external source high-carbon substance, can cause significant changes in the quality and quantity of humus compounds (Malińska, 2012). Moreover, recent studies show that increasing the carbon content in soils can help in the restoration of heavy metal contaminated soils (Topçu et al., 2022; Wang et al., 2023). Biocarbon can also absorb oil from the soil, making it an effective method for oil spill remediation (Deng et al., 2023). Furthermore, biocarbon can stimulate the growth of oil-degrading microorganisms without the need for oxygen, making it a sustainable and environmentally friendly remediation method (Masciandaro et al., 2018). All of this shows that the use of biocarbon in soil management practices can contribute to key ecosystem services provided by soil, in particular carbon storage, primary production, water-holding capacity, biodiversity, nutrient cycling and soil fertility.

Today, perhaps the most important doctrine for progress in agricultural development is its sustainability and resilience to climate change. The model of sustainable, balanced, and climate-neutral agriculture implies making conscious choices between economic growth and environmental protection, which will be reflected in the quality of life (limiting the negative effects of agricultural intensification, improving the environment, and conserving natural resources). One product that can reduce the negative effects of agricultural intensification is biocarbon. Biocarbon, its properties and how it can be used to address current challenges in agriculture have been the focus of research worldwide in recent years. The dynamic development of the production and modification of biocarbon and products based on it has become a research topic for many scientists. Biocarbon used for agricultural purposes was defined in 2005 by Peter Read (2009) as pyrolysed carbon (carbon produced by thermal decomposition of biomass under anaerobic or oxygen-limited conditions) for use as a soil amendment to increase soil fertility or for carbon sequestration. The International Biochar Initiative defines biocarbon produced by pyrolysis of biomass and biodegradable waste as a fine-grained carbonaceous material with high organic carbon content and negligible degradability.

Biocarbon is used primarily in the energy industry. In agriculture, 90% of the biocarbon produced (in Europe) is used in animal husbandry (additive to feed, litter, manure, etc.). Only a small percentage of the total production goes into the soil as an additive to improve its physical and chemical properties. It can be used in its pure form as well as an additive mixed with manure or compost or other nutrient sources (Gerlach, Schmidt, 2014). There are very few scientific studies and reports from agricultural practice, on the use of biocarbon in large scale production fields. Most of the available studies on the use of biocarbon have focused on pot experiments conducted in greenhouses and micro-plots. These experiments confirm the beneficial effects of biocarbon on plant growth and development. Studies by have shown that biochar can improve, in the firs place, soil physical properties. It can reduce soil bulk density (up to 31%) and increase soil porosity (even up to 64%), leading to improved soil aeration. This reduction in bulk density and increase in porosity create a more favorable environment for root growth and microbial activity, ultimately enhancing soil structure (Mukherjee, Lal, 2013; Blanco-Canqui, 2017). Biochar can also decrease soil compaction, increase water retention capacity, and improve soil quality for plant growth (Hussein, Ravi, 2022). This in turn have its direct effect on crop yields. The beneficial effect of biocarbon application on yield increase was, for example, indicated by the study of Gebremedhin et al. (2015) where the application of biocarbon at the rate of 4 t ha^{-1} resulted in the increase of wheat grain and straw yield of about 16% compared to the control object. The addition of biocarbon from sewage sludge at 10 t ha^{-1} in a pot experiment increased tomato yield by 64% compared to the control facility. This was the result of increased plant nutrient availability and improved soil properties (Hossain et al., 2011). In an experiment conducted by Uzoma et al. (2011), soil pH increased from 6.4 (control) to 8 (biocarbon at 20 t ha^{-1}) after biocarbon application, while grain yield increased by 150% and 98% after 15 and 20 t ha^{-1} application respectively. In his study, Graber et al. (2010) found a difference in the size of tomato and pepper plants. Plants on the biocarbon treated plots were on average larger by 39% than those without biocarbon. The fruit yield of pepper plants was 3% higher in the biocarbon-treated plots. No statistically significant difference in fruit yield was found for tomato plants. The results of an experiment conducted by Major et al. (2010) showed an increase in soil pH after biocarbon application and an increase in yield of maize plants in the second, third and fourth years of the study for biocarbon applications at 8 and 20 t ha^{-1}. Maize yield increased by 28%, 30% and 140%, compared to the control in the second, third and fourth year respectively for the application of 20 t ha^{-1}. Jones et al. (2012) found in their study that after biocarbon application at the rates of 25 and 50 t ha^{-1} the height and total biomass of the grass improved due to the increased uptake of macro- and micronutrients by the plants.

Biocarbon can also be used as a fertiliser to increase soil organic matter when added to crop residues, manure, or organic wastes of various origins (Kwiatkowska-Malina, Maciejewska, 2009). Studies by Ciećko et al. (2001), Sienkiewicz et al. (2005), Wołoszyk et al. (2004) confirm the positive effect of organic matter addition on soil fertility which translates into an increased crop yields. To date, studies on the incorporation of biocarbon into soils indicate its significant impact on soil properties. Biocarbon has the potential to increase the stability of soil organic matter, leading to improved soil structure and nutrient retention, which are essential for maintaining healthy and productive soils (Allohverdi et al., 2021). The beneficial effects of biocarbon include the formation of an improved sorption complex, particularly in light soils of poor agricultural quality. This is largely due to the porous structure of biocarbon, which is also resistant to decomposition by soil microorganisms. Moreover, the introduction of biocarbon does not promote lower soil pH as it is not decomposed rapidly by microorganisms (as fresh organic matter is), thereby addition of biochar to soil does not lead to the release of organic acids that lower the soil pH (Malisa et al., 2011).

The beneficial effect of biocarbon on soil structure-forming microorganisms has been demonstrated in studies by Kurth et al. (2006), Malińska, Dach (2014), Dias et al. (2010) or Steiner et al. (2011). The authors showed that biocarbon (mainly from lignocellulosic biomass) has a beneficial effect on optimising the composting process, mainly due to reduced greenhouse gas emissions and reduced losses of nitrogen that can be captured and retained by biochar. Structure-forming microorganisms can add new properties to composts if properly managed. They are responsible for the decomposition of plant residues, and the addition of biocarbon supports their activity (Fischer, Glaser, 2012). Lehmann et al. (2011) claim that the application of biocarbon to soil has a significant impact on the biotic properties of the soil. Due to its porous structure and its specific surface area, biocarbon can provide a suitable habitat for many microorganisms by supplying them with carbon, energy, and minerals, thus creating favourable conditions for their activity and growth. The increase in bacterial activity and abundance may be related to the sorptive surface of the biocarbon, leading to the increase in the respiration rate and increased access to oxygen (Fischer, Glaser, 2012). Biocarbon protects microorganisms from drought through its sorption properties. Seasonal droughts in soils where biocarbon has not been applied lead to stress and subsequent mortality of some bacteria. Research of Woolf (2008) also suggests that biocarbon has a positive effect on mycorrhiza. This shows that the use of biocarbon in soil amendment applications is recognised for its ability to enhance soil microbial activity, which is essential for overall soil health, organic matter decomposition, soil nutrient cycling, and thus, soil productivity (Patil et al., 2020).

BIOCHAR – IMPORTANCE FOR CARBON FARMING AND SUSTAINABLE DEVELOPMENT

The agricultural challenges that we have to face in order to achieve the goals of sustainable development of agricultural systems include the adverse climatic changes that contribute to the loss of agricultural productivity, high cost and scarcity of labor, and plant and animal diseases (Grimblatt, 2021), unsustainability and adverse environmental impacts of pesticide use (Gokul et al., 2023), soil degradation, land degradation, biodiversity loss and water pollution (Yadav et al., 2020; Bashir et al., 2022; Adedibu, 2023). The excessive use of agrochemicals and the depletion of natural resources are also major challenges (Grimblatt, 2021; Tian et al., 2021; Rukhsana, Alam, 2022). To meet these challenges, new sustainable agricultural practices must be developed, such as the use of biocontrol. Other approaches include efficient nutrient management, minimising the use of chemicals and improving the use efficiency of crop inputs. Precision farming techniques, conservation agriculture practices, and agro-ecological approaches are also promising solutions. Furthermore, adopting innovative technologies such as precision agriculture and Internet of Things (IoT) can improve sustainable agriculture while ensuring environmental quality.

Carbon farming is a land management approach whose main objective is to mitigate the negative impact of agriculture on current climate change through carbon sequestration in soils and plants, thereby reducing greenhouse gas emissions. One of the main environmentally friendly strategies of carbon farming are agroforestry (enhanced carbon sequestration in plants, increased SOM content, more diverse and resilient ecosystem), cover crops (erosion control, carbon sequestration, SOM content increase), conservation tillage (improved soil structure, increased carbon sequestration, reduced mineralization rate), rational grazing (reduced GHG emissions from enteric fermentation), organic farming (improved soil health and ecosystem services delivery) (Samruthi et al., 2020; Sharma et al., 2021; Sardiñas et al., 2022; Dewi, Nurhutami, 2023; Leifeld, 2023; Nogues et al., 2023). The concept of carbon farming extends beyond traditional agricultural practices and includes innovative approaches such as the sustainable utilization of weed biomass, aquaculture blue growth with low carbon emission technologies, and the development and assessment of carbon farming solutions. These initiatives aim to integrate climate change mitigation into agricultural activities, promoting sustainable and efficient use of resources while reducing carbon emissions. Additionally, carbon farming solutions have been explored in different contexts, including dairy farm management and agricultural land allocation around forest areas, highlighting the multifaceted nature of carbon farming and its potential to address environmental challenges in different agricultural systems (Bumbiere et al., 2022). Carbon farming aims to mitigate climate change by increasing carbon sequestration in agricultural soils, which helps offset carbon dioxide emissions. The approach is based on sustainable agricultural practices that enhance soil health, promote biodiversity, and reduce the carbon footprint of farms. By incorporating practices that promote carbon farming, such as soil amendment with biochar and integrating trees and crops with livestock, it is possible to enhance carbon sequestration and reduce greenhouse gas emissions from terrestrial ecosystems (Baumber et al., 2020; Almaraz et al., 2021; Holzleitner, Gawlik, 2022; Hönle, Heidecke, 2023). Carbon farming can potentially improve soil health, fertility, and water-holding capacity, particularly in regions where erosion and loss of organic matter are major challenges. Additionally, carbon farming can create habitats that support wild pollinators, thereby contributing to the resilience of agricultural systems in the face of climate change (Sardiñas et al., 2022). Efforts should be made to promote resource use efficiency and soil conservation skills among farmers to maximise the benefits of carbon farming.

The properties of biochar, if used properly, can help achieve sustainable agriculture's goals. As mentioned before, it acts as a soil amendment system, improving the physical, chemical, and biological properties of soils, and increasing crop yield (Zulfiqar et al., 2022; Banu et al., 2023; Bassey, Oko, 2023; Rodrigues et al., 2023). Biochar increases water retention, porosity, and aggregation of soils, leading to improved water infiltration and retention capacity (Hamidzadeh et al., 2023). It also darkens soil colour and moderates soil temperature (Murtaza et al., 2023). Additionally, biochar increases cation exchange capacity, soil pH, nutrient supply and uptake, and reduces nutrient leaching losses (Dey et al., 2023).

It can remediate soils contaminated with heavy metals and organic pollutants. Biochar promotes microbial colonisation and increases microbial biomass carbon, enzyme activity, and mycorrhizal colonisation of roots (Solaiman et al., 2010; Chen et al., 2016; Palansooriya et al., 2019; Sandhu et al., 2019; Ajeng et al., 2023). Furthermore, biochar contributes to carbon sequestration, reducing greenhouse gas emissions, and helps mitigate climate change. However, the effectiveness of biochar can vary depending on factors such as feedstock, pyrolysis temperature, application rate and method, soil type, and crop species. Further research is needed to fully understand the potential of biochar to improve nutrient retention, crop productivity, and remediate contaminated soils (Singh, 2023).

The role of biocarbon in carbon farming is multifaceted, encompassing various applications that contribute to sustainable agricultural practices and climate change mitigation. Biocarbon, derived from renewable sources through pyrolysis, has been identified as a valuable tool for carbon sequestration and soil improvement in carbon farming initiatives. It also aligns with the principles of sustainable agriculture, offering a low-cost, permanent and environmentally friendly alternative for soil improvement and carbon sequestration (Tripathi et al., 2022). The potential of biocarbon in carbon farming has been recognized for its role in enhancing soil carbon stocks and contributing to climate change mitigation efforts, making an opportunity to promote sustainable land management practices and improve the overall resilience of agricultural ecosystems (Stępień et al., 2017; Dimobe et al., 2018). Moreover, the development of biocarbon from waste biomass, or its amendment to waste biomass, offers a sustainable solution for managing agricultural residues and promoting carbon sequestration (Tripathi et al., 2022). The incorporation of biocarbon into agricultural systems has been linked to improved soil health, increased crop productivity, and enhanced carbon sequestration, highlighting its role in promoting sustainable agricultural development (Quosai et al., 2018). Biocarbon plays a crucial role in carbon farming by offering sustainable solutions for soil improvement, carbon sequestration, and the promotion of environmentally friendly agricultural practices. Its diverse applications in carbon farming initiatives contribute to the overall sustainability of agricultural systems and align with efforts to mitigate climate change.

The agricultural use of biochar can a beneficial an important part of carbon farming. However, there are limitations and risks associated with its use. Its positive impact on crop yield and soil fertility can be different in different soil and climatic conditions. A higher, positive impact have been observed particularly in low-nutrient, acidic soils in tropical regions (Jeffery et al., 2017). However, it is crucial to consider also the potential negative impacts of biochar. Application of biochar without considering its interaction with greenhouse gases can lead to adverse effects (Cheng et al., 2020). Additionally, the high content of polycyclic aromatic hydrocarbons (PAHs) in biochar could have negative impacts on soil biota and human health if translocated to edible plant parts, raising concerns about its use in agriculture (Ventura et al., 2014). Negative effects of biochar have been reported when specific types of biochar were used, leading to reduced yields (Cornelissen et al., 2013). The ageing of biochar can influence herbicide sorption capacity in soil, resulting in both positive and negative impacts (Wang et al., 2015). A careful consideration of biochar type, application methods, and its interaction with the environment is crucial to maximize benefits and minimize adverse effects.

The EU has implemented various policies and initiatives to support carbon farming, including the development of results-based carbon farming schemes. The European Commission has emphasised the need for Member States and local authorities to define solutions to reduce emissions through improved farming practices, thereby promoting carbon sequestration and environmental sustainability (Bumbiere et al., 2022). The EU in its European Green Deal Strategy (EC, 2019) aims to achieve climate-neutral farming by 2050. A large number of carbon farming schemes have been implemented across Europe. According to Smit & van der Kolk (2023) at least 175 schemes have already been implemented with varying characteristics such as documentation availability, payment/buyers information, monitoring, reporting and verification (MRV), safeguards, transparency, and attractiveness to support carbon farming mechanisms. Public funding under the Common Agricultural Policy (CAP) and other EU programmes, such as LIFE and Horizon Europe support the development and implementation of carbon farming practices.

SUMMARY

Available research on selected properties of biocarbon allow us to conclude that the introduction of biocarbon into the soil environment not only has a beneficial effect on the soil, but also on the activity of soil structure-forming microorganisms that are important for agriculture. Biocarbon acts as a sorbent, and based on the literature presented, it can be concluded that it positively affects crop yields through combined effects of positive changes, including:

Carbon sequestration: Biochar is a stable form of carbon that can persist in the soil for hundreds to thousands of years. It acts as a carbon sink, helping to mitigate climate change by sequestering carbon and preventing its release into the atmosphere.

Soil fertility improvement: Biochar enhances soil fertility by improving nutrient retention and availability. Thanks to its porous structure, it can hold water, nutrients, and beneficial microorganisms.

Water retention: The porous nature of biochar also allows it to retain water, promoting better water availability and lower water needs for irrigation.

Reduced greenhouse gas emissions: By enhancing soil health and nutrient cycling, biochar can reduce the emissions of greenhouse gases such as nitrous oxide and methane from agricultural soils.

Soil structure improvement: Biochar can improve soil structure by preventing compaction and promoting aeration. This is beneficial for root growth and allows for better infiltration of water and nutrients into the soil.

Waste management: Biochar can be produced from various organic materials, including agricultural residues and organic wastes. This could help to meet the goals of circular economy by recycling organic wastes and converting them into a valuable agricultural inputs.

Reduced dependency on chemical inputs: The nutrient retention properties of biochar can reduce the leaching of nutrients from the soil, minimizing the need for synthetic fertilizers and promoting environmentally friendly practices.

All this shows that the use of biocarbon may prove to be one of the best possible strategies, that can be introduced into agricultural management practice to enable agriculture to achieve its sustainable development goals. Its use is also in line with the objectives of carbon farming, which are mainly aimed at minimising the negative impact of agriculture on the climate change.

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