The Role of Biochar in Agriculture

Written by

Dr. Y.K. Singh

Associate Professor

Department of Agronomy

Dr. Manmeet Kaur

Assistant professor

Department of Extension Education and Communication Management

College of Agriculture

Swami Keshwanand Rajasthan Agriculture University

Bikaner, Rajasthan, India

CHAPTER -1
Introduction

Integrated farming is an agricultural approach that combines various components of farming systems, such as crop production, livestock rearing, aquaculture, and agroforestry, to create a synergistic and sustainable environment (Manjunatha *et al.*, 2014). This holistic approach aims to optimize resource utilization, minimize waste generation, and enhance the overall productivity and profitability of the farming system (Behera *et al.*, 2015). Integrated farming has gained prominence in recent years due to its potential to address the growing challenges of food security, environmental degradation, and climate change (FAO, 2018).

Table 1. Physicochemical properties of biochar derived from different feedstocks

Feedstock	**Pyrolysis Temperature (°C)**	**pH**	**Surface Area (m^2/g)**	**CEC (cmol/kg)**	**Carbon Content (%)**	**Ash Content (%)**
Wood	500	7.5	120	40	75	5
Rice husk	600	9.2	80	25	45	40
Manure	400	8.1	60	90	55	30
Straw	550	10.3	40	70	60	20
Blanco-Canqui (2017)	Corn stover	40		Silt loam	Improved aggregate stability by 44%	

1.2. The role of soil health in sustainable agriculture Soil health is a critical factor in sustainable agriculture, as it directly influences crop growth, yield, and quality (Doran & Zeiss, 2000). A healthy soil is characterized by optimal physical, chemical, and biological properties that support plant growth, nutrient cycling, water retention, and disease suppression (Karlen *et al.*, 2003). However, intensive agricultural practices, such as monocropping, excessive tillage, and indiscriminate use of agrochemicals, have led to soil degradation, erosion, and loss of fertility (Montgomery, 2007). Therefore, maintaining and enhancing soil health has become a priority for sustainable agriculture (Lal, 2015).

1.3. Biochar: Definition, production, and properties

Biochar is a carbon-rich material produced by the thermal decomposition of organic biomass under limited oxygen conditions, a process known as pyrolysis (Lehmann & Joseph, 2015). The feedstocks for biochar production can include agricultural waste, forestry residues, animal manure, and other organic materials (Woolf *et al.*, 2010). Biochar is characterized by its high surface area, porous structure, and stable aromatic carbon compounds, which contribute to its unique properties and potential applications in agriculture (Sohi *et al.*, 2010). These properties include high cation exchange capacity (CEC), water retention, nutrient adsorption, and resistance to decomposition (Atkinson *et al.*, 2010).

CHAPTER - 2

Biochar production and characterization

2.1. Feedstocks for biochar production

Biochar can be produced from a wide range of organic feedstocks, each with unique properties and potential applications in agriculture.

The most common feedstocks for biochar production include:

2.1.1. Agricultural waste

Agricultural waste, such as crop residues, straw, and husks, is an abundant and readily available feedstock for biochar production (Purakayastha *et al.*, 2019). Rice husk, wheat straw, and corn stover are among the most extensively studied agricultural waste feedstocks for biochar production (El-Naggar *et al.*, 2019). The utilization of agricultural waste for biochar production not only provides a sustainable waste management solution but also adds value to these otherwise underutilized resources (Sadaka *et al.*, 2014).

Table 2. Effects of biochar application on soil physical properties in various studies

Study	Biochar Feedstock	Application Rate (t/ha)	Soil Type	Effects on Soil Physical Properties
Basso *et al.* (2013)	Hardwood	20	Sandy loam	Increased water holding capacity by 23%
Burrell *et al.* (2016)	Mixed wood	10	Clay loam	Reduced bulk density by 12%
Blanco-Canqui (2017)	Corn stover	40	Silt loam	Improved aggregate stability by 44%

2.1.2. Forestry residues

Forestry residues, such as wood chips, sawdust, and bark, are another significant source of feedstock for biochar production (Wrobel-Tobiszewska *et al.*, 2015). These residues are generated during various forestry operations, including logging, pruning, and wood processing

(Nanda *et al.,* 2016). The use of forestry residues for biochar production can contribute to the sustainable management of forest resources and reduce the risk of forest fires by removing excess biomass (Page-Dumroese *et al.,* 2017).

2.1.3. Animal manure

Animal manure, particularly from poultry, cattle, and swine, has been explored as a potential feedstock for biochar production (Cantrell *et al.,* 2012). The conversion of animal manure into biochar not only provides a sustainable waste management solution but also reduces the environmental risks associated with manure storage and application, such as nutrient leaching and greenhouse gas emissions (Ro *et al.,* 2010). Moreover, manure-derived biochar has been shown to possess unique properties, such as high nutrient content and surface functionality, which can enhance its performance as a soil amendment (Subedi *et al.,* 2017).

2.2. Pyrolysis process and its influence on biochar properties

The pyrolysis process, which involves the thermal decomposition of biomass under limited oxygen conditions, is a critical factor in determining the properties and quality of the resulting biochar (Lehmann & Joseph, 2015).

The three main types of pyrolysis processes are:

2.2.1. Slow pyrolysis

Slow pyrolysis is characterized by low heating rates (< 10°C/min), long residence times (hours to days), and relatively low temperatures (300-600°C) (Kambo & Dutta, 2015). This process favors the production of biochar with a high yield (30-50%), moderate surface area, and high carbon content (Demirbas, 2004). Slow pyrolysis is the most common method for biochar production, as it allows for better control over the product quality and is relatively simple to implement (Wang *et al.,* 2013).

2.2.2. Fast pyrolysis

Fast pyrolysis involves high heating rates (> 100°C/s), short residence times (seconds to minutes), and moderate temperatures (400-650°C) (Bridgwater, 2012). This process primarily aims to maximize the production of bio-oil, with biochar being a byproduct (Mohan *et al.,* 2006). Fast pyrolysis-derived biochar typically has a lower yield (10-20%), higher surface area, and lower carbon content compared to slow pyrolysis biochar (Zhang *et al.,* 2017).

2.2.3. Gasification

Gasification is a high-temperature (> 700°C) process that converts biomass into syngas (CO, H_2, and CH_4) under controlled oxygen conditions (Kumar *et al.,* 2009). Biochar is a byproduct of gasification, with yields typically ranging from 5-15% (Meyer *et al.,* 2011). Gasification-derived biochar is characterized by a high surface area, low carbon content, and high ash content (Hansen *et al.,* 2015). Due to its unique properties, gasification biochar has been explored for various applications, such as soil remediation and adsorption of contaminants (Xie *et al.,* 2015).

2.3. Physical and chemical properties of biochar

The physical and chemical properties of biochar are crucial factors in determining its performance as a soil amendment and its potential applications in agriculture (Lehmann & Joseph, 2015).

The key properties of biochar include:

2.3.1. Surface area and porosity

Biochar is characterized by its high surface area and porous structure, which are influenced by the feedstock type and pyrolysis conditions (Gray *et al.,* 2014). The surface area of biochar can range from a few m^2/g to over 500 m^2/g, depending on the production method (Downie *et al.,* 2009). The high surface area and porosity of biochar contribute to its ability to adsorb nutrients, retain water, and provide habitat for soil microorganisms (Atkinson *et al.,* 2010).

2.3.2. Elemental composition

The elemental composition of biochar varies depending on the feedstock and pyrolysis conditions (Lehmann & Joseph, 2015). Carbon is the dominant element in biochar, typically ranging from 50-90% by weight (Sohi *et al.,* 2010). Other important elements in biochar include oxygen, hydrogen, nitrogen, sulfur, and various mineral nutrients, such as potassium, phosphorus, and calcium (Singh *et al.,* 2010). The elemental composition of biochar influences its stability, nutrient retention capacity, and interactions with soil components (Bruun *et al.,* 2012).

2.3.3. pH and electrical conductivity

Biochar is generally alkaline, with pH values ranging from 6.5 to 12, depending on the feedstock and pyrolysis conditions (Yuan *et al.,* 2011). The high pH of biochar can be beneficial for acidic soils, as it can help to neutralize soil acidity and improve nutrient availability (Lehmann *et al.,* 2011). However, in alkaline soils, the application of high-pH biochar may lead to nutrient imbalances and micronutrient deficiencies (Limwikran *et al.,* 2018). The electrical conductivity (EC) of biochar is another important property, as it indicates the presence of soluble salts (Chintala *et al.*, 2014). High-EC biochars may be less suitable for application in saline soils, as they can exacerbate salt stress in plants (Lashari *et al.*, 2013).

2.4. Factors affecting biochar quality and stability

Several factors influence the quality and stability of biochar, including feedstock type, pyrolysis conditions, and post-production treatments (Lehmann & Joseph, 2015). The selection of appropriate feedstocks and pyrolysis parameters is crucial for producing biochar with desired properties for specific soil and crop requirements (Zhao *et al.*, 2013). For instance, woody biomass generally produces biochar with higher carbon content and stability compared to herbaceous biomass (Windeatt *et al.*, 2014). Similarly, higher pyrolysis temperatures (> 500°C) typically result in biochar with greater surface area, porosity, and aromatic carbon content, which contribute to its long-term stability in soil (Singh *et al.*, 2012). Post-production treatments, such as activation or chemical modification, can further enhance the properties of biochar for specific applications (Rajapaksha *et al.*, 2016).

CHAPTER - 3

Biochar and soil physical properties

Biochar has been shown to have a significant impact on soil structure and aggregation, which are critical factors in maintaining soil health and productivity (Blanco-Canqui, 2017). The porous structure and high surface area of biochar can contribute to the formation and stability of soil aggregates by promoting the binding of soil particles and organic matter (Ouyang *et al.*, 2013). The improved soil structure and aggregation can enhance water infiltration, aeration, and root growth, thereby creating favorable conditions for plant development (Burrell *et al.*, 2016).

3.2. Soil water retention and hydraulic conductivity

The application of biochar to soil has been demonstrated to improve water retention and hydraulic conductivity, particularly in sandy and coarse-textured soils (Basso *et al.*, 2013). The high porosity and surface area of biochar enable it to absorb and retain water, reducing water loss through evaporation and leaching (Novak *et al.*, 2009). Moreover, the presence of biochar can enhance the soil's water holding capacity by increasing the number of micropores and improving the pore size distribution (Liu *et al.*, 2017). The improved water retention and hydraulic conductivity can help to mitigate drought stress and optimize water use efficiency in crops (Kammann *et al.*, 2011).

Table 3. Influence of biochar amendment on soil chemical properties and nutrient availability

Study	**Biochar Feedstock**	**Application Rate (t/ha)**	**Soil Type**	**Effects on Soil Chemical Properties**
Yuan *et al.* (2011)	Crop residue	20	Ultisol	Increased pH from 4.3 to 6.5
Laird *et al.* (2010)	Hardwood	5	Midwestern agricultural soil	Increased CEC by 20%
Lehmann *et al.* (2003)	Wood	140	Oxisol	Increased available P by 60%

3.3. Soil bulk density and porosity

Biochar amendment has been reported to reduce soil bulk density and increase soil porosity, particularly in compacted and degraded soils (Rogovska *et al.,* 2014). The low bulk density and high porosity of biochar can contribute to the loosening of the soil structure, improving soil aeration and root penetration (Laird *et al.*, 2010). The reduction in soil bulk density can also facilitate the movement of water and nutrients through the soil profile, enhancing their availability to plants (Barnes *et al.*, 2014). However, the extent of biochar's impact on soil bulk density and porosity depends on the application rate, soil type, and biochar properties (Blanco-Canqui, 2017).

3.4. Soil temperature regulation

Biochar has been shown to influence soil temperature dynamics, which can have implications for crop growth and soil microbial activity (Zhang *et al.*, 2013). The dark color and high thermal conductivity of biochar can lead to increased soil temperature, particularly in the upper soil layers (Vaccari *et al.*, 2011). This effect can be beneficial in cold regions, where higher soil temperatures can promote seed germination, root growth, and nutrient uptake (Luo *et al.*, 2017). However, in hot and arid regions, the increased soil temperature may exacerbate heat stress and water loss, necessitating careful management of biochar application (Xie *et al.*, 2015).

CHAPTER - 4

Biochar and soil chemical properties

Biochar application has been widely reported to increase soil pH, particularly in acidic soils (Yuan *et al.,* 2011). The alkaline nature of most biochars can help to neutralize soil acidity and improve nutrient availability (Lehmann *et al.,* 2011). The liming effect of biochar is attributed to its high ash content and the presence of basic cations, such as Ca, Mg, and K (Wang *et al.,* 2015). Moreover, biochar has been shown to enhance the soil's buffering capacity, which can help to stabilize soil pH and reduce the risk of nutrient imbalances (Xu *et al.,* 2012). However, the extent of biochar's impact on soil pH depends on the initial soil pH, biochar application rate, and biochar properties (Biederman & Harpole, 2013).

4.2. Cation exchange capacity (CEC) and nutrient retention

Biochar has been demonstrated to increase the cation exchange capacity (CEC) of soils, which is a critical factor in nutrient retention and availability (Liang *et al.,* 2006). The high surface area and negative surface charge of biochar enable it to adsorb and retain cations, such as ammonium ($NH4^{+}$) and potassium (K^{+}), reducing their loss through leaching (Lehmann *et al.,* 2003). The improved CEC can also enhance the soil's ability to buffer against changes in pH and maintain a stable nutrient supply for plants (Glaser *et al.,* 2002). The effects of biochar on nutrient retention have been extensively studied for various nutrients, including:

4.2.1. Nitrogen

Biochar has been shown to reduce nitrogen (N) leaching and improve N use efficiency in crops (Steiner *et al.,* 2008). The adsorption of ammonium ($NH4^{+}$) onto biochar's surface can reduce its conversion to nitrate ($NO3^{-}$) and subsequent loss through leaching (Zheng *et al.,* 2013). Moreover, biochar can promote the immobilization of N by stimulating microbial growth and activity, further reducing N losses (Xu *et al.,* 2016). However, the impact of biochar on N dynamics depends on the biochar type, soil properties, and environmental conditions (Nguyen *et al.,* 2017).

4.2.2. Phosphorus

Biochar has been reported to increase phosphorus (P) availability and reduce P leaching in soils (Parvage *et al.,* 2013). The high surface area and porosity of biochar can facilitate the adsorption of P, reducing its loss through leaching and surface runoff (Laird *et al.,* 2010). Biochar can also interact with soil minerals, such as iron (Fe) and aluminum (Al) oxides, to form stable complexes that increase P retention and availability (DeLuca *et al.*, 2009). Additionally, biochar can stimulate microbial activity and enhance the solubilization of soil P by releasing organic acids and enzymes (Vassilev *et al.,* 2013). However, the effectiveness of biochar in improving P availability depends on the biochar feedstock, pyrolysis conditions, and soil properties (Wang *et al.,* 2012).

Table 4. Biochar-induced changes in soil microbial communities and enzyme activities

Study	**Biochar Feedstock**	**Application Rate (t/ha)**	**Soil Type**	**Effects on Soil Biological Properties**
Lehmann *et al.* (2011)	Wood	20	Calcareous soil	Doubled microbial biomass carbon
Bailey *et al.* (2011)	Papermill waste	10	Mine soil	Increased β-glucosidase activity by 30%
Feng *et al.* (2012)	Rice straw	40	Paddy soil	Stimulated methanotrophic community

4.2.3. Potassium

Biochar has been shown to increase potassium (K) availability and retention in soils, particularly in sandy and low-CEC soils (Lehmann *et al.,* 2003). The high K content of some biochars, particularly those derived from wood and crop residues, can act as a direct source of K for plants (Gaskin *et al.,* 2010). Moreover, the high CEC of biochar can adsorb and retain K^+ ions, reducing their loss through leaching (Laird *et al.,* 2010). The improved K retention can help to maintain an adequate K supply for crops, especially in soils prone to K deficiency (Rogovska *et al.,* 2014). However, the impact of biochar on K dynamics depends on the biochar properties, soil type, and cropping system (Blanco-Canqui, 2017).

4.3. Soil organic carbon and carbon sequestration

Biochar has been increasingly recognized as a potential tool for enhancing soil organic carbon (SOC) and promoting carbon sequestration in agricultural soils (Woolf *et al.,* 2010). The high carbon content and recalcitrant nature of biochar make it resistant to microbial decomposition, allowing it to persist in soils for hundreds to thousands of years (Wang *et al.,* 2016). The incorporation of biochar into soil can directly increase SOC stocks, while also promoting the stabilization of native soil organic matter through various mechanisms, such as adsorption, aggregation, and reduced mineralization (Weng *et al.*, 2017). Moreover, biochar can indirectly enhance SOC accumulation by increasing plant biomass production and root exudation, which contribute to the formation of stable soil organic matter (Sohi *et al.*, 2010). The potential of biochar for carbon sequestration has been widely studied, with estimates suggesting that biochar application could sequester up to 1.8 Gt C per year globally (Woolf *et al.*, 2010). However, the actual carbon sequestration potential of biochar depends on various factors, such as biochar production and application rates, soil properties, climate conditions, and land management practices (Smith, 2016).

4.4. Interactions with soil contaminants and heavy metals

Biochar has been explored as a potential amendment for the remediation of soils contaminated with heavy metals and organic pollutants (Beesley *et al.*, 2011). The high surface area, porous structure, and surface functional groups of biochar can facilitate the adsorption and immobilization of various contaminants, reducing their bioavailability and toxicity to plants and soil organisms (Zhang *et al.*, 2013). For instance, biochar has been shown to effectively adsorb heavy metals, such as lead (Pb), cadmium (Cd), and zinc (Zn), through mechanisms such as ion exchange, complexation, and precipitation (Lu *et al.*, 2012). Similarly, biochar can adsorb organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs) and pesticides, through hydrophobic interactions and π-π bonding (Cao *et al.*, 2011). The immobilization of contaminants by biochar can reduce their uptake by plants and minimize their leaching into groundwater (Uchimiya *et al.*, 2010). However, the effectiveness of biochar in soil remediation depends on the biochar properties, soil characteristics, contaminant type, and environmental conditions (Rajapaksha *et al.*, 2016). Moreover, the long-term stability and fate of adsorbed contaminants in biochar-amended soils require further investigation to ensure the safety and sustainability of this approach (Sohi *et al.*, 2010).

CHAPTER - 5

Biochar and soil biological properties

Biochar amendment has been shown to significantly influence soil microbial communities and diversity, which play critical roles in soil health and ecosystem functions (Lehmann *et al.,* 2011). The porous structure and high surface area of biochar provide a favorable habitat for soil microorganisms, protecting them from predation and desiccation (Thies *et al.,* 2015). Biochar can also serve as a source of carbon and other nutrients for microbial growth and activity (Warnock *et al.,* 2007). Several studies have reported increased microbial biomass, diversity, and activity in biochar-amended soils, particularly in the rhizosphere (Lehmann *et al.,* 2011). For instance, biochar has been shown to stimulate the growth and abundance of beneficial soil bacteria, such as Pseudomonas and Bacillus spp., which are involved in nutrient cycling, plant growth promotion, and disease suppression (Kolton *et al.,* 2011). Similarly, biochar has been found to enhance the diversity and activity of arbuscular mycorrhizal fungi (AMF), which facilitate plant nutrient uptake and improve soil structure (Warnock *et al.,* 2007). However, the impact of biochar on soil microbial communities depends on the biochar properties, soil type, and environmental conditions (Lehmann & Joseph, 2015). Moreover, the long-term effects of biochar on soil microbial dynamics and their implications for soil health and ecosystem functions require further investigation (Thies *et al.,* 2015).

5.2. Soil enzyme activities

Soil enzymes are essential for the decomposition of organic matter, nutrient cycling, and other vital soil processes (Dick, 1994). Biochar amendment has been reported to influence soil enzyme activities, either directly by providing substrates and stimulating microbial activity or indirectly by altering soil properties and microbial community structure (Bailey *et al.,* 2011). Several studies have observed increased activities of various soil enzymes, such as β-glucosidase, chitinase, and phosphatase, in biochar-amended soils (Jin, 2010). For instance, biochar has been shown to enhance the activity of β-glucosidase, an enzyme involved in the decomposition of cellulose and the release of glucose, which can stimulate microbial growth and activity (Jin *et al.,* 2016). Similarly, biochar has been found to increase the activity of acid phosphatase, an enzyme that catalyzes the hydrolysis of organic phosphate esters, thereby improving P availability for plants (Cui *et al.,* 2011).

However, the impact of biochar on soil enzyme activities varies depending on the biochar properties, soil type, and specific enzymes (Bailey *et al.*, 2011). Moreover, the mechanisms underlying biochar-induced changes in soil enzyme activities and their implications for soil health and ecosystem functions require further elucidation (Thies *et al.*, 2015).

Table 5. Crop yield responses to biochar application in different cropping systems

Study	**Biochar Feedstock**	**Application Rate (t/ha)**	**Crop**	**Yield Increase (%)**
Major *et al.* (2010)	Wood	20	Maize	28
Vaccari *et al.* (2011)	Wheat straw	30	Tomato	25
Solaiman *et al.* (2010)	Oil mallee	10	Wheat	45

5.3. Interactions with beneficial microorganisms

Biochar has been shown to interact with various beneficial soil microorganisms, such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting bacteria (PGPB), which can enhance plant growth, nutrient uptake, and stress resistance (Lehmann *et al.*, 2011). These interactions can occur through several mechanisms, including:

5.3.1. Arbuscular mycorrhizal fungi

AMF are symbiotic fungi that colonize plant roots and form extensive hyphal networks in the soil, facilitating plant nutrient uptake and improving soil structure (Smith & Read, 2008). Biochar has been reported to stimulate AMF colonization and hyphal growth, particularly in soils with low fertility or under stress conditions (Warnock *et al.*, 2007). The porous structure and high surface area of biochar can provide a suitable habitat for AMF, protecting them from predation and desiccation (Thies *et al.*, 2015). Moreover, biochar can adsorb and retain nutrients, such as P and N, which can be accessed by AMF and transferred to the host plant (Hammer *et al.*, 2014). The enhanced AMF activity in biochar-amended soils can improve plant nutrient acquisition, water uptake, and stress tolerance (Solaiman *et al.*, 2010). However, the impact of biochar on AMF varies depending on the biochar properties, soil type, and plant species (Lehmann *et al.*, 2011).

5.3.2. Plant growth-promoting bacteria

PGPB are soil bacteria that colonize plant roots and promote plant growth through various mechanisms, such as nitrogen fixation, phosphate solubilization, and phytohormone production (Glick, 2012). Biochar has been shown to stimulate the growth and activity of PGPB, particularly in the rhizosphere (Kolton *et al.,* 2011). The porous structure and high surface area of biochar can provide a favorable microhabitat for PGPB, protecting them from environmental stresses and predation (Thies *et al.*, 2015). Moreover, biochar can adsorb and retain nutrients, such as N and P, which can be accessed by PGPB and made available to plants (Zheng *et al.,* 2013). The enhanced PGPB activity in biochar-amended soils can improve plant nutrient uptake, growth, and stress resistance (Saxena *et al.,* 2013). However, the impact of biochar on PGPB varies depending on the biochar properties, soil type, and plant species (Lehmann *et al.*, 2011).

5.4. Biochar as a habitat for soil organisms

Biochar has been increasingly recognized as a potential habitat for various soil organisms, including microorganisms, invertebrates, and small vertebrates (Lehmann *et al.*, 2011). The porous structure and high surface area of biochar provide a suitable microenvironment for soil organisms, protecting them from predation, desiccation, and extreme temperatures (Thies *et al.,* 2015). Moreover, biochar can adsorb and retain water, nutrients, and organic compounds, which can support the growth and activity of soil organisms (Lehmann *et al.,* 2011). Several studies have reported increased abundance and diversity of soil fauna, such as nematodes, collembolans, and mites, in biochar-amended soils (McCormack *et al.,* 2013). For instance, biochar has been shown to increase the abundance and diversity of soil nematodes, which are important indicators of soil health and play critical roles in nutrient cycling and pest suppression (Zhang *et al.,* 2013). Similarly, biochar has been found to stimulate the activity of earthworms, which contribute to soil structure formation, organic matter decomposition, and nutrient mineralization (Weyers & Spokas, 2011). The enhanced activity of soil organisms in biochar-amended soils can improve soil health, fertility, and ecosystem functions (Lehmann *et al.,* 2011). However, the impact of biochar on soil organisms varies depending on the biochar properties, soil type, and environmental conditions (Thies *et al.,* 2015).

CHAPTER - 6

Biochar and soil chemical properties

Biochar has been widely reported to improve crop growth and productivity through various mechanisms, including:

6.1.1. Nutrient availability and uptake

Biochar has been shown to increase the availability and uptake of essential plant nutrients, such as N, P, and K, in biochar-amended soils (Lehmann *et al.,* 2003). The high surface area and CEC of biochar can adsorb and retain nutrients, reducing their loss through leaching and making them more accessible to plants (Laird *et al.,* 2010). Moreover, biochar can stimulate the activity of soil microorganisms involved in nutrient cycling, such as N-fixing bacteria and P-solubilizing fungi, further enhancing nutrient availability (Thies *et al.,* 2015). The improved nutrient status of biochar-amended soils can promote plant growth, yield, and quality (Major *et al.,* 2010). However, the impact of biochar on nutrient availability and uptake depends on the biochar properties, soil type, and crop species (Jeffery *et al.,* 2011).

Table 6. Greenhouse gas emissions from biochar-amended soils compared to control treatments

Study	Biochar Feedstock	Application Rate (t/ha)	Soil Type	GHG Emissions Reduction
Zhang *et al.* (2010)	Wheat straw	20	Paddy soil	21% decrease in CH_4 emissions
Cayuela *et al.* (2015)	Various	5-50	Various	54% decrease in N_2O emissions
Woolf *et al.* (2010)	Various	1-50	Global	12% of current anthropogenic CO_2 emissions potentially offset

6.1.2. Water use efficiency

Biochar has been reported to improve water use efficiency and mitigate drought stress in crops (Kammann *et al.,* 2011). The porous structure and high surface area of biochar can increase soil water retention and reduce water loss through evaporation and leaching (Novak *et al.,* 2009). Moreover, biochar can improve soil structure and hydraulic conductivity, facilitating water infiltration and root penetration (Barnes *et al.*, 2014). The enhanced water holding capacity and soil moisture status of biochar-amended soils can alleviate drought stress and improve crop water use efficiency (Mulcahy *et al.,* 2013). However, the effectiveness of biochar in improving water use efficiency depends on the biochar properties, soil type, and climate conditions (Jeffery *et al.,* 2011).

6.1.3. Disease suppression and pest control

Biochar has been shown to suppress various plant diseases and pests, thereby improving crop health and productivity (Elad *et al.,* 2010). The mechanisms underlying biochar-induced disease suppression are not fully understood but may involve several factors, such as:

- Stimulation of beneficial soil microorganisms, such as PGPB and AMF, which can improve plant resistance to pathogens (Kolton *et al.,* 2011).
- Adsorption and inactivation of plant pathogens and their toxins by biochar's high surface area and reactive functional groups (Elad *et al.,* 2010).
- Induction of systemic resistance in plants through the activation of defense-related genes and pathways (Mehari *et al.,* 2015).
- Improvement of soil physical and chemical properties, such as pH, CEC, and nutrient availability, which can create unfavorable conditions for pathogens (Jaiswal *et al.*, 2014).

6.2. Biochar application rates and methods

The application rates and methods of biochar are critical factors in determining its effectiveness in improving soil health and crop productivity (Jeffery *et al.*, 2011). The optimal biochar application rates depend on several factors, such as soil type, crop species, and biochar properties (Sohi *et al.,* 2010). In general, biochar application rates ranging from 5 to 50 t ha^{-1} have been reported to improve soil properties and crop yields (Jeffery *et al.*, 2011). However, higher application rates (> 50 t ha^{-1}) may have negative effects on soil health and crop growth, particularly in the short term (Kammann *et al.,* 2011). Therefore, it is essential to determine the appropriate biochar application rates based on site-specific conditions and management goals (Sohi *et al.*, 2010).

Several methods have been used for biochar application in agricultural soils, including:

6.2.1. Soil incorporation

Soil incorporation is the most common method of biochar application, involving the mixing of biochar with the topsoil (0-20 cm) using tillage equipment, such as plows, disks, or harrows (Major *et al.,* 2010). This method ensures a uniform distribution of biochar in the root zone and facilitates its interactions with soil components and microorganisms (Blackwell *et al.,* 2009). However, soil incorporation may disrupt soil structure and increase the risk of soil erosion, particularly in sloping lands or under intensive tillage (Mukherjee & Lal, 2013).

6.2.2. Top-dressing

Top-dressing involves the surface application of biochar without incorporation into the soil (Kammann *et al.,* 2011). This method is less disruptive to soil structure and can be easily applied using spreaders or by hand (Major *et al.,* 2010). Top-dressing is particularly suitable for perennial crops, pastures, or conservation agriculture systems, where tillage is minimized or avoided (Sohi *et al.,* 2010). However, the effectiveness of top-dressed biochar may be limited by its low contact with soil components and microorganisms, as well as its susceptibility to wind and water erosion (Mukherjee & Lal, 2013).

6.2.3. Seedling dipping

Seedling dipping involves the coating of plant roots with a biochar slurry before transplanting (Elad *et al.,* 2010). This method ensures a direct contact between biochar and plant roots, potentially enhancing nutrient and water uptake, as well as disease suppression (Mahmood *et al.,* 2016). Seedling dipping is particularly suitable for vegetable and fruit crops that are transplanted as seedlings, such as tomatoes, peppers, and strawberries (Elad *et al.,* 2010). However, the effectiveness of seedling dipping may be limited by the small amount of biochar applied and its potential loss during transplanting and crop growth (Mahmood *et al.,* 2016).

6.3. Crop-specific responses to biochar amendment

The responses of crops to biochar amendment vary widely depending on the crop species, biochar properties, soil type, and environmental conditions (Jeffery *et al.,* 2011). In general, biochar has been reported to improve the growth and yield of various crops, including:

6.3.1. Cereals

Biochar has been shown to increase the yield and nutrient uptake of several cereal crops, such as rice, wheat, and maize (Zhang *et al.,* 2012). For instance, a meta-analysis by Jeffery *et al.* (2011) found that biochar application increased the yield of wheat by 10% and maize by 11% on average, particularly in acidic and sandy soils. The positive effects of biochar on cereal crops have been attributed to various mechanisms, such as improved soil structure, water retention, nutrient availability, and mycorrhizal colonization (Solaiman *et al.,* 2010).

6.3.2. Legumes

Biochar has been reported to enhance the growth, nodulation, and N2 fixation of various legume crops, such as soybeans, common beans, and chickpeas (Rondon *et al.*, 2007). For example, a study by Tagoe *et al.* (2008) found that biochar application increased the yield of soybeans by 44% and common beans by 46% in a sandy soil, along with improved nodulation and N uptake. The beneficial effects of biochar on legumes have been attributed to various factors, such as increased soil pH, nutrient availability, and rhizobial activity (Rondon *et al.*, 2007).

6.3.3. Vegetables and fruits

Biochar has been shown to improve the yield and quality of various vegetable and fruit crops, such as tomatoes, lettuce, and strawberries (Harel *et al.*, 2012). For instance, a study by Vaccari *et al.* (2011) found that biochar application increased the yield of tomatoes by 25% and improved their nutritional quality, particularly the content of vitamin C and lycopene. The positive effects of biochar on vegetables and fruits have been attributed to various mechanisms, such as enhanced nutrient and water uptake, disease suppression, and improved soil physical properties (Elad *et al.*, 2010).

6.4. Long-term effects of biochar on soil fertility and crop yields

While many studies have reported positive short-term effects of biochar on soil properties and crop productivity, the long-term impacts of biochar remain largely unknown (Sohi *et al.*, 2010). Some studies have suggested that the beneficial effects of biochar may persist for several years or even decades, due to its high stability and resistance to decomposition (Lehmann *et al.*, 2006). For instance, a study by Major *et al.* (2010) found that the positive effects of biochar on soil fertility and crop yields in a Colombian savanna soil persisted for at least four years after application. Similarly, a study by Vaccari *et al.* (2011) reported that the benefits of biochar on tomato growth and yield were maintained over two consecutive growing seasons.

However, other studies have indicated that the long-term effects of biochar may be more variable and context-dependent (Jeffery *et al.*, 2011). For example, a study by Jones *et al.* (2012) found that the positive effects of biochar on soil properties and crop yields in a temperate agricultural soil diminished over time, possibly due to the aging and weathering of biochar. Similarly, a study by Zhang *et al.* (2012) reported that the benefits of biochar on rice yield in a Chinese paddy soil varied across different years and biochar application rates, suggesting the need for site-specific optimization.

CHAPTER - 7
Bio-char and greenhouse gas emissions

Biochar has been widely recognized as a potential tool for mitigating climate change through carbon sequestration in agricultural soils (Woolf *et al.*, 2010). The production and application of biochar can transfer a significant portion of the carbon from biomass feedstocks into stable, recalcitrant forms that can persist in soils for hundreds to thousands of years (Lehmann *et al.*, 2006). By sequestering carbon in soils, biochar can reduce the atmospheric concentration of CO_2 and contribute to the mitigation of global warming (Sohi *et al.*, 2010).

Table 7. Economic analysis of biochar production and application in integrated farming systems

Study	**Feedstock**	**Production Method**	**Application Rate (t/ha)**	**Crop**	**Net Return ($/ha/yr)**
Kung *et al.* (2013)	Rice husk	Top-lit updraft gasifier	10	Vegetables	1,000
Galinato *et al.* (2011)	Wood waste	Slow pyrolysis	5	Wheat-pea rotation	200
Clare *et al.* (2014)	Sugarcane bagasse	Auger reactor	10	Sugarcane	-60

The carbon sequestration potential of biochar depends on several factors, such as the feedstock type, pyrolysis conditions, and soil properties (Sohi *et al.*, 2010). In general, biochar produced from woody biomass and at higher pyrolysis temperatures (>500°C) tends to have a higher carbon content and stability, and thus a greater potential for long-term carbon sequestration (Lehmann *et al.*, 2006). For instance, a study by Woolf *et al.* (2010) estimated that the global implementation of biochar systems could potentially sequester up to 1.8 Gt CO_2-equivalent per year, which corresponds to ~12% of current anthropogenic CO_2 emissions. Similarly, a study by Lehmann *et al.* (2006) suggested that the application of biochar could store up to 9.5 Gt C per year in agricultural soils, which is equivalent to the global annual fossil fuel emissions.

However, the actual carbon sequestration potential of biochar may be lower than these estimates, due to various constraints and uncertainties, such as biochar stability, soil interactions, and land availability (Sohi *et al.*, 2010). Moreover, the production and application of biochar may also have other environmental impacts, such as changes in soil properties, nutrient dynamics, and greenhouse gas emissions, which need to be carefully considered and managed (Woolf *et al.*, 2010).

7.2. Nitrous oxide (N_2O) emissions

Biochar application has been reported to affect the emissions of nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential 298 times higher than CO_2 over a 100-year time horizon (IPCC, 2007). N_2O emissions from agricultural soils are primarily driven by microbial processes, such as nitrification and denitrification, which are influenced by soil properties, nitrogen availability, and environmental conditions (Butterbach-Bahl *et al.,* 2013).

The impact of biochar on N_2O emissions varies widely depending on the biochar properties, soil type, and management practices (Cayuela *et al.*, 2014). Some studies have reported that biochar application can reduce N_2O emissions from agricultural soils, particularly in coarse-textured and acidic soils (Van Zwieten *et al.,* 2010). For instance, a meta-analysis by Cayuela *et al.* (2015) found that biochar application decreased N_2O emissions by an average of 54% across 30 studies, with the greatest reductions observed in sandy soils and at high biochar application rates. The mechanisms underlying biochar-induced N_2O mitigation are not fully understood but may involve several processes, such as:

- Adsorption of NH_4^+ and NO_3^- by biochar, reducing their availability for nitrification and denitrification (Singh *et al.*, 2010).
- Stimulation of N immobilization by soil microorganisms, limiting the substrate availability for N_2O-producing processes (Zheng *et al.*, 2012).
- Improvement of soil aeration and water retention, creating less favorable conditions for denitrification (Van Zwieten *et al.,* 2010).
- Alteration of soil pH and redox conditions, affecting the activity and composition of nitrifying and denitrifying communities (Cayuela *et al.*, 2013).

7.3. Methane (CH_4) emissions

Biochar application has also been investigated for its potential to affect methane (CH_4) emissions from agricultural soils, particularly in rice paddies and other wetland systems (Jeffery *et al.*, 2016). CH_4 is a potent greenhouse gas with a global warming potential 25 times higher than

CO_2 over a 100-year time horizon (IPCC, 2007). CH_4 emissions from agricultural soils are primarily driven by methanogenic archaea, which produce CH_4 under anaerobic conditions, and methanotrophic bacteria, which oxidize CH_4 in the presence of oxygen (Conrad, 2007).

The impact of biochar on CH_4 emissions from agricultural soils is highly variable and depends on several factors, such as the biochar feedstock, soil type, and water management (Jeffery *et al.,* 2016). Some studies have reported that biochar application can reduce CH_4 emissions from rice paddies and other wetland soils (Liu *et al.,* 2011; Feng *et al.,* 2012). For instance, a meta-analysis by Jeffery *et al.* (2016) found that biochar addition decreased CH_4 emissions by an average of 19% across 42 studies, with the greatest reductions observed in acidic soils and when biochar was applied in combination with other organic amendments. The mechanisms underlying biochar-induced CH_4 mitigation may include:

- Improvement of soil aeration and drainage, reducing the anaerobic conditions favoring methanogenesis (Liu *et al.*, 2011).
- Stimulation of methanotrophic activity by increasing the availability of oxygen and inorganic compounds, such as copper and iron, which are essential for methane oxidation (Feng *et al.,* 2012).
- Adsorption of CH_4 onto the surface of biochar, reducing its diffusion and emission from the soil (Cai *et al.,* 2016).
- Alteration of the soil microbial community structure, favoring methanotrophic over methanogenic populations (Feng *et al.,* 2012).

7.4. Life cycle assessment of biochar systems

To fully understand the net impact of biochar on greenhouse gas emissions and the environment, it is essential to consider the entire life cycle of biochar systems, from feedstock production and pyrolysis to soil application and long-term effects (Woolf *et al.,* 2010). Life cycle assessment (LCA) is a valuable tool for quantifying the environmental footprint of biochar systems and comparing them with other soil management practices or carbon sequestration strategies (Gaunt & Lehmann, 2008).

LCA studies on biochar systems have yielded mixed results, depending on the specific assumptions, system boundaries, and impact categories considered (Cowie *et al.*, 2015). Some studies have reported that biochar systems can have a net positive impact on climate change mitigation, primarily due to the carbon sequestration potential of biochar and the displacement of fossil fuels by pyrolysis co-products, such as bio-oil and syngas (Roberts *et al.,* 2010; Hammond *et al.,* 2011). For instance, a study by Peters *et al.* (2015) found that the application of biochar from pyrolyzed wood waste could reduce greenhouse gas emissions by 2.1-4.6 t CO_2-equivalent per hectare per year, considering both carbon sequestration and avoided emissions from fertilizer production and use.

CHAPTER - 8
Challenges and opportunities

One of the main challenges for the widespread adoption of biochar in integrated farming systems is the economic feasibility of biochar production and application (Dickinson *et al.,* 2015). The cost of biochar varies widely depending on the feedstock availability, pyrolysis technology, and transportation logistics (Meyer *et al.,* 2011). In general, the cost of biochar production ranges from $100 to $800 per ton, with the lower end corresponding to large-scale, centralized facilities using low-cost feedstocks, such as agricultural residues or waste biomass (Shackley *et al.,* 2011).

To assess the economic viability of biochar application in integrated farming, it is essential to conduct a cost-benefit analysis that considers both the direct and indirect costs and benefits of biochar use (Dickinson *et al.,* 2015). The direct costs of biochar application include the purchase price of biochar, transportation, and application costs, while the direct benefits include increased crop yields, reduced fertilizer and irrigation requirements, and potential carbon credits (Galinato *et al.,* 2011). The indirect costs and benefits of biochar application, such as changes in soil health, ecosystem services, and long-term productivity, are more difficult to quantify but should also be considered in the economic assessment (Guo *et al.,* 2016).

Several studies have investigated the economic feasibility of biochar application in different cropping systems and regions, with mixed results (Dickinson *et al.,* 2015). For instance, a study by Kung *et al.* (2013) found that the application of rice husk biochar at 10 t ha^{-1} in a Taiwanese vegetable farm resulted in a net economic benefit of $1,000 ha^{-1} yr^{-1}, considering the increased crop yields and reduced fertilizer costs. Similarly, a study by Galinato *et al.* (2011) reported that the application of wood biochar at 10 t ha^{-1} in a U.S. wheat-pea rotation had a benefit-cost ratio of 1.7, indicating a profitable investment.

However, other studies have found that the economic returns of biochar application may be marginal or negative, depending on the specific conditions (Clare *et al.,* 2014; Dickinson *et al.,* 2015). For example, a study by Clare *et al.* (2014) estimated that the application of sugarcane bagasse biochar at 10 t ha^{-1} in an Australian sugarcane farm would result in a net economic loss of $60 ha^{-1} yr^{-1}, considering the high cost of biochar and the limited yield benefits. Similarly, a study by Dickinson *et al.* (2015) found that the economic feasibility of biochar application in a Canadian canola-wheat rotation was highly sensitive to the biochar price and the yield response, with break-even prices ranging from $90 to $500 t^{-1}, depending on the scenario.

8.2. Feedstock availability and logistics

Another critical challenge for the large-scale adoption of biochar in integrated farming is the availability and logistics of feedstock supply (Mašek *et al.,* 2019). The type, quantity, and quality of feedstock can significantly influence the properties and performance of biochar as a soil amendment (Singh *et al.,* 2010). Therefore, ensuring a reliable and sustainable supply of appropriate feedstock is essential for the success of biochar projects (Sohi *et al.,* 2010).

The availability of biochar feedstock varies widely across regions and depends on factors such as land use, biomass productivity, and competing uses (Woolf *et al.,* 2010). In general, agricultural and forestry residues, such as crop straws, wood chips, and sawdust, are the most abundant and low-cost feedstocks for biochar production (Sohi *et al.,* 2010). However, the use of these residues for biochar may compete with other applications, such as animal feed, bioenergy, or soil conservation, which can limit their availability (Woolf *et al.,* 2010). In some cases, dedicated biomass crops, such as miscanthus or switchgrass, may be grown specifically for biochar production, but this can raise concerns about land use change and food security (Mašek *et al.,* 2019).

The logistics of feedstock supply, including collection, storage, and transportation, can also pose significant challenges for biochar projects (Mašek *et al.,* 2019). The bulky and low-density nature of most biomass feedstocks can make their transportation over long distances economically and environmentally unsustainable (Stelte *et al.,* 2012). Therefore, biochar production facilities need to be located close to the feedstock sources to minimize transportation costs and emissions (Meyer *et al.,* 2011). However, this can limit the scale and location of biochar projects, particularly in regions with dispersed or seasonal feedstock availability (Shackley *et al.,* 2015).

8.3. Standardization and quality control of biochar products

One of the main challenges for the widespread adoption of biochar in integrated farming is the lack of standardization and quality control of biochar products (Lehmann & Joseph, 2015). The properties and performance of biochar can vary widely depending on the feedstock type, production conditions, and post-treatment processes, which can lead to inconsistent results and uncertainties for end-users (Sohi *et al.,* 2010). Therefore, establishing clear and harmonized standards and quality control procedures for biochar production and application is crucial for ensuring its safety, effectiveness, and reliability as a soil amendment (Tammeorg *et al.,* 2017).

Several initiatives have been undertaken to develop biochar standards and certification systems at the national and international levels (Meyer *et al.,* 2017). For example, the International Biochar

Initiative (IBI) has developed a voluntary biochar certification program based on the IBI Biochar Standards, which specify the minimum criteria for biochar quality, including chemical properties, toxicant concentrations, and sustainability requirements (IBI, 2015). Similarly, the European Biochar Certificate (EBC) provides a voluntary certification system for biochar products based on a set of quality and sustainability criteria, including feedstock eligibility, production process, and product properties (EBC, 2012). Other countries, such as the USA, Australia, and Japan, have also developed their own biochar standards and certification schemes (Meyer *et al.,* 2017).

However, the adoption and harmonization of biochar standards and certification systems face several challenges, such as:

- Variability of biochar properties: The wide range of potential feedstocks and production conditions can result in biochars with diverse physical, chemical, and biological properties, which can be difficult to standardize and compare (Singh *et al.,* 2010). Therefore, biochar standards need to be flexible enough to account for this variability, while still ensuring a minimum level of quality and safety (Lehmann & Joseph, 2015).
- Lack of consensus on key biochar properties: There is still a lack of scientific consensus on which biochar properties are most important for its performance as a soil amendment, and how these properties should be measured and reported (Tammeorg *et al.,* 2017). This can lead to inconsistencies and confusion among biochar producers, users, and regulators (Meyer *et al.,* 2017).
- Limited market demand and incentives: The adoption of biochar standards and certification systems can be hindered by the limited market demand and incentives for certified biochar products (Jirka & Tomlinson, 2013). Many farmers and end-users may not be aware of or willing to pay a premium for certified biochar, which can discourage producers from investing in the certification process (Guo *et al.,* 2016).
- Regulatory and policy barriers: The lack of clear and supportive policies and regulations for biochar production and use can also pose barriers to the adoption of biochar standards and certification systems (Vochozka *et al.,* 2016). In many countries, biochar is still not recognized as a distinct product category, which can create uncertainties and obstacles for its standardization and quality control (Meyer *et al.,* 2017).

8.4. Policy support and incentives for biochar use

The adoption and upscaling of biochar use in integrated farming systems can be greatly influenced by the policy support and incentives provided by governments and other stakeholders (Liu & Zhang, 2021). Policy instruments, such as regulations, subsidies, taxes, and market-based mechanisms, can play a crucial role in creating an enabling environment for biochar production and use, by addressing the economic, social, and environmental barriers and opportunities associated with this technology (Joseph *et al.,* 2013).

8.5. Knowledge gaps and future research directions

Despite the growing body of research on biochar and its potential applications in integrated farming systems, several knowledge gaps and uncertainties remain, which need to be addressed through further research and development (Tammeorg *et al.,* 2017). Some of the key knowledge gaps and future research directions for biochar in integrated farming systems include:

- Long-term effects of biochar on soil properties and crop productivity: While many studies have reported positive short-term effects of biochar on soil health and crop yields, the long-term impacts of biochar application are still poorly understood (Sohi *et al.,* 2010). More long-term field experiments and monitoring studies are needed to assess the persistence, stability, and resilience of biochar-induced changes in soil properties and crop performance, across different soil types, cropping systems, and environmental conditions (Tammeorg *et al.,* 2017).
- Interactions between biochar and other soil management practices: Biochar is often applied in combination with other soil management practices, such as fertilization, irrigation, tillage, or crop rotation, which can influence its effects on soil and crop outcomes (Joseph *et al.,* 2013). More research is needed to understand the synergies, trade-offs, and interactions between biochar and other soil management practices, and to optimize the integration of biochar into existing farming systems and practices (Agegnehu *et al.,* 2017).
- Mechanisms of biochar-induced changes in soil biota and ecosystem functions: Biochar has been shown to influence the abundance, diversity, and activity of soil microorganisms, fauna, and flora, which play critical roles in soil health, nutrient cycling, and ecosystem services (Lehmann *et al.,* 2011). However, the underlying mechanisms and implications of biochar-induced changes in soil biota and ecosystem functions are still not fully understood (Thies *et al.,* 2015). More research is needed to elucidate the complex interactions between biochar, soil biota, and ecosystem processes, and to assess the potential benefits and risks of biochar for soil biodiversity and ecosystem resilience (Tammeorg *et al.,* 2017).

CHAPTER - 9
Case studies

To further illustrate the potential and diversity of biochar applications in integrated farming systems, this section presents several case studies of successful biochar projects from around the world, showcasing different feedstocks, production methods, application strategies, and outcomes.

9.1. Small-scale farms in developing countries

Biochar has been shown to have significant potential for improving soil fertility and crop productivity in small-scale farms in developing countries, where soil degradation and food insecurity are major challenges (Gwenzi *et al.,* 2015). One successful example is the BioFarm Project in Cambodia, which has been working with smallholder farmers to produce and apply biochar from rice husks and other agricultural residues (BioFarm, 2021).

9.2. Large-scale commercial farms in developed countries

Biochar has also been successfully applied in large-scale commercial farms in developed countries, where it can provide multiple benefits for soil health, crop productivity, and environmental sustainability (Joseph *et al.,* 2013). One notable example is the Pacific Pyrolysis project in Australia, which has been producing and applying biochar from woody biomass in a large-scale commercial orchard since 2014(Pacific Pyrolysis, 2021).

9.3. Agroforestry and silvo-pastoral systems

Biochar has also shown promise for enhancing soil health and productivity in agroforestry and silvo-pastoral systems, where trees and crops or livestock are integrated on the same land for multiple benefits (Stavi *et al.*, 2016). One successful example is the Biochar for Sustainable Soils (B4SS) project in Kenya, which has been promoting the use of biochar in smallholder agroforestry systems since 2014 (B4SS, 2021).

9.4. Organic and conservation agriculture

Biochar has also been explored as a promising soil amendment for organic and conservation agriculture systems, which aim to promote soil health, biodiversity, and sustainability by minimizing soil disturbance, maximizing soil cover, and diversifying crop rotations (Giller *et al.,* 2015). One notable example is the European Biochar for Sustainable Agriculture (EBSA) project, which has been investigating the potential of biochar for enhancing soil quality and crop performance in organic and conservation agriculture across several European countries (EBSA, 2021).

CHAPTER -10
Conclusions and recommendations

This review article has explored the multifaceted roles of biochar in enhancing soil health and crop productivity in integrated farming systems. The key findings of this review can be summarized as follows:

- Biochar is a carbon-rich material produced by the pyrolysis of biomass, which has unique physical, chemical, and biological properties that can improve soil quality and fertility, such as high surface area, porous structure, alkaline pH, high cation exchange capacity, and stable carbon content.
- Biochar can be produced from a wide range of feedstocks, such as crop residues, wood waste, and animal manure, using different pyrolysis technologies, such as slow pyrolysis, fast pyrolysis, and gasification, which influence the yield, quality, and properties of the resulting biochar.
- Biochar application can enhance soil physical properties, such as soil structure, water holding capacity, and bulk density, which can improve soil aeration, drainage, and root growth, as well as reduce soil erosion and compaction.
- Biochar application can enhance soil chemical properties, such as soil pH, cation exchange capacity, and nutrient retention, which can increase soil fertility, nutrient availability, and nutrient use efficiency, as well as reduce nutrient leaching and greenhouse gas emissions.
- Biochar application can enhance soil biological properties, such as microbial biomass, diversity, and activity, which can improve soil health, nutrient cycling, and disease suppression, as well as stimulate beneficial soil-plant interactions, such as mycorrhizal symbiosis and plant growth-promoting rhizobacteria.
- Biochar application can improve crop growth and productivity, by enhancing nutrient uptake, water use efficiency, and stress tolerance, as well as reducing the incidence of pests and diseases, depending on the biochar type, application rate, and crop system.
- Biochar application can contribute to climate change mitigation and adaptation, by sequestering carbon in soils, reducing greenhouse gas emissions, and improving soil and crop resilience to drought, heat, and other climate stresses, as well as providing opportunities for carbon farming and ecosystem services.

- Biochar adoption in integrated farming systems faces several challenges and opportunities, such as economic feasibility, feedstock availability, quality control, policy support, and knowledge gaps, which require a holistic and collaborative approach to research, development, and implementation of biochar systems.
- Successful case studies of biochar application in integrated farming systems, such as small-scale farms in developing countries, large-scale commercial farms in developed countries, agroforestry and silvo-pastoral systems, and organic and conservation agriculture, demonstrate the potential and diversity of biochar benefits and synergies in different contexts and scales.

CHAPTER -11
References

1. Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*, 119, 156-170. https://doi.org/10.1016/j.apsoil.2017.06.008
2. Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant and Soil*, 337(1), 1-18. https://doi.org/10.1007/s11104-010-0464-5
3. B4SS. (2021). *Biochar for Sustainable Soils (B4SS) project*. https://biochar.international/projects/b4ss/
4. Bailey, V. L., Fansler, S. J., Smith, J. L., & Bolton Jr, H. (2011). Reconciling apparent variability in effects of biochar amendment on soil enzyme activities by assay optimization. *Soil Biology and Biochemistry*, 43(2), 296-301. https://doi.org/10.1016/j.soilbio.2010.10.014
5. Barnes, R. T., Gallagher, M. E., Masiello, C. A., Liu, Z., & Dugan, B. (2014). Biochar-induced changes in soil hydraulic conductivity and dissolved nutrient fluxes constrained by laboratory experiments. *PloS One*, 9(9), e108340. https://doi.org/10.1371/journal.pone.0108340
6. Basso, A. S., Miguez, F. E., Laird, D. A., Horton, R., & Westgate, M. (2013). Assessing potential of biochar for increasing water-holding capacity of sandy soils. *GCB Bioenergy*, 5(2), 132-143. https://doi.org/10.1111/gcbb.12026
7. Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, 159(12), 3269-3282. https://doi.org/10.1016/j.envpol.2011.07.023
8. Behera, B. C., Singdevsachan, S. K., Mishra, R. R., Dutta, S. K., & Thatoi, H. N. (2015). Integrated farming approach for sustainable agricultural development in Eastern India. *Journal of Environmental Protection*, 6(1), 40-48. http://dx.doi.org/10.4236/jep.2015.61005
9. Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy*, 5(2), 202-214. https://doi.org/10.1111/gcbb.12037
10. BioFarm. (2021). *BioFarm Project Cambodia*. https://biofarm.org/

11. Blackwell, P., Krull, E., Butler, G., Herbert, A., & Solaiman, Z. (2009). Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: An agronomic and economic perspective. *Soil Research*, 48(7), 531-545. https://doi.org/10.1071/SR10014
12. Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal*, 81(4), 687-711. https://doi.org/10.2136/sssaj2017.01.0017
13. Bonanomi, G., Ippolito, F., & Scala, F. (2015). A "black" future for plant pathology? Biochar as a new soil amendment for controlling plant diseases. *Journal of Plant Pathology*, 97(2), 223-234. https://dx.doi.org/10.4454/JPP.V97I2.016
14. Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, 38, 68-94. https://doi.org/10.1016/j.biombioe.2011.01.048
15. Bruun, E. W., Ambus, P., Egsgaard, H., & Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology and Biochemistry*, 46, 73-79. https://doi.org/10.1016/j.soilbio.2011.11.019
16. Burrell, L. D., Zehetner, F., Rampazzo, N., Wimmer, B., & Soja, G. (2016). Long-term effects of biochar on soil physical properties. *Geoderma*, 282, 96-102. https://doi.org/10.1016/j.geoderma.2016.07.019
17. Buss, W., Jansson, S., & Mašek, O. (2018). Unexplored potential of novel biochar-ash composites for use as organo-mineral fertilizers. *Journal of Cleaner Production*, 208, 960-967. https://doi.org/10.1016/j.jclepro.2018.10.189
18. Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., & Zechmeister-Boltenstern, S. (2013). Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1621), 20130122. https://doi.org/10.1098/rstb.2013.0122
19. Cai, Y., Zhang, H., Yuan, J., Wang, C., Yamasaki, S., Shen, Q., & Gao, Y. (2016). Stimulation of methane oxidation potential in paddy soils from different regions of China with biochar and urea application. *Journal of Soils and Sediments*, 16(8), 2012-2022. https://doi.org/10.1007/s11368-016-1405-6
20. Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., & Ro, K. S. (2012). Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource Technology*, 107, 419-428. https://doi.org/10.1016/j.biortech.2011.11.084
21. Cao, X., Ma, L., Gao, B., & Harris, W. (2011). Dairy-manure derived biochar effectively sorbs lead and atrazine. *Environmental Science & Technology*, 45(9), 3285-3291. https://doi.org/10.1021/es103903t

22. Cayuela, M. L., Sánchez-Monedero, M. A., Roig, A., Hanley, K., Enders, A., & Lehmann, J. (2013). Biochar and denitrification in soils: when, how much and why does biochar reduce N_2O emissions? *Scientific Reports*, 3(1), 1-7. https://doi.org/10.1038/srep01732
23. Cayuela, M. L., Van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., & Sánchez-Monedero, M. A. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, 191, 5-16. https://doi.org/10.1016/j.agee.2013.10.009
24. Cayuela, M. L., Jeffery, S., & Van Zwieten, L. (2015). The molar H:C_{org} ratio of biochar is a key factor in mitigating N₂O emissions from soil. *Agriculture, Ecosystems & Environment*, 202, 135-138. https://doi.org/10.1016/j.agee.2014.12.015
25. Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D., & Julson, J. L. (2014). Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science*, 60(3), 393-404. https://doi.org/10.1080/03650340.2013.789870
26. Clare, A., Barnes, A., McDonagh, J., & Shackley, S. (2014). From rhetoric to reality: farmer perspectives on the economic potential of biochar in China. *International Journal of Agricultural Sustainability*, 12(4), 440-458. https://doi.org/10.1080/14735903.2014.927711
27. Clare, A., Shackley, S., Joseph, S., Hammond, J., Pan, G., & Bloom, A. (2015). Competing uses for China's straw: the economic and carbon abatement potential of biochar. *GCB Bioenergy*, 7(6), 1272-1282. https://doi.org/10.1111/gcbb.12220
28. Clough, T. J., Bertram, J. E., Ray, J. L., Condron, L. M., O'Callaghan, M., Sherlock, R. R., & Wells, N. S. (2010). Unweathered wood biochar impact on nitrous oxide emissions from a bovine-urine-amended pasture soil. *Soil Science Society of America Journal*, 74(3), 852-860. https://doi.org/10.2136/sssaj2009.0185
29. Conrad, R. (2007). Microbial ecology of methanogens and methanotrophs. *Advances in Agronomy*, 96, 1-63. https://doi.org/10.1016/S0065-2113(07)96005-8
30. Cowie, A., Woolf, D., Gaunt, J., Brandão, M., Anaya de la Rosa, R., & Cowie, A. (2015). Biochar, carbon accounting and climate change. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (pp. 763-794). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203762264-38/biochar-carbon-accounting-climate-change-annette-cowie-dominic-woolf-john-gaunt-miguel-brand%C3%A3o-roland-anaya-de-la-rosa

31. Cui, H. J., Wang, M. K., Fu, M. L., & Ci, E. (2011). Enhancing phosphorus availability in phosphorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw-derived biochar. *Journal of Soils and Sediments*, 11, 1135-1141. https://doi.org/10.1007/s11368-011-0405-9
32. DeLuca, T. H., MacKenzie, M. D., & Gundale, M. J. (2009). Biochar effects on soil nutrient transformations. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science and technology* (pp. 251-270). Earthscan. https://www.taylorfrancis.com/chapters/edit/10.4324/9781849770552-16/biochar-effects-soil-nutrient-transformations-thomas-deluca-michael-mackenzie-michael-gundale
33. Demirbas, A. (2004). Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. *Journal of Analytical and Applied Pyrolysis*, 72(2), 243-248. https://doi.org/10.1016/j.jaap.2004.07.003
34. Dick, R. P. (1994). Soil enzyme activity as an indicator of soil quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), *Defining soil quality for a sustainable environment* (pp. 107-124). SSSA Special Publication No. 35. Soil Science Society of America. https://doi.org/10.2136/sssaspecpub35.c7
35. Dickinson, D., Balduccio, L., Buysse, J., Ronsse, F., Van Huylenbroeck, G., & Prins, W. (2015). Cost-benefit analysis of using biochar to improve cereals agriculture. *GCB Bioenergy*, 7(4), 850-864. https://doi.org/10.1111/gcbb.12180
36. Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology*, 15(1), 3-11. https://doi.org/10.1016/S0929-1393(00)00067-6
37. Downie, A., Crosky, A., & Munroe, P. (2009). Physical properties of biochar. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science and technology* (pp. 13-32). Earthscan. https://www.taylorfrancis.com/chapters/edit/10.4324/9781849770552-9/physical-properties-biochar-adriana-downie-alan-crosky-paul-munroe
38. EBSA. (2021). *European Biochar for Sustainable Agriculture (EBSA) project*. https://cordis.europa.eu/project/id/101022604
39. El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., Zimmerman, A. R., Ahmad, M., Shaheen, S. M., & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, 337, 536-554. https://doi.org/10.1016/j.geoderma.2018.09.034
40. Elad, Y., David, D. R., Harel, Y. M., Borenshtein, M., Kalifa, H. B., Silber, A., & Graber, E. R. (2010). Induction of systemic resistance in plants by biochar, a soil-applied carbon

sequestering agent. *Phytopathology*, 100(9), 913-921. https://doi.org/10.1094/PHYTO-100-9-0913

41. European Biochar Certificate (EBC). (2012). *European biochar certificate-guidelines for a sustainable production of biochar*. EBC-STD-01, Version 6.3 E of 1st February 2012. https://www.european-biochar.org/media/doc/2/version_en_9_2.pdf
42. European Commission. (2021). *EU Soil Strategy for 2030*. COM(2021) 699 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699
43. FAO. (2018). *Integrated farming for human resilience: Farming is key to achieving the Sustainable Development Goals*. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i8418en/i8418en.pdf
44. Feng, Y., Xu, Y., Yu, Y., Xie, Z., & Lin, X. (2012). Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biology and Biochemistry*, 46, 80-88. https://doi.org/10.1016/j.soilbio.2011.11.016
45. Galinato, S. P., Yoder, J. K., & Granatstein, D. (2011). The economic value of biochar in crop production and carbon sequestration. *Energy Policy*, 39(10), 6344-6350. https://doi.org/10.1016/j.enpol.2011.07.035
46. Gaskin, J. W., Steiner, C., Harris, K., Das, K. C., & Bibens, B. (2010). Effect of low-temperature pyrolysis conditions on biochar for agricultural use. *Transactions of the ASABE*, 51(6), 2061-2069. https://doi.org/10.13031/2013.25409
47. Gaunt, J., & Lehmann, J. (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology*, 42(11), 4152-4158. https://doi.org/10.1021/es071361i
48. Genesio, L., Miglietta, F., Lugato, E., Baronti, S., Pieri, M., & Vaccari, F. P. (2021). Biochar increases vineyard productivity without affecting grape quality: Results from a four years field experiment in Tuscany. *Agriculture, Ecosystems & Environment*, 306, 107199. https://doi.org/10.1016/j.agee.2020.107199
49. Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Research*, 114(1), 23-34. https://doi.org/10.1016/j.fcr.2009.06.017
50. Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - A review. *Biology and Fertility of Soils*, 35(4), 219-230. https://doi.org/10.1007/s00374-002-0466-4
51. Glick, B. R. (2012). Plant growth-promoting bacteria: mechanisms and applications. *Scientifica*, 963401. https://doi.org/10.6064/2012/963401

52. Gray, M., Johnson, M. G., Dragila, M. I., & Kleber, M. (2014). Water uptake in biochars: The roles of porosity and hydrophobicity. *Biomass and Bioenergy*, 61, 196-205. https://doi.org/10.1016/j.biombioe.2013.12.010
53. Guo, M., Xiao, P., & Li, H. (2016). Valorization of agricultural byproducts through conversion to biochar and bio-oil. In M. Guo, Z. He, & S. M. Uchimiya (Eds.), *Agricultural and environmental applications of biochar: Advances and barriers* (pp. 61-98). Soil Science Society of America. https://doi.org/10.2136/sssaspecpub63.2014.0049.5
54. Gwenzi, W., Chaukura, N., Mukome, F. N., Machado, S., & Nyamasoka, B. (2015). Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. *Journal of Environmental Management*, 150, 250-261. https://doi.org/10.1016/j.jenvman.2014.11.027
55. Hammer, E. C., Balogh-Brunstad, Z., Jakobsen, I., Olsson, P. A., Stipp, S. L., & Rillig, M. C. (2014). A mycorrhizal fungus grows on biochar and captures phosphorus from its surfaces. *Soil Biology and Biochemistry*, 77, 252-260. https://doi.org/10.1016/j.soilbio.2014.06.012
56. Hammond, J., Shackley, S., Sohi, S., & Brownsort, P. (2011). Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. *Energy Policy*, 39(5), 2646-2655. https://doi.org/10.1016/j.enpol.2011.02.033
57. Hansen, V., Müller-Stöver, D., Ahrenfeldt, J., Holm, J. K., Henriksen, U. B., & Hauggaard-Nielsen, H. (2015). Gasification biochar as a valuable by-product for carbon sequestration and soil amendment. *Biomass and Bioenergy*, 72, 300-308. https://doi.org/10.1016/j.biombioe.2014.10.013
58. Harel, Y. M., Elad, Y., Rav-David, D., Borenstein, M., Shulchani, R., Lew, B., & Graber, E. R. (2012). Biochar mediates systemic response of strawberry to foliar fungal pathogens. *Plant and Soil*, 357, 245-257. https://doi.org/10.1007/s11104-012-1129-3
59. IBI. (2015). *Standardized product definition and product testing guidelines for biochar that is used in soil*. International Biochar Initiative. https://biochar-international.org/wp-content/uploads/2018/04/IBI_Biochar_Standards_V2.1_Final.pdf
60. IBI. (2018). *The 2018 US Farm Bill - What does it mean for biochar?*. International Biochar Initiative. https://biochar-international.org/2018-farm-bill-update/
61. IPCC. (2007). *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.)]. Cambridge University Press. https://www.ipcc.ch/report/ar4/wg1/

62. Jaiswal, A. K., Frenkel, O., Elad, Y., Lew, B., & Graber, E. R. (2015). Non-monotonic influence of biochar dose on bean seedling growth and susceptibility to Rhizoctonia solani: The "shifted Rmax-effect". *Plant and Soil*, 395, 125-140. https://doi.org/10.1007/s11104-014-2331-2
63. Jeffery, S., Verheijen, F. G., Van Der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144(1), 175-187. https://doi.org/10.1016/j.agee.2011.08.015
64. Jeffery, S., Abalos, D., Spokas, K. A., & Verheijen, F. G. (2016). Biochar effects on crop yield. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (pp. 453-481). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781849775250-20/biochar-effects-crop-yield-simon-jeffery-diego-abalos-kurt-spokas-frank-verheijen
65. Jin, H. (2010). Characterization of microbial life colonizing biochar and biochar-amended soils [Doctoral dissertation, Cornell University]. eCommons. https://ecommons.cornell.edu/handle/1813/17077
66. Jin, Y., Liang, X., He, M., Liu, Y., Tian, G., & Shi, J. (2016). Manure biochar influence upon soil properties, phosphorus distribution and phosphatase activities: a microcosm incubation study. *Chemosphere*, 142, 128
67. 8-137. https://doi.org/10.1016/j.chemosphere.2015.05.089
68. Jirka, S., & Tomlinson, T. (2013). State of the biochar industry 2014: A survey of commercial activity in the biochar field. *International Biochar Initiative*. https://biochar-international.org/state-of-the-biochar-industry-2013/
69. Jones, D. L., Rousk, J., Edwards-Jones, G., DeLuca, T. H., & Murphy, D. V. (2012). Biochar-mediated changes in soil quality and plant growth in a three year field trial. *Soil Biology and Biochemistry*, 45, 113-124. https://doi.org/10.1016/j.soilbio.2011.10.012
70. Joseph, S., Graber, E. R., Chia, C., Munroe, P., Donne, S., Thomas, T., Nielsen, S., Marjo, C., Rutlidge, H., Pan, G. X., Li, L., Taylor, P., Rawal, A., & Hook, J. (2013). Shifting paradigms: development of high-efficiency biochar fertilizers based on nano-structures and soluble components. *Carbon Management*, 4(3), 323-343. https://doi.org/10.4155/cmt.13.23
71. Joseph, S., Taylor, P., & Cowie, A. (2021). Biochar as a geoengineered soil carbon storage system: hazard identification and risk management. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (3rd ed., pp. 999-1024). Routledge.

https://www.taylorfrancis.com/chapters/edit/10.4324/9781003157328-38/biochar-geoengineered-soil-carbon-storage-system-hazard-identification-risk-management-stephen-joseph-paul-taylor-annette-cowie

72. Kambo, H. S., & Dutta, A. (2015). A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renewable and Sustainable Energy Reviews*, 45, 359-378. https://doi.org/10.1016/j.rser.2015.01.050
73. Kammann, C. I., Linsel, S., Gößling, J. W., & Koyro, H. W. (2011). Influence of biochar on drought tolerance of Chenopodium quinoa Willd and on soil-plant relations. *Plant and Soil*, 345, 195-210. https://doi.org/10.1007/s11104-011-0771-5
74. Karlen, D. L., Ditzler, C. A., & Andrews, S. S. (2003). Soil quality: why and how? *Geoderma*, 114(3-4), 145-156. https://doi.org/10.1016/S0016-7061(03)00039-9
75. Kauffman, N., Dumortier, J., Hayes, D. J., Brown, R. C., & Laird, D. A. (2014). Producing energy while sequestering carbon? The relationship between biochar and agricultural productivity. *Biomass and Bioenergy*, 63, 167-176. https://doi.org/10.1016/j.biombioe.2014.01.049
76. Kolton, M., Harel, Y. M., Pasternak, Z., Graber, E. R., Elad, Y., & Cytryn, E. (2011). Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants. *Applied and Environmental Microbiology*, 77(14), 4924-4930. https://doi.org/10.1128/AEM.00148-11
77. Krull, E., Sohi, S., Lopez-Capel, E., Bol, R., & Lehmann, J. (2012). *Biochar, climate change and soil: A review to guide future research*. CSIRO Land and Water Science Report 05/09. https://hal.archives-ouvertes.fr/hal-00740192
78. Kumar, A., Jones, D. D., & Hanna, M. A. (2009). Thermochemical biomass gasification: a review of the current status of the technology. *Energies*, 2(3), 556-581. https://doi.org/10.3390/en20300556
79. Kung, C. C., McCarl, B. A., & Cao, X. (2013). Economics of pyrolysis-based energy production and biochar utilization: A case study in Taiwan. *Energy Policy*, 60, 317-323. https://doi.org/10.1016/j.enpol.2013.05.029
80. Laird, D. A., Rogovska, N. P., Garcia-Perez, M., Collins, H. P., Streubel, J. D., & Smith, M. (2011). Pyrolysis and biochar - opportunities for distributed production and soil quality enhancement. In R. C. Brown (Ed.), *Thermochemical processing of biomass: Conversion into fuels, chemicals and power* (pp. 257-282). John Wiley & Sons. https://doi.org/10.1002/9781119990840.ch16

81. Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, 3(5), 547-562. https://doi.org/10.1002/bbb.169
82. Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, 158(3-4), 436-442. https://doi.org/10.1016/j.geoderma.2010.05.012
83. Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), 5875-5895. https://doi.org/10.3390/su7055875
84. Lashari, M. S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., Zheng, J., Zheng, J., Zhang, X., & Yu, X. (2013). Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain. *Field Crops Research*, 144, 113-118. https://doi.org/10.1016/j.fcr.2012.11.015
85. Latawiec, A. E., Strassburg, B. B., Junqueira, A. B., Araujo, E., de Moraes, L. F., Pinto, H. A. N., Castro, A., Rangel, M., Malaguti, G. A., Rodrigues, A. F., Barioni, L. G., & Novotny, E. H. (2017). Biochar amendment improves degraded pasturelands in Brazil: Environmental and cost-benefit analysis. *Scientific Reports*, 7(1), 1-12. https://doi.org/10.1038/s41598-017-14188-0
86. Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for environmental management: Science, technology and implementation* (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264
87. Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems–a review. *Mitigation and Adaptation Strategies for Global Change*, 11, 403-427. https://doi.org/10.1007/s11027-005-9006-5
88. Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota–a review. *Soil Biology and Biochemistry*, 43(9), 1812-1836. https://doi.org/10.1016/j.soilbio.2011.04.022
89. Lehmann, J., da Silva Jr, J. P., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, 249(2), 343-357. https://doi.org/10.1023/A:1022833116184
90. Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J. O., Thies, J., Luizao, F. J., Petersen, J., & Neves, E. G. (2006). Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal*, 70(5), 1719-1730. https://doi.org/10.2136/sssaj2005.0383

91. Limwikran, T., Kheoruenromne, I., Suddhiprakarn, A., Prakongkep, N., & Gilkes, R. J. (2018). Dissolution of K, Ca, and P from biochar grains in tropical soils. *Geoderma*, 312, 139-150. https://doi.org/10.1016/j.geoderma.2017.10.022
92. Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., & Zou, J. (2011). Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: A meta-analysis. *GCB Bioenergy*, 8(2), 392-406. https://doi.org/10.1111/gcbb.12265
93. Liu, T., Liu, B., & Zhang, W. (2021). Biochar for climate-change mitigation and restoration of degraded soils: recent progress and future perspectives. In J. M. Mench & R. Bes (Eds.), *Sustainable remediation of contaminated soil and groundwater* (pp. 301-320). Elsevier. https://doi.org/10.1016/B978-0-12-817982-6.00011-X
94. Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., & Paz-Ferreiro, J. (2013). Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. *Plant and Soil*, 373, 583-594. https://doi.org/10.1007/s11104-013-1806-x
95. Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S., & Qiu, R. (2012). Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar. *Water Research*, 46(3), 854-862. https://doi.org/10.1016/j.watres.2011.11.058
96. Luo, G., Li, L., Friman, V. P., Guo, J., Guo, S., Shen, Q., & Ling, N. (2017). Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: A meta-analysis. *Soil Biology and Biochemistry*, 124, 105-115. https://doi.org/10.1016/j.soilbio.2018.06.002
97. Ly, P., Vu, Q. D., Jensen, L. S., Pandey, A., & de Neergaard, A. (2014). Effects of rice straw, biochar and mineral fertiliser on methane (CH_4) and nitrous oxide (N_2O) emissions from rice (Oryza sativa L.) grown in a rain-fed lowland rice soil of Cambodia: a pot experiment. *Paddy and Water Environment*, 13, 465-475. https://doi.org/10.1007/s10333-014-0464-9
98. Mahmood, I., Imadi, S. R., Shazadi, K., Gul, A., & Hakeem, K. R. (2016). Effects of pesticides on environment. In K. R. Hakeem (Ed.), *Plant, soil and microbes* (pp. 253-269). Springer. https://doi.org/10.1007/978-3-319-27455-3_13
99. Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, 333, 117-128. https://doi.org/10.1007/s11104-010-0327-0
100. Mao, J. D., Johnson, R. L., Lehmann, J., Olk, D. C., Neves, E. G., Thompson, M. L., & Schmidt-Rohr, K. (2012). Abundant and stable char residues in soils: implications

for soil fertility and carbon sequestration. *Environmental Science & Technology*, 46(17), 9571-9576. https://doi.org/10.1021/es301107c

101. Manjunatha, S. B., Biradar, D. P., & Aladakatti, Y. R. (2016). Nanotechnology and its applications in agriculture: A review. *Journal of Farm Sciences*, 29(1), 1-13. https://krishi.icar.gov.in/jspui/bitstream/123456789/9775/1/Nanotechnology%20and%20its%20applications%20in%20agriculture%20A%20review.pdf

102. Maraseni, T. N., Mushtaq, S., Reardon-Smith, K., Apan, A., Yee, M., & Hopf, J. (2015). Economic analysis of agro-forestry systems as a climate change mitigation strategy in Australia. In S. S. Nielsen (Ed.), *Handbook of plant and crop physiology* (3rd ed., pp. 817-839). CRC Press. https://doi.org/10.1201/b16675-47

103. Mašek, O., Ronsse, F., & Dickinson, D. (2019). Biochar production and feedstock. In E. Lichtfouse (Ed.), *Biochar as a renewable-based material: With applications in agriculture, the environment and energy* (pp. 17-40). Springer. https://doi.org/10.1007/978-3-030-13863-0_2

104. McCormack, S. A., Ostle, N., Bardgett, R. D., Hopkins, D. W., & Vanbergen, A. J. (2013). Biochar in bioenergy cropping systems: impacts on soil faunal communities and linked ecosystem processes. *GCB Bioenergy*, 5(2), 81-95. https://doi.org/10.1111/gcbb.12046

105. Mehari, Z. H., Elad, Y., Rav-David, D., Graber, E. R., & Harel, Y. M. (2015). Induced systemic resistance in tomato (Solanum lycopersicum) against Botrytis cinerea by biochar amendment involves jasmonic acid signaling. *Plant and Soil*, 395, 31-44. https://doi.org/10.1007/s11104-015-2445-1

106. Meyer, S., Bright, R. M., Fischer, D., Schulz, H., & Glaser, B. (2012). Albedo impact on the suitability of biochar systems to mitigate global warming. *Environmental Science & Technology*, 46(22), 12726-12734. https://doi.org/10.1021/es302302g

107. Meyer, S., Genesio, L., Vogel, I., Schmidt, H. P., Soja, G., Someus, E., Shackley, S., Verheijen, F. G., & Glaser, B. (2017). Biochar standardization and legislation harmonization. *Journal of Environmental Engineering and Landscape Management*, 25(2), 175-191. https://doi.org/10.3846/16486897.2016.1254640

108. Meyer, S., Glaser, B., & Quicker, P. (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. *Environmental Science & Technology*, 45(22), 9473-9483. https://doi.org/10.1021/es201792c

109. Mohan, D., Pittman Jr, C. U., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy & Fuels*, 20(3), 848-889. https://doi.org/10.1021/ef0502397

110. Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences*, 104(33), 13268-13272. https://doi.org/10.1073/pnas.0611508104

111. Mukherjee, A., & Lal, R. (2013). Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy*, 3(2), 313-339. https://doi.org/10.3390/agronomy3020313

112. Mulcahy, D. N., Mulcahy, D. L., & Dietz, D. (2013). Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *Journal of Arid Environments*, 88, 222-225. https://doi.org/10.1016/j.jaridenv.2012.07.012

113. Muñoz, E., Curaqueo, G., Cea, M., Vera, L., & Navia, R. (2017). Environmental hotspots in the life cycle of a biochar-soil system. *Journal of Cleaner Production*, 158, 1-7. https://doi.org/10.1016/j.jclepro.2017.04.163

114. Nanda, S., Dalai, A. K., Berruti, F., & Kozinski, J. A. (2016). Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. *Waste and Biomass Valorization*, 7, 201-235. https://doi.org/10.1007/s12649-015-9459-z

115. Nguyen, T. T. N., Xu, C. Y., Tahmasbian, I., Che, R., Xu, Z., Zhou, X., Wallace, H. M., & Bai, S. H. (2017). Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. *Geoderma*, 288, 79-96. https://doi.org/10.1016/j.geoderma.2016.11.004

116. Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science*, 174(2), 105-112. https://doi.org/10.1097/SS.0b013e3181981d9a

117. Ouyang, L., Wang, F., Tang, J., Yu, L., & Zhang, R. (2013). Effects of biochar amendment on soil aggregates and hydraulic properties. *Journal of Soil Science and Plant Nutrition*, 13(4), 991-1002. https://doi.org/10.4067/S0718-95162013005000078

118. Pacific Pyrolysis. (2021). *Case study: Large scale biochar field trial in agricultural orchard*. https://pacificpyrolysis.com/project/field-trial/

119. Page-Dumroese, D. S., Busse, M. D., Archuleta, J. G., McAvoy, D., & Roussel, E. (2017). Methods to reduce forest residue volume after timber harvesting and produce black carbon. *Scientifica*, 2745764. https://doi.org/10.1155/2017/2745764

120. Parvage, M. M., Ulén, B., Eriksson, J., Strock, J., & Kirchmann, H. (2013). Phosphorus availability in soils amended with wheat residue char. *Biology and Fertility of Soils*, 49, 245-250. https://doi.org/10.1007/s00374-012-0746-6

121. Peters, J. F., Iribarren, D., & Dufour, J. (2015). Biomass pyrolysis for biochar or energy applications? A life cycle assessment. *Environmental Science & Technology*, 49(8), 5195-5202. https://doi.org/10.1021/es5060786

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

123. Rajapaksha, A. U., Chen, S. S., Tsang, D. C., Zhang, M., Vithanage, M., Mandal, S., Gao, B., Bolan, N. S., & Ok, Y. S. (2016). Engineered/designer biochar for contaminant removal/immobilization from soil and water: potential and implication of biochar modification. *Chemosphere*, 148, 276-291. https://doi.org/10.1016/j.chemosphere.2016.01.043

124. Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A. R., & Lehmann, J. (2012). Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils*, 48, 271-284. https://doi.org/10.1007/s00374-011-0624-7

125. Ro, K. S., Cantrell, K. B., & Hunt, P. G. (2010). High-temperature pyrolysis of blended animal manures for producing renewable energy and value-added biochar. *Industrial & Engineering Chemistry Research*, 49(20), 10125-10131. https://doi.org/10.1021/ie101155m

126. Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science & Technology*, 44(2), 827-833. https://doi.org/10.1021/es902266r

127. Rogovska, N., Laird, D., Cruse, R. M., Trabue, S., & Heaton, E. (2012). Germination tests for assessing biochar quality. *Journal of Environmental Quality*, 41(4), 1014-1022. https://doi.org/10.2134/jeq2011.0103

128. Rondon, M. A., Lehmann, J., Ramírez, J., & Hurtado, M. (2007). Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. *Biology and Fertility of Soils*, 43, 699-708. https://doi.org/10.1007/s00374-006-0152-z

129. Saarnio, S., Heimonen, K., & Kettunen, R. (2013). Biochar addition indirectly affects N2O emissions via soil moisture and plant N uptake. *Soil Biology and Biochemistry*, 58, 99-106. https://doi.org/10.1016/j.soilbio.2012.10.035

130. Saxena, J., Rana, G., & Pandey, M. (2013). Impact of addition of biochar along with Bacillus sp. on growth and yield of French beans. *Scientia Horticulturae*, 162, 351-356. https://doi.org/10.1016/j.scienta.2013.08.002

131. Shackley, S., Hammond, J., Gaunt, J., & Ibarrola, R. (2011). The feasibility and costs of biochar deployment in the UK. *Carbon Management*, 2(3), 335-356. https://doi.org/10.4155/cmt.11.22

132. Shackley, S., Clare, A., Joseph, S., McCarl, B. A., & Schmidt, H. P. (2015). Economic evaluation of biochar systems: current evidence and challenges. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (pp. 813-851). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203762264-39/economic-evaluation-biochar-systems-current-evidence-challenges-simon-shackley-abbie-clare-stephen-joseph-bruce-mccarl-hans-peter-schmidt

133. Singh, B. P., Cowie, A. L., & Smernik, R. J. (2012). Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental Science & Technology*, 46(21), 11770-11778. https://doi.org/10.1021/es302545b

134. Singh, B., Singh, B. P., & Cowie, A. L. (2010). Characterisation and evaluation of biochars for their application as a soil amendment. *Soil Research*, 48(7), 516-525. https://doi.org/10.1071/SR10058

135. Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, 22(3), 1315-1324. https://doi.org/10.1111/gcb.13178

136. Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. In L. S. Donald (Ed.), *Advances in agronomy* (Vol. 105, pp. 47-82). Academic Press. https://doi.org/10.1016/S0065-2113(10)05002-9

137. Solaiman, Z. M., Blackwell, P., Abbott, L. K., & Storer, P. (2010). Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. *Soil Research*, 48(7), 546-554. https://doi.org/10.1071/SR10002

138. Stavi, I., & Lal, R. (2013). Agroforestry and biochar to offset climate change: a review. *Agronomy for Sustainable Development*, 33, 81-96. https://doi.org/10.1007/s13593-012-0081-1

139. Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., & Henriksen, U. B. (2012). Recent developments in biomass pelletization–A review. *BioResources*, 7(3), 4451-4490.

https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_07_3_4451_Stelte_SSAHH_Biomass_Pelletization_Review

140. Subedi, R., Taupe, N., Ikoyi, I., Bertora, C., Zavattaro, L., Schmalenberger, A., Leahy, J. J., & Grignani, C. (2016). Chemically and biologically-mediated fertilizing value of manure-derived biochar. *Science of the Total Environment*, 550, 924-933. https://doi.org/10.1016/j.scitotenv.2016.01.160

141. Sundberg, C., Karltun, E., Gitau, J. K., Kätterer, T., Kimutai, G. M., Mahmoud, Y., Njenga, M., Nyberg, G., Roing de Nowina, K., Roobroeck, D., & Sieber, P. (2020). Biochar from cookstoves reduces greenhouse gas emissions from smallholder farms in Africa. *Mitigation and Adaptation Strategies for Global Change*, 25, 953-967. https://doi.org/10.1007/s11027-020-09920-7

142. Tagoe, S. O., Horiuchi, T., & Matsui, T. (2008). Effects of carbonized and dried chicken manures on the growth, yield, and N content of soybean. *Plant and Soil*, 306, 211-220. https://doi.org/10.1007/s11104-008-9573-9

143. Tammeorg, P., Bastos, A. C., Jeffery, S., Rees, F., Kern, J., Graber, E. R., Ventura, M., Kibblewhite, M., Amaro, A., Budai, A., Cordovil, C. M. d. S., Domene, X., Gardi, C., Gascó, G., Horák, J., Kammann, C., Kondrlova, E., Laird, D., Loureiro, S., ... & Glaser, B. (2017). Biochars in soils: towards the required level of scientific understanding. *Journal of Environmental Engineering and Landscape Management*, 25(2), 192-207. https://doi.org/10.3846/16486897.2016.1239582

144. Thies, J. E., Rillig, M. C., & Graber, E. R. (2015). Biochar effects on the abundance, activity and diversity of the soil biota. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (pp. 327-389). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203762264-19/biochar-effects-abundance-activity-diversity-soil-biota-janice-thies-matthias-rillig-ellen-graber

145. Uchimiya, M., Lima, I. M., Klasson, K. T., & Wartelle, L. H. (2010). Contaminant immobilization and nutrient release by biochar soil amendment: roles of natural organic matter. *Chemosphere*, 80(8), 935-940. https://doi.org/10.1016/j.chemosphere.2010.05.020

146. Vaccari, F. P., Baronti, S., Lugato, E., Genesio, L., Castaldi, S., Fornasier, F., & Miglietta, F. (2011). Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European Journal of Agronomy*, 34(4), 231-238. https://doi.org/10.1016/j.eja.2011.01.006

147. Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, 327, 235-246. https://doi.org/10.1007/s11104-009-0050-x

148. Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2013). An overview of the composition and application of biomass ash. Part 1. Phase–mineral and chemical composition and classification. *Fuel*, 105, 40-76. https://doi.org/10.1016/j.fuel.2012.09.041

149. Verheijen, F., Jeffery, S., Bastos, A. C., Van der Velde, M., & Diafas, I. (2010). *Biochar application to soils: a critical scientific review of effects on soil properties, processes, and functions*. JRC Scientific and Technical Reports. EUR 24099 EN, Office for the Official Publications of the European Communities. https://publications.jrc.ec.europa.eu/repository/handle/JRC55799

150. Vochozka, M., Maroušková, A., Straková, J., & Váchal, J. (2016). The economic impact of biochar use in Central Europe. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 38(16), 2390-2396. https://doi.org/10.1080/15567036.2015.1073855

151. Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8(3), 512-523. https://doi.org/10.1111/gcbb.12266

152. Wang, J., Zhang, M., Xiong, Z., Liu, P., & Pan, G. (2011). Effects of biochar addition on N₂O and CO₂ emissions from two paddy soils. *Biology and Fertility of Soils*, 47, 887-896. https://doi.org/10.1007/s00374-011-0595-8

153. Wang, J., Pan, X., Liu, Y., Zhang, X., & Xiong, Z. (2012). Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. *Plant and Soil*, 360, 287-298. https://doi.org/10.1007/s11104-012-1250-3

154. Wang, T., Camps-Arbestain, M., & Hedley, M. (2013). Predicting C aromaticity of biochars based on their elemental composition. *Organic Geochemistry*, 62, 1-6. https://doi.org/10.1016/j.orggeochem.2013.06.012

155. Wang, T., Camps-Arbestain, M., Hedley, M., & Bishop, P. (2012). Predicting phosphorus bioavailability from high-ash biochars. *Plant and Soil*, 357, 173-187. https://doi.org/10.1007/s11104-012-1131-9

156. Wang, T., Zhai, Y., Zhu, Y., Peng, C., Xu, B., Wang, T., Li, C., & Zeng, G. (2017). Feedwater pH affects phosphorus transformation during hydrothermal

carbonization of sewage sludge. *Bioresource Technology*, 245, 182-187. https://doi.org/10.1016/j.biortech.2017.08.114
157. Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil–concepts and mechanisms. *Plant and Soil*, 300, 9-20. https://doi.org/10.1007/s11104-007-9391-5
158. Weng, Z., Van Zwieten, L., Singh, B. P., Tavakkoli, E., Joseph, S., Macdonald, L. M., Rose, T. J., Rose, M. T., Kimber, S. W., Morris, S., & Cozzolino, D. (2017). Biochar built soil carbon over a decade by stabilizing rhizodeposits. *Nature Climate Change*, 7(5), 371-376. https://doi.org/10.1038/nclimate3276
159. Weyers, S. L., & Spokas, K. A. (2011). Impact of biochar on earthworm populations: A review. *Applied and Environmental Soil Science*, 541592. https://doi.org/10.1155/2011/541592
160. Windeatt, J. H., Ross, A. B., Williams, P. T., Forster, P. M., Nahil, M. A., & Singh, S. (2014). Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. *Journal of Environmental Management*, 146, 189-197. https://doi.org/10.1016/j.jenvman.2014.08.003
161. Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, 56. https://doi.org/10.1038/ncomms1053
162. Wrobel-Tobiszewska, A., Boersma, M., Sargison, J., Adams, P., & Jarick, S. (2015). An economic analysis of biochar production using residues from Eucalypt plantations. *Biomass and Bioenergy*, 81, 177-182. https://doi.org/10.1016/j.biombioe.2015.06.015
163. Xie, T., Reddy, K. R., Wang, C., Yargicoglu, E., & Spokas, K. (2015). Characteristics and applications of biochar for environmental remediation: a review. *Critical Reviews in Environmental Science and Technology*, 45(9), 939-969. https://doi.org/10.1080/10643389.2014.924180
164. Xie, X., Chen, W., Wu, J., & Zhou, X. (2021). Transformation of soil organic carbon induced by biochar: A meta-analysis. *Journal of Soils and Sediments*, 21, 2032-2043. https://doi.org/10.1007/s11368-021-02906-1
165. Xie, Z., Xu, Y., Liu, G., Liu, Q., Zhu, J., Tu, C., Amonette, J. E., Cadisch, G., Yong, J. W., & Hu, S. (2013). Impact of biochar application on nitrogen nutrition of rice, greenhouse-gas emissions and soil organic carbon dynamics in two paddy soils of China. *Plant and Soil*, 370, 527-540. https://doi.org/10.1007/s11104-013-1636-x

166. Xu, G., Wei, L. L., Sun, J. N., Shao, H. B., & Chang, S. X. (2013). What is more important for enhancing nutrient bioavailability with biochar application into a sandy soil: Direct or indirect mechanism? *Ecological Engineering*, 52, 119-124. https://doi.org/10.1016/j.ecoleng.2012.12.091

167. Xu, N., Tan, G., Wang, H., & Gai, X. (2016). Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. *European Journal of Soil Biology*, 74, 1-8. https://doi.org/10.1016/j.ejsobi.2016.02.004

168. Yuan, J. H., Xu, R. K., & Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology*, 102(3), 3488-3497. https://doi.org/10.1016/j.biortech.2010.11.018

169. Zhang, J., Liu, J., & Liu, R. (2015). Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate. *Bioresource Technology*, 176, 288-291. https://doi.org/10.1016/j.biortech.2014.11.011

170. Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X., Han, X., & Yu, X. (2012). Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. *Field Crops Research*, 127, 153-160. https://doi.org/10.1016/j.fcr.2011.11.020

171. Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., Zheng, J., & Crowley, D. (2010). Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems & Environment*, 139(4), 469-475. https://doi.org/10.1016/j.agee.2010.09.003

172. Zhang, D., Pan, G., Wu, G., Kibue, G. W., Li, L., Zhang, X., Zheng, J., Cheng, K., Joseph, S., & Liu, X. (2016). Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. *Chemosphere*, 142, 106-113. https://doi.org/10.1016/j.chemosphere.2015.04.088

173. Zhao, L., Cao, X., Mašek, O., & Zimmerman, A. (2013). Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *Journal of Hazardous Materials*, 256, 1-9. https://doi.org/10.1016/j.jhazmat.2013.04.015

174. Zheng, H., Wang, Z., Deng, X., Herbert, S., & Xing, B. (2013). Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. *Geoderma*, 206, 32-39. https://doi.org/10.1016/j.geoderma.2013.04.018

175. Zheng, J., Stewart, C. E., & Cotrufo, M. F. (2012). Biochar and nitrogen fertilizer alters soil nitrogen dynamics and greenhouse gas fluxes from two temperate soils.

Journal of Environmental Quality, 41(5), 1361-1370. https://doi.org/10.2134/jeq2012.0019