VYTAUTAS MAGNUS UNIVERSITY
LITHUANIAN RESEARCH CENTRE FOR AGRICULTURE AND FORESTRY

Muhammad AYAZ

PERSPECTIVES OF BIOCHAR WITH MINERAL NITROGEN FERTILIZERS FOR IMPROVEMENT OF SOIL SUSTAINABILITY AND CROP PRODUCTION IN NEMORAL CLIMATIC ZONE

Doctoral Dissertation
Agricultural Sciences, Agronomy (A 001)

Kaunas, 2023

The research was carried out during 2019-2023 and has been prepared at Lithuanian Research Centre for Agriculture and Forestry under the doctoral program right conferred to Vytautas Magnus University, Lithuanian Research Centre for Agriculture and Forestry, on 22nd February 2019, by decision No. V-160 of the Government of the Republic of Lithuania.

Scientific Supervisor

Dr. Dalia Feizienė (Lithuanian Research Centre for Agriculture and Forestry, Agricultural Sciences, Agronomy (A 001).

Scientific Consultant

Dr. Vita Tilvikienė (Lithuanian Research Centre for Agriculture and Forestry, Agricultural Sciences, Agronomy (A 001).

Dissertation will be defended at the Committee of Agronomy:

Council of defence of the doctoral dissertation:

Chairman

Dr. Karolina Barčauskaitė (Lithuanian Research Centre for Agriculture and Forestry, Agricultural Sciences, Agronomy, A 001).

Members:

Dr. Giedrė Samuolienė (Lithuanian Research Centre for Agriculture and Forestry, Agricultural Sciences, Agronomy, A 001);

Doc. dr. Zita Kraučiūnienė (Vytautas Magnus University, Agriculture Science Academy, Agronomy, A 001);

Dr. Marius Praspaliauskas (Lithuanian Energy Institute, Technological Sciences, Energetics and Thermal Engineering, T 006);

Prof. dr. Catherine Brewer (Department of Chemical and Materials Engineering, New Mexico State University, Agricultural Sciences, Agronomy, A 001).

The official defence of the dissertation will be held on the 12/10/2023, at 10 am. in the seminar room No. 1–12, Lithuania Research Centre for Agriculture and Forestry.

Address: Instituto al. 1, Akademija, Kėdainiai distr., LT-58344, Lithuania.

The doctoral dissertation is available at Martynas Mažvydas National Library of Lithuania and the libraries of Lithuanian Research Centre for Agriculture and Forestry and Vytautas Magnus University.

VYTAUTO DIDŽIOJO UNIVERSITETAS
LIETUVOS AGRARINIŲ IR MIŠKŲ MOKSLŲ CENTRAS

Muhammad AYAZ

BIOANGLIES IR MINERALINIŲ AZOTO TRĄŠŲ NAUDOJIMO PERSPEKTYVUMAS DIRVOŽEMIO TVARUMO IR AUGALŲ DERLINGUMO GERINIMUI NEMORALINĖJE KLIMATINĖJE ZONOJE

Mokslo daktaro disertacija
Žemės ūkio mokslai, Agronomija (A 001)

Kaunas, 2023

Mokslo daktaro disertacija rengta 2019–2023 metais Lietuvos agrarinių ir miškų mokslų centre pagal LR švietimo, mokslo ir sporto ministro 2019 m. vasario 22 d. įsakymu Nr. V-160 suteiktą doktorantūros teisę Vytauto Didžiojo universiteto ir Lietuvos agrarinių ir miškų mokslų centro institucijoms.

Mokslinė vadovė

Dr. Dalia Feizienė (Lietuvos agrarinių ir miškų mokslų centras, Žemės ūkio mokslai, Agronomija, A 001).

Mokslinė konsultantė

Dr. Vita Tilvikienė (Lietuvos agrarinių ir miškų mokslų centras, Žemės ūkio mokslai, Agronomija, A 001).

Mokslo daktaro disertacija ginama Agronomijos mokslo krypties gynimo taryboje:

Pirmininkė

Dr. Karolina Barčauskaitė (Lietuvos agrarinių ir miškų mokslų centras, Žemės ūkio mokslai, Agronomija, A 001).

Nariai:

Dr. Giedrė Samuolienė (Lietuvos agrarinių ir miškų mokslų centras, Žemės ūkio mokslai, Agronomija, A 001);

Doc. dr. Zita Kraučiūnienė (Vytauto Didžiojo universitetas, Žemės ūkio mokslai, Agronomija, A 001);

Dr. Marius Praspaliauskas (Lietuvos energetikos institutas, Technologijos mokslai, Energetika ir termoinžinerija, T 006);

Prof. dr. Catherine Brewer (Department of Chemical and Materials Engineering, New Mexico State University, Žemės ūkio mokslai, Agronomy, A 001).

Mokslo daktaro disertacija bus ginama viešame Agronomijos mokslo krypties gynimo tarybos posėdyje 2023 m. spalio 12 d., 10 val. Lietuvos Agrarinių ir miškų mokslų centre adresu: Instituto al. 1, Akademija, Kėdainių r.

Su daktaro Disertacija galima susipažinti Nacionalinėje Martyno Mažvydo , Lietuvos agrarinių ir miškų mokslų centro ir Vytauto Didžiojo universiteto bibliotekose.

Table of Contents

Abbreviations

AWCD – Average Well Color Development
B – Biochar
Bd – Bulk Density
Ca – Calcium
Cd – Cadmium
CH_4 – Methane
C – Carbon
cc – Cubic Centimeter
CO_2 – Carbon Dioxide
Cr – Chromium
Cu – Copper
DTPA – Diethylenetriamine Pentaacetate
D – Simpson Index
FC – Field Capacity
GWP – Global Warming Potential
H – Shannon Index
HMs – Heavy Metals
ICP-OES – Inductively Coupled Plasma Optical Emission spectroscopy
K – Potassium
Mg – Magnesium
N – Nitrogen
Ni – Nikel
N_2O – Nitrous Oxide
P – Phosphorus
PAW – Plant-Available Water
Pb – Lead
R – Richness
SCS – Soil Carbon Sources
TP – Total Porosity
TGA – Thermogravimetric Analysis
U – Mcintosh Index
WHC – Water Holding Capacity
Zn – Zinc

INTRODUCTION

Significant global environmental issues, food security, and energy scarcity accompany an ever-increasing human population in a civilization that is still heavily reliant on fossil fuels, making it imperative that humans find creative, effective, long-term, and financially-appealing solutions to these problems (Zhang *et al.*, 2019). Agriculture is currently facing a substantial issue in the form of food insecurity. There may be negative environmental consequences, such as disturbances of basic soil processes, if output is increased by means such as excessive tillage or the application of high mineral fertilizer doses (Tripathi *et al.*, 2020). Effective food production that is both safe and of good quality requires great environmental care (Council, 2010). Agronomic methods that preserve or even improve soil fertility continue to be in high demand (Ullah *et al.*, 2019). The use of farming system technologies has allowed some regions of the world to meet their food demands. Among these are agroforestry, agroecology, sustainable agriculture, and organic agriculture (Nair *et al.*, 2017). Increasing crop yields, decreasing pollution, and creating environmentally-sustainable agriculture and habitats are the goals of all of these approaches (Lehmann and Joseph, 2015). This strategy has shifted the attention of scientists and farmers away from industrially-processed goods and toward natural residues and organic materials (Paas *et al.*, 2019), such as biochar (K. Khan *et al.*, 2022). Permeability, aeration, and water retention capacity are all influenced by the soil's physical qualities that, in turn, affect soil fertility (Oladosu *et al.*, 2022). Several studies have found that the soil profile is better able to make use of water and nutrients when its structure, porosity, hydraulic conductivity, and specific gravity are all optimal (Rostami *et al.*, 2021; Singh *et al.*, 2021). Root growth and nutrient retention were enhanced by biochar treatment compared to soils in poor physical condition (A O Adekiya *et al.*, 2020). Soil hydraulic conductivity was improved after biochar addition by decreasing soil bulk density and increasing soil porosity (Zhou *et al.*, 2019). Some studies have concluded that biochar does not significantly alter the soil's physical characteristics. For example, Fan et al. reported that the use of biochar decreased macropores and pore connectivity (Fan *et al.*, 2020). The impact of biochar on soil hydrological factors is still not well understood.

Greenhouse gases (GHG), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), that are released into the atmosphere due to human activity have emerged as a major factor in the warming of the planet (Doyeni *et al.*, 2021; Sonwani and Saxena, 2022). These emissions are related to soil temperature and moisture content, which biochar application can impact (Li *et al.*, 2023). Nemoral climate zone soils were expected to have low response ratios of GHG emissions that would decrease with time due to the cool temperature. Such changes may be more successfully observed in controlled conditions than in field tests due to large variations in soil moisture content and microbial activity (Lehtinen *et al.*, 2014). In waterlogged conditions, organic matter decomposition tends to be slower because the availability of oxygen is limited, which reduces microbial activity responsible for decomposing organic material and thus, reduces soil CO_2 emissions (Bot and Benites, 2005). In dry soils, decomposition can be accelerated during increased microbial activity when moisture is available. However, if protracted drought causes widespread reductions in soil organic matter, this benefit may be temporary (Gao *et al.*, 2016). Soil moisture levels have a significant impact on methane emissions from soils. Conditions devoid of oxygen, like those seen in waterlogged or flooded soils, are ideal for methane generation (Conrad, 2020). Soil moisture impacts the microbial processes of nitrification and denitrification, which contribute to N_2O emissions (Butterbach-Bahl *et al.,* 2013). Nitrification, the conversion of ammonium to nitrate, is typically inhibited under soggy or saturated circumstances, resulting in reduced N_2O emissions (Reddy, Patrick and Broadbent, 1984).

Biochar can have a significant impact on the mobility of metals in soil through sorption, the binding of heavy metal ions to biochar particle surfaces. Biochar has a strong affinity towards lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) due to their nature as cations. These metals are absorbed and retained by the negatively-charge functional groups on biochar surfaces (Shahrokhi-Shahraki *et al.*, 2021).

The impact of biochar on microbial abundance and diversity is still not well understood. Biochar has been shown in multiple studies to significantly increase soil microbial activity (Bandara *et al.*, 2021; Jabborova *et al.*, 2021; Q. Zhang *et al.*, 2021). Theoretically, biochar, which is practically antiseptic, can reduce the number of soil microbes present (Yin *et al.*, 2021). Long-term benefits to soil microbiota are created by the loss of volatiles during pyrolysis, creating biochar's macropores and large surface areas (Wang, K. Zhang, *et al.*, 2021). Biochar has also been shown to have a negative effect on soil microbes and mycorrhizal fungi, similar to that seen with high levels of nitrogen and phosphorus (Warnock *et al.*, 2010), but with less of a negative impact due to biochar's lower mineral content (Jiang *et al.*, 2017). Soil physicochemical properties, for example, can greatly affect microbial abundance (Quilliam *et al.*, 2013). Soil water content, pH, aeration, and other physicochemical properties are all affected by the presence of biochar particles, which may act as an unusual niche for soil bacteria (Bruun *et al.*, 2014). Soil bacteria may directly utilize the organic carbon that biochar has adsorbed from the soil nearby as a source of energy. Addressing all of these factors is essential to account for the impact of biochar on soil microbial activities with respect to biochar type, and soil parameters (Thies and Rillig, 2012). Ecosystem resources and soil function are critically dependent on the distribution, quantity (Wang, W. Zhang, *et al.*, 2021), and diversity of soil microorganisms (Rahman, 2012). The plate counting approach can only observe a small percentage of total soil microbial diversity, but has been widely used and has been shown to correctly reflect the biomass of microbial species. For artificial media-adapted bacterial species with particular activity, this is a formal procedure. Soil microbial diversity is of relevance as a measure of soil quality (Kirchman *et al.*, 1982).

The use of biochar as a filter media in the treatment of wastewater, and as an amendment for environmental rehabilitation, reduction of pollutant mobility in soils, and mitigation of risky elemental changes in agricultural products, are under investigation (Chen *et al.*, 2022). Biochar is typically produced from agricultural byproducts, animal manures, and wood scraps (Van Nguyen *et al.*, 2022). Waste can be converted into a valuable product by using these feedstocks to make biochar (Brewer *et al.*, 2014). Biochar's effectiveness for increased crop output may be affected by the biochar feedstock, manufacturing process, soil condition and type, and the type of crop to be produced (Yasser Mahmoud Awad *et al.*, 2018; Arif *et al.*, 2021) (Shown in paper 1).

Researchers from a variety of disciplines, including agronomists and soil scientists, can learn from these studies about the benefits of biochar as an organic amendment for the enhancement of soil health, thereby ensuring the long-term viability of agriculture and the natural environment.

Research hypothesis

Biochar is potential beneficial amendment to soil such that use of swine manure digestate-derived biochar can help reduce heavy metal uptake in plants under different moisture regimes, mitigate soil GHG emissions (CO_2, N_2O, and CH_4), improve soil functional diversity, and improve crop yield.

Research aim

The research aim is to assess the impact of biochar made from swine manure digestate on soil heavy metal uptake by plants, greenhouse gas emissions, hydro-physical characteristics, microbial richness and diversity, and crop productivity.

Research objectives

1. To investigate the impact of swine manure digestate-derived biochar on heavy metal uptake into the plants under different moisture regimes.
2. To quantify the impact of swine manure digestate-derived biochar on greenhouse gas emissions (CO_2, N_2O, and CH_4).
3. To assess the impact of swine manure digestate-derived biochar amendment on soil carbon source utilization and soil microbiological indices (Shannon, Simpson, Richness, Mclntosh and Species evenness).
4. To investigate the influence of swine manure digestate-derived biochar fertilization on the physicochemical parameters of soil, and the photosynthesis indices (chlorophyll fluorescence and SPAD chlorophyll) and yields of spring wheat, spring barley and pea.

Defended statements

1. The use of swine manure digestate-derived biochar lowers heavy metal uptake in plants under different moisture regimes (optimal moisture, drought conditions and flooded condition).
2. Biochar application helps mitigate individual, cumulative emission and global warming potential caused by greenhouse gas emissions (CO_2, N_2O, and CH_4).
3. Application of swine manure digestate-derived biochar improves soil physicochemical parameters, and crop photosynthetic responses and yields.
4. Application of swine manure digestate-derived biochar influences the soil microbial richness and diversity and improves soil hydrophysical properties.

Novelty of the research

This study has shown that swine manure digestate-derived biochar application can substantially lower the usage of synthetic fertilizer in an agriculture system, help mitigate GHG emissions (carbon dioxide, nitrous oxide and methane), and lower heavy metals uptake into the plants. Biochar application enhanced crop biomass and productivity and improved soil functional diversity (carbon sources utilization, soil microbiological indices) and soil physiochemical properties (soil porosity, bulk density, volumetric water content and hydraulic conductivity).

1. LITERATURE REVIEW

1.1. Morphology and biochemistry of biochar

Biochar is the by-product of the zero- or low-oxygen (O) thermal breakdown of renewable feedstock (forest residues, agricultural residues, hard woods, bambo, animal dung, etc.) (Dai *et al.*, 2013; Sewu *et al.*, 2020) . Feedstocks undergo thermal breakdown of the pulp and lose mass when pyrolyzed at a minimum of 200-250 °C, leaving behind a porous structure. After 15-20 min at 200-300°C, the biomass begins to lose moisture content and, following further loss of volatiles, becomes pure black and acquires a porous structure (Fig. 1) (Ayaz *et al.*, 2021).

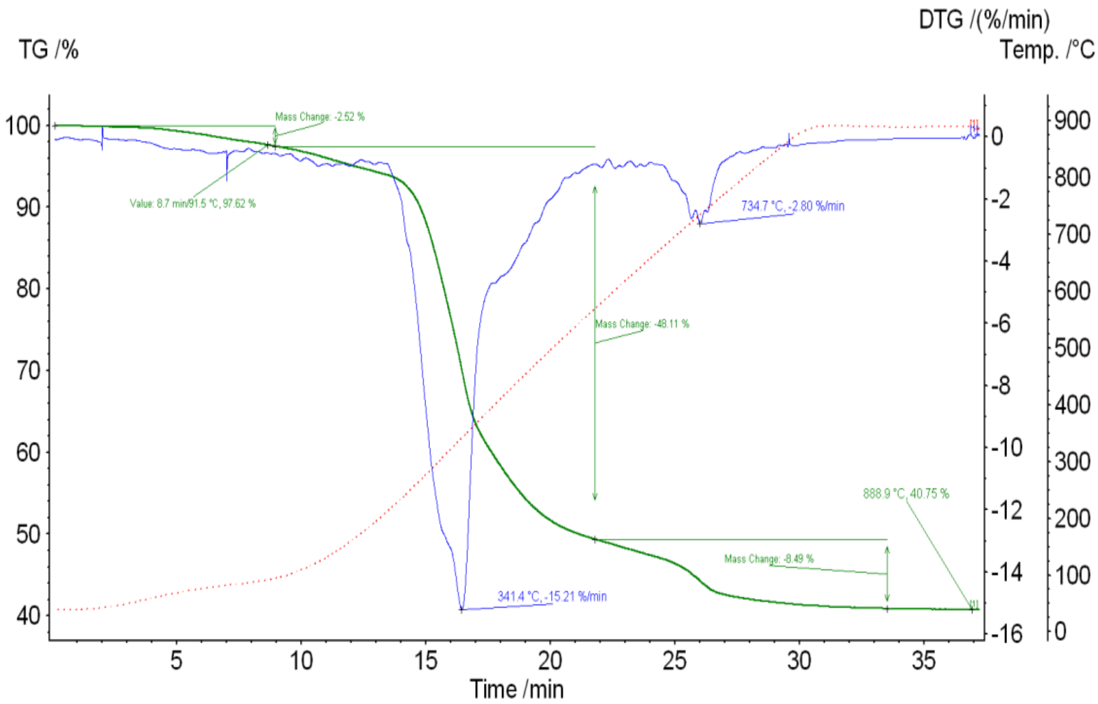

Figure 1. Thermo gravity of swine manure digestate (Ayaz *et al.*, 2021)

1 pav. *Kiaulių mėšlo digestato termogravitacija* (Ayaz *et al.*, 2021)

According to published accounts of biochar's preparation, specimens of rice straw (RS), vinasse (VI), *Phyllostachys pubescens* (PP), *Arundo donax* (AD), chicken manure (CM), and sugarcane bagasse (SB) were either cut into pieces (<5 cm) or crushed and dried for 24 h until they achieved constant weight (Hongyu Chen *et al.*, 2020; Jia *et al.*, 2020; Tang, Liu and Tsang, 2020). Two-kilogram (kg) samples were placed in the furnace and heated to the target temperature. A sieve with an 80-mm mesh was used to refine the obtained biochar (Lehmann *et al.*, 2011). The resulting biochar was very porous, alkaline, and rich in important elements and organic matter (C, H, N, S, O) with notably-changed C/N and C/H molar ratios (Hongyu Chen *et al.*, 2020; Jia *et al.*, 2020). Biochars derived from switchgrass and poultry manure (SGB and PLB, respectively) were obtained by thermal decomposition at 300 and 700 °C (Antonangelo and Zhang, 2019). For pyrolysis, 0.5–1.5 kg of prepared samples were placed in a non-corrodible tray and inserted into a Lindburg electric box furnace connected with a gas retort (Model 51662; Lindburg/MPH, Riverside, MI) (Cantrell *et al.*, 2012; Antonangelo and Zhang, 2019). The temperature at which biochar is burned has a significant impact on the characteristics of the resulting product, including the pH, pore size distribution, surface area, and other physical and chemical properties (Fidel *et al.*, 2017). As the pyrolysis temperature increases, the pH of the biochar normally rises as well (Yuan and Xu, 2011). Organic matter is decomposed to a greater extent at higher temperatures, which causes acidic functional groups to be expelled, leaving behind a biochar that is noticeably more alkaline (Mukherjee and Zimmerman, 2013). High-temperature biochars typically have more micropores and fewer meso- and macropores. Pore diameters range from micro, which are less than 2 nm in diameter, to meso, between 2 and 50 nm, to macro, greater than 50 nm. As the temperature increases, the pore size distribution shifts, becoming more skewed toward micropores. Biochar's large surface area is due to micropores, which are essential for the adsorption and retention of various chemicals. High-temperature biochars typically have higher surface areas (Speratti *et al.*, 2017; Wong, Webber and Ogbonnaya, 2019). The BET (Brunauer-Emmett-Teller) method shows an upward trend in the specific surface area of biochar as pyrolysis temperature increases (Wani *et al.*, 2020).

1.2. Nutrient release dynamics of biochar

Biochar's nutritional composition is affected by the type of biomass and the rate of thermal breakdown. Biochar made from pyrolyzing plants at the same temperature may have a higher nutrient concentration than biochar made from animals (Hanbo Chen *et al.*, 2020). Available P (0.64 mg kg^{-1}), Ca (5880 mg kg^{-1}), Mg (1010 mg kg^{-1}), and Na (1145 mg kg^{-1}) were all present in high concentrations in biochar made from *Lantana camara* at 300 °C (Mukherjee and Zimmerman, 2013). Soil micronutrients and macronutrients, such Ca, Mg, Na, Fe, Mn, Cu, Zn, N, P, and K, were abundant in biochar produced from dried swine manure waste via slow pyrolysis (300-750 °C) (K. Wang *et al.*, 2020). Total N content was considerably higher in silt loam and sandy soils treated with biochar generated from poultry manure pyrolyzed at 400 °C and 600 °C than in the same soils treated with biochar generated from swine manure (pyrolyzed at 400 °C and 600 °C) or wood chips (pyrolyzed at 1000 °C). Freshly-generated biochar is a nutrient-dense material that can release a substantial N, ranging from 23 to 635 mg kg^{-1}, and P, ranging from 46 to 1664 mg kg^{-1} (Lin and Chang, 2013; Zheng, Wang, Deng, Zhao, *et al.*, 2013). Because they are easily taken up by agricultural plants and soil microbes, major nutrients in biochars, like N, P, and K, function as fertilizer. Transient and long-term leaching experiments over the past decade have been used to learn more about the nutrient availability in biochar. After 24 h, biochar made from mallee wood (15-20% Ca, 10-60% P, and 2% N) was easily leachable with double-distilled water (Wu *et al.*, 2020). More research is being conducted on the effects of biochar combined with organic matter and humic compounds on soil fertility and agricultural output (Spokas *et al.*, 2012). Soil pH was raised and dissolved organic matter was released when biochar was made from cacao shells and rice husks at 600 °C and 500 °C, respectively (Zhang *et al.*, 2020). Biochar produced by heating straw between 500 and 600 ° C has been shown to improve soil quality (Cantrell *et al.*, 2012). Biochar affects the dynamics of composting by accelerating the breakdown of organic waste and increasing soil porosity (Qian *et al.*, 2013; Antonangelo *et al.*, 2019). This has a positive effect on the efficiency of composting and the humification process. Carbon content in humic and fulvic acids increased after applying 10% of poultry or cow manure biochar to a compost (Gul *et al.*, 2015). Potential sources of humic compounds were identified in biochars produced from *Acacia saligna* at 380 °C and from sawdust at 450 °C (Spokas, 2010). Sandier soils had higher available water content when biochar was added during the composting of maize straw and sewage sludge (Bolan *et al.*, 2014). Polycyclic aromatic hydrocarbon biodegradation was accelerated by using biochar made from mushroom ash or corn straw (Qian *et al.*, 2015). Biochar is a multipurpose supplement that has been shown to increase soil quality and sequester C (Laghari *et al.*, 2016; Radwan *et al.*, 2020; Razzaghi, Obour and Arthur, 2020; Werdin *et al.*, 2020). Since thermal decomposition has such a profound effect on biochar characterization (Uzoma *et al.*, 2011; Blanco-Canqui, 2017), more research is needed comparing the physicochemical and morphological characteristics of biochar from different feedstocks and at different pyrolysis temperatures (low, medium, and high) on their effects when used as soil amendments. Low-temperature thermal breakdown typically results in biochars with a high carbon concentration (Barrow, 2012; Sánchez-Monedero *et al.*, 2019). Incorporating biochar into soil is a practical and effective strategy to improve soil quality and fertility because of its high C content, high adsorption capacity, porous structure, and high alkalinity (Rutigliano *et al.*, 2014; Rasa *et al.*, 2018; Lu *et al.*, 2020). Biochar's alkaline nature and organic C content both increase cation exchange capacity (CEC), which, in turn, improves soil quality (Dempster *et al.*, 2012) and increases soil heavy metal adsorption capacity (Otsuka *et al.*, 2008). Many studies have compared biochar physicochemical properties and their effects on soil nutrients and crop yields (Table 1).

Table 1. Outline of literature about biochar effect on crop yields (Ayaz *et al.*, 2021)

***1 lentelė**. Literatūros apie bioanglies poveikį augalų derliui apžvalga*

Biochar Types	Temp.	Application rate	Soil type/texture	Result	Reference
Wheat Straw	300-500°C	3% w/w	Psammaquent and Plinthudult	Increased rice yields in both the soil	(Muhammad *et al.*, 2017)
Wheat Straw	300, 400, and 500°C	1% w/w	Sandy clay loam, Calcisols Yermi	Biochar prepared at 300°C, significantly increased maize crop yield	(Naeem *et al.*, 2017)
Rice Straw and Corn Stalk	450°C	1, 2 and 4 ton ha^{-1}	Inceptisol	Increased corn, peanut, and sweet potato 5%–15% and 20%	(Yang *et al.*, 2015)
Miscanthus giganteous Straw	500-750°C	8 and 25 ton ha^{-1}	Silty clay loam Albeluvisol	No effect on crop yield	(O'toole *et al.*, 2018)
Cow Manure	600°C	0, 10, 15 and 20 ton ha^{-1}	Sandy soil	Significantly enhanced maize crop yield	(Uzoma *et al.*, 2011)
Rice Husks	450°C	0, 10, 25 and 50 ton ha^{-1}	Upland soil and paddy soil	Increased rice and wheat yield by 12% and 17% respectively	(Wang, Pan and Liu, 2012)
Maize Stover	600°C	0, 1, 3, 12, and 30 ton ha^{-1}	Kendaia silt loam	No significant effect on crop yield	(Güereña *et al.*, 2013)
Wood Chips	290°C	2% w/w	Clay texture and sandy loam texture	No significant effect on crop yield	(Lai *et al.*, 2013)
Rice Straw	300, 400, and 500°C	1% w/w	Sandy clay loam, Calcisols Yermi	No effect on maize crop yield	(Naeem *et al.*, 2017)
Maize Cobs	300-550°C	0, 2, and ton ha^{-1}	Sand and loamy sandy soil	Positive effect on crop yield	(Martinsen *et al.*, 2014)
Hard Wood	500°C	0,10, 20, and 30 ton ha^{-1}	Sandy loam	30 ton ha^{-1} significantly enhanced cocoyam crop yield	(Aruna Olasekan Adekiya *et al.*, 2020)
Eucalyptus polybractea	550°C	10 ton ha^{-1}	Ferrosol Soil	No effect on cauliflower, pea, or broccoli yield	(Boersma *et al.*, 2017)

1.3. Biochar effect on bioavailability of heavy metals

Biochar can significantly reduce the bioavailability of heavy metals to plants in polluted soils (Nkoh *et al.*, 2022). The presence of heavy metals in soils is a cause for concern for human and environmental health because these metals can be absorbed by plants and progress up the food chain (Pouresmaieli *et al.*, 2022). Biochar's ability to adsorb and compound with heavy metals is a significant effect (J. Zhang *et al.*, 2021). Heavy metal ions are less mobile and available for uptake by plants when bound to biochar's porous structure and high surface area. Biochar binds and sequesters toxic metals, preventing them from leaching into the soil solution (Z. Khan *et al.*, 2022). Biochar, which is alkaline in nature, can increase the soil's pH and reduce the heavy metal solubility and mobility, making the metals less bioavailable to plants (Bolan *et al.*, 2014). Biochar and heavy metals might compete for the same absorption sites on plant roots. Inhibiting heavy metal cation uptake by plant roots and limiting their translocation to above-ground plant tissues, biochar has been shown to have a high cation affinity (Jia *et al.*, 2017; Mohamed *et al.*, 2017). Biochar's effectiveness in reducing heavy metal bioavailability to plants depends on a variety of factors, including the type and quality of the biochar, the specific heavy metal, the quantity of heavy metals in the soil, the soil pH, and the soil's organic matter concentration.

1.4. Understanding biochar's effect on soil bulk density and water retention

The large surface area of biochar increases the efficiency with which water and nutrients are used in the soil by reducing bulk density (De Boer and Kowalchuk, 2001; Farrell et al., 2013; Gao et al., 2017). A promising behavior of WHC and NHC in sandy soil due to its macropores and low surface areas, biochar reduced soil bulk density by 3% to 31% and enhanced porosity by 14% to 64% (Smith, Collins and Bailey, 2010). Biochar increased soil WHC and NHC, thereby increasing water availability to plants in sandy soil (Novak et al., 2009). Biochar amendment could be an effective technique to prevent desertification and enhance plant growth (Kammann et al., 2011). In a coarse-textured Planosol, biochar made from straw at 525°C and 400°C had the most substantial long-term effect on soil physicochemical parameters (Sánchez-Monedero et al., 2019).

1.5. Effect of biochar on microbiota

Biochar's impact on soil microbial activity vary by crop type and soil composition. The beneficial effects on microbial population from applying wood-derived biochar at 30 and 60 tons ha^{-1} were short-lived (Rutigliano *et al.*, 2014). The porous structure of biochar has been shown to significantly improve soil microbiota, with this improvement being attributed to biochar's provision of a favorable niche environment for bacteria (Lu *et al.*, 2020). Biochar addition increased the diversity of soil microbes by 25% compared to untreated soils (Otsuka *et al.*, 2008). De Boer and Kowalchuk (2001) and Dempster et al. (2012) found that biochar addition reduced microbial biomass C and N mineralization, indicating that any benefit from biochar's liming action may be offset by a decline in soil microbial community mass. An increase in alkaline microsites caused by biochar application may also affect the population of ammonia oxidizers, especially in acidic soil (De Boer and Kowalchuk, 2001; Dempster *et al.*, 2012). Although the *Actinobacteria* and *Ascomycota* fungus communities were reduced following biochar application to rice straw (Gao *et al.*, 2017), the diversity and abundance of soil microbes varied. Biochar affects the microbial community as the soil's nutrient cycle and nutrient availability are changed (Farrell *et al.*, 2013).

1.6. The influence of biochar on mitigation greenhouse gases

Human activity is widely believed to be the cause for the escalation in atmospheric GHG concentrations that have been linked to climate change. The three main GHG, CO_2, CH_4, and N_2O, account for 90% of anthropogenic climate warming (He *et al.*, 2017). Biochar is considered to have potential as a soil supplement for C sequestration as a long-term strategy to reduce CO_2 emissions and the abundance of CO_2 in the environment (Novak *et al.*, 2009). Due to the significance and complexity of the application and environmental benefits of biochar, the term, "biochar culture," has been introduced (Reddy, 2014). Significant improvements in soil physicochemical properties (soil moisture retention and air permeability), chemical properties (CEC and damping capacity of soil organic carbon), and microbial activity make biochar a highly valuable soil conditioner (Jindo *et al.*, 2014; Mclennon *et al.*, 2020). Biochar amendment helps reduce GHG emissions by improving agricultural management. Prior to the goal of decreasing emissions by enhancing C sequestration, the "carbon footprint" of a given land management strategy must be determined. Biochar predominantly contains cyclic carbon with high aromaticity and little H and O (Gross *et al.*, 2022). This high C resiliency helps reduce GHG emissions by slowing the breakdown of organic biomass by microbial degradation. The first researchers to report N_2O emissions from a greenhouse experiment supplemented with biochar were Rondon, Ramirez and Lehmann, (2005). Potentially more effective in lowering CO_2 and N_2O emissions is high-temperature biochar pyrolysis with a low N concentration. Biochar has been shown to reduce CO_2 emissions over hundreds to thousands of years, as evidenced by tests conducted on Amazonian *terra preta* soil (Glaser *et al.*, 2001). Dimensional analysis showed that only 3% of biochar C is bioavailable, while the rest is transformed into long-term stable C in soil (Wang, Xiong and Kuzyakov, 2016). Increases in greenhouse gas (GHG) concentrations in the atmosphere have been associated with the 4°C-increase in temperature at the end of the 21st century and environmental shifts (Luschkova, Traidl-Hoffmann and Ludwig, 2022; Zhou, Yu and Zhang, 2023). Biochar from plant or animal remains aids in the emission of CO_2 into the atmosphere and traps C, becoming a significant part of the world's rapidly expanding carbon-negative economy (Vanholme *et al.*, 2013). Adding biochar to soil can reduce GHG emissions as much as one hundred times, specifically those of nitrous oxide and methane (Downie *et al.*, 2012). A greater agronomic benefit in terms of increased crop growth and yield also encourages the sequestration of atmospheric carbon as plant biomass, followed by a gradual pyrolysis to biochar and bioenergy production. Biochar application in land use under vegetable production has been shown in numerous studies to significantly cut emissions of CO_2, N_2O, and CH_4 (Jia *et al.*, 2012; Sun *et al.*, 2014).

1.7. The role of biochar in soil fertility management

The amount of total N, P, and K in biochar may not be directly proportional to the amount of N, P, and K available to plants (Koide, 2017). For instance, in highly thermally degraded biochar, overall N loss causes a decrease in available N (Mohanty *et al.*, 2013). Variations in CEC and pH of biochar-amended soil cause differences in the absorption and release of certain nutrient ions on the surface of biochar (Filiberto and Gaunt, 2013). According to (Yao *et al.*, 2012)., biochar application greatly reduces the frequency of N and P as ammonium/nitrate and phosphate ions in soil leachates. Biochar's potential to absorb nutrients can be affected by factors such as the soil's texture, SOC, clay-to-sand ratio, and pH (Oguntunde *et al.*, 2004). Biochar boosts the efficiency with which nutrients in organic fertilizer are used. Amending with biochar can increase nitrogen's dynamism, which is important for optimizing N use efficiency, which mostly manifests as a decrease in nitrate transformation (Jindo *et al.*, 2014). Biochar's nutritional dynamics aid in the temperature- and pH-dependent delayed release of adsorbed nutrients by capturing nutrients during drainage, runoff, leaching, microbial digestion, and physical volatilization processes. Therefore, plants and crops can make use of these nutrients because they will be present in plant-available forms in the root zone. Soil aggregate stability and formation are improved by biochar amendment, and the microbiota and activities of the soil are altered in ways that affect the retention of highly- and moderately- mobile nutrients like N and P (Jindo *et al.*, 2014).

1.8. Effect of biochar on soil organic matter

Biochar addition is thought to increase soil fertility based on research about *terra preta* soils, which have a disproportionately high amount of black carbon (Oguntunde *et al.*, 2004). Biochar was found to improve the proportion of C held inside macroaggregates of fine-coarse soil, which, in turn, raised the physical security of soil organic matter (SOM) (Wang *et al.*, 2017)(Six *et al.*, 2002). Partially-carbonized, highly-degradable organic wastes are more typical of low-temperature biochars (Novak *et al.*, 2009; Zimmerman, 2010), which may explain why biochar stimulates physical fixation of C. Biochars made from *Eucalyptus saligna* wood were found to increase the mineralization of native organic C in sandy soil but not in clayey soil (Fang, Balwant and Bhupinder Pal, 2015), suggesting that SOM is more susceptible to digestion in coarser-textured soils due to the lower surface area of mineral binding sites that can protect organic particles. The short-term priming effects of biochars when added to a grassland soil can stimulate the mineralization of native soil organic C (Singh and Cowie, 2014).

1.9. Affinity of biochar and soil characteristics

Although biochar amendment to soil can boost water and nutrient holding capacity, these properties are influenced by soil's retention capacity (Wu *et al.*, 2020). P retention is especially important (Burrell *et al.*, 2016). Sandy soils tend to have faster P leaching times than clay soils. Biochar acts as a retaining agent and prevents the leaching or runoff losses of P from sandy soil (Glaser and Lehr, 2019). The pyrolysis temperature is irrelevant to the P release characteristic of biochar-treated soil (Dharmakeerthi *et al.*, 2019). Regardless of heating rate, biochar takes on the characteristics of its feedstock (Li *et al.*, 2019). After undergoing pyrolysis between 400 and 900 °C, the porous arrangement in corncobs (Pottmaier *et al.*, 2013), the " beehive-like" pore structures in sugarcane (Bourke *et al.*, 2007), the symmetrical structure in wood (Kondo *et al.*, 2012), and the surface morphological structure in rice husk (Burhenne, Damiani and Aicher, 2013) and sawdust were all preserved. Melting with significant deformation of biochar structure may be seen at higher pyrolysis temperatures (>1000 °C) (Zeng *et al.*, 2015). Pyrolysis at 2000 °C causes the macropores on the biochar surface to melt away, while the buildup of bead-like tiny grains occurs (Burhenne, Damiani and Aicher, 2013). The oxidized carbon components present in organic debris are stabilized throughout the pyrolysis process, resulting in biochar that can last in soils for years (Song *et al.*, 2019). "Black Diamond" is a nickname given to biochar (Yasser M Awad *et al.*, 2018). Several studies have indicated that using biochar on crops can improve harvest success. For example, despite the alkaline character of biochar, which raises soil pH (Yasser M Awad *et al.*, 2018; Zheng *et al.*, 2018; Elshony *et al.*, 2019), biochar amendment to soil considerably increases soil micro and macronutrients (Abdelhafez, Abbas and Li, 2017). Biochar can be used as a slow-release fertilizer (Dai *et al.*, 2020). Therefore, biochar works better in acidic soil than in calcareous or alkaline soil. Soil K management objectives have received less attention from researchers than N and P in soil (Bilias *et al.*, 2023). Several reports have shown that biochar addition to soils can alter the soil's N dynamics, including an increase in net nitrification rate (Bi *et al.*, 2017), stimulation of N immobilization (Nelissen *et al.*, 2012), reduction in N_2O emissions

(Cayuela *et al.*, 2013), decrease in NH_3 volatilization (Mandal, Thangarajan, *et al.*, 2016), enhancement of ammonium-oxidizing bacterial abundance (M. Zhang *et al.*, 2021), and alteration of N availability for crops (Wang, Pan and Liu, 2012). Biosolids, swine manure, composted green waste, and bovine urine are all sources of N shown to be affected by biochar addition (Zheng, Wang, Deng, Herbert, *et al.*, 2013; Karim *et al.*, 2022).

1.10. Soil organic matter and configuration immutability

The effects of biochar on the aggregation and stability of organic components must be carefully considered. Biochar, particularly if it has a coarse texture and a little organic content, has been suggested as a viable amendment for the stabilization of aggregates (Pituello *et al.*, 2018). Three consecutive years of biochar application demonstrated the large increase in aggregate stability and soil organic carbon (Ma *et al.*, 2016). Soil aggregates in tropical Ultisol were found to be unaffected by biochar in a two-year experiment (Fungo *et al.*, 2017). Adding more biochar to soils with a fine sand or sandy loam texture dramatically reduced aggregate strength (Ajayi and Rainer, 2017). Therefore, biochar's effects are highly dependent on soil type and texture. Soil structure and fertility efficiency are both enhanced by biochar (Yuan *et al.*, 2019). A sizable portion of the biochar in *terra preta* is located in unstable fractions (Glaser *et al.*, 2000). However, biochar, rather than being available as a free organic matter, was largely present in soil aggregates (Brodowski *et al.*, 2006). Biochar may operate as a binding agent for organic materials in aggregate formation and then guard against degradation (Liang *et al.*, 2008). Large macro-aggregate fractions were identified with a minor part of biochar particles (> 2 mm). Biochar's interactions with soil organic matter, microorganisms and minerals may impact soil aggregates and their stability (Piccolo, Pietramellara and Mbagwu, 1997; Verheijen *et al.*, 2010). Biochar's long-term impact on soil aggregation is determined by its slow oxidation qualities (Verheijen *et al.*, 2010).

1.11. Biochar and sustainability

Improving crop productivity in a way that is both environmentally responsible and long-lasting has been identified as one of the primary challenges facing the modern agricultural system (Patel *et al.*, 2015; Hamilton *et al.*, 2016). In spite of increasing agricultural yields, the use of chemical fertilizers is linked to a number of serious environmental issues (Srivastav, 2020; Ye *et al.*, 2020), such as a loss of biodiversity, increased temperatures, and increased levels of toxic metals in the soil. Switching to a more organic farming method will lessen the need for artificial mineral fertilizers (Reganold and Wachter, 2016; Bi *et al.*, 2022). Recently, biochar has been seen as a beneficial soil conditioner that can keep carbon and nutrients in organic feedstocks for longer (Mandal, Sarkar, *et al.*, 2016; El-Naggar *et al.*, 2018). This reflects environmental issues with sustainable agricultural nutrient management. The primary focus of modern biochar research has been on optimizing biochar characteristics to increase their utility toxicity toward containment or removal of organic and inorganic contaminants (He *et al.*, 2022). Biochar's unique qualities, such as its high adsorption capacity and ion exchange ability, allow biochar to be used in a wide variety of environmental applications (Koide, 2017). The efficacy and potential for improving environmental sustainability of biochar are greatly affected by differences in the material properties. About 87% of the carbon released during the conversion of feedstock into biochar is sequestered (Yu *et al.*, 2018). The problems associated with agricultural waste disposal are thereby addressed, and a feasible and cost-effective method of repurposing waste into valuable products is made available. Antibiotics, herbicides, dyes, pesticides, and heavy metals can all be removed from the environment with efficiently using biochar's porous surface (Panwar, Pawar and Salvi, 2019). Long-term C loss, especially from soil, may be avoided with the help of biochar (Schiermeier, 2006). Improved crop yields have been linked to the use of biochar because of its unique ability to trap heavy metals and farm chemicals (Bolan *et al.*, 2013; Dang *et al.*, 2019). Combining organic and inorganic fertilizers with biochar has a synergistic impact between nutrient accessibility and plant uptake, leading to increased crop productivity and soil fertility (Aziz *et al.*, 2010; Alshankiti and Gill, 2016). Further, the potential for increased crop yield and growth has been linked to biochar's ability to conserve soil nutrients and moisture, reduce nutrient losses, and boost nutrient uptake (Brockhoff *et al.*, 2010; Bohara *et al.*, 2019). By increasing nutrient availability, biochar can boost crop biomass and growth (Lehmann *et al.*, 2003). Biochar has been proposed by numerous researchers to improve soil quality, increase C storage (Lehmann, Gaunt and Rondon, 2006), add value to agricultural goods, and stimulate plant development for sustainable agriculture (Oguntunde *et al.*, 2008).

1.12. Effectiveness of biochar prepared at different temperature

Pyrolysis temperature directly affects biochar’s physical and chemical properties. More gases, liquids, and dissolved chemicals can be absorbed by biochars that were produced at higher temperatures (Jia *et al.*, 2017; Ambaye *et al.*, 2021)(Almutairi, 2022). The acidity and nutritional content of the original organic matter may be preserved in biochars produced at lower temperatures (Hossain *et al.*, 2020). an be enhanced by high-temperature biochars, which form stable aggregates and boost water retention (Wang *et al.*, 2017), while low-temperature biochars may have a less noticeable effect on soil physical properties. Biochar's effectiveness depends on the specific goals and applications. Carbon sequestration or long-term soil enhancement, may be better suited to high-temperature biochars. Pollutant removal or nutrient management tasks might be better suited to biochars made at lower temperatures.

1.13 Summary

Soil management practices have developed due to the rising need for sustainable agriculture induced by global population expansion and soil resource deterioration (Ayaz *et al.*, 2021). Biochar, an organic soil amendment derived from external sources, is one of these management approaches. Biochar, a result of anaerobic pyrolysis of different wastes, can be utilized as a bio-fertilizer. There is a knowledge gap regarding the effects of a wide range of organic waste processing residues on heavy metal remediation, GHG mitigation, soil carbon source and index, and other positive functions over short to long term durations (Ayaz *et al.*, 2021).

2. MATERIALS METHODS

2.1. Experimental design

The experiment was conducted in both field and controlled (laboratory) conditions. Trials were conducted in the fields of the Lithuania Research Centre for Agriculture and Forestry (55°40′ N, 23°87′ E). The soil of the experimental field was *Endocalcari- Epihypogleyic Cambisol* (WRB soil classification system 2015). The field experiments were carried out in three replicates in a complete randomized design with 6 treatments (Fig. 2). Each treatment plot was 1.5 m^2 (1.5 m × 1.0 m). The experimental treatments included a control, N0B0 (No fertilizer + No biochar), N1 (100% of recommended N fertilizer, 160 kg ha^{-1} for spring barley), N2 (75% of recommended N fertilizer, 120 kg ha^{-1} for spring barley), N1B (100% of recommended N fertilizer + 25 ton ha^{-1} biochar), N2B (75% of recommended N fertilizer + 25 ton ha^{-1} biochar), and B (25 ton ha^{-1} biochar). Application of N fertilizers was done for spring barley only. The biochar used was derived from swine manure digestate pyrolyzed at 550 °C. Both fertilizer and biochar amendments were applied before sowing.

The two experimental plots were planted with the *'Luoke'* cultivar of spring barley *(Hordeum vulgare L.*) in 2020 and 2021, and with the *'Respect'* cultivar of pea (*Pisum sativum*) in 2021 and 2022. The crops were sown in April at 280 kg ha^{-1} for pea and 180 kg ha^{-1} for spring barley. Each year, the fields were fertilized with phosphorus (54 kg ha^{-1}) and potassium (78 kg ha^{-1}). The same procedure was used for both experimental plots in terms of experimental design, crop rotation, sowing rate, and cultivation period.

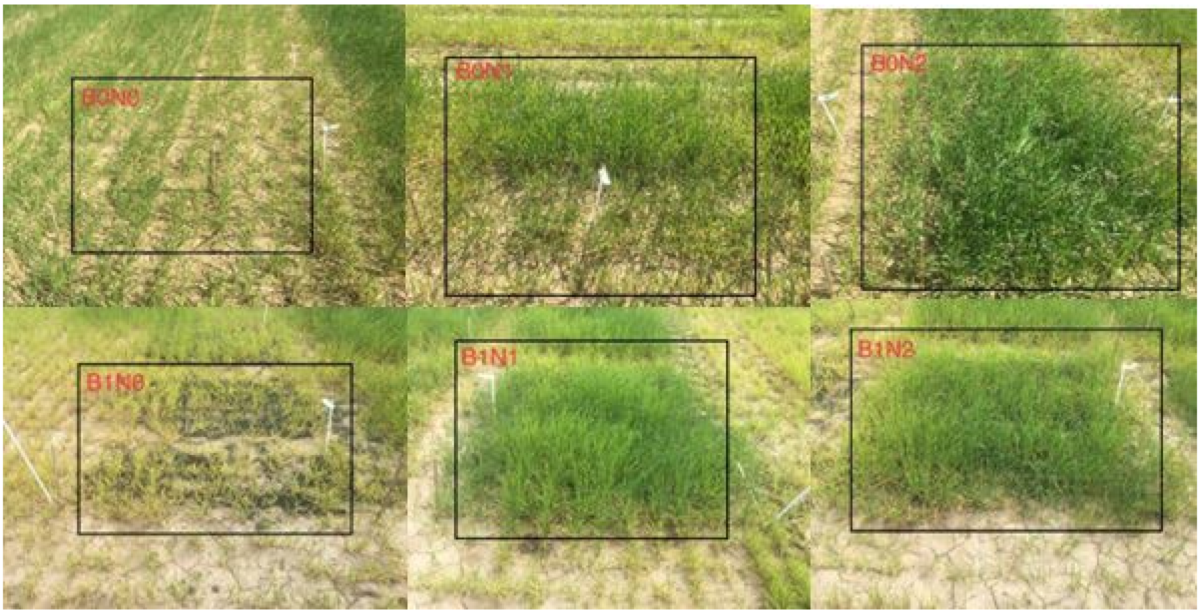

Figure 2. Visual representation of spring barley in different treatments

2 pav. *Vasarinių miežių vizualinis vaizdas skirtinguose variantuose*

The laboratory experiment was carried out in 2020 (January to April) at the Institute of Agriculture of Lithuanian Research Centre for Agriculture and Forestry, Department of Plant Nutrition and Agroecology. *Endocalcaric Epigleyic Cambisol* soil (WRB soil classification system 2015) was obtained from the top 0–20 cm layer of a field at the Institute of Agriculture (55°23′49″N 23°51′40″E). The soil was air-dried and passed through a 2-mm mesh sieve. Swine manure digestate-derived biochar was manually mixed with soil at the rate of 15 t ha^{-1}. Synthetic N fertilizer in form of ammonium nitrate was applied at 160 kg ha^{-1} on day 20 after sowing. Small plastic pots (27 cm diameter and 25 cm height) were filled with 10 kg of soil. The pots were installed with a closed-loop irrigation system to control irrigation and soil moisture. A randomized complete block design (RCBD) with six treatments and three replications was used: M1B1 (soil and biochar + normal moisture, $W \leq 15\%$), M2B1 (soil and biochar + drought condition, $W \leq 5\%$), M3B1 (soil and biochar + excess moisture, $W \geq 35\%$), M1B0 (soil without biochar + normal moisture, $W \leq 15\%$), M2B0 (soil without biochar + drought condition, $W \leq 5\%$ condition), M3B0 (soil without biochar + excess moisture, $W \geq 35\%$). Ten seeds of spring wheat "C*ollada"* cultivar were sown in each pot. After two weeks, each pot was thinned to six healthy plants.

2.2. Soil and biochar sampling and chemical analysis

Before planting began each year, soil samples were taken from experimental plots at two depths (0-10 and 0-20 cm). Soil pH was measured by dissolving a 1:5 soil suspension in 1M KCl. Using an ammonium lactate-acetic acid extraction, the available potassium (K_2O), phosphorus (P_2O_5), Ca, and Mg in the soil were examined in triplicate (Egnér, Riehm and Domingo, 1960). Papers 1, 2, and 3 (Ayaz *et al.*, 2021; Ayaz *et al*, 2022; Ayaz *et al.,* 2023) present the comprehensive soil chemical analysis for both the field and the controlled laboratory studies. The swine manure was from a local farm. After air drying for 48 h, the manure was manually crushed. Biochar was made by heating the manure in an anaerobic cylindrical furnace at 550 °C for 5-6 h (Boostani *et al.*, 2019). Biochar's physical and chemical properties were tested using customary laboratory techniques (shown in Table 2). A 1:5 (vol vol^{-1}) dilution was used to determine the pH of biochar (Buneviciene *et al.*, 2021). Diethylenetriamine pentaacetate (DTPA)-extractable nutrients were determined by inductively-coupled plasma optical emission spectroscopy (ICP-OES) (Perkin Elmer ICP-OES, Waltham, MA, USA) (Prasad, Tzortzakis and McDaniel, 2018). Using a standard protocol (Flisch *et al.*, 2017), total nitrogen (TN) and Mg concentrations were determined. TGA results presented in Paper 1 (Ayaz *et al.*, 2021) provide information on the ash content, moisture, volatiles, and fixed C contents of the biochar. Table 2 provides an overview of the phyco-chemical properties of the soil and biochar; further information can be found in Papers 2 and 3 (Ayaz *et al.,* 2022; Ayaz *et al.,* 2023).

Table 2. Physicochemical properties of soil and Biochar during field experiments

2 lentelė. *Dirvožemio ir bioanglies fizikinės ir cheminės savybės lauko eksperimentų metu*

Soil characteristics in 1st experiment							
Depths (cm)	pH	P_2O_5 (mg/kg)	Total N (%)	Organic carbon (%)	Mineral Nitrogen (mg/kg)	NH_4-N (mg/kg)	NO_3-N +N_2O-N (mg/kg)
0-10	6.8	147.6	0.14	1.02	-	-	-
0-20	6.9	142.9	0.14	0.98	-	-	-
0-60	-	-	-	-	11.21	1.21	10
Soil characteristics in 2nd experiment							
0-10		272.9	0.18	1.02			
0-20		241.1	0.15	0.99			
0-60					11.19	1.19	10
Biochar							
-	pH	Ash content (%)	Moisture wt. (%)	Volatiles wt. (%)	Fixed carbon wt (%)	Total Mg (g/kg)	Organic C (%)
	9.1	32.21	2.52	56.73	40.75	10.50	62.33

P_2O_5 = phosphorus pentoxide, NH_4-N= ammonium nitrogen, NO_3-N +N_2O-N = nitrate plus nitrite.

2.3. Soil and biochar heavy metals analysis

Soil samples from the pot experiment were taken from each container for the determination of heavy metals content. Dried soil and biochar samples (1 g) were mixed with 25 ml 0.1 M $CaCl_2$ solution and shaken for 2 h on an orbital shaker before being centrifuged for 15 min. ICP-OES (Optima 2000, PerkinElmer Co.) was used to analyze the filtered solution for HMs (Ni, Cr, Cd, Pb, Cu, Zn). Heavy metal fractions were determined by dissolving soil and biochar samples in HF-$HClO_4$-HNO_3, filtering the solution, and then analyzing the solutions by ICP-OES (Carignan and Tessier, 1988). After DTPA extraction, the levels of P, K, Ca, and Mg were determined by ICP-OES (Zaccheo, Crippa and Bedussi, 2017). Paper 2 contains the specifics (Ayaz, Stulpinaite, *et al.*, 2022).

2.4. Crop biomass and dry matter analysis

Plants were harvested after 2 months from all pots. Plants were separated into leaves, stems, roots and ears for fresh weight determination. The biomass was dried in an industrial over (Thermolab) at 105°C until constant weight and the dry biomass was calculated.

2.5. Determination of chlorophyl and grain yield

Harvesting of plants in all small experimental plots was performed manually through hands. Grain yield and 1000-grain weight were determined. All analyses were performed in duplicate, and the procedures followed those outlined in the first study (Ayaz *et al.*, 2021). For the physiological parameters of plants chlorophyll index and fluorescence were measured together every 2 weeks with five SPAD and fluorescence measurements taken per per plant and averaged. The chlorophyll index was measured with a MINOLTA SPAD 502 instrument (Ling, Huang and Jarvis, 2011) based on the ability of chlorophyll to absorb blue (400‑500 nm) and red (600‑700 nm) waves. Chlorophyll fluorescence II indices (Fmin, Fmax, Fv/ Fm,) were identified in vivo with the chlorophyll fluorometer OS-30p (OptiScience, USA), and their values were identified by means of the equations of the OJIP test (Strasser et al., 2004). In papers 1 and 2 (Ayaz *et al.*, 2021 and Ayaz *et al.*, 2022).

2.6. Soil hydro-physical study

For analysis of water retention qualities and pore-size distribution, undisturbed soil samples were taken from each treatment and placed in stainless steel cylinders (51 mm in height and 53 mm in diameter). The water retention qualities were tested at suction pressures of −4, −10, −30, −50, −100, and 300 hPa in a sand box and a sand-kaolin box. The pressure required to cause permanent wilting was calculated to be around −15,500 hPa (Klute, 1986). The water content values at 100 and −15,500 hPa were calculated to be the field capacity (FC) and permanent wilting point (WP), respectively. The amount of water available to plants, or plant-available water (PAW), was described as the difference between these two suctions. Soil cores were stored in a refrigerator at a constant temperature of 2 degrees Celsius. You can get all the gory details in the second publication (Ayaz *et al.,* 2022).

2.7. Substrate utilization using Biolog®Ecoplate

Specifically designed for community analysis and microbial environmental research, the Biology system and the Biolog-EcoPlate approach were used to identify 31 carbon sources and the metabolic functional diversity of soil microorganisms (Luo *et al.*, 2020). This was accomplished by collecting recent soil samples from each treatment. Soil samples were mesh and ground using a 2 mm sieve. A 250 mL flask containing 90 mL of distilled water and 10 g of dry soil was used for each treatment. The mixture was shaken at 250 rpm for 30 minutes. Each culture was diluted by a factor of 10-3, and 150 L was transferred to a 96-well Biolog® EcoPlate (Biolog, Hayward, CA, USA) to test the effects of 31 different carbon sources and a control treatment (without a C source). 24-hour absorbance readings at 590 nm (dual-wavelength data: OD590-OD750) were taken at 25 degrees Celsius for 24, 48, 72, and 96 hours (L. Wang *et al.*, 2020). The second study (Ayaz *et al.,* 2022) provides the methods in greater depth.

2.8. Species diversity indices calculation

One measure of species richness is the number of species found in a given sample; another is the even distribution of individuals across species. Shannon's index is a measure of the information required to characterize each species in the community, and it may be determined using the equation given in paper (Ayaz, Feizienė, *et al.*, 2022). Simpson's index (D) quantifies the likelihood that two randomly picked species from a sample are members of the same species. The species richness (R), is defined as the total number of species present in a given area. Mclntosh index was also calculated along with species evenness as by Magurran (1988). All the equations are summarized in paper 4 (Ayaz, Feizienė, *et al.*, 2022).

2.9. Greenhouse gases measurements

The static gas-chamber was utilized to collect gas samples at the experimental site, and the samples were analyzed using gas chromatography in accordance with previous studies (Kanerva *et al.*, 2007; Zhang *et al.*, 2015). The static gas chamber's specifications included a base box (frame) with a □-shaped groove that was 50 cm wide and 50 cm long. There are stainless steel frames that have been permanently inserted 10 cm beneath the surface and cover 0.25 m^2. After the chamber was sealed, a 3-minute interval was employed for each gas measurement. A well-sealed 20 cc syringe was used to extract the gas samples, and they were then put into well-sealed glass vials. Paper 4 provides the in-depth methods (Ayaz *et al.*, 2023).

2.10. Soil temperature and moisture measurements

Near-surface soil temperatures were measured at 5 cm deep across all stages of development in 2020 and 2021 (Akhtar *et al.*, 2020). Additionally, soil samples were obtained from 0-10 cm with a soil auger, and then dried in an oven for 24 hours at 105 °C to determine the soil moisture (in mass percent) at each development stage. A linear regression was used to analyze the relationship between CO_2, N_2O and CH_4 emission with moisture content and temperature.

2.11. Meteorological conditions

Dotnuva meteorological station of Lithuanian Hydrometeorological Service data under the Ministry of Environment of the Republic of Lithuania, were used, provided data on the mean annual temperature and mean precipitation for the three years of investigation at the experimental location. The average air temperature during the months of January to December in 2020, 2021, and 2022 was 9.3 °C, 7.4 °C, and 8.0 °C respectively. The cumulative annual precipitation value was 591.8 mm, 573.0 mm, and 627.9 mm respectively (Fig. 3). The years 2021 and 2022 saw a notable increase in the frequency of dry weather with low precipitation during summer.

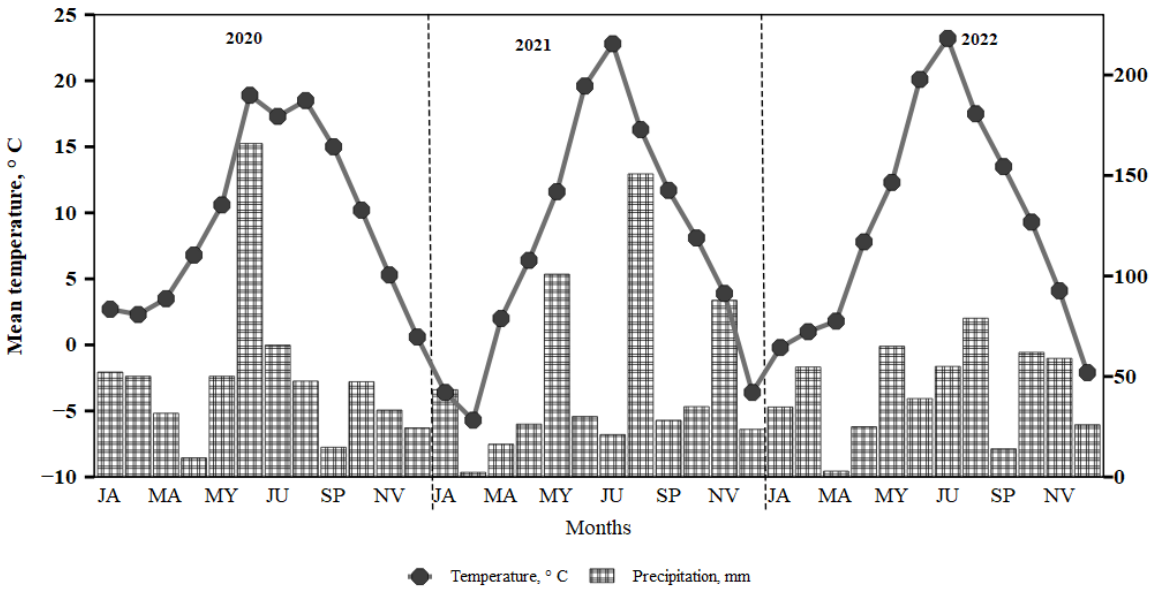

Figure 3: Temperature and precipitation from the year 2020–2022

3 pav. *Temperatūra ir krituliai 2020–2022 m.*

2.12. Statistical Analysis

All data sets were examined using analysis of variance (ANOVA) and the least significant difference (LSD) test because they all followed a normal distribution. Statistix 8.1 and GraphPad PRISM 8 were used for all statistical analyses. R-studio was used to do the ranking coefficient analysis.

3. RESULTS AND DISCUSSION

3.1. Heavy metals' study

Biochar made from pig manure digestate has shown promise as a soil amendment in pot experiments, and may have a positive effect on both soil and plant health. Heavy metal content in plants was reduced by 90% for Cr, 50% for Ni, 9% for Cd, and 34% for Pb when applied to spring wheat during its early growth stages compared to non-biochar treatments *($p \geq 0.01$)*. Sewage sludge biochar (used at 500-550 °C) and broiler litter-derived biochar (applied at 700 °C) greatly decreased heavy metals in plants due to the breaking of metals from exchangeable form to less accessible organic bond proportion (Liu *et al.*, 2021). Biochar significantly reduces the availability of heavy metals to plants under flooded, optimum, and wet moisture regimes (Chen *et al.*, 2023) because of its ability to retain water. Similarly, biochar made from rice straw considerably reduced the amount of Cd accessible to the plants (Akca *et al.*, 2022). Biochar's ability to immobilize heavy metals has been linked to an increase in soil absorptive capacity brought about by modifications to the soil's physical and chemical properties, including dynamoelectric attraction, cation and anion exchange, and physical absorptivity. However, the heavy metal concentration of the soil was also raised by the swine manure digestate biochar across all moisture regimes (by 21% for Cr, 43% for Ni, 55% for Cu, 70% for Zn, and 12% for Pb). Biochar application resulted in substantial enhancements of soil and plant main elements (P, K, Mg, and Ca) throughout a range of moisture conditions. The optimal soil humidity (15–20%) was shown to have the maximum concentration of these components, while drought and flooded regimes may account for their loss, with flooded soils having a particularly high risk for leaching. Biochar's beneficial effects have been attributed to several factors, including its ability to increase soil aeration and porosity (Kalus, Koziel and Opaliński, 2019), which in turn decreases soil bulk density (Bd) and boosts water holding capacity (WHC) (Chang *et al.*, 2021; Guo *et al.*, 2021); and its ability to improve surface area (Kalus, Koziel, & Opaliski, 2019). The source for the whole report in paper 2 (Ayaz, Stulpinaite, *et al.*, 2022).

3.2. Crop yield analysis

During The chlorophyll fluorescence and chlorophyll index of plants can be used as indicators of their vitality in the pot experiment. Increases in aboveground biomass and dry matter content occurred after biochar was introduced to the soil and persisted during the growing interval (days 12^{th} to 62^{nd}). Above-ground biomass and dry matter content were both considerably *($p \leq$*

0.05) increased when biochar was applied to the soil as an amendment. Treatments M1B1, M2B1, and M3B1 with a factorial interaction increased above-ground biomass by 71.87% *($p \leq 0.05$)*, 66.66% *($p \leq 0.05$)*, and 68.64% *($p \leq 0.05$)*, respectively, compared to M1B0, M2B0, and M3B0. The dry mater content of mixtures including biochar and water (M1B1, M2B1, and M3B1) was 45.83%, 55.17%, and 40.90% greater than that of M1B0, M2B0, and M3B0, respectively. This suggests that compared to no biochar treatments, biomass could benefit from biochar addition under a variety of moisture conditions. In a similar vein, biochar treatments significantly increased spring barley and pea crop grain output in a 2020-2022 field trial. In contrast to the control treatment (CK), the spring barley N_1B, N_2B, B, and N_1 treatments all significantly increased 1000 grain yield by 9, 3, 15, 2, 8, and 16 percent in 2021, respectively. Grain yield increased by 46, 09, 42, 84, and 32 percent. In contrast, 1000-grain yields from pea crops rose dramatically in both 2021 and 2022. Soil pH and ions generated from biochar work together to boost crop yields when biochar is applied (Pulka *et al.*, 2020). There have been reports that using biochar made from straw (at a rate of 5 Mg ha^{-1}) can increase harvests (Gupta *et al.*, 2020; Feng *et al.*, 2021). Soil quality can be improved, which in turn increases agricultural yields, thanks to its revitalizing effects (Zahra *et al.*, 2021). Paper 2 (Ayaz, Stulpinaite, *et al.*, 2022).provides further information.

3.3. Biochar effect on the soil's physical characteristics and functional diversity

3.3.1. Total porosity and bulk density of the soil

Soil hydrophysical analyses were carried out at the beginning and at the end of the experiment I (Spring barley). Thus in the beginning of the experiment, At a soil depth of 5–10 cm, the application of 25 tons ha^{-1} of biochar alone (B1N0) and 25 tons ha^{-1} of biochar mixed with 120 kg ha^{-1} of N fertilizer (B1N2) significantly increased *($p \geq 0.05$)* the soil bulk density (BD) by 10-12%. Similar to this, we discovered that the application of biochar alone and biochar combined with 160 kg ha^{-1} of N fertilizer (B1N1) led to an improvement in soil BD of 8–10% over treatments without biochar that was statistically significant *($p \geq 0.05$)*. Following harvest, the addition of biochar, both on its own and in combination with N fertilizers in the amounts of 160 kg ha^{-1} and 120 kg ha^{-1}, considerably reduced soil BD and increased total porosity (TP). At both studied depths, there was also a significant improvement in soil macropores. Therefore, using biochar made from swine digestate can be seen as a helpful soil supplement for dealing with difficulties like high BD, low TP, and compacted soil with limited porosity. Biochar's active huge surface area, particle size, and porosity, as well as the soil's intrinsic qualities, all contribute to its ability to lower BD levels in the soil (Toková *et al.*, 2020). Biochar can also reduce BD since it forms soil pores when mixed with soil particles (Šimanský *et al.*, 2016). The second study (Ayaz *et al.*, 2022) provides further information.

3.3.2. Biochar's impact on soil hydrology

We summarized that the addition of biochar to 160 kg ha^{-1} of N fertilizer within 5-10 cm depth at -4 to -100 hPa suction significantly increased water retention, while increasing field capacity and the soil's wilting point at both 5-10 and 15-20 cm depths was found to have higher suction and pressure (-100 hPa and -15,500 hPa, respectively). Biochar application has the potential to improve drought conditions by increasing soil water content. Soil hydraulic conductivity was reduced by 35% to 40% from the non-biochar treatments to the biochar treatments between 5 and 10 centimeters deep. Therefore, biochar does not accelerate the rate at which water moves through the soil's top layer. Because biochar increased soil evaporation and thus soil temperatures, this occurred. Soil water retention was shown to be significantly improved when biochar was added (Šimanský *et al.*, 2016) due to the massive surface area of the biochar. Also compatible with these findings is the work of Claire L. Phillips, who discovered that adding biochar manufactured from conifer wood and wheat straw significantly increased soil porosity (from 9 to 36 Mg ha^{-1}) and, consequently, soil volumetric water content and soil field capacity (Atkinson, 2018). Biochar and other organic compounds may enhance the soil's physical condition (Igaz *et al.*, 2018; Šrank and Šimanský, 2020).

3.3.3. Biochar effect on soil carbon sources utilization and soil biological indices

According to the findings of this study, biochar made from swine digestate, either with or without N fertilizer, may be a helpful amendment. Depending on the kind of soil and other environmental parameters, it may help to improve hydro-physical characteristics and microbial abundance. Biochar has been shown to improve soil microbial activity (Fig. 4) and was found to have a positive link with the usage of carbon sources in this investigation. Soil carbon sources (SCS) ranging from carboxylic acids to amines were used with amines being used the least. In compared to non-biochar treatments, the overall consumption of all SCSs was greater in soil treated with biochar. All of the diversity indices, including average well color development (AWCD) and richness (R) tested in the *Biolog EcoPlate* incubated for 96 h, showed increased rates of biodiversity in biochar-treated soil and with the B0N1 treatment. The B1N2 treatment considerably decreased the U index from 24 to 96 h, 20-30% lower than the control treatment (Paper 3) (Ayaz, Feizienė, *et al.*, 2022).

These findings suggest that combining biochar with organic N fertilizer can improve SCS consumption, which in turn tends to boost soil microbial diversity (Esmaeelnejad *et al.*, 2017).

The consumption of a wider variety of substrates is typically observed in shallow soil, where microbial diversity is greater (Wolińska *et al.*, 2020; Duan *et al.*, 2021). It was found that a decrease in both nutrient availability and oxygen rate caused by a soil depth gradient had a deleterious effect on soil bacteria and the regulation of their metabolic process (Sandén *et al.*, 2019; Koner *et al.*, 2021). Soil microbial diversity is reflected in the physiological functions that are reflected in the average well color development (AWCD) (Xun *et al.*, 2016; Koner *et al.*, 2021). As a result, it is possible to predict that some of the consumption of the chosen C-sources may benefit the functional variety of soil microbes and their metabolic activity.

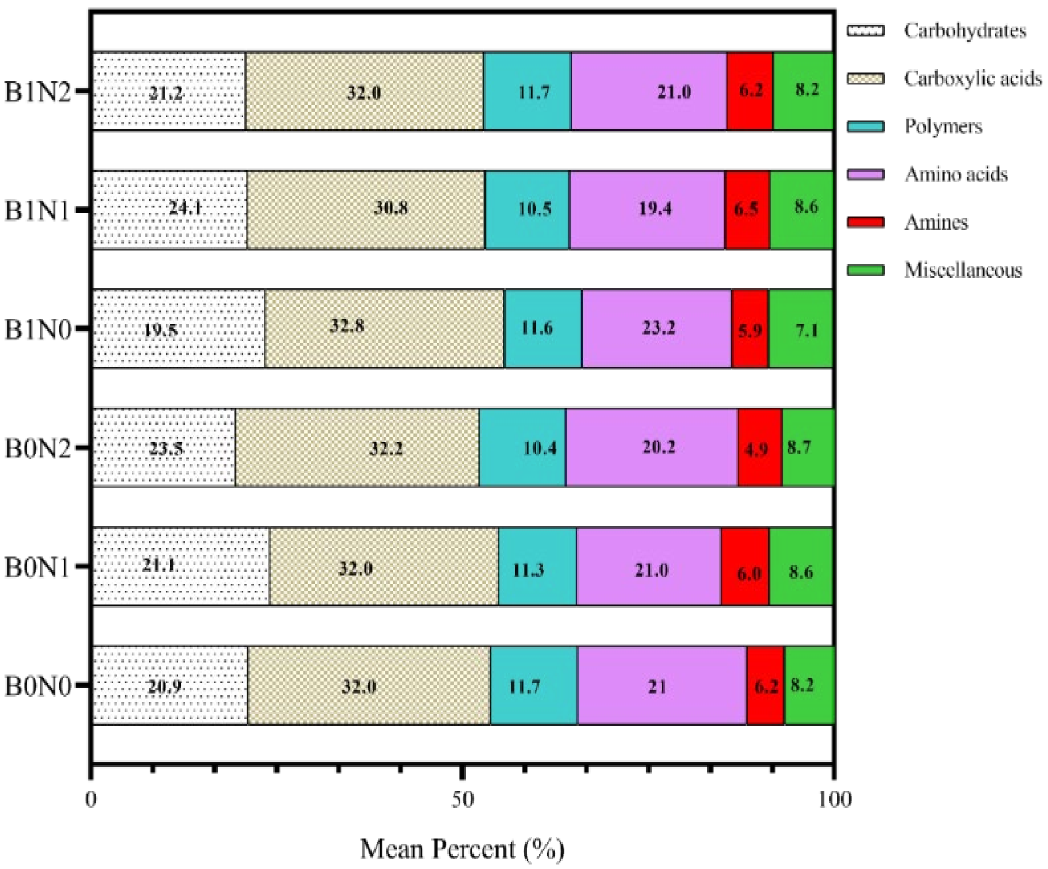

Figure 4. Effect of biochar in combination with N fertilizer on soil carbon sources (Ayaz *et al.*, 2022).

B0N0 (without biochar and N fertilization); B0N1 (Without Biochar and 160 kg ha^{-1} N); B0N2 (Without Biochar and 120 kg ha^{-1} N fertilization); B1N0 (Biochar 25 ton ha^{-1} only); B1N1 (Biochar 25 ton ha^{-1} and 120 kg ha^{-1} N); B1N2 (Biochar 25 ton ha^{-1}, 160 kg ha^{-1} N)

4 pav. *Bioanglies ir azoto trąšų poveikis dirvožemio anglies šaltiniams*

B0N0 (be biochar ir N tręšimo), poveikis; B0N1 (Be Biochar ir 160 kg ha^{-1} N); B0N2 (Be Biochar ir 120 kg ha^{-1} N tręšimo); B1N0 (tik biochar 25 tonų ha^{-1}); B1N1 (Biochar 25-tonu ha^{-1} ir 120 kg ha^{-1} N); B1N2 (Biochar 25-tonu ha^{-1}, 160 kg ha^{-1} N)

3.4. Effect of biochar on GHGs emission

3.4.1. Individual CO_2, CH_4, and N_2O emissions

During the three years of experiment on greenhouse gases emissions, periodic fluctuation was seen between the spring barley and the pea crop 2020-2022 seasons. CO_2 emissions during spring barley 2020 were greater throughout the season, except during the jointing stage (inflorescence emergence in case of pea crop) throughout the experiment compare to 2021 and 2022. CO_2 emissions were observed to be significantly *($p \geq 0.05$)* lower under biochar treated soils throughout the 2021, 2022 in comparison to the year 2020. All biochar treated soils (B, N_1B, and N_2B) reduced CO_2 emission by 57%, 55%, and 59%, respectively, when compared to non-biochar treated soils across all pea crop growth stages *($p \geq 0.05$)*. Treatment N_2B considerably *($p \geq 0.05$)* reduced CO_2 emissions by 58% compared to the control treatment during the tillering stage. Similarly, compared to non-biochar treatments, CO_2 emissions were reduced by 50%, 51%, and 50% throughout the joining, flowering, and maturity stages, respectively *($p \geq 0.05$)*. Soil CO_2 emission variability is said to be higher in carbon-rich soil (Ahirwal *et al.*, 2021; S. Zhang *et al.*, 2021). While CO_2 emissions are a major concern, biochar may help reduce them (Lehmann *et al.*, 2021; Shakoor *et al.*, 2021). Applications of biochar in 2021 had a significant impact on the seasonal variations in soil CO_2.

Nonetheless, there was a considerable variance in N_2O emission seen during various growth stages of both crop seasons. In accordance with the aforementioned pattern, biochar-treated soils (B, N_1B, and N_2B) significantly *($p \geq 0.05$)* reduced N_2O emission by 48%, 49%, and 48%, respectively, throughout the pea crop's growth stages, in comparison to non-biochar treatments. Treatment N_2 tends to increase N_2O emission during the pea crop season, particularly during the inflorescence emergence and maturity stage. Negative impacts on the environment and a rise in greenhouse gas emissions are associated with the use of excessive amounts of nitrogen fertilizer (Jamali *et al.*, 2021; L. Zhang *et al.*, 2021). The outcome of the research highlight that nitrogen fertilizer treatments (N1, N2, and N3) significantly increased soil N_2O emissions in 2021 during the growing seasons. Soil amendment with biochar and synthetic fertilizers can lower N_2O emissions depending on the N applied and the emission factors (Han *et al.*, 2021). Organic fertilizers have intricate chemical makeups, making it difficult to predict their emission components (Singh, 2010; Akhtar *et al.*, 2020). N fertilization and mulching treatments have been shown to increase N_2O flux by a combined 71-123% (Novoa and Tejeda, 2006; Kim *et al.*, 2021; Ma *et al.*, 2022).

Methane gas (CH_4) emission during the spring barley season did not significantly vary. Results, however, showed that CH_4 emission varied significantly in 2021, 2022 and 2023 during the growing stages. During the blossoming and maturity stages, the treatment N_1B significantly *($p \geq 0.05$)* reduced CH_4 emission by 17% and 19%, respectively. However, biochar did not affect CH_4 emission the way it effected CO_2 and N_2O emission. Several studies have found that the relationship between biochar application to soil and CH_4 flux is poorly understood (Jeffery *et al.*, 2016; Kammann *et al.*, 2017). Biochar applications to soil have been observed to either increase CH_4 emission flow (Yu *et al.*, 2013), decrease CH_4 emission flux (Feng *et al.*, 2012; Lin *et al.*, 2015), or have no significant effect on CH_4 emission flux at all (Xie *et al.*, 2013). In anaerobic settings, methanotrophic CH_4 consumption was said to be boosted by biochar in the soil. The quantity of CH_4 that could enter a plant's aerenchyma and exit was also reduced because the addition of biochar enhanced the oxidation of CH_4 by methanotrophic organisms at the oxicanoxic root interface (Feng *et al.*, 2012). Paper 4 provides additional information (Ayaz *et al.*, 2023).

3.4.2. Cumulative CO_2, CH_4, and N_2O emissions

The amount of CO_2, N_2O, and CH_4 emissions overall during the spring barley crop's growth stages were impacted through the use of biochar. Nonetheless, there was a significant amount of heterogeneity observed during the pea crop's growth phases. The biochar treatments (B, N1B, and N2B) substantially *($p \geq 0.05$)* reduced cumulative CO_2 emission by 16%, 19%, and 17%, respectively, in comparison to the control treatment. However, only the treatment B significantly *($p \geq 0.05$)* reduced cumulative N_2O emission by 6% in comparison to the control treatment. Similar to treatment B, treatment N_1B considerably reduced cumulative CH_4 emission by 7% relative to control treatment.

3.4.3. Global Warming potential (GWP)

The trend in total emissions and the GWP of CO_2, N_2O, and CH_4 emissions were comparable. GWP did not significantly fluctuate during the spring barley growing stages, according to the data. However, biochar treatments (B, N_1B, and N_2B) recorded significantly *($p \geq 0.05$)* lower GWP caused by CO_2 during growth phases of pea crop 2021 and 2022 than other treatments, by 39%, 35%, and 39% correspondingly. The GHG emissions data (Li *et al.*, 2015) supported the claim that biochar addition significantly decreased the GWP. Treatment B considerably reduced the GWP produced by CH_4 and N_2O by 19% and 34%, compared to control treatment, respectively. GWP is the primary factor in determining the global impact of the three most prominent greenhouse gases (CO_2, CH_4, and N_2O) ((Team, 2007). Net GWP was considerably lower in treated biochar plots in 2021 and 2022. According to the following reports, however, there will be no major changes in 2020. Non-decomposition of biochar in the first year may account for the lack of a statistically significant difference in GWP (Mukherjee and Lal, 2013); however, greater biochar decomposition in years two and three may account for the decrease in GWP (Lehmann *et al.*, 2021). Soil carbon sequestration is reported to be higher when the GWP is lower (Yao *et al.*, 2021). In general, research show that using biochar can greatly reduce global warming due to its structural behavior. Under biochar applications, the biochar C:N ratio may be a key element driving GWP (Xu et al., 2021). Paper 4 (Ayaz *et al.*, 2023) provides additional information.

CONCLUSION

1. In a controlled environment, biochar-treated soils significantly *($p \leq 0.05$)* enhanced the mean aboveground biomass and dry matter content of spring wheat compared with non-biochar treatments. Under field conditions, biochar with N fertilizer (160 and 120 kg ha^{-1}) treated soils significantly enhanced 1000-grain mass and grain yield of spring barley by 46%, and 42%, respectively, in 2021 compared to control treatment (CK). For pea, the 1000-grain mass and grain yield significantly increased in 2021 and in 2022. Thus, biochar application can be helpful in improving crop yield.
2. In a controlled environment, biochar application substantially lowered heavy metal uptake into the plants. Soil and plant P, K, Mg, and Ca concentrations were raised after biochar application, regardless of the moisture conditions. Biochar produced from swine manure digestate can be a potential tool to improve soil and plant quality.
3. Biochar alone, and biochar with 160 kg ha^{-1} and 120 kg ha^{-1} of mineral nitrogen fertilizer, significantly reduced soil bulk density, increased total porosity, and increased soil macroporosity within the 5–10 and 15–20 cm soil layers. Therefore, biochar produced from swine manure digestate can be useful to improve the physical properties, bulk density (BD) and total porosity (TP), of compacted soils.
4. Biochar combined with a 160 kg ha^{-1} mineral N fertilizer rate substantially increased the water retention within the 5–10 cm layer at a suction pressure of 4 -100 hPa. At higher suction -100 hPa and -15,500 hPa both field capacity and plant wilting point were found to be higher for soils taken from 5–10 and 15–20 cm. Biochar with and without mineral N fertilizer at the 5–10 cm depth reduced soil hydraulic conductivity (35-40%) compared to soil without biochar. Biochar may be useful to increase soil water retention under drought conditions.
5. In a controlled environment, the addition of biochar to soil improved chlorophyll fluorescence (Fmin, Fmax, Fv/ Fm) and chlorophyll index throughout the plant's growth period (12 to 62 days), leading to an increase in aboveground biomass and dry matter. Likewise, for the field experiments, biochar application substantially enhanced chlorophyll fluorescence (Fmin, Fmax, Fv/ Fm) and chlorophyll index compared to control.

6. Soil carbon source utilization increased with the shallow incorporation of biochar into soil, which also improves the functional variety of soil microbes. The overall utilization of all SCS was greater with biochar application compared to no biochar. Between 24 and 96 h of the test period, the index U was significantly decreased with the addition of biochar (B1N2) compared to the control.
7. Biochar application lowered CO_2, N_2O, and CH_4 emissions from the soil significantly in the second and third years of the field experiment when compared to the first year, resulting in a considerable impact on global warming potential. GHG emissions and soil moisture and temperature were found to have a positive correlation. In temperate areas, shallow incorporation of carbon generated by swine manure digestate biochar into soil may be an appropriate method of lowering GHG emissions.

Practical importance / Recommendation

Based on these experiments, we recommend that biochar produced from swine manure digestate, in combination with and without N mineral fertilizers, could be beneficial tool in agriculture to improve soil conditions, physico-chemical properties and micro-organism abundance. Biochar can be used to reduce GHG emissions from cultivated soils. In soils that are extensively contaminated by chemical components, we would advise using different dosages of biochar as a soil improver. Additional study is required to analyze the long-term effects on soil and plant quality and productivity of biochar produced from swine manure digestate.

REFERENCES

1. Abdelhafez, A. A., Abbas, M. H. H. and Li, J. (2017) 'Biochar: the black diamond for soil sustainability, contamination control and agricultural production', Engineering applications of biochar, 2.
2. Adekiya, A O et al. (2020) 'Contribution of Biochar in Improving Soil Health', in Soil Health. Springer, pp. 99–113.
3. Adekiya, Aruna Olasekan et al. (2020) 'Effect of biochar on soil properties, soil loss, and cocoyam yield on a tropical sandy loam Alfisol', The Scientific World Journal, 2020.
4. Ahirwal, J. et al. (2021) 'Changes in soil properties and carbon fluxes following afforestation and agriculture in tropical forest', Ecological indicators, 123, p. 107354.
5. Ajayi, A. E. and Rainer, H. (2017) 'Biochar-induced changes in soil resilience: effects of soil texture and biochar dosage', Pedosphere, 27(2), pp. 236–247.
6. Akca, M. O. et al. (2022) 'Biochar applications reduces the mobility of cadmium under differing soil moisture regimes', Gesunde Pflanzen, pp. 1–14.
7. Akhtar, K. et al. (2020) 'Straw mulching with inorganic nitrogen fertilizer reduces soil CO2 and N2O emissions and improves wheat yield', Science of the Total Environment, 741, p. 140488. doi: 10.1016/j.scitotenv.2020.140488.
8. Almutairi, A. A. (2022) 'Variations in composition and stability of biochars derived from different feedstock types at varying pyrolysis temperature. J Saudi Soc Agric Sci 22: 25–34'.
9. Alshankiti, A. and Gill, S. (2016) 'Integrated Plant Nutrient Management for Sandy Soil Using Chemical Fertilizers, Compost, Biochar and Biofertilizers-Case Study in UAE-and Biofertilizers', Journal of Arid Land Studies, 26(3), pp. 101–106.
10. Ambaye, T. G. et al. (2021) 'Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater', International Journal of Environmental Science and Technology, pp. 1–22.
11. Antonangelo, J. A. et al. (2019) 'Physicochemical properties and morphology of biochars as affected by feedstock sources and pyrolysis temperatures', Biochar, 1(3), pp. 325–336.
12. Antonangelo, J. A. and Zhang, H. (2019) 'Heavy metal phytoavailability in a contaminated soil of northeastern Oklahoma as affected by biochar amendment', Environmental Science and Pollution Research, 26(32), pp. 33582–33593.
13. Arif, M. et al. (2021) 'Enhancing phosphorus availability, soil organic carbon, maize productivity and farm profitability through biochar and organic–inorganic fertilizers in an irrigated maize agroecosystem under semi-arid climate', Soil Use and Management, 37(1), pp. 104–119.

14. Atkinson, C. J. (2018) 'How good is the evidence that soil-applied biochar improves water-holding capacity?', Soil Use and Management, 34(2), pp. 177–186.
15. Awad, Yasser M et al. (2018) 'Biochar effects on rice paddy: meta-analysis', Advances in agronomy, 148, pp. 1–32.
16. Awad, Yasser Mahmoud et al. (2018) 'Carbon and nitrogen mineralization and enzyme activities in soil aggregate-size classes: Effects of biochar, oyster shells, and polymers', Chemosphere, 198, pp. 40–48.
17. Ayaz, M. et al. (2021) 'Biochar Role in the Sustainability of Agriculture and Environment', pp. 1–22.
18. Ayaz, M., Stulpinaite, U., et al. (2022) 'Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil', Soil Use and Management, 38(2), pp. 1307–1321.
19. Ayaz, M., Feizienė, D., et al. (2022) 'The Impact of Swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils', Plants, 11(13), p. 1729.
20. Ayaz, M. et al. (2023) 'Biochar with Inorganic Nitrogen Fertilizer Reduces Direct Greenhouse Gas Emission Flux from Soil', Plants, 12(5), p. 1002.
21. Aziz, T. et al. (2010) 'Nutrient availability and maize (Zea mays) growth in soil amended with organic manures', Int. J. Agric. Biol, 12(4), pp. 621–624.
22. Bandara, T. et al. (2021) 'Biochar aging alters the bioavailability of cadmium and microbial activity in acid contaminated soils', Journal of Hazardous Materials, 420, p. 126666.
23. Barrow, C. J. (2012) 'Biochar: potential for countering land degradation and for improving agriculture', Applied Geography, 34, pp. 21–28.
24. Bi, Q.-F. et al. (2017) 'Effects of combined application of nitrogen fertilizer and biochar on the nitrification and ammonia oxidizers in an intensive vegetable soil', Amb Express, 7(1), pp. 1–9.
25. Bi, R. et al. (2022) 'Biochar and organic substitution improved net ecosystem economic benefit in intensive vegetable production', *Biochar*, 4(1), p. 46.
26. Bilias, F. et al. (2023) 'Biochar application as a soil potassium management strategy: A review', Science of the Total Environment, 858, p. 159782.
27. Blanco-Canqui, H. (2017) 'Biochar and soil physical properties', Soil Science Society of America Journal, 81(4), pp. 687–711.
28. De Boer, W. and Kowalchuk, G. A. (2001) 'Nitrification in acid soils: micro-organisms and mechanisms', Soil Biology and Biochemistry, 33(7–8), pp. 853–866.

29. Boersma, M. et al. (2017) 'Impact of biochar application on the productivity of a temperate vegetable cropping system', New Zealand Journal of Crop and Horticultural Science, 45(4), pp. 277–288.
30. Bohara, H. et al. (2019) 'Influence of poultry litter and biochar on soil water dynamics and nutrient leaching from a very fine sandy loam soil', Soil and Tillage Research, 189, pp. 44–51.
31. Bolan, N. et al. (2014) 'Remediation of heavy metal (loid) s contaminated soils–to mobilize or to immobilize?', Journal of hazardous materials, 266, pp. 141–166.
32. Bolan, N. S. et al. (2013) 'Microbial transformation of trace elements in soils in relation to bioavailability and remediation', Reviews of environmental contamination and toxicology, pp. 1–56.
33. Boostani, H. R. et al. (2019) 'Comparison of Pb stabilization in a contaminated calcareous soil by application of vermicompost and sheep manure and their biochars produced at two temperatures', Applied Geochemistry, 102, pp. 121–128.
34. Bot, A. and Benites, J. (2005) The importance of soil organic matter: Key to drought-resistant soil and sustained food production. Food & Agriculture Org.
35. Bourke, J. et al. (2007) 'Do all carbonized charcoals have the same chemical structure? 2. A model of the chemical structure of carbonized charcoal', Industrial & Engineering Chemistry Research, 46(18), pp. 5954–5967.
36. Brewer, C. E. et al. (2014) 'New approaches to measuring biochar density and porosity', Biomass and bioenergy, 66, pp. 176–185.
37. Brockhoff, S. R. et al. (2010) 'Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar', Agronomy journal, 102(6), pp. 1627–1631.
38. Brodowski, S. et al. (2006) 'Aggregate-occluded black carbon in soil', European journal of soil science, 57(4), pp. 539–546.
39. Bruun, E. W. et al. (2014) 'Biochar amendment to coarse sandy subsoil improves root growth and increases water retention', Soil use and management, 30(1), pp. 109–118.
40. Buneviciene, K. et al. (2021) 'Granulated biofuel ash as a sustainable source of plant nutrients', Waste Management & Research, 39(6), pp. 806–817.
41. Burhenne, L., Damiani, M. and Aicher, T. (2013) 'Effect of feedstock water content and pyrolysis temperature on the structure and reactivity of spruce wood char produced in fixed bed pyrolysis', Fuel, 107, pp. 836–847.
42. Burrell, L. D. et al. (2016) 'Long-term effects of biochar on soil physical properties', Geoderma, 282, pp. 96–102.

43. Butterbach-Bahl, K. et al. (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), p. 20130122.
44. Cantrell, K. B. et al. (2012) ‘Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar’, Bioresource technology, 107, pp. 419–428.
45. Carignan, R. and Tessier, A. (1988) ‘The co-diagenesis of sulfur and iron in acid lake sediments of southwestern Quebec’, Geochimica et Cosmochimica Acta, 52(5), pp. 1179–1188.
46. Cayuela, M. L. et al. (2013) ‘Biochar and denitrification in soils: when, how much and why does biochar reduce N2O emissions?’, Scientific reports, 3(1), pp. 1–7.
47. Chang, Y. et al. (2021) ‘Biochar improves soil physical characteristics and strengthens root architecture in Muscadine grape (Vitis rotundifolia L.)’, Chemical and Biological Technologies in Agriculture, 8(1), pp. 1–11.
48. Chen, Hanbo et al. (2020) ‘Animal carcass-and wood-derived biochars improved nutrient bioavailability, enzyme activity, and plant growth in metal-phthalic acid ester co-contaminated soils: A trial for reclamation and improvement of degraded soils’, Journal of environmental management, 261, p. 110246.
49. Chen, Hongyu et al. (2020) ‘Effects of microbial culture and chicken manure biochar on compost maturity and greenhouse gas emissions during chicken manure composting’, Journal of Hazardous Materials, 389, p. 121908.
50. Chen, L. et al. (2023) ‘Effect of biochar on the form transformation of heavy metals in paddy soil under different water regimes’, Archives of Agronomy and Soil Science, 69(3), pp. 387–398.
51. Chen, W.-H. et al. (2022) ‘Biomass-derived biochar: From production to application in removing heavy metal-contaminated water’, Process Safety and Environmental Protection, 160, pp. 704–733.
52. Conrad, R. (2020) ‘Methane production in soil environments—anaerobic biogeochemistry and microbial life between flooding and desiccation’, Microorganisms, 8(6), p. 881.
53. Council, N. R. (2010) Toward sustainable agricultural systems in the 21st century. National Academies Press.
54. Dai, Y. et al. (2020) ‘Utilization of biochar for the removal of nitrogen and phosphorus’, Journal of Cleaner Production, 257, p. 120573.
55. Dai, Z. et al. (2013) ‘The potential feasibility for soil improvement, based on the properties of biochars pyrolyzed from different feedstocks’, Journal of soils and sediments, 13(6), pp. 989–1000.

56. Dang, V. M. et al. (2019) ‘Immobilization of heavy metals in contaminated soil after mining activity by using biochar and other industrial by-products: the significant role of minerals on the biochar surfaces’, Environmental technology, 40(24), pp. 3200–3215.
57. Dempster, D. N. et al. (2012) ‘Decreased soil microbial biomass and nitrogen mineralisation with Eucalyptus biochar addition to a coarse textured soil’, Plant and Soil, 354(1), pp. 311–324.
58. Dharmakeerthi, R. S. et al. (2019) ‘Phosphorus release from unamended and gypsum-or biochar-amended soils under simulated snowmelt and summer flooding conditions’, *Journal of environmental quality*, 48(4), pp. 822–830.
59. Downie, A. *et al.* (2012) ‘Biochar as a geoengineering climate solution: hazard identification and risk management’, *Critical reviews in environmental science and technology*, 42(3), pp. 225–250.
60. Doyeni, M. O. *et al.* (2021) ‘Greenhouse gas emissions in agricultural cultivated soils using animal waste-based digestates for crop fertilization’, *The Journal of Agricultural Science*, 159(1–2), pp. 23–30.
61. Duan, Y. *et al.* (2021) ‘Clean technology for biochar and organic waste recycling, and utilization in apple orchard’, *Chemosphere*, 274, p. 129914.
62. Egnér, H., Riehm, H. and Domingo, W. R. (1960) ‘Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II’, *Chemische Extraktionsmethoden zur Phosphor-und Kaliumbestimmung. Kungliga Lantbrukshögskolans Annaler*, 26, pp. 199–215.
63. El-Naggar, A. *et al.* (2018) ‘Biochar influences soil carbon pools and facilitates interactions with soil: A field investigation’, *Land degradation & development*, 29(7), pp. 2162–2171.
64. Elshony, M. *et al.* (2019) ‘Ameliorating a sandy soil using biochar and compost amendments and their implications as slow release fertilizers on plant growth’, *Egyptian Journal of Soil Science*, 59(4), pp. 305–322.
65. Esmaeelnejad, L. *et al.* (2017) ‘Impacts of woody biochar particle size on porosity and hydraulic conductivity of biochar-soil mixtures: an incubation study’, *Communications in soil science and plant analysis*, 48(14), pp. 1710–1718.
66. Fan, R. *et al.* (2020) ‘Straw-derived biochar mitigates CO_2 emission through changes in soil pore structure in a wheat-rice rotation system’, *Chemosphere*, 243, p. 125329.
67. Fang, Y., Balwant, S. and Bhupinder Pal, S. (2015) ‘Effect of temperature on biochar priming effects and its stability in soils’, *Soil Biology and Biochemistry*, 80, pp. 136–145.
68. Farrell, M. *et al.* (2013) ‘Microbial utilisation of biochar-derived carbon’, *Science of the Total Environment*, 465, pp. 288–297.

69. Feng, W. *et al.* (2021) ‘Effects of straw biochar application on soil temperature, available nitrogen and growth of corn’, *Journal of Environmental Management*, 277, p. 111331.
70. Feng, Y. *et al.* (2012) ‘Mechanisms of biochar decreasing methane emission from Chinese paddy soils’, *Soil Biology and Biochemistry*, 46, pp. 80–88.
71. Fidel, R. B. *et al.* (2017) ‘Characterization and quantification of biochar alkalinity’, *Chemosphere*, 167, pp. 367–373.
72. Filiberto, D. M. and Gaunt, J. L. (2013) ‘Practicality of biochar additions to enhance soil and crop productivity’, *Agriculture*, 3(4), pp. 715–725.
73. Flisch, R. *et al.* (2017) ‘2/Bodeneigenschaften und Bodenanalysen’, *Grundlagen der Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017)(Hrsg. W. Richner & S. Sinaj). Agrarforschung Schweiz*, 8(6), pp. 1–2.
74. Fungo, B. *et al.* (2017) ‘Aggregate size distribution in a biochar-amended tropical Ultisol under conventional hand-hoe tillage’, *Soil and Tillage Research*, 165, pp. 190–197.
75. Gao, J. *et al.* (2016) ‘Drying-rewetting cycles alter carbon and nitrogen mineralization in litter-amended alpine wetland soil’, *Catena*, 145, pp. 285–290.
76. Gao, L. *et al.* (2017) ‘Effects of biochar on nutrients and the microbial community structure of tobacco-planting soils’, *Journal of soil science and plant nutrition*, 17(4), pp. 884–896.
77. Giagnoni, L. *et al.* (2019) ‘Long-term soil biological fertility, volatile organic compounds and chemical properties in a vineyard soil after biochar amendment’, *Geoderma*, 344, pp. 127–136.
78. Glaser, B. *et al.* (2000) ‘Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region’, *Organic Geochemistry*, 31(7–8), pp. 669–678.
79. Glaser, B. *et al.* (2001) ‘The’Terra Preta’phenomenon: a model for sustainable agriculture in the humid tropics’, *Naturwissenschaften*, 88(1), pp. 37–41.
80. Glaser, B. and Lehr, V.-I. (2019) ‘Biochar effects on phosphorus availability in agricultural soils: A meta-analysis’, *Scientific reports*, 9(1), pp. 1–9.
81. Gross, C. D. *et al.* (2022) ‘Biochar and its manure-based feedstock have divergent effects on soil organic carbon and greenhouse gas emissions in croplands’, *Science of the Total Environment*, 806, p. 151337.
82. Güereña, D. *et al.* (2013) ‘Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system’, *Plant and soil*, 365(1), pp. 239–254.
83. Gul, S. *et al.* (2015) ‘Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions’, *Agriculture, Ecosystems & Environment*, 206, pp. 46–59.

84. Guo, X. *et al.* (2021) ‘Impact of biochar addition on three-dimensional structural changes in aggregates associated with humus during swine manure composting’, *Journal of Cleaner Production*, 280, p. 124380.
85. Gupta, R. K. *et al.* (2020) ‘Rice straw biochar improves soil fertility, growth, and yield of rice–wheat system on a sandy loam soil’, *Experimental Agriculture*, 56(1), pp. 118–131.
86. Hamilton, C. E. *et al.* (2016) ‘Mitigating climate change through managing constructed-microbial communities in agriculture’, *Agriculture, ecosystems & environment*, 216, pp. 304–308.
87. Han, Z. *et al.* (2021) ‘Differential responses of soil nitrogen-oxide emissions to organic substitution for synthetic fertilizer and biochar amendment in a subtropical tea plantation’, *GCB Bioenergy*, 13(8), pp. 1260–1274.
88. He, M. *et al.* (2022) ‘Waste-derived biochar for water pollution control and sustainable development’, *Nature Reviews Earth & Environment*, 3(7), pp. 444–460.
89. He, Y. *et al.* (2017) ‘Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis’, *Gcb Bioenergy*, 9(4), pp. 743–755.
90. Hossain, M. Z. *et al.* (2020) ‘Biochar and its importance on nutrient dynamics in soil and plant’, *Biochar*, 2, pp. 379–420.
91. Igaz, D. *et al.* (2018) ‘Can a single dose of biochar affect selected soil physical and chemical characteristics?’, *Journal of hydrology and hydromechanics*, 66(4), pp. 421–428.
92. Jabborova, D. *et al.* (2021) ‘Growth response of Ginger (Zingiber Officinale), its physiological properties and soil enzyme activities after biochar application under greenhouse conditions’, *Horticulturae*, 7(8), p. 250.
93. Jamali, M. *et al.* (2021) ‘A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran’, *Renewable and Sustainable Energy Reviews*, 139, p. 110704.
94. Jeffery, S. *et al.* (2016) ‘Biochar effects on methane emissions from soils: a meta-analysis’, *Soil Biology and Biochemistry*, 101, pp. 251–258.
95. Jia, J. *et al.* (2012) ‘Effects of biochar application on vegetable production and emissions of N2O and CH4’, *Soil science and plant nutrition*, 58(4), pp. 503–509.
96. Jia, W. *et al.* (2017) ‘Tourmaline and biochar for the remediation of acid soil polluted with heavy metals’, *Journal of environmental chemical engineering*, 5(3), pp. 2107–2114.
97. Jia, Y. *et al.* (2020) ‘Preparation of biochar as a coating material for biochar-coated urea’, *Science of the Total Environment*, 731, p. 139063.

98. Jiang, L. *et al.* (2017) 'Corn cob biochar increases soil culturable bacterial abundance without enhancing their capacities in utilizing carbon sources in Biolog Eco-plates', *Journal of integrative agriculture*, 16(3), pp. 713–724.
99. Jindo, K. *et al.* (2014) 'Physical and chemical characterization of biochars derived from different agricultural residues', *Biogeosciences*, 11(23), pp. 6613–6621.
100. Kalus, K., Koziel, J. A. and Opaliński, S. (2019) 'A review of biochar properties and their utilization in crop agriculture and livestock production', *Applied Sciences*, 9(17), p. 3494.
101. Kammann, C. *et al.* (2017) 'Biochar as a tool to reduce the agricultural greenhouse-gas burden–knowns, unknowns and future research needs', *Journal of Environmental Engineering and Landscape Management*, 25(2), pp. 114–139.
102. Kammann, C. I. *et al.* (2011) 'Influence of biochar on drought tolerance of Chenopodium quinoa Willd and on soil–plant relations', *Plant and soil*, 345(1), pp. 195–210.
103. Kanerva, T. *et al.* (2007) 'Fluxes of N_2O, CH_4 and CO_2 in a meadow ecosystem exposed to elevated ozone and carbon dioxide for three years', *Environmental Pollution*, 145(3), pp. 818–828. doi: 10.1016/j.envpol.2006.03.055.
104. Karim, A. A. *et al.* (2022) 'Enrichment of primary macronutrients in biochar for sustainable agriculture: A review', *Critical Reviews in Environmental Science and Technology*, 52(9), pp. 1449–1490.
105. Khan, K. *et al.* (2022) 'Biochar produced from Saudi agriculture waste as a cement additive for improved mechanical and durability properties—SWOT analysis and techno-economic assessment', *Materials*, 15(15), p. 5345.
106. Khan, Z. *et al.* (2022) 'The toxicity of heavy metals and plant signaling facilitated by biochar application: Implications for stress mitigation and crop production', *Chemosphere*, p. 136466.
107. Kim, G. W. *et al.* (2021) 'Effect of Rice planting on nitrous oxide (N2O) emission under different levels of nitrogen fertilization', *Agronomy*, 11(2), p. 217.
108. Kirchman, D. *et al.* (1982) 'Statistical analysis of the direct count method for enumerating bacteria', *Applied and Environmental Microbiology*, 44(2), pp. 376–382.
109. Klute, A. (1986) 'Methods of soil analysis. Part I. Physical and mineralogical methods', *Soil Science Society of America, Inc. Publisher, Madison, WI.*
110. Koide, R. T. (2017) 'Biochar—Arbuscular mycorrhiza interaction in temperate soils', in *Mycorrhizal mediation of soil*. Elsevier, pp. 461–477.
111. Kondo, Y. *et al.* (2012) 'A new application of bagasse char as a solar energy absorption and accumulation material', *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 103(1), pp. 31–38.

112. Koner, S. *et al.* (2021) 'Depth-resolved microbial diversity and functional profiles of trichloroethylene-contaminated soils for Biolog EcoPlate-based biostimulation strategy', *Journal of Hazardous Materials*, p. 127266.
113. Laghari, M. *et al.* (2016) 'Recent developments in biochar as an effective tool for agricultural soil management: a review', *Journal of the science of food and agriculture*, 96(15), pp. 4840–4849.
114. Lai, W.-Y. *et al.* (2013) 'The effects of woodchip biochar application on crop yield, carbon sequestration and greenhouse gas emissions from soils planted with rice or leaf beet', *Journal of the Taiwan Institute of Chemical Engineers*, 44(6), pp. 1039–1044.
115. Lehmann, J. *et al.* (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), pp. 343–357.
116. Lehmann, J. *et al.* (2011) 'Biochar effects on soil biota–a review', *Soil biology and biochemistry*, 43(9), pp. 1812–1836.
117. Lehmann, J. *et al.* (2021) 'Biochar in climate change mitigation', *Nature Geoscience*, 14(12), pp. 883–892.
118. Lehmann, J., Gaunt, J. and Rondon, M. (2006) 'Bio-char sequestration in terrestrial ecosystems–a review', *Mitigation and adaptation strategies for global change*, 11(2), pp. 403–427.
119. Lehmann, J. and Joseph, S. (2015) 'Biochar for environmental management: an introduction', in *Biochar for environmental management*. Routledge, pp. 1–13.
120. Lehtinen, T. *et al.* (2014) 'Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils', *Soil use and management*, 30(4), pp. 524–538.
121. Li, B. *et al.* (2015) 'Combined effects of nitrogen fertilization and biochar on the net global warming potential, greenhouse gas intensity and net ecosystem economic budget in intensive vegetable agriculture in southeastern China', *Atmospheric Environment*, 100, pp. 10–19.
122. Li, F. *et al.* (2019) 'Effects of biochar amendments on soil phosphorus transformation in agricultural soils', *Advances in agronomy*, 158, pp. 131–172.
123. Li, Y. Q. *et al.* (2023) 'Effects of Corn Straw Biochar, Soil Bulk Density and Soil Water Content on Thermal Properties of a Light Sierozem Soil', *Nature Environment and Pollution Technology*, 22(2), pp. 895–903.
124. Liang, B. *et al.* (2008) 'Stability of biomass-derived black carbon in soils', *Geochimica et Cosmochimica Acta*, 72(24), pp. 6069–6078.

125. Lin, H. Y. and Chang, S. T. (2013) 'Antioxidant potency of phenolic phytochemicals from the root extract of Acacia confusa', *Industrial Crops and Products*, 49, pp. 871–878.
126. Lin, X. W. *et al.* (2015) 'Effects of biochar application on greenhouse gas emissions, carbon sequestration and crop growth in coastal saline soil', *European Journal of Soil Science*, 66(2), pp. 329–338.
127. Ling, Q., Huang, W. and Jarvis, P. (2011) 'Use of a SPAD-502 meter to measure leaf chlorophyll concentration in Arabidopsis thaliana', *Photosynthesis research*, 107, pp. 209–214.
128. Liu, L. *et al.* (2021) 'Immobilization of heavy metals in biochar derived from co-pyrolysis of sewage sludge and calcium sulfate', *Journal of Hazardous Materials*, 403, p. 123648.
129. Lu, H. *et al.* (2020) 'Effects of biochar on soil microbial community and functional genes of a landfill cover three years after ecological restoration', *Science of The Total Environment*, 717, p. 137133.
130. Luo, M. *et al.* (2020) 'The influence of corncob-based biochar on remediation of arsenic and cadmium in yellow soil and cinnamon soil', *Science of The Total Environment*, 717, p. 137014.
131. Luschkova, D., Traidl-Hoffmann, C. and Ludwig, A. (2022) 'Climate change and allergies', *Allergo Journal International*, 31(4), pp. 114–120.
132. Ma, N. *et al.* (2016) 'Biochar improves soil aggregate stability and water availability in a mollisol after three years of field application', *PloS one*, 11(5), p. e0154091.
133. Ma, R. *et al.* (2022) 'Data-driven estimates of fertilizer-induced soil NH3, NO and N2O emissions from croplands in China and their climate change impacts', *Global Change Biology*, 28(3), pp. 1008–1022.
134. Magurran, A. E. (1988) *Ecological diversity and its measurement*. Princeton university press.
135. Mandal, S., Thangarajan, R., *et al.* (2016) 'Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat', *Chemosphere*, 142, pp. 120–127.
136. Mandal, S., Sarkar, B., *et al.* (2016) 'Designing advanced biochar products for maximizing greenhouse gas mitigation potential', *Critical Reviews in Environmental Science and Technology*, 46(17), pp. 1367–1401.
137. Martinsen, V. *et al.* (2014) 'Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming', *Journal of Plant Nutrition and Soil Science*, 177(5), pp. 681–695.

138. Mclennon, E. *et al.* (2020) ‘Biochar and nitrogen application rates effect on phosphorus removal from a mixed grass sward irrigated with reclaimed wastewater’, *Science of the Total Environment*, 715, p. 137012.
139. Mohamed, B. A. *et al.* (2017) ‘The role of tailored biochar in increasing plant growth, and reducing bioavailability, phytotoxicity, and uptake of heavy metals in contaminated soil’, *Environmental Pollution*, 230, pp. 329–338.
140. Mohanty, P. *et al.* (2013) ‘Evaluation of the physiochemical development of biochars obtained from pyrolysis of wheat straw, timothy grass and pinewood: effects of heating rate’, *Journal of analytical and applied pyrolysis*, 104, pp. 485–493.
141. Muhammad, N. *et al.* (2017) ‘Impact of wheat straw biochar on yield of rice and some properties of Psammaquent and Plinthudult’, *Journal of soil science and plant nutrition*, 17(3), pp. 808–823.
142. Mukherjee, A. and Lal, R. (2013) ‘Biochar impacts on soil physical properties and greenhouse gas emissions’, *Agronomy*, 3(2), pp. 313–339.
143. Mukherjee, A. and Zimmerman, A. R. (2013) ‘Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures’, *Geoderma*, 193, pp. 122–130.
144. Naeem, M. A. *et al.* (2017) ‘Effect of wheat and rice straw biochar produced at different temperatures on maize growth and nutrient dynamics of a calcareous soil’, *Archives of Agronomy and Soil Science*, 63(14), pp. 2048–2061.
145. Nair, V. D. *et al.* (2017) ‘Biochar in the agroecosystem-climate-change-sustainability Nexus’, *Frontiers in Plant Science*, 8(December). doi: 10.3389/fpls.2017.02051.
146. Nelissen, V. *et al.* (2012) ‘Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil’, *Soil Biology and Biochemistry*, 55, pp. 20–27.
147. Van Nguyen, T. T. *et al.* (2022) ‘Valorization of agriculture waste biomass as biochar: As first-rate biosorbent for remediation of contaminated soil’, *Chemosphere*, p. 135834.
148. Nkoh, J. N. *et al.* (2022) ‘Reduction of heavy metal uptake from polluted soils and associated health risks through biochar amendment: A critical synthesis’, *Journal of Hazardous Materials Advances*, 6, p. 100086.
149. Novak, J. M. *et al.* (2009) ‘Characterization of designer biochar produced at different temperatures and their effects on a loamy sand’, *Ann. Environ. Sci*, 3(2), pp. 195–206.
150. Novoa, R. S. A. and Tejeda, H. R. (2006) ‘Evaluation of the N 2 O emissions from N in plant residues as affected by environmental and management factors’, *Nutrient Cycling in Agroecosystems*, 75(1), pp. 29–46.

151. O'toole, A. *et al.* (2018) 'Miscanthus biochar had limited effects on soil physical properties, microbial biomass, and grain yield in a four-year field experiment in Norway', *Agriculture*, 8(11), p. 171.
152. Oguntunde, P. G. *et al.* (2004) 'Effects of charcoal production on maize yield, chemical properties and texture of soil', *Biology and Fertility of soils*, 39(4), pp. 295–299.
153. Oguntunde, P. G. *et al.* (2008) 'Effects of charcoal production on soil physical properties in Ghana', *Journal of Plant Nutrition and Soil Science*, 171(4), pp. 591–596.
154. Oladosu, Y. *et al.* (2022) 'Superabsorbent polymer hydrogels for sustainable agriculture: A review', *Horticulturae*, 8(7), p. 605.
155. Otsuka, S. *et al.* (2008) 'Community structure of soil bacteria in a tropical rainforest several years after fire', *Microbes and Environments*, 23(1), pp. 49–56.
156. Paas, W. *et al.* (2019) 'Participatory impact assessment of sustainability and resilience of EU farming systems'.
157. Panwar, N. L., Pawar, A. and Salvi, B. L. (2019) 'Comprehensive review on production and utilization of biochar', *SN Applied Sciences*, 1(2), pp. 1–19.
158. Patel, J. S. *et al.* (2015) 'Plant genotype, microbial recruitment and nutritional security', *Frontiers in plant science*, 6, p. 608.
159. Piccolo, A., Pietramellara, G. and Mbagwu, J. S. C. (1997) 'Use of humic substances as soil conditioners to increase aggregate stability', *Geoderma*, 75(3–4), pp. 267–277.
160. Pituello, C. *et al.* (2018) 'Effects of biochar on the dynamics of aggregate stability in clay and sandy loam soils', *European Journal of Soil Science*, 69(5), pp. 827–842.
161. Pottmaier, D. *et al.* (2013) 'Comparison of rice husk and wheat straw: from slow and fast pyrolysis to char combustion', *Energy & fuels*, 27(11), pp. 7115–7125.
162. Pouresmaieli, M. *et al.* (2022) 'Recent progress on sustainable phytoremediation of heavy metals from soil', *Journal of Environmental Chemical Engineering*, p. 108482.
163. Prasad, M., Tzortzakis, N. and McDaniel, N. (2018) 'Chemical characterization of biochar and assessment of the nutrient dynamics by means of preliminary plant growth tests', *Journal of environmental management*, 216, pp. 89–95.
164. Pulka, J. *et al.* (2020) 'Waste-to-carbon: Is the torrefied sewage sludge with high ash content a better fuel or fertilizer?', *Materials*, 13(4). doi: 10.3390/ma13040954.
165. Qian, K. *et al.* (2013) 'Effects of biomass feedstocks and gasification conditions on the physiochemical properties of char', *Energies*, 6(8), pp. 3972–3986.
166. Qian, K. *et al.* (2015) 'Recent advances in utilization of biochar', *Renewable and Sustainable Energy Reviews*, 42, pp. 1055–1064.

167. Quilliam, R. S. *et al.* (2013) 'Life in the "charosphere"–Does biochar in agricultural soil provide a significant habitat for microorganisms?', *Soil Biology and Biochemistry*, 65, pp. 287–293.

168. Radwan, N. M. *et al.* (2020) 'Improving soil properties by using biochar under drainage conditions in North Sinai', *Sinai Journal of Applied Sciences*, 9(2), pp. 157–168.

169. Rahman (2012) 'Abundance and diversity of soil invertebrates in annual crops, agroforestry and forest ecosystems in the Nilgiri biosphere reserve of Western Ghats, India', *Agroforestry systems*, 85(1), pp. 165–177.

170. Rasa, K. *et al.* (2018) 'How and why does willow biochar increase a clay soil water retention capacity?', *Biomass and Bioenergy*, 119, pp. 346–353.

171. Razzaghi, F., Obour, P. B. and Arthur, E. (2020) 'Does biochar improve soil water retention? A systematic review and meta-analysis', *Geoderma*, 361(October 2019), p. 114055. doi: 10.1016/j.geoderma.2019.114055.

172. Reddy, K. R., Patrick, W. H. and Broadbent, F. E. (1984) 'Nitrogen transformations and loss in flooded soils and sediments', *Critical Reviews in Environmental Science and Technology*, 13(4), pp. 273–309.

173. Reddy, S. B. N. (2014) 'Biochar culture: Biochar for environment and development', *MetaMeta: s-Hertogenbosch, The Netherlands*.

174. Reganold, J. P. and Wachter, J. M. (2016) 'Organic agriculture in the twenty-first century', *Nature plants*, 2(2), pp. 1–8.

175. Rondon, M., Ramirez, J. A. and Lehmann, J. (2005) 'Greenhouse gas emissions decrease with charcoal additions to tropical soils', in *Proceedings of the 3rd USDA symposium on greenhouse gases and carbon sequestration, baltimore, USA*.

176. Rostami, S. *et al.* (2021) 'Current methods and technologies for degradation of atrazine in contaminated soil and water: A review', *Environmental Technology & Innovation*, p. 102019.

177. Rutigliano, F. A. *et al.* (2014) 'Effect of biochar addition on soil microbial community in a wheat crop', *European Journal of Soil Biology*, 60, pp. 9–15.

178. Sánchez-Monedero, M. A. *et al.* (2019) 'Agronomic evaluation of biochar, compost and biochar-blended compost across different cropping systems: Perspective from the European project FERTIPLUS', *Agronomy*, 9(5). doi: 10.3390/agronomy9050225.

179. Sandén, T. *et al.* (2019) 'Out of sight: profiling soil characteristics, nutrients and bacterial communities affected by organic amendments down to one meter in a long-term maize experiment', *Applied Soil Ecology*, 134, pp. 54–63.

180. Schiermeier, Q. (2006) ‘Putting the carbon back: The hundred billion tonne challenge’, *Nature*, 442(7103), pp. 620–624.
181. Sewu, D. D. *et al.* (2020) ‘Facile magnetic biochar production route with new goethite nanoparticle precursor’, *Science of the Total Environment*, 717, p. 137091.
182. Shahrokhi-Shahraki, R. *et al.* (2021) ‘High efficiency removal of heavy metals using tire-derived activated carbon vs commercial activated carbon: Insights into the adsorption mechanisms’, *Chemosphere*, 264, p. 128455.
183. Shakoor, A. *et al.* (2021) ‘Does biochar accelerate the mitigation of greenhouse gaseous emissions from agricultural soil?-A global meta-analysis’, *Environmental Research*, 202, p. 111789.
184. Šimanský, V. *et al.* (2016) ‘How dose of biochar and biochar with nitrogen can improve the parameters of soil organic matter and soil structure?’, *Biologia*, 71(9), pp. 989–995.
185. Singh, B. (2010) ‘Characterisation and evaluation of biochars for their application as a soil amendment’, *Soil Research*, 48(7), pp. 516–525.
186. Singh, B. P. and Cowie, A. L. (2014) ‘Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil’, *Scientific reports*, 4(1), pp. 1–9.
187. Singh, Y. *et al.* (2021) ‘Impact of Conservation Agriculture and Residue Management on Soil Properties Under Sugarcane-Based Cropping Systems’, in *Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security*. Springer, pp. 239–266.
188. Six, J. *et al.* (2002) ‘Stabilization mechanisms of soil organic matter: implications for C-saturation of soils’, *Plant and soil*, 241(2), pp. 155–176.
189. Smith, J. L., Collins, H. P. and Bailey, V. L. (2010) ‘The effect of young biochar on soil respiration’, *Soil Biology and Biochemistry*, 42(12), pp. 2345–2347.
190. Song, X. *et al.* (2019) ‘Effect of cotton straw-derived materials on native soil organic carbon’, *Science of the Total Environment*, 663, pp. 38–44.
191. Sonwani, S. and Saxena, P. (2022) ‘Introduction to Greenhouse Gases: Sources, Sinks and Mitigation’, in *Greenhouse Gases: Sources, Sinks and Mitigation*. Springer, pp. 1–7.
192. Speratti, A. B. *et al.* (2017) ‘Impact of different agricultural waste biochars on maize biomass and soil water content in a Brazilian Cerrado Arenosol’, *Agronomy*, 7(3), p. 49.
193. Spokas, K. A. (2010) ‘Review of the stability of biochar in soils: predictability of O: C molar ratios’, *Carbon management*, 1(2), pp. 289–303.
194. Spokas, K. A. *et al.* (2012) ‘Biochar: a synthesis of its agronomic impact beyond carbon sequestration’, *Journal of environmental quality*, 41(4), pp. 973–989.
195. Šrank, D. and Šimanský, V. (2020) ‘Physical Properties of Texturally Different Soils After Application of Biochar Substrates.’, *Agriculture/Pol’nohospodárstvo*, 66(2).

196. Srivastav, A. L. (2020) ‘Chemical fertilizers and pesticides: role in groundwater contamination’, in *Agrochemicals detection, treatment and remediation*. Elsevier, pp. 143–159.

197. Sun, L. *et al.* (2014) ‘Combined effects of nitrogen deposition and biochar application on emissions of N_2O, CO_2 and NH_3 from agricultural and forest soils’, *Soil Science and Plant Nutrition*, 60(2), pp. 254–265.

198. Tang, Y.-H., Liu, S.-H. and Tsang, D. C. W. (2020) ‘Microwave-assisted production of CO_2-activated biochar from sugarcane bagasse for electrochemical desalination’, *Journal of hazardous materials*, 383, p. 121192.

199. Team, C. W. (2007) ‘Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change’, *IPCC 2007: Climate Change 2007: Synthesis Report*, 104.

200. Thies, J. E. and Rillig, M. C. (2012) ‘Characteristics of biochar: biological properties’, in *Biochar for environmental management*. Routledge, pp. 117–138.

201. Toková, L. *et al.* (2020) ‘Effect of biochar application and re-application on soil bulk density, porosity, saturated hydraulic conductivity, water content and soil water availability in a silty loam Haplic Luvisol’, *Agronomy*, 10(7), p. 1005.

202. Tripathi, S. *et al.* (2020) ‘Influence of synthetic fertilizers and pesticides on soil health and soil microbiology’, in *Agrochemicals detection, treatment and remediation*. Elsevier, pp. 25–54.

203. Ullah, H. *et al.* (2019) ‘Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review’, *Advances in agronomy*, 156, pp. 109–157.

204. Uzoma, K. C. *et al.* (2011) ‘Effect of cow manure biochar on maize productivity under sandy soil condition’, *Soil use and management*, 27(2), pp. 205–212.

205. Vanholme, B. *et al.* (2013) ‘Towards a carbon-negative sustainable bio-based economy’, *Frontiers in plant science*, 4, p. 174.

206. Verheijen, F. *et al.* (2010) ‘Biochar application to soils’, *A critical scientific review of effects on soil properties, processes, and functions. EUR*, 24099, p. 162.

207. Wang, Zhang, K., *et al.* (2021) ‘Expansive soil-biochar-root-water-bacteria interaction: Investigation on crack development, water management and plant growth in green infrastructure’, *International Journal of Damage Mechanics*, 30(4), pp. 595–617.

208. Wang, Zhang, W., *et al.* (2021) ‘Identification of microbial strategies for labile substrate utilization at phylogenetic classification using a microcosm approach’, *Soil Biology and Biochemistry*, 153, p. 107970.

209. Wang, D. *et al.* (2017) 'Biochar additions can enhance soil structure and the physical stabilization of C in aggregates', *Geoderma*, 303, pp. 110–117.

210. Wang, J., Pan, X. and Liu, Y. (2012) 'Effects of biochar amendment in two soils on greenhouse gas emissions and crop production'. doi: 10.1007/s11104-012-1250-3.

211. Wang, J., Xiong, Z. and Kuzyakov, Y. (2016) 'Biochar stability in soil: meta-analysis of decomposition and priming effects', *Gcb Bioenergy*, 8(3), pp. 512–523.

212. Wang, K. *et al.* (2020) 'Effects of pyrolysis temperature and holding time on physicochemical properties of swine-manure-derived biochar', *Waste and Biomass Valorization*, 11(2), pp. 613–624.

213. Wang, L. *et al.* (2020) 'Effects of endophytes inoculation on rhizosphere and endosphere microecology of Indian mustard (Brassica juncea) grown in vanadium-contaminated soil and its enhancement on phytoremediation', *Chemosphere*, 240, p. 124891.

214. Wani, I. *et al.* (2020) 'Effect of pH, volatile content, and pyrolysis conditions on surface area and O/C and H/C ratios of biochar: towards understanding performance of biochar using simplified approach', *Journal of Hazardous, Toxic, and Radioactive Waste*, 24(4), p. 4020048.

215. Warnock, D. D. *et al.* (2010) 'Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: results from growth-chamber and field experiments', *Applied Soil Ecology*, 46(3), pp. 450–456.

216. Werdin, J. *et al.* (2020) 'Biochar made from low density wood has greater plant available water than biochar made from high density wood', *Science of the Total Environment*, 705, p. 135856.

217. Wolińska, A. *et al.* (2020) 'Soil microbial community profiling and bacterial metabolic activity of technosols as an effect of soil properties following land reclamation: a case study from the abandoned iron sulphide and uranium mine in Rudki (South-Central Poland)', *Agronomy*, 10(11), p. 1795.

218. Wong, J. W. C., Webber, J. B. W. and Ogbonnaya, U. O. (2019) 'Characteristics of biochar porosity by NMR and study of ammonium ion adsorption', *Journal of Analytical and Applied Pyrolysis*, 143, p. 104687.

219. Wu, L. *et al.* (2020) 'Phosphorus retention using iron (II/III) modified biochar in saline-alkaline soils: Adsorption, column and field tests', *Environmental Pollution*, 261, p. 114223.

220. Xie, Z. *et al.* (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(1), pp. 527–540.

221. Xun, W. *et al.* (2016) ‘Significant alteration of soil bacterial communities and organic carbon decomposition by different long-term fertilization management conditions of extremely low-productivity arable soil in S outh C hina’, *Environmental microbiology*, 18(6), pp. 1907–1917.
222. Yang, Y. *et al.* (2015) ‘A field experiment on enhancement of crop yield by rice straw and corn stalk-derived biochar in Northern China’, *Sustainability*, 7(10), pp. 13713–13725.
223. Yao, P. *et al.* (2021) ‘Greenhouse gas emissions and net ecosystem carbon budget from tobacco-planted soil with different organic amendments’, *Soil Research*, 59(5), pp. 452–462.
224. Yao, Y. *et al.* (2012) ‘Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation’, *Journal of hazardous materials*, 209, pp. 408–413.
225. Ye, L. *et al.* (2020) ‘Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality’, *Scientific reports*, 10(1), pp. 1–11.
226. Yin, D. *et al.* (2021) ‘Impact of Different Biochars on Microbial Community Structure in the Rhizospheric Soil of Rice Grown in Albic Soil’, *Molecules*, 26(16), p. 4783.
227. Yu, K. L. *et al.* (2018) ‘Biochar production from microalgae cultivation through pyrolysis as a sustainable carbon sequestration and biorefinery approach’, *Clean Technologies and Environmental Policy*, 20(9), pp. 2047–2055.
228. Yu, L. *et al.* (2013) ‘Effects of biochar application on soil methane emission at different soil moisture levels’, *Biology and Fertility of Soils*, 49(2), pp. 119–128.
229. Yuan, J. and Xu, R. (2011) ‘The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol’, *Soil use and management*, 27(1), pp. 110–115.
230. Yuan, P. *et al.* (2019) ‘Review of biochar for the management of contaminated soil: Preparation, application and prospect’, *Science of the total environment*, 659, pp. 473–490.
231. Zaccheo, P., Crippa, L. and Bedussi, F. (2017) ‘Biochar can enhance potassium availability during cyclamen cultivation’, in *International Symposium on Growing Media, Soilless Cultivation, and Compost Utilization in Horticulture 1266*, pp. 35–42.
232. Zahra, M. B. *et al.* (2021) ‘Cumulative effect of biochar and compost on nutritional profile of soil and maize productivity’, *Journal of Plant Nutrition*, pp. 1–13.
233. Zeng, K. *et al.* (2015) ‘The effect of temperature and heating rate on char properties obtained from solar pyrolysis of beech wood’, *Bioresource technology*, 182, pp. 114–119.

234. Zhai, L. *et al.* (2011) ‘Long-term application of organic manure and mineral fertilizer on N_2O and CO_2 emissions in a red soil from cultivated maize-wheat rotation in China’, *Agricultural Sciences in China*, 10(11), pp. 1748–1757.
235. Zhang, C. *et al.* (2019) ‘Biochar for environmental management: Mitigating greenhouse gas emissions, contaminant treatment, and potential negative impacts’, *Chemical Engineering Journal*, 373, pp. 902–922.
236. Zhang, J. *et al.* (2015) ‘Understory management and fertilization affected soil greenhouse gas emissions and labile organic carbon pools in a Chinese chestnut plantation’, *Forest Ecology and Management*, 337, pp. 126–134.
237. Zhang, J. *et al.* (2021) ‘Effects of biochar on heavy metal bioavailability and uptake by tobacco (Nicotiana tabacum) in two soils’, *Agriculture, Ecosystems & Environment*, 317, p. 107453.
238. Zhang, L. *et al.* (2021) ‘Environmental, human health, and ecosystem economic performance of long-term optimizing nitrogen management for wheat production’, *Journal of Cleaner Production*, 311, p. 127620.
239. Zhang, M. *et al.* (2021) ‘Biochar enhances the retention capacity of nitrogen fertilizer and affects the diversity of nitrifying functional microbial communities in karst soil of southwest China’, *Ecotoxicology and Environmental Safety*, 226, p. 112819.
240. Zhang, Q. *et al.* (2021) ‘Biochar and earthworms synergistically improve soil structure, microbial abundance, activities and pyraclostrobin degradation’, *Applied Soil Ecology*, 168, p. 104154.
241. Zhang, S. *et al.* (2021) ‘Linking soil carbon availability, microbial community composition and enzyme activities to organic carbon mineralization of a bamboo forest soil amended with pyrogenic and fresh organic matter’, *Science of The Total Environment*, 801, p. 149717.
242. Zhang, X. *et al.* (2020) ‘Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar’, *Bioresource technology*, 296, p. 122318.
243. Zheng, H., Wang, Z., Deng, X., Zhao, J., *et al.* (2013) ‘Characteristics and nutrient values of biochars produced from giant reed at different temperatures’, *Bioresource Technology*, 130, pp. 463–471.
244. Zheng, H., Wang, Z., Deng, X., Herbert, S., *et al.* (2013) ‘Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil’, *Geoderma*, 206, pp. 32–39.

245. Zheng, H. *et al.* (2018) ‘Biochar-induced negative carbon mineralization priming effects in a coastal wetland soil: roles of soil aggregation and microbial modulation’, *Science of the Total Environment*, 610, pp. 951–960.
246. Zhou, H. *et al.* (2019) ‘Biochar enhances soil hydraulic function but not soil aggregation in a sandy loam’, *European journal of soil science*, 70(2), pp. 291–300.
247. Zhou, S., Yu, B. and Zhang, Y. (2023) ‘Global concurrent climate extremes exacerbated by anthropogenic climate change’, *Science Advances*, 9(10), p. eabo1638.
248. Zimmerman, A. R. (2010) ‘Abiotic and microbial oxidation of laboratory-produced black carbon (biochar)’, *Environmental science & technology*, 44(4), pp. 1295–1301.

LIST OF PUBLISHED ARTICLES AND PARTICIPATION IN CONFERENCES

1. **Ayaz, Muhammad**, Dalia Feizienė, Vita Tilvikienė, Virginijus Feiza, Edita Baltrėnaitė Gedienė, and Sana Ullah. "Biochar with inorganic nitrogen fertilizer reduces direct greenhouse gas emission flux from soil." Plants 12, no. 5 **(2023):** 1002
2. **Ayaz, Muhammad**, Dalia Feizienė, Virginijus Feiza, Vita Tilvikienė, Edita Baltrėnaitė-Gedienė, and Attaullah Khan. "The impact of swine manure biochar on the physical properties and microbial activity of loamy soils." Plants 11, no 13 **(2022):** 1729
3. **Ayaz, Muhammad,** Urte Stulpinaite, Dalia Feizienė, Vita Tilvikienė, Kashif Akthar, Edita Baltrėnaitė-Gedienė, and Nerijus Striugas. "Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil." Soil Use and Management 38, no.2 **(2022):** 1307-1321.
4. **Ayaz, Muhammad,** Dalia Feizienė, Vita Tilvikienė, Kashif Akthar, Urte Stulpinaite, and Rashid Iqbal. "Biochar role in the sustainability of agriculture and environment." Sustainability 13, no. 3 **(2021)**: 1330.

Research result presented at conferences

1. Conference of Young Scientists - Future of Lithuania, Vilnius, 2020- Oral Presentation- Effect of Biochar of Heavy metals under different moisture regimes.
2. 3^{rd} International Scientific Virtual Conference "AgroEco2020 VDU" - Oral Presentation- Biochar Effect on Heavy Metals Remediation in Contiminated Coils.
3. 17^{th} CYSENI Conference of Young Scientists on Energy and Natural Sciences. May 24-27, 2021. Oral Presentation- Effect of Biochar of Greenhouses gases emission flux
4. 18^{th} CYSENI Conference of Young Scientists on Energy and Natural Sciences. May 24-27, 2022. Oral presentation-Biochar with Inorganic Nitrogen Fertilizer Reduces Direct Greenhouse Gas Emission Flux from Soil
5. 19^{th} CYSENI Conference of Young Scientists on Energy and Natural Sciences. May 23-26, poster presentation- The Impact of Swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils**.**

PUBLICATIONS ON THE TOPIC OF THE DOCTORAL DISSERTATION

1. Biochar role in the sustainability of Agriculture and Environment.
2. Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil.
3. Biochar with Inorganic Nitrogen Fertilizer Reduces Direct Greenhouse Gas Emission Flux from Soil.
4. The Impact of swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils.

sustainability

MDPI

Review

Biochar Role in the Sustainability of Agriculture and Environment

Muhammad Ayaz [1,*], Dalia Feizienė [1], Vita Tilvikienė [1], Kashif Akhtar [2], Urte Stulpinaitė [1] and Rashid Iqbal [3]

[1] Institute of Agriculture, Lithuanian Research Center for Agriculture and Forestry, LT-58344 Kedainiu r, Lithuania; dalia.feiziene@lammc.lt (D.F.); vita.tilvikiene@lammc.lt (V.T.); urte.stulpinaite@lammc.lt (U.S.)

[2] Institute of Nuclear Agricultural Sciences, College of Agriculture and Biotechnology, Zhejiang University, Hangzhou 310058, China; kashif@zju.edu.cn

[3] Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur 63100, Punjab, Pakistan; rashid.iqbal@iub.edu.pk

* Correspondence: muhammad.ayaz@lammc.lt; Tel.: +370-654-22-196

Abstract: The exercise of biochar in agribusiness has increased proportionally in recent years. It has been indicated that biochar application could strengthen soil fertility benefits, such as improvement in soil microbial activity, abatement of bulk density, amelioration of nutrient and water-holding capacity and immutability of soil organic matter. Additionally, biochar amendment could also improve nutrient availability such as phosphorus and nitrogen in different types of soil. Most interestingly, the locally available wastes are pyrolyzed to biochar to improve the relationship among plants, soil and the environment. This can also be of higher importance to small-scale farming, and the biochar produced can be utilized in farms for the improvement of crop productivity. Thus, biochar could be a potential amendment to a soil that could help in achieving sustainable agriculture and environment. However, before mainstream formulation and renowned biochar use, several challenges must be taken into consideration, as the beneficial impacts and potential use of biochar seem highly appealing. This review is based on confined knowledge taken from different field-, laboratory- and greenhouse-based studies. It is well known that the properties of biochar vary with feedstock, pyrolysis temperature (300, 350, 400, 500, and 600 °C) and methodology of preparation. It is of high concern to further investigate the negative consequences: hydrophobicity; large scale application in farmland; production cost, primarily energy demand; and environmental threat, as well as affordability of feedstock. Nonetheless, the current literature reflects that biochar could be a significant amendment to the agroecosystem in order to tackle the challenges and threats observed in sustainable agriculture (crop production and soil fertility) and the environment (reducing greenhouse gas emission).

Keywords: biochar; food security; socio-economics benefits; sustainable agriculture; sustainable environment

Citation: Ayaz, M.; Feizienė, D.; Tilvikienė, V.; Akhtar, K.; Stulpinaitė, U.; Iqbal, R. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. https://doi.org/10.3390/su13031330

Received: 3 January 2021
Accepted: 20 January 2021
Published: 27 January 2021

1. Introduction

The world's population is increasing day by day and is expected to reach 9.8 billion by 2050 (United Nations Department of Economics and Social Affairs, New York, NY, USA), which will put the world's agricultural system under an increasing threat. Thus, to feed the increasing population and fulfil the constantly growing demand for grains and organic food, the farming system has become dependent on technological and chemical inputs [1]. Some parts of the world have met the needs for food through improved farming system technologies. Such farming systems have been classified as agroforestry, agroecology, sustainable agriculture, organic agriculture, etc. [2]. The objective of all these improvements in the farming systems is to reduce hankering and enhance crop yield to obtain sustainable agriculture and the environment [3]. This concept has directed the attention of the scientific community and farmers towards natural residue and organic matters instead of commercially prepared products [4]. Biochar is one of the outcomes of scientific experiments, which has an important role in achieving sustainable agriculture and the environment [5]. Biochar, a type of charcoal obtained after the combustion of feedstock under no or very limited supply of oxygen, is considered as a potential soil conditioner [3]. It is also an efficient measure to sequestrate carbon to tackle climate change and global warming. It is highly durable when applied to the soil and can remain in soil for hundreds to thousands of years [5]. Biochar has become a public interest in the framework of bio-based industries, which depends on the alteration of feedstock into value-added chemicals and energy.

The term "sustainable agriculture" is defined as the consolidation of bioprocesses, chemical processes, physical activities, ecological processes, and socio-economic sciences in a holistic manner to design new agricultural practices that are safe and environmentally friendly [6]. Sustainable agriculture is a procedure by which agrofarming can nourish itself over an extended period by preserving and maintaining all its natural resources, e.g., maintaining the fertility of the soil, safeguarding surfaces and underground resources, developing renewable sources of energy, and seeking solutions to revamp farming methods to climate change [7,8]. Agrofarming must also consider the sustainability of the vast area and social groups.

Biochar is also being examined to rehabilitate environments, to diminish pollutant mobility in contaminated soils, and to reduce alteration of perilous elements to agronomic crops [7]. Mostly, biochar is produced from waste residues such as agricultural wastes, animal manures, and forest residues. The significance of these feedstocks is to produce biochar in a way that potentially transforms waste into a useful and valuable product [9]. Its impact on soil amendment includes increased soil quality and plant growth with enhancement in crop yield. The response and behavior of biochar can be substantially influenced by its manufacturing process, soil conditions and types where applied, and as well as the kind of crop to be grown [10,11]. In keeping with the importance of biochar, many researchers have studied the adaptability of biochar for the improvement of soil and environmental health. This review highlights the production processes of various feedstocks and pyrolysis temperatures at which biochar is produced and their impact on agriculture sustainability via improving soil ecosystem functions and services. This review is intended to help researchers globally in the selection of proper biochar produced at a certain temperature to improve agriculture and environment sustainability without compromising crop yield.

2. Brief Methodology

Data and literature were collected from Web of Science eBooks Freedom Collection (ScienceDirect) https://www.sciencedirect.com/; EBSCO Publishing (elFL.net duomenų bazių paketas) http://search.epnet.com/; Emerald Management e-Journals Collection https://www.emeraldinsight.com; Science Direct; Taylor & Francis https://www.tandfonline.com/; Springer LINK https://link.springer.com/. We collected and synthesized published literature from 1997 to 2020 using keywords "biochar", biochar and soil nutrients, "biochar and environment", etc., in the database. Though more than 1000 articles were downloaded, we focused on those indicating empirical outcomes. The cited literature was based on field studies as well as greenhouse pot or laboratory studies (Figure 1a,b). The online data search was irrespective of the region, biochar type, etc.

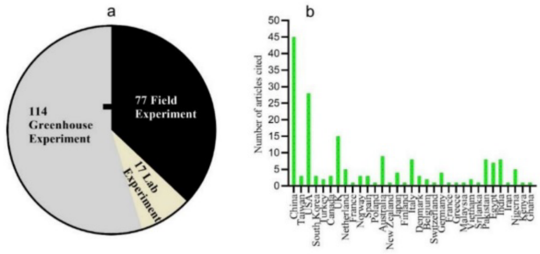

Figure 1. The details of cited information are (**a**) types of experiment and (**b**) countrywise published cited research.

3. Formulation, Morphology and Biochemistry of Biochar

Biochar is the bioproduct of thermal decomposition of renewable feedstock (forest and agricultural residues, hard woods, bamboos, livestock manure, etc.) under zero or low oxygen (O) conditions [12,13]. Feedstocks lose their mass when pyrolyzed at a minimum of 200–250 °C, as the thermal deterioration of the pulp occurs and leaves behind a spongy structure. Slow pyrolysis at low to intermediate heating (around 300 °C) and outstretched reaction times have been used for a long time to transform wood feedstock into high yields of biochar (biocarbon) [14]. The slow pyrolysis process also produces lower yields of bio-oil and gaseous by-products. In the past three decades, fast pyrolysis accomplished at medium temperatures (≤500 °C) and very short processing times (couple of seconds) has received substantial interest as a method for generating higher yields with considerably higher energy density than the original feedstock, in conjunction with 20% of biochar and 15% of gas. Biochar yield and physiochemical properties considerably depend upon the pyrolysis process and feedstock used [15,16]. Biochar produced at a low temperature contains more aliphatic compounds in the pores that increase the hydrophobicity [17,18], while high temperature pyrolysis allows a much smaller number of aliphatic compounds to remain in the pores [17]. In a few studies, biochar had no significant influence on soil water repellency (SWR) and water holding capacity (WHC) of hydrophobic soil with high total organic carbon content [19]. In this study, to better understand the dynamics of biochar, thermogravimetric analysis (TGA) of swine manure (feedstock) was performed prior to its conversion to biochar for the ongoing field experiment. It was found that the digestate starts losing humidity in between 15 and 20 min at 200–300 °C of temperature followed by the loss of different volatiles, which leads to pure black carbon at 900 °C and evolution of porous structure.

The formulation of biochar was reported in [10–22] rice straw (RS), vinasse (VI), *Phyllostachys pubescens* (PP), *Arundo donax* (AD), chicken manure (CM) and sugarcane bagasse (SB) residues. The samples were cut into pieces (<5 cm) or crushed and dried for 24 h to achieve a constant weight before pyrolysis. Two kilograms (Kg) of each sample was put into the furnace and heated to the recommended temperature. The obtained biochar was passed through an 80 mm-mesh sieve to obtain finer biochar. Similarly, in [23], the same process of preparing biochar from Pine and Jarrah wood was indicated. The biochar obtained was alkaline in nature and had a large surface area, with tremendous porosity and molar ratio, e.g., C/N; H/C; and a large number of beneficial elements and organic matter, e.g., C, H, N, S, and O [20,22]. The aromaticity and the surface charge of the biochars decreased after coating with FA [15] and humic acid [12]. Antonangelo [24] reported that biochar obtained from witchgrass (*Panicum capillare*) and poultry manure (SGB and PLB, respectively) was thermally decomposed at various temperatures, e.g., 350 and 700 °C. The pH and elemental configuration of biochars were found to be alkaline and nutrient rich, and a strong correlation between accessible nutrients and ash contents was recorded [24,25]. The internal porosity of the biochar influences the surface chemistry and the bulk density of the biochar. Additionally, the source of feedstock controls the hydrophobicity and porosity of the material, along with production temperature.

4. Biochar and Nutrients

The nutrient composition of biocarbon always differs with the type of biomass and pyrolysis temperature (Table 1). The concentration of nutrients in animal-derived biochar would not necessarily be higher than in plant-derived biochar pyrolyzed at the same temperature [26]. Biochar produced from lantana camara at 300 °C was rich in available P (0.64 mg kg^{-1}), available Ca (5880 mg kg^{-1}), available Mg (1010 mg kg^{-1}) and available Na (1145 mg kg^{-1}) [24]. Dried swine manure waste-derived biochar under slow pyrolysis (300–750 °C) was found to be rich in soil micronutrients and macronutrients, such as Ca, Mg, Na, Fe, Mn, Cu, Zn, N, P and K [25]. Total N contents were significantly greater for poultry manure-derived biochar pyrolyzed at 400 and 600 °C treatments in silt loam and sandy soils; however, they were not affected by swine manure-derived biochar (400 and 600 °C) and wood chip biochar (1000 °C) in the same soils [26]. Similarly, freshly prepared biochar is a rich source of available nutrients and could discharge a significant amount of N ranging from 23 to 635 mg kg^{-1} and P ranging from 46 to 1664 mg kg^{-1} [27]. Jiang et al.

reported that old biochar was not as effective for soil organic carbon (SOC) protection as fresh biochar. The decline in SOC stability with old biochar might be associated with the attenuated sorption of SOC on aged biochar [28]. Compared with old biochar, the addition of fresh biochar in sandy loam soil increased the biomass production [29]. Major nutrients such as N, P and K could assume the role of fertilizer and be absorbed by plants and soil microbes. Therefore, these examples indicate that biochar can potentially influence soil nutrition. Several studies have assessed the availability of nutrients in biochar by carrying out transient and long-term leaching experiments in recent decades. Mallee wood-derived biochar was easily drainable with double distilled water after a day (24 h) (15–20% Ca, 10–60% of P and 2% of N) [30]. However, it is necessary to choose the suitable biochar for its long-term nutrient availability to plants.

Table 1. Nutrient composition of various biochars at different pyrolysis temperatures.

Biochar Feedstock	Pyrolysis Temp. (°C)	pH	C	N	C/N	P	K	CA	MG	References
						(%)				
Corn cob	600	10.1	79.1	4.25	19	-	-	-	-	[31]
Corn stover	600	9.95	69.8	1.01	70	0.181	2.461	0.938	0.858	[32]
Peanut hull	400	10.0	65.5	2.0	33	0.00162	0.0015	0.00044	-	[33]
Pearl millet	400	10.6	64	1.10	58	1.60	2.52	1.47	1.06	[34]
Corn stover	300	7.33	59.5	1.16	51	0.137	1.705	0.648	0.588	[32]
Dairy manure	700	9.9	56.7	1.51	38	1.69	2.31	4.48	2.06	[35]
Poultry litter	350	8.7	51.1	4.45	12	2.08	4.58	2.66	0.94	[35]
Turkey litter	700	9.9	44.8	1.94	23	3.63	5.59	5.61	1.24	[35]
Cow manure	500	9.20	33.6	0.15	22	0.814	0.005	0.042	0.034	[36]

5. Biochar and Chemical Properties

The additions of biochar with organic matter and humic substances are getting increasing attention regarding their influence on soil fertility and crop yield [37]. Cacao shell- and rice husk-derived biochar at 600 and 500 °C, respectively, increased the pH and released dissolved organic matter from the soil [38]. Straw-derived (500–600 °C) biochar enhanced the degradation of organic matter and maturity and increased soil nutrients [39]. Composting dynamics are influenced by biochar via increasing the speed of organic matter decomposition and enhancing soil porosity, therefore improving composting efficiency and humification processes [40,41]. Ten percent of poultry manure-derived biochar and cow manure-derived biochar application into a composting mixture increased carbon content in humic and fulvic acids [42]. Acacia saligna-derived biochar at 380 °C and sawdust-derived biochar at 450 °C were the potential sources of humic substances (17.7 and 16.2%, respectively) [43]. Adding biochar during the composting process to maize straw and sewage sludge increased the available water content in sandy soil [44]. Biochar with mushroom residues and with corn straw could accelerate biodegradation of polycyclic aromatic hydrocarbon [45]. The amendments of biochar help in carbon (C) abetment and improving soil quality [46–48]. However, there are several studies comparing the physicochemical and morphological characteristics of biochar obtained from various feedstock sources and at different temperatures (slow, medium and high), as their effect when used in soil acclimatization may vary, since thermal decomposition has a great impact on biochar characterization [49,50]. Biochar produced at low thermal decomposition is often rich in carbon biomass content [51,52]. Liard [53] reported that slow pyrolyzed biochar has a higher amount of available P content compared to fast pyrolyzed biochar. This could be attributed to the lower percentage of crystallized P-associated minerals in slow pyrolyzed biochar. Moreover, the total K and available K (water soluble) content increases with an increase in pyrolysis temperature [54]. C richness allied with high adsorption capacity, porous structure and high alkalinity makes biochar inclusion into soil a practicable and effectual way to enhance soil quality and fertility [55–58]. The alkaline nature of biochar and organic carbon richness also enhance cation exchange capacity (CEC), which leads to a greater heavy metal adsorption capacity [59], and thus improves soil quality [60]. Further, numerous studies have focused on the physicochemical properties of biochar and its influence on soil nutrients and crop yield (Tables 1 and 2).

Table 2. Outline of the primary literature cited about biochar dynamics and its effect on crop yields.

Biochar Types	Temperature	Country/Type of Experiment	Application Rate	Biochar Properties	Soil Type/Texture	Result	Reference
Wheat Straw	300–500 °C	China/Greenhouse	3% *w*/*w*	pH 10.60	Psammaquent and Plinthudult	Increased rice yields in both soils	[61]
Wheat Straw	300, 400 and 500 °C	China/Greenhouse	1% *w*/*w*	pH = 6.74, 7.8 and 8.0 C = 52, 62 and 66 g % *N* = 23.8, 19.4 and 18 g kg^{-1}	Sandy clay loam and Calcisols Yermi	Biochar prepared at 300 °C significantly increased Maize crop yield	[62]
Rice Straw and Corn Stalk	450 °C	China/Field	1, 2 and 4 ton/ha	C = 71.7 and 63.5%, H = 3.70% and 1.6, O = 16.50 and 9.2% *N* = 2.40 and 1.3%	Inceptisol	Increased Corn, peanut and sweet potato by 5%, 15% and 20%, respectively	[63]
Miscanthus Giganteous Straw	500–750 °C	Norway/Field	8 and 25 ton/ha	pH = 7.86 C = 80% H = 1.2% O = 0.6% *N* = 6.6%	Silty clay loam Albeluvisol	No effect on crop yield	[64]
Cow Manure	600 °C	Japan/Greenhouse	0, 10, 15 and 20 ton/ha	pH = 9.20 C = 33.61% *N* = 1.51%	Sandy soil	Significantly enhanced Maize crop yield	[65]
Rice Husks	450 °C	China/Greenhouse	0, 10, 25 and 50 tha^{-1}	pH = 9.21 C = 465.4 g kg^{-1} *N* = 6.2 g kg^{-1}	Upland soil and paddy soil	Increased rice and wheat yield by 12% and 17%, respectively	[66]
Maize Stover	600 °C	USA/Field	0, 1, 3, 12 and 30 tha^{-1}	pH = 10.02 C = 290 mg g^{-1} *N* = 3.02 mg g^{-1}	Kendaia silt loam	No significant effect on crop yield	[67]
Woodchips	290 °C	Taiwan/Greenhouse	2% *w*/*w*	pH 6.3 C = 59.1%, *N* = 0.35%, H = 5.73%, K = 0.78 g kg^{-1}	Clay texture and sandy loam texture	No significant effect on crop yield	[68]
Woodchips	700 °C	USA/Field	5% *w*/*w*	pH = 9.6 C = 83.0%, *N* = 0.34%, H = 2.57%, K = 3.90 g kg^{-1}	Clay texture and sandy loam texture	No significant effect on crop yield	[68]

Table 2. *Cont.*

Biochar Types	Temperature	Country/Type of Experiment	Application Rate	Biochar Properties	Soil Type/Texture	Result	Reference
Rice straw	300,400 and 500 °C	Taiwan/Greenhouse	1% *w*/*w*	pH = 6.74, 7.8 and 8.0 C = 52, 62 and 66 g kg^{-1} *N* = 23.8, 19.4, 18 g kg^{-1}	Sandy clay loam, Calcisols Yermi	No effect on Maize crop yield	[62]
Sorghum	500 °C	USA/Laboratory	200 bushels ha^{-1}	C = 750.5 g kg^{-1} *N* = 13.5 g kg^{-1}	Norfolk soil and Dunbar soil (fine, kaolinitic, thermic, Aeric Paleaquults)	Wheat yield increased by 31%	[69]
Maize Cobs	300–550 °C	Ghana/Field	0, 2 and 6 t ha^{-1}	pH = 7.6–9.7 C = 69–81g kg^{-1} *N* = 0.6–0.7%	Sand and loamy sandy soil	Has positive effect on crop yield	[70]
Wheat Straw	370 °C	Spain/Greenhouse	0, 0.5, 1 and 2.5% *w*/*w*	pH = 9.8–11 Total C = 483–894 g kg^{-1} Total *N* = 3.7–8.3 g kg^{-1}	Haplic Luvisol	20–30% increase in wheat grain yield	[71]
Hard Wood	500 °C	Nigeria/Field	0,10, 20 and 30 t ha^{-1}	pH = 7.5 Total *N* = 0.65% Organic carbon = 52%	Sandy loam	30 t ha^{-1} of biochar significantly enhanced Cocoyam crop yield	[72]
Eucalyptus Polybractea	550 °C	UK/Greenhouse	10 t ha^{-1}	pH = 9.5 Total *N* = 1.1% Total C = 42	Ferrosol Soil	No effect on Cauliflower, peas or broccoli crops	[73]

6. Biochar and Physical Properties

Biochar amendment reduces soil bulk density and enhances water holding capacity (WHC) and nutrient holding capacity (NHC) as a result of its large surface area which increases water and nutrient use efficiency (Figure 2) [74–77]. Biochar could decrease soil bulk density by 3 to 31% and increase porosity by 14 to 64%. It shows a promising behavior of WHC and NHC in sandy soil due to its macropores and lower surface area [78]. Biochar could have a positive impact on WHC (Figure 2) and NHC, thus increasing water and nutrient availability to plants in sandy soil [79]. Barrow [80] proposed that biochar amendment could be an effective strategy to combat desertification and promote plant growth. Straw-derived biochar at 525 and 400 °C has a long-term effect on soil physiochemical properties, as it is most efficient in enhancing plant available water and soil aggregate stability in a coarse-textured Planosol [81]. The information on the physical and chemical properties of biochar is also presented in Table 1.

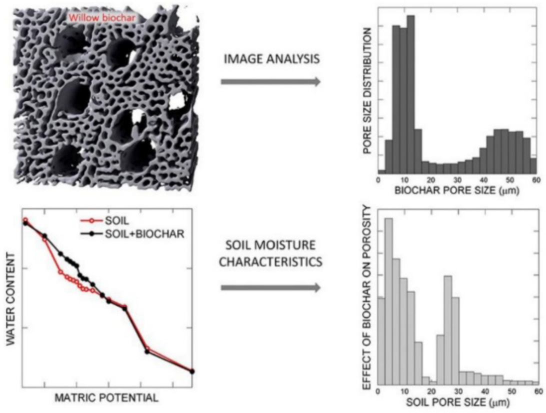

Figure 2. Determination of pore size distribution by 3D image analysis of X-ray tomography image (top panel) and the change in the pore size distribution due to biochar addition and determination of soil water content [82].

7. Effect of Biochar on Microbiota

The effect of biochar on the activity of soil microbes is dependent on types of soil and crop [83]. Wood-derived biochar application at a rate of 30 and 60 t ha^{-1} has a very short-lived positive effect on the microbial community [84]. In a recent study, Lu [85] reported that the porous structure of biochar substantially enhanced soil microbiota, due to the niche environment favorable to microbes. Otsuka [86] reported that multifariousness of the soil bacterial community expanded by 25% following biochar amendment compared to untreated soils. However, microbial biomass carbon and N mineralization were lowered with biochar amendment, thus reflecting that any boon from the liming effect of biochar is counterbalanced by a decrease in mass and community of soil microbes [87,88]. The application of biochar may increase soil pH. An increase in alkaline microsites may also alter the ammonia oxidizer population, particularly in acidic soil [89,90]. Similarly, rice straw biochar application significantly decreased Actinobacteria and Ascomycota fungi communities; however, soil microbial species diversification and copiousness may vary after biochar application [91]. Further, biochar amendment alters the soil nutrient cycling and nutrient supply, which in turn may affect the microbial community [92].

8. Biochar and Abatement of Greenhouse Gases

Climate change is usually attributed to the enhancing atmospheric abundance of greenhouse gases (GHGs) due to anthropogenic activities. Ninety percent of the anthropogenic climate warming is caused by three major GHGs, i.e., CO_2, CH_4 and N_2O [93].

Biochar has been suggested as an idle matter and beneficial soil amendment for carbon (C) sequestration to reduce CO_2 emission and its abundance from the environment [94,95]. Biochar offers a multitude of benefits for ensuring environmental safety. In view of their importance and diverse dynamics, a new terminology, "biochar culture", has been introduced to encircle the implementational and environmental gains of biochar [96]. It is an extremely valuable soil conditioner, as it changes a number of soil physicochemical characteristics (enhances soil moisture retention and increases air permeability) and impacts the soil microbial activity [97]. Biochar amendment also helps in the mitigation of greenhouse gases or setback by efficient management of agrofarming. Consequently, the "carbon foot-printing" of a specific land management has to be distinguished earlier than the targeted use for reducing emission by increasing "carbon sequestration" [96,97]. As "carbon sequestration" aims to reduce global warming by capturing the GHGs for a longer period, it can be proficient, because biochar overwhelmingly contains cyclic carbon with high aromaticity and exhausted H and O, which confer defiance to microbial strike on amendment in soil [98]. This increased obstinacy aspect, which helped in mitigating the emission of GHGs by reducing microbial decay and carbon digestion of organic biomass. Therefore, manufacturing of biochar and its amendment principally exploits the natural process of photosynthesis for crop biomass generation with the exception of removing atmospheric CO_2 by autotrophic microbes, that is, plants, mitigation of CO_2 to carbohydrate and other materials. Rondon [99] was the first scientist who reported N_2O emissions from a greenhouse experiment amended with biochar. Biochar pyrolysis at high temperatures and low N content might be more suitable to mitigate CO_2 and N_2O emission. A study from Terra Preta soil of the Amazonian region [100] reported that biochar can mitigate CO_2 emission for hundreds to thousands of years. Further, Wang [101] demonstrated from his dimensional analysis studies of the putrefaction and dressing effects on biochar stability in soil that only 3% of biochar C is bioavailable, and the rest is rendered into long-term stability. We expect a 4.0 °C rise in temperature by the end of the 21st century. Such environmental changes are the result of an increase in the atmospheric denseness of GHGs [102]. Biochar is anticipated to possess the desirable conditions for combating global warming and climate change. Biochar helps in atmospheric expulsion of CO_2, and due to its intractable nature, it captures the carbon to facilitate a huge carbon-negative economy [103]. Biochar amendment to soil curbs the emission of not only CO_2 but also about a hundred other potent GHGs, particularly nitrous oxide and methane [104]. Numerous studies advocate a substantial reduction in emissions of CO_2, N_2O and CH_4 gasses due to biochar application in land use under vegetable cultivation [105,106], but more long-term studies are needed.

9. Biochar and Soil Fertility

9.1. Effect of Biochar on Soil Nutrients

The effects of biochar on soil physicochemical properties are shown in Table 3. Biochar application is an effective practice for restoration of the functionality of degraded soils, and maintenance of long-term soil functions and fertility [107]. The addition of biochar improves degraded and low fertility soils, and thus improves crop production [108,109]. A. El-Naggar reported that biochar has the potential to be the best management practice for low fertility soils [110]. Major nutrients in biochar might not be necessarily available to plants in the desired amount [111]; the available NH^{4+}, $NO3^-$, $PO4^{-3}$ and K^+ might be associated with the amount of total N, P and K. For instance, the total N loss leads to a reduction in available N in highly thermally decomposed biochar [112]. The absorptivity of different nutrient ions on the surface of biochar and release occur due to variation in the CEC and pH of soil amended with biochar [113]. Yao [114] reported that the uptake of N and P as ammonium/nitrate and phosphate ions is significantly decreased by biochar application, decreasing their frequency in soil leachates by a high proportion. The properties of soil, e.g., texture, SOC, clay-to-sand contents and pH can change the biochar nutrient-sorption characteristics [114]. Additionally, the nutrient movement also changes biochar adsorption and succeeding release properties. The nutrient use efficiency of added organic fertilizer also increases with biochar amendment. The dynamism of nitrogen, principally engaging a decrease in nitrate transformation for subsequent reduced N loss, happens in response to biochar amendment, which can be deemed significant for optimal nitrogen use efficiency [78]. Thus, nutrient dynamics of biochar also assist in temperature and pH- reliant slow release of adsorbed nutrients by capturing nutrients from draining, runoff, leaching, microbial digestion and physical volatility processes. Therefore, plants and crops can potentially uptake nutrients, as these will be in plant-available forms in the root zone [112,113]. A sustained improvement of the physical characteristics of soil with biochar amendment involves better aggregate stability and formation, and alteration in the soil microbial community and activities imposes an indirect effect on retaining highly and reasonably mobile nutrients such as N and P [114].

Table 3. Different feedstock of biochar alters soil physicochemical properties.

Biochar Feedstock	Type of Soil	Sand	Silt	Clay	pH	TN	TC	References
			%					
Wheat straw	Sandy loam	-	-	16	5.6	0.18%	2.01%	[115]
Charcoal biochar	sandy	90.9	4.6	4.5	6.8	0.1 g kg^{-1}	1.0 g kg^{-1}	[116]
Charcoal biochar	Sandy loam	67.3	25.9	6.8	6.1	1.7 g kg^{-1}	31.0 g kg^{-1}	[116]
Oak and wood Bamboo	Clay loam	22	40	38	4.57	0.94 g kg^{-1}	5.50 g kg^{-1}	[117]
Poultry litter	Silt loam	26.6	33.7	39.7	7.99	0.13%	0.70%	[118]
Fruit tree and stem branches	Sandy loam	61.7	32.1	6.17	7.33	0.71	12.6 g kg^{-1}	[119]
Poultry litter	Sandy clay loam	52	17	31	3.95	0.25%	3.5%	[120]
Sewage sludge	Loam	71	25	4	6.50	0.04	5.48%	[121]
Wheat straw	Silt clay loam	16	52	32	8.3	1.0 g kg^{-1}	8.1 g kg^{-1}	[122]
Maize straw	Silty loam	13	72	15	7.9	0.99 g kg^{-1}	15.1 g kg^{-1}	[123]
Commercial biochar	Silt loam	16.1	64.1	19.8	6.90	0.13%	1.96%	[123]
Bamboo biochar	Sandy loam	49.2	39.2	11.6	4.72	0.17%	1.83%	[124]
Pine sawdust	Silt loam	30	56	14	5.7	2.2 g kg^{-1}	21.3 g kg^{-1}	[125]
Apple branches	Silty clay	10.7	73.0	16.8	6.23	0.47 g kg^{-1}	3.32 g kg^{-1}	[126]
Wheat straw (WSB) and miscanthus straw (MSB)	Sandy loam	73	15	12	6.46	1.28 g kg^{-1}	9.84 g kg^{-1}	[127]
Corncob	Silty loam	12.0	85.1	2.94	7.94	0.95 g kg^{-1}	8.23 g kg^{-1}	[128]
Sugarcane bagasse	Sandy loam	77.3	20.3	14.5	7.54	13.40 g kg^{-1}	4.20 g kg^{-1}	[129]
Pine sawdust	Clay loam	29	36	35	6.3	9.0 g kg^{-1}	97.2 g kg^{-1}	[125]

9.2. Effect of Biochar on Soil Organic Matter

The anticipation of enhanced soil fertility assigned to biochar amendment originates from the investigation of the terra preta that comprises a large percentage of black carbon [130]. Terra preta soil was found to be rich in organic matter content, which reflects the earlier evidence of biochar existence in the soil. Wang [131] reported that biochar enhanced C storage in macroaggregates of the fine-coarse soil and thereby increased the physical security of soil organic matter (SOM); C storage in stable microaggregates can promote the stabilization of SOM for a long period of time [132]. Biochar-stimulated physical fixation of C may be related to the existence of partially carbonized, highly degradable organic residues, often a characteristic of low thermally decomposed biochars [133]. Though SOM is usually more vulnerable to digestion in coarser rather than finer textured soils because of the lower surface area of mineral binding sites that can brace organic particles, Fang [134] indicated that Eucalyptus saligna wood biochars enhanced the mineralization of indigenous organic C in sandy soil, but not in a clayey textured soil. Moreover, biochar amendment to a grassland soil results in the arousal of mineralization of indigenous soil organic C because of the positive short-term priming effects [135].

10. Affinity of Biochar and Soil Characteristics

Biochar increases water and nutrient holding capacity (Table 2, Figure 3); however, these characteristics depend not only on biochar types but also on retention capability of soil [136]. Jien [136] reported that due to the physical structure of biochar, it improves soil porosity and structure, aggregate stabilization [137], nutrient cycle [138], penetration resistance [139] and tensile strength [140]. Asai [141] added that biochar enhances soil infiltration and lowers water runoff, thus decreasing erosion due to its bulkiness and spongy structure. Biochar amendment alters the physiochemical properties of soil, which highly influences P retention in soil. [142]. Thus, the effect could be different depending on soil properties when biochar produced from the same feedstock is added to various soil types. The release of phosphorus in sandy soil is quicker compared with that in clay soil. Therefore, biochar acts as a holding agent of P and prevents the leaching or runoff loss of P from sandy soil [143,144]. The P release characteristic of biochar-amended soil is even independent of the pyrolysis temperature at which biochar is produced [145].

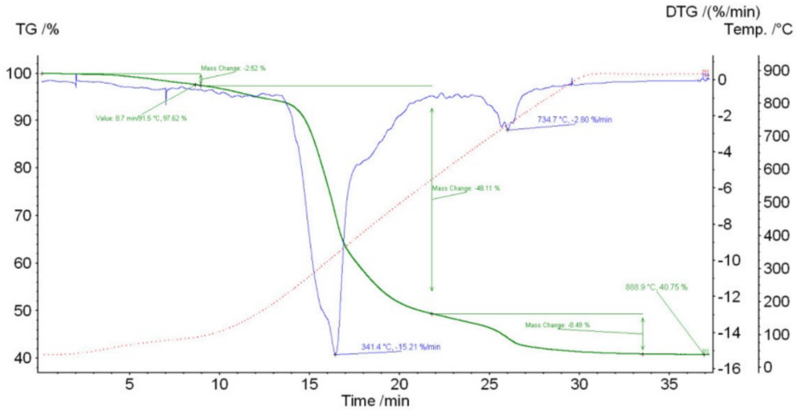

Figure 3. Thermogravity of swine digestate performed by author.

With the evolution of pore structure, the morphology of biochar also undergoes tremendous fluctuation under pyrolysis. Biochar gains the parental features of feedstock irrespective of the rate of temperature [146]. The permeable configuration in corncob [147], "beehive-like" pore structures in sugarcane [148], the symmetrical structure in wood [149] and the origin of surface morphological structure in rice husk and sawdust [150] were all retained after pyrolysis at 400–900 °C. At higher pyrolysis temperature (>1000 °C), melting with substantial deformation of biochar structure could be observed [150]. Under pyrolysis at 2000 °C, the macropores of biochar surface disappeared due to melting, while small grains emerged as the accumulation of beads on the surface of biochar [151].

The process of pyrolysis of organic feedstock into biochar brings stability to oxidized carbon fractions existing in the organic debris [152] that can persist in soils for years [153]. Therefore, biochar amendment substantially reduces greenhouses gases [154] and can be deemed as a climate change mitigation strategy. Due to these facts, biochar, the black diamond, acts as an optimistic soil conditioner of high economic and environmental value [155]. Several studies demonstrated the positive effect of biochar application on crop yield enhancement via different mechanisms. For instance, biochar amendment to soil significantly improves soil micro and macronutrients [156], despite the fact that biochar bears a higher pH value [155–158]. Nonetheless, biochar serves as a slow-release fertilizer due the strong adsorption of soil nutrients [159]. So, it is considered that biochar could be a perfect utility to acidic soil rather than alkaline or calcareous soil. Additionally, biochar, due to its high surface area and large porous structure [160], causes indirect impacts on soil physical characteristics, for instance, it significantly enhances water retention [158–162] and hydraulic conductivity [163] while decreasing soil bulk density in sandy soil [164]. However, the efficiency of biochar application to soil is not always the same. Rather, it depends on properties of applied biochar and soil conditions. Due to large surface area porosity, biochar has a significant adsorbing ability in increasing the water holding capacity (WHC) [165] and plant-available water capacity of soil (AWC) [166]. In the case of coarse sandy soil, the water and nutrient storage is generally lower under a drought condition, and thus large proportions of hydrophilic micropores (0.2–30 mm) are found in biochar, potentially retaining plant-available water and benefiting coarse sandy soils [167]. Further, gasification of biochar (GB) improves root development and thus enhances soil water retention, hence improving crop productivity [168].

11. Immutability of Soil Organic Matter and Soil Configuration

The influence of biochar on aggregate formation and organic matter stability is of high importance. Pituello [169] stated that biochar is a potential amendment for the stabilization of aggregates, especially if soil has a coarse texture and a low organic content [169]. These recommendations were further supported by Ma [170], who reported a significant increase in aggregate stability and soil organic carbon. However, Fungo [171] reported from his two year experiment that biochar had no effect on soil aggregates in tropical Ultisol. Moreover, increasing biochar amendment to fine sand and sandy loam textured soil may decrease aggregate strength [172]. Thus, the effect of biochar is multifarious and could vary with soil types and textures.

Biochar improves the structure and fertility of soil [117,118]. Glaser [173] reported that a substantial amount of biochar in terra preta was present in vulnerable fractions. However, in [174], it was indicated that biochar was associated primarily with the ultrafine, sub-50 μm soil chunk, and in [175], it was found that biochar, rather than as a free organic matter, was preponderantly available in small clumps of soil particles or soil aggregates. Brodowski [176] also found large macro-aggregate fractions with a small amount of practical biochar (>2 mm); thus, biochar might act as a binding agent for organic matter in aggregate formation and soil against degradation. Due to the interaction of biochar with soil organic matter and microorganisms and minerals, it may influence soil aggregates and its stability [177,178]. The slow oxidation properties of biochar determine the long-term effect on soil aggregation [179].

12. Biochar and Sustainability

The key obstacles with the current agrofarming systems are to enhance crop yield in a more sustainable and environmentally friendly manner [180,181]. Post-green revolution, agricultural practices enhanced their dependency on organic fertilizer for securing higher crop yield. Chemical fertilizers do increase crop yield, but they also risk the sustainability of the environment by provoking key ecological disparities, such as biodiversity loss, global warming and inclusion of heavy metals in living organisms [182,183]. Thus, adopting a more natural way of farming will reduce the reliance on organic fertilizers and sustain agricultural production and productivity.

More recently, biochar is thought to be an auspicious soil conditioner to sustain carbon and nutrients in soil, and thereby reflects the environmental problems regarding sustainable agricultural nutrient management [184,185]. Contemporary research on biochar is predominantly focused on customizing biochar properties to enhance their elimination capability for organic and inorganic pollutants [89]. Biochar has comprehensive environmental use due to its idiosyncratic properties, e.g., large surface area, microporosity, higher adsorption capacity and ion exchange capacity [99,100]. These properties have substantial consequences to its competency and potency in sustainability of the environment. The transformation of feedstock into biochar is a carbon-negative technique and has been indicated to sequestrate around 87% of carbon [186]. This not only reduces the problems of waste disposal of agricultural residues but also provides a viable and frugal method of waste transformation into value-added products. Due to its exceptional surface characteristics, biochar shows remarkable efficacy in reducing contaminants such as antibiotics, herbicides, dyes, pesticides and heavy metals and plays a key role in alleviating global climate change [187]. Biochar is thus a promising way to return lost C into the soil [188].

Many investigators have suggested biochar as an efficient soil supplement to encourage C storage [189], to augment value to agricultural products and to foster plant growth for sustainable agriculture [190]. Biochar has an exceptional function to immobilize rhizospheric heavy metals and farm chemicals on its large surface and inhibits their movement into the plants/crops, thus improving crop productivity [191]. Biochar substantially increased crop grain yield and biomass, and such favorable impacts of biochar were greater under rational P fertilization where half (50%) of P is from a natural source and the remaining 50% is from an inorganic fertilizer. The synergetic effect on nutrient accessibility and plant uptake is necessary for better crop yield and soil fertility, which can be gained by combinative use of organic and inorganic fertilizers with biochar [192]. In addition, biochar amendment increase in grain yield could signal the instrumental role of biochar in the conservation of soil nutrients and moisture, increasing nutrient uptake for potential crop yield and development [193]. Biochar can strengthen crop biomass and growth by enhancing nutrient availability [194]. Biochar application has been shown to decrease the saturated hydraulic conductivity of the soil, especially in light textured soils [195,196]. For example, Ajayi and Horn reported a decrease between 23 and 82% in the saturated hydraulic conductivity of a fine-sand soil when amended with a large application rate (2–5%, w/w) of biochar [197]. Several field trials have been conducted side by side to greenhouse pot experiments on biochar effects on soil nutrients (Table 2). While soil amendment with biochar resulted in an increase in crop production and improved soil fertility under different natural and agricultural environments [198], the immediate impact of biochar addition on soil fertility and nutrition is incoherent and weakly understood. Biochar has a consistent effect on some parameters of soil but not in all conditions [199]. While the beneficial effects and usage of biochar are widely discussed, more research is warranted to understand its perks and magnitudes, as well as the constraints of biochar amendment, in agroecosystems (Figure 4). Farming systems mostly depend upon the locally produced waste materials, e.g., crop residues and animal manures, as farmers have very limited resources to buy commercially prepared organic fertilizers [200]. The Oxisol class of soil by its very nature is poor in nutrients and organic matter content [201], which further limits microbial activities, thus leading to low crop yield. Smallholder farmers have access to bundles of local waste, so mutually rewarding benefits of crop yield and waste management can be gained, if policies associated with biochar are made for its governance in developing countries.

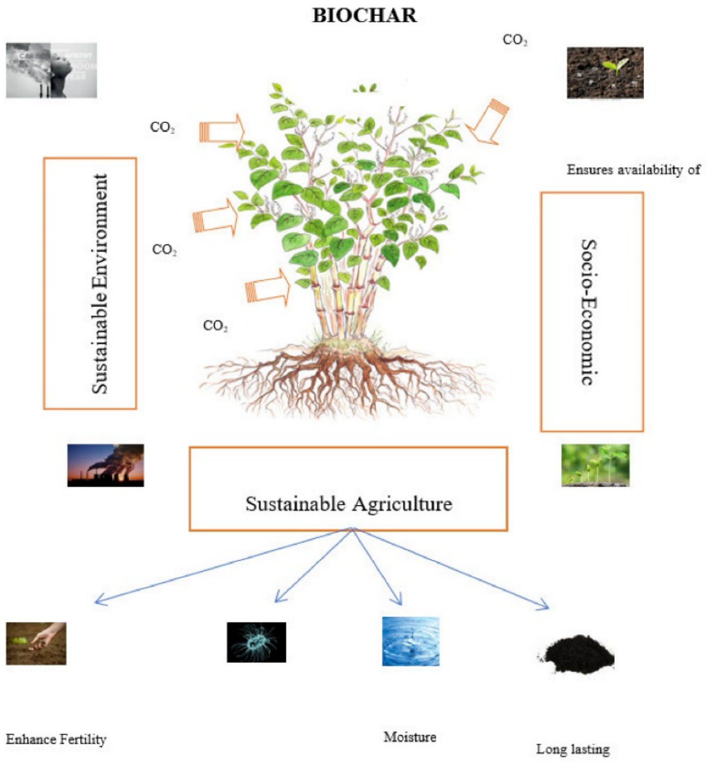

Figure 4. A diagrammatic representation of biochar dynamics and its role in agroecosystem and environmental sustainability.

13. Constraints of Biochar Application

Even though, overwhelmingly, the literature outcomes reflect the valuable prospect of biochar application, there are some constraints of biochar application which deserve attention. It is documented that weed yield increased by 200% with an increase in wheat straw-derived biochar (300–1100 °C) application rate from 15 t ha^{-1}, thus becoming a big competitor for soil nutrients to the main crop [202]. Biochar has a repressive effect on soil aging, and sporadic amendment of fresh biochar might be needed for the maximum nutrient cycling and aqua environment in soil [203]. For example, Anyanwu [204] reported that aged biochar derived from rice husk in soil has a substantially negative effect on the growth of soil earthworms and fungi. Biochar application may cause a delay in flowering in plants [205]. Additionally, Zhao [206] reported that aged biochar led to a significant reduction in the root biomass of Oryza sativa and Solanum lycopersicum in the soil. Biochar application at 14 t ha^{-1} enhanced vegetative growth but not tomato crop fruit yield, thus indicating the impact of biocarbon and crop yield dependency on plant species or the targeted part of the plant [207]. Furthermore, biochar is characterized by a selective capability to assimilate pollutants. For example, dichlorodiphenyltrichloroethane (DDT) chemical pesticide absorption was not limited by biochar application in a soil [208]. Thus, Table 2 presents the current research cited on the effect of biochar amendment on crop yield and fertility dynamics. The results fluctuate, both positively and negatively, depending on the biochar type, amount, soil type, crop type, etc.

14. Conclusions

Agroecosystems are extremely important to ensure food security and abate GHG emissions. Measures to reduce chemical fertilizer inputs and alleviate GHGs emissions include increasing soil C sequestration by addition of biochar, and thus increased crop-use efficiency of fertilizer-N. Smart choice of biochar type, rate, and affinity with agrofarming systems should not be ignored before its application. Biochar is an approach to slow the release of nutrients, and thus protect the environment without compromising crop yield. The beneficial capacity of biochar to amend agroecosystems and achieve a sustainable environment needs rational research knowledge as well as economic and social research. The practice of biochar application could enhance soil quality, increase the resilience of agroecosystems and agroforestry and support their adaptation capacity to the fluctuating climatic conditions. Nevertheless, the effects of biochar would be site dependent. Of course, biochar is not a solution to all agroecosystem problems; however, it could be a substantial strategy that deserves cognizance to achieve a sustainable agroecosystem in the future. This review has indicated many benefits, complexities and effects of biochar; however, more research is needed to provide a better understanding of biochar mechanisms and their interactive effects on plants, soil and the environment.

Author Contributions: M.A. and K.A., Collection of literature; M.A., Writing original draft; D.F., Review and editing, visualization, investigation and conceptualization; V.T., Review and editing, resource investigation and fund acquisition, U.S. Review and editing, grammar, etc.; K.A. and R.I., Review and editing, grammar, etc. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to thank the scientific community of the Lithuanian Research Centre for Agriculture and Forestry for strong intellectual discussions, recommendations and changes made to the article. We are also thankful to the Lithuanian Research Council for continuous support to this study.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

1. Mueller, N.D.; Gerber, J.S.; Johnston, M.; Ray, D.K.; Ramankutty, N.; Foley, J.A. Closing yield gaps through nutrient and water management. *Nature* **2012**, *490*, 254–257. [CrossRef]
2. Nair, V.D.; Nair, P.K.; Dari, B.; Freitas, A.M.; Chatterjee, N.; Pinheiro, F.M. Biochar in the agroecosystem–climate-change–sustainability nexus. *Front. Plant. Sci.* **2017**, *8*, 2051. [CrossRef] [PubMed]
3. Lehmann, J.; Joseph, S. Biochar for environmental management: An introduction. Biochar for environmental management. *Sci. Technol.* **2009**, *1*, 1–12.
4. Ilvo, P.; Uog, P.; Slu, P.; Inra, P.; Upm, P.; Unitus, P.; Iamo, P.; Iea-ar, P. D5.2 Participatory Impact Assessment of Sustainabil-ity and Resilience of EU Farming Systems. *2019*. No. June 2017. Available online: https://www.surefarmproject.eu/wordpress/wp-content/uploads/2019/06/D5.2-FoPIA-SURE-Farm-Cross-country-report.pdf (accessed on 26 January 2021).
5. Lu, L.; Yu, W.; Wang, Y.; Zhang, K.; Zhu, X.; Zhang, Y.; Chen, B. Application of biochar-based materials in environmental remediation: From multi-level structures to specific devices. *Biochar* **2020**, *2*, 1–31. [CrossRef]
6. Lichtfouse, E.; Navarrete, M.; Debaeke, P.; Souchère, V.; Alberola, C.; Ménassieu, J. Agronomy for sustainable agriculture: A review. In *Sustainable Agriculture*; Springer: Dordrecht, The Netherlands, 2009; pp. 1–7.
7. Jalal, F.; Arif, M.; Akhtar, K.; Khan, A.; Naz, M.; Said, F.; Ali, M. Biochar Integration with Legume Crops in Summer Gape Synergizes Nitrogen Use Efficiency and Enhance Maize Yield. *Agronomy* **2020**, *10*, 58. [CrossRef]
8. Akhtar, K.; Wang, W.; Ren, G.; Khan, A.; Nie, E.; Khan, A.; Feng, Y.; Yang, G.; Wang, H. Straw mulching with inorganic nitrogen fertilizer reduces soil CO_2 and N_2O emissions and improves wheat yield. *Sci. Total Environ.* **2020**, *741*, 140488. [CrossRef]

9. Brewer, C.E.; Chuang, V.J.; Masiello, C.A.; Gonnermann, H.; Gao, X.; Dugan, B.; Davies, C.A. New approaches to measuring biochar density and porosity. *Biomass Bioenergy* **2014**, *66*, 176–185. [CrossRef]
10. Awad, Y.M.; Lee, S.S.; Kim, K.H.; Ok, Y.S.; Kuzyakov, Y. Carbon and nitrogen mineralization and enzyme activities in soil aggregate-size classes: Effects of biochar, oyster shells, and polymers. *Chemosphere* **2018**, *198*, 40. [CrossRef]
11. Arif, M.; Ali, S.; Ilyas, M.; Riaz, M.; Akhtar, K.; Ali, K.; Wang, H. Enhancing phosphorus availability, soil organic carbon, maize productivity, and farm profitability through biochar and organic-inorganic fertilizers in an irrigated maize agroecosystem under semi-arid climate. *Soil Use Manag.* **2020**. [CrossRef]
12. Pandey, D.; Daverey, A.; Arunachalam, K. Biochar: Production, properties, and emerging role as a support for enzyme immobilization. *J. Clean. Prod.* **2020**, *255*, 120267. [CrossRef]
13. Sewu, D.D.; Tran, H.N.; Ohemeng-Boahen, G.; Woo, S.H. Facile magnetic biochar production route with new goethite nanoparticle precursor. *Sci. Total Environ.* **2020**, *717*, 137091. [CrossRef] [PubMed]
14. Dai, Z.; Meng, J.; Muhammad, N.; Liu, X.; Wang, H.; He, Y.; Xu, J. The potential feasibility for soil improvement, based on the properties of biochars pyrolyzed from different feedstocks. *J. Soils Sediments* **2013**, *13*, 989–1000. [CrossRef]
15. Demirbas, A. Combustion characteristics of different biomass fuels. *Prog. Energy Combust. Sci.* **2004**, *30*, 219–230. [CrossRef]
16. De Freitas, M.I.; Lucas, A.A.T.; Gonzaga, M.I.S. Biochar and Its Impact on Soil Properties and on The Growth of Okra Plants. *Colloquium Agrariae.* 2020, Volume 16, pp. 29–39. Available online: http://revistas.unoeste.br/index.php/ca/article/view/3302 (accessed on 26 January 2021).
17. Chen, B.; Zhou, D.; Zhu, L. Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environ. Sci. Technol.* **2008**, *42*, 5137–5143. [CrossRef]
18. Gray, M.; Johnson, M.G.; Dragila, M.I.; Kleber, M. Water uptake in biochars: The roles of porosity and hydrophobicity. *Biomass Bioenergy* **2014**, *61*, 196–205. [CrossRef]
19. Jiefei, M.; Zhang, K.; Chen, B. Linking hydrophobicity of biochar to the water repellency and waterholding capacity of biochar-amended soil. *Environ. Pollut.* **2019**, *253*, 779–789.
20. Jia, Y.; Hu, Z.; Mu, J.; Zhang, W.; Xie, Z.; Wang, G. Preparation of biochar as a coating material for biochar-coated urea. *Sci. Total Environ.* **2020**, *731*, 139063. [CrossRef]
21. Tang, Y.H.; Liu, S.H.; Tsang, D.C. Microwave-assisted production of CO^2-activated biochar from sugarcane bagasse for electrochemical desalination. *J. Hazard. Mater.* **2020**, *383*, 121192. [CrossRef]
22. Chen, H.; Awasthi, S.K.; Liu, T.; Duan, Y.; Ren, X.; Zhang, Z.; Awasthi, M.K. Effects of microbial culture and chicken manure biochar on compost maturity and greenhouse gas emissions during chicken manure composting. *J. Hazard. Mater.* **2020**, *389*, 121908. [CrossRef]
23. Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockaday, W.C.; Crowley, D. Biochar effects on soil biota–A review. *Soil Boil. Biochem.* **2011**, *43*, 1812–1836. [CrossRef]
24. Antonangelo, J.A.; Zhang, H. Heavy metal phytoavailability in a contaminated soil of northeastern Oklahoma as affected by biochar amendment. *Environ. Sci. Pollut. Res.* **2019**, *26*, 33582–33593. [CrossRef] [PubMed]
25. Albert, H.A.; Li, X.; Jeyakumar, P.; Wei, L.; Huang, L.; Huang, Q.; Kamran, M.; Shaheen, S.M.; Hou, D.; Rinklebe, J. Influence of Biochar and Soil Properties on Soil and Plant Tissue Concentrations of Cd and Pb: A Meta-Analysis. *Sci. Total Environ.* **2020**, *755*, 142582. [CrossRef] [PubMed]
26. Chen, H.; Yang, X.; Wang, H.; Sarkar, B.; Shaheen, S.M.; Gielen, G.; Rinklebe, J. Animal carcass-and wood-derived biochars improved nutrient bioavailability, enzyme activity, and plant growth in metal-phthalic acid ester co-contaminated soils: A trial for reclamation and improvement of degraded soils. *J. Environ. Manag.* **2020**, *261*, 110246. [CrossRef]
27. Xinyu, J.; Tan, X.; Cheng, J.; Michelle, L.; Haddix, M.; Cotrufo, F. Interactions between aged biochar, fresh low molecular weight carbon and soil organic carbon after 3.5 years soil-biochar incubations. *Geoderma* **2019**, *333*, 99–107.
28. Aller, D.; Rathke, S.; Laird, D.; Cruse, R.; Hatfield, J. Impacts of fresh and aged biochars on plant available water and water use efficiency. *Geoderma* **2017**, *307*, 114–121. [CrossRef]
29. Mukherjee, A.; Zimmerman, A.R. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma* **2013**, *193*, 122–130. [CrossRef]
30. Wang, K.; Peng, N.; Lu, G.; Dang, Z. Effects of pyrolysis temperature and holding time on physicochemical properties of swine-manure-derived biochar. *Waste Biomass Valoriz.* **2020**, *11*, 613–624. [CrossRef]
31. Zheng, H.; Wang, Z.; Deng, X.; Zhao, J.; Luo, Y.; Novak, J.; Herbert, S.; Xing, B. Characteristics and nutrient values of biochars produced from giant reed at different temperatures. *Bioresour. Technol.* **2013**, *130*, 463–471. [CrossRef]
32. Mandal, A.; Singh, N.; Purakayastha, T.J. Characterization of pesticide sorption behaviour of slow pyrolysis biochars as low cost adsorbent for atrazine and imidacloprid removal. *Sci. Total Environ.* **2017**, *577*, 376. [CrossRef]
33. Enders, A.; Hanley, K.; Whitman, T.; Joseph, S.; Lehmann, J. Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresour. Technol.* **2012**, *114*, 644. [CrossRef]
34. Gaskin, J.W.; Das, K.C.; Tassistro, A.S.; Sonon, L.; Harris, K.; Hawkins, B. Characterization of char for agricultural use in the soils of the southeastern United States. In *Amazonian Dark Earths: Wim Sombroek's Vision*; Springer: Dordrecht, Germany, 2009; p. 433.
35. Purakayastha, T.J.; Kumari, S.; Pathak, H. Characterization, stability, and microbial effects of four biochars produced from crop residues. *Geoderma* **2015**, *239*, 293. [CrossRef]

36. El-Bassi, L.; Azzaz, A.A.; Jellali, S.; Akrout, H.; Marks, E.A.N.; Ghimbeu, C.M.; Jeguirim, M. Application of Olive Mill Waste-Based Biochars in Agriculture: Impact on Soil Properties, Enzymatic Activities and Tomato Growth. *Sci. Total Environ.* **2021**, *755*, 142531. [CrossRef] [PubMed]
37. Lin, H.Y.; Chang, S.T. Antioxidant potency of phenolic phytochemicals from the root extract of Acacia confusa. *Ind. Crops Prod.* **2013**, *49*, 871–878. [CrossRef]
38. Mandal, S.; Pu, S.; Adhikari, S.; Ma, H.; Kim, D.-H.; Bai, Y.; Hou, D. Progress and Future Prospects in Biochar Composites: Application and Reflection in the Soil Environment. *Crit. Rev. Environ. Sci. Technol.* **2020**, 1–53. [CrossRef]
39. Wei, L.; Shutao, W.; Jin, Z.; Tong, X. Biochar influences the microbial community structure during tomato stalk composting with chicken manure. *Bioresour. Technol.* **2014**, *154*, 148–154.
40. Smebye, A.; Alling, V.; Vogt, R.D.; Gadmar, T.C.; Mulder, J.; Cornelissen, G.; Hale, S.E. Biochar amendment to soil changes dissolved organic matter content and composition. *Chemosphere* **2016**, *142*, 100–105. [CrossRef]
41. Zhang, J.; Chen, G.; Sun, H.; Zhou, S.; Zou, G. Straw biochar hastens organic matter degradation and produces nutrient-rich compost. *Bioresour. Technol.* **2016**, *200*, 876–883. [CrossRef]
42. Jain, M.S.; Jambhulkar, R.; Kalamdhad, A.S. Biochar amendment for batch composting of nitrogen rich organic waste: Effect on degradation kinetics, composting physics, and nutritional properties. *Bioresour. Technol.* **2018**, *253*, 204–213. [CrossRef]
43. Masto, R.E.; Ansari, M.A.; George, J.; Selvi, V.; Ram, L. Co-application of biochar and lignite fly ash on soil nutrients and biological parameters at different crop growth stages of Zea mays. *Ecol. Eng.* **2013**, *58*, 314–322. [CrossRef]
44. Jindo, K.; Sonoki, T.; Matsumoto, K.; Canellas, L.; Roig, A.; Sanchez-Monedero, M.A. Influence of biochar addition on the humic substances of composting manures. *Waste Manag.* **2016**, *49*, 545–552. [CrossRef]
45. Ding, Y.; Liu, Y.; Liu, S.; Li, Z.; Tan, X.; Huang, X.; Zheng, B. Biochar to improve soil fertility. A review. *Agron. Sustain. Dev.* **2016**, *36*, 36. [CrossRef]
46. Głąb, T.; Żabiński, A.; Sadowska, U.; Gondek, K.; Kopeć, M.; Mierzwa–Hersztek, M.; Tabor, S. Effects of co-composted maize, sewage sludge, and biochar mixtures on hydrological and physical qualities of sandy soil. *Geoderma* **2018**, *315*, 27–35. [CrossRef]
47. Bao, H.; Wang, J.; Zhang, H.; Li, J.; Li, H.; Wu, F. Effects of biochar and organic substrates on biodegradation of polycyclic aromatic hydrocarbons and microbial community structure in PAHs-contaminated soils. *J. Hazard. Mater.* **2020**, *385*, 121595. [CrossRef] [PubMed]
48. Okareh, O.T.; Gbadebo, A.O. Enhancement of Soil Health Using Biochar. *Appl. Biochar Environ. Saf.* **2020**, *143*. [CrossRef]
49. Pariyar, P.; Kumari, K.; Jain, M.K.; Jadhao, P.S. Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. *Sci. Total Environ.* **2020**, *713*, 136433. [CrossRef]
50. Lehmann, J.; Joseph, S. *Biochar for Environmental Management: Science, Technology, and Implementation*; Routledge: Abingdon, UK, 2015; pp. 1–33.
51. Spokas, K.A.; Cantrell, K.B.; Novak, J.M.; Archer, D.W.; Ippolito, J.A.; Collins, H.P.; Lentz, R.D. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *J. Environ. Q.* **2012**, *41*, 973–989. [CrossRef]
52. Zhang, X.; Zhang, P.; Yuan, X.; Li, Y.; Han, L. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. *Bioresour. Technol.* **2020**, *296*, 122318. [CrossRef]
53. Laird, D.A.; Fleming, P.; Davis, D.D.; Horton, R.; Wang, B.; Karlen, D.L. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* **2010**, *158*, 443–449. [CrossRef]
54. Mullen, C.A.; Boateng, A.A.; Goldberg, N.M.; Lima, I.M.; Laird, D.A.; Hicks, K.B. Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. *Biomass Bioenergy* **2010**, *34*, 67–74. [CrossRef]
55. Laird, D.A.; Brown, R.C.; Amonette, J.E.; Lehmann, J. Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels Bioprod. Biorefining* **2009**, *3*, 547–562. [CrossRef]
56. Cantrell, K.B.; Hunt, P.G.; Uchimiya, M.; Novak, J.M.; Ro, K.S. Impact of pyrolysis temperature and manure source on physico-chemical characteristics of biochar. *Bioresour. Technol.* **2012**, *107*, 419–428. [CrossRef] [PubMed]
57. Antonangelo, J.A.; Zhang, H.; Sun, X.; Kumar, A. Physicochemical properties and morphology of biochars as affected by feedstock sources and pyrolysis temperatures. *Biochar* **2019**, *1*, 325–336. [CrossRef]
58. Qian, K.; Kumar, A.; Patil, K.; Bellmer, D.; Wang, D.; Yuan, W.; Huhnke, R.L. Effects of biomass feedstocks and gasification conditions on the physiochemical properties of char. *Energies* **2013**, *6*, 3972–3986. [CrossRef]
59. Gul, S.; Whalen, J.K.; Thomas, B.W.; Sachdeva, V.; Deng, H. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agric. Ecosyst. Environ.* **2015**, *206*, 46–59. [CrossRef]
60. Spokas, K.A. Review of the stability of biochar in soils: Predictability of O: C molar ratios. *Carbon Manag.* **2010**, *1*, 289–303. [CrossRef]
61. Muhammad, N.; Aziz, R.; Brookes, P.C.; Xu, J. Impact of wheat straw biochar on yield of rice and some properties of Psammaquent and Plinthudult. *J. Soil Sci. Plant. Nutr.* **2017**, *17*, 808–823. [CrossRef]
62. Naeem, M.A.; Khalid, M.; Aon, M.; Abbas, G.; Tahir, M.; Amjad, M.; Akhtar, S.S. Effect of wheat and rice straw biochar produced at different temperatures on maize growth and nutrient dynamics of a calcareous soil. *Arch. Agron. Soil Sci.* **2017**, *63*, 2048–2061. [CrossRef]
63. Yang, Y.; Ma, S.; Zhao, Y.; Jing, M.; Xu, Y.; Chen, J. A field experiment on enhancement of crop yield by rice straw and corn stalk-derived biochar in Northern China. *Sustainability* **2015**, *7*, 13713–13725. [CrossRef]

64. O'toole, A.; Moni, C.; Weldon, S.; Schols, A.; Carnol, M.; Bosman, B.; Rasse, D.P. Miscanthus biochar had limited effects on soil physical properties, microbial biomass, and grain yield in a four-year field experiment in Norway. *Agriculture* **2018**, *8*, 171. [CrossRef]
65. Azeem, M.; Hayat, R.; Hussain, Q.; Ahmed, M.; Pan, G.; Tahir, M.I.; Imran, M.; Irfan, M. Biochar Improves Soil Quality and N2-Fixation and Reduces Net Ecosystem CO2 Exchange in a Dryland Legume-Cereal Cropping System. *Soil Tillage Res.* **2019**, *186*, 172–182. [CrossRef]
66. Wang, J.; Pan, X.; Liu, Y.; Zhang, X.; Xiong, Z. Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. *Plant. Soil* **2012**, *360*, 287–298. [CrossRef]
67. Güereña, D.; Lehmann, J.; Hanley, K.; Enders, A.; Hyland, C.; Riha, S. Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system. *Plant. Soil* **2013**, *365*, 239–254. [CrossRef]
68. Lai, W.Y.; Lai, C.M.; Ke, G.R.; Chung, R.S.; Chen, C.T.; Cheng, C.H.; Chen, C.C. The effects of woodchip biochar application on crop yield, carbon sequestration and greenhouse gas emissions from soils planted with rice or leaf beet. *J. Taiwan Inst. Chem. Eng.* **2013**, *44*, 1039–1044. [CrossRef]
69. Sigua, G.C.; Stone, K.C.; Hunt, P.G.; Cantrell, K.B.; Novak, J.M. Increasing biomass of winter wheat using sorghum biochars. *Agron. Sustain. Dev.* **2015**, *35*, 739–748. [CrossRef]
70. Martinsen, V.; Mulder, J.; Shitumbanuma, V.; Sparrevik, M.; Børresen, T.; Cornelissen, G. Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *J. Plant. Nutr. Soil Sci.* **2014**, *177*, 681–695. [CrossRef]
71. Alburquerque, J.A.; Salazar, P.; Barrón, V.; Torrent, J.; del Campillo, M.D.C.; Gallardo, A.; Villar, R. Enhanced wheat yield by biochar addition under different mineral fertilization levels. *Agron. Sustain. Dev.* **2013**, *33*, 475–484. [CrossRef]
72. Adekiya, A.O.; Agbede, T.M.; Olayanju, A.; Ejue, W.S.; Adekanye, T.A.; Adenusi, T.T.; Ayeni, J.F. Effect of Biochar on Soil Properties, Soil Loss, and Cocoyam Yield on a Tropical Sandy Loam Alfisol. *Sci. World J.* **2020**. [CrossRef]
73. Boersma, M.; Wrobel-Tobiszewska, A.; Murphy, L.; Eyles, A. Impact of biochar application on the productivity of a temperate vegetable cropping system. *N. Z. J. Crop. Horticult. Sci.* **2017**, *45*, 277–288. [CrossRef]
74. Bolan, N.; Kunhikrishnan, A.; Thangarajan, R.; Kumpiene, J.; Park, J.; Makino, T.; Scheckel, K. Remediation of heavy metal (loid) s contaminated soils–to mobilize or to immobilize? *J. Hazard. Mater.* **2014**, *266*, 141–166. [CrossRef]
75. Qian, K.; Kumar, A.; Zhang, H.; Bellmer, D.; Huhnke, R. Recent advances in utilization of biochar. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1055–1064. [CrossRef]
76. Werdin, J.; Fletcher, T.D.; Rayner, J.P.; Williams, N.S.; Farrell, C. Biochar made from low density wood has greater plant available water than biochar made from high density wood. *Sci. Total Environ.* **2020**, *705*, 135856. [CrossRef]
77. Razzaghi, F.; Obour, P.B.; Arthur, E. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* **2020**, *361*, 114055. [CrossRef]
78. Radwan, N.M.; Marzouk, E.R.; El-Melegy, A.M.; Hassan, M.A. Improving Soil Properties by Using Biochar Under Drainage Conditions in North Sinai. *Sinai J. Appl. Sci.* **2020**. [CrossRef]
79. Laghari, M.; Naidu, R.; Xiao, B.; Hu, Z.; Mirjat, M.S.; Hu, M.; Abudi, Z.N. Recent developments in biochar as an effective tool for agricultural soil management: A review. *J. Sci. Food Agric.* **2016**, *96*, 4840–4849. [CrossRef] [PubMed]
80. Barrow, C.J. Biochar: Potential for countering land degradation and for improving agriculture. *Appl. Geogr.* **2012**, *34*, 21–28. [CrossRef]
81. Blanco-Canqui, H. Biochar and soil physical properties. *Soil Sci. Soc. Am. J.* **2017**, *81*, 687–711. [CrossRef]
82. Rasa, K.; Heikkinen, J.; Hannula, M.; Arstila, K.; Kulju, S.; Hyväluoma, J. How and why does willow biochar increase a clay soil water retention capacity? *Biomass Bioenergy* **2018**, *119*, 346–353. [CrossRef]
83. Uzoma, K.C.; Inoue, M.; Andry, H.; Fujimaki, H.; Zahoor, A.; Nishihara, E. Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use Manag.* **2011**, *27*, 205–212. [CrossRef]
84. Sánchez-Monedero, M.A.; Cayuela, M.L.; Sánchez-García, M.; Vandecasteele, B.; D'Hose, T.; López, G.; Mondini, C. Agronomic evaluation of biochar, compost, and biochar-blended compost across different cropping systems: Perspective from the European project FERTIPLUS. *Agronomy* **2019**, *9*, 225. [CrossRef]
85. Lu, H.; Yan, M.; Wong, M.H.; Mo, W.Y.; Wang, Y.; Chen, X.W.; Wang, J.J. Effects of biochar on soil microbial community and functional genes of a landfill cover three years after ecological restoration. *Sci. Total Environ.* **2020**, *717*, 137133. [CrossRef]
86. Otsuka, S.; Sudiana, I.; Komori, A.; Isobe, K.; Deguchi, S.; Nishiyama, M.; Shimizu, H.; Senoo, K. Community structure of soil bacteria in a tropical rainforest several years after fire. *Microbes Environ.* **2008**, *23*, 49–56. [CrossRef] [PubMed]
87. Rutigliano, F.A.; Romano, M.; Marzaioli, R.; Baglivo, I.; Baronti, S.; Miglietta, F.; Castaldi, S. Effect of biochar addition on soil microbial community in a wheat crop. *Eur. J. Soil Biol.* **2014**, *60*, 9–15. [CrossRef]
88. Dempster, D.N.; Gleeson, D.B.; Solaiman, Z.I.; Jones, D.L.; Murphy, D.V. Decreased soil microbial biomass and nitrogen mineralisation with Eucalyptus biochar addition to a coarse textured soil. *Plant. Soil* **2012**, *354*, 311–324. [CrossRef]
89. De Boer, W.; Kowalchuk, G.A. Nitrification in acid soils: Micro-organisms and mechanisms. *Soil Biol. Biochem.* **2001**, *33*, 853–866. [CrossRef]
90. Gao, L.; Wang, R.; Shen, G.; Zhang, J.; Meng, G.; Zhang, J. Effects of biochar on nutrients and the microbial community structure of tobacco-planting soils. *J. Soil Sci. Plant. Nutr.* **2017**, *17*, 884–896. [CrossRef]
91. Farrell, M.; Kuhn, T.K.; Macdonald, L.M.; Maddern, T.M.; Murphy, D.V.; Hall, P.A.; Singh, B.P.; Baumann, K.; Krull, E.S.; Baldock, J.A. Microbial utilization of biochar-derived carbon. *Sci. Total Environ.* **2013**, *465*, 288–297. [CrossRef]

92. He, Y.; Zhou, X.; Jiang, L.; Li, M.; Du, Z.; Zhou, G.; Wallace, H. Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy* **2017**, *9*, 743–755. [CrossRef]
93. Smith, J.L.; Collins, H.P.; Bailey, V.L. The effect of young biochar on soil respiration. *Biol. Biochem.* **2010**, *42*, 2345–2347. [CrossRef]
94. Lunde, C.F.; Hake, S. Florets & Rosettes: Meristem Genes in Maize and Arabidopsis. *Maydica* **2005**, *50*, 451–458.
95. Reddy, S.B.N. *Biochar Culture: Biochar for Environment and Development*; MetaMeta: s-Hertogenbosch, The Netherlands, 2014.
96. Jindo, K.; Mizumoto, H.; Sawada, Y.; Sanchez-Monedero, M.A.; Sonoki, T. Physical and chemical characterization of biochars derived from different agricultural residues. *Biogeoscience* **2014**, *11*, 6613–6621. [CrossRef]
97. Mclennon, E.; Solomon, J.K.Q.; Neupane, D.; Davison, J. Biochar and Nitrogen Application Rates Effect on Phosphorus Removal from a Mixed Grass Sward Irrigated with Reclaimed Wastewater. *Sci. Total Environ.* **2020**, *715*, 137012. [CrossRef] [PubMed]
98. Glaser, B.; Haumaier, L.; Guggenberger, G.; Zech, W. The 'Terra Preta' phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften* **2001**, *88*, 37–41. [CrossRef] [PubMed]
99. Rondon, M.; Ramirez, J.A.; Lehmann, J. Greenhouse gas emissions decrease with charcoal additions to tropical soils. In Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, MD, USA, 21–24 March 2005; Volume 208.
100. Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller, H.L. *IPCC. Climate change, the physical science basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007; p. 996.
101. Wang, J.; Xiong, Z.; Kuzyakov, Y. Biochar stability in soil: Metaanalysis of decomposition and priming effects. *GCB Bioenergy* **2016**, *8*, 512–523. [CrossRef]
102. Vanholme, B.; Desmet, T.; Ronsse, F.; Rabaey, K.; van Breusegem, F.; De Mey, M. Towards a carbon negative sustainable bio-based economy. *Front. Plant. Sci.* **2013**, *4*, 174. [CrossRef] [PubMed]
103. Downie, A.; Munroe, P.; Cowie, A.; van Zwieten, L.; Lau, D.M.S. Biochar as a geo engineering climate solution: Hazard identification and risk management. *Crit. Rev. Environ. Sci. Technol.* **2012**, *42*, 225–250. [CrossRef]
104. Jia, J.; Li, B.; Chen, Z.; Xie, Z.; Xiong, Z. Effects of biochar application on vegetable production and emissions of N_2O and CH_4. *Soil Sci. Plant. Nutr.* **2012**, *58*, 503–509. [CrossRef]
105. Sun, L.; Li, L.; Chen, Z.; Wang, J.; Xiong, Z. Combined effects of nitrogen deposition and biochar application on emissions of N2O, CO2 and NH3 from agricultural and forest soils. *Soil Sci. Plant. Nutr.* **2014**, *60*, 254–265. [CrossRef]
106. Hale, S.E.; Nurida, N.L.; Mulder, J.; Sørmo, E.; Silvani, L.; Abiven, S.; Joseph, S.; Taherymoosavi, S.; Cornelissen, G. The Effect of Biochar, Lime and Ash on Maize Yield in a Long-Term Field Trial in a Ultisol in the Humid Tropics. *Sci. Total Environ.* **2020**, *719*, 137455. [CrossRef]
107. Kuppusamy, S.; Thavamani, P.; Megharaj, M.; Venkateswarlu, K.; Naidu, R. Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions. *Environ. Int.* **2016**, *87*, 1–12. [CrossRef]
108. Randolph, P.; Bansode, R.R.; Hassan, O.A.; Rehrah, D.; Ravella, R.; Reddy, M.R.; Watts, D.W.; Novak, J.M.; Ahmedna, M. Effect of biochars produced from solid organic municipal waste on soil quality parameters. *J. Environ. Manag.* **2017**, *192*, 271–280. [CrossRef]
109. El-Naggara, A.; Lee, S.S.; Rinklebed, J.; Farooq, M.; Song, H.; Sarmah, A.K.; Zimmerman, A.R.; Ahmad, M.; Shaheend, S.M.; Ok, Y.S. Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma* **2019**, *337*, 536–554. [CrossRef]
110. Koide, R.T. Biochar—Arbuscular mycorrhiza interaction in temperate soils. In *Mycorrhizal Mediation of Soil*; Elsevier: New York, NY, USA, 2017; pp. 461–477.
111. Mohanty, P.; Nanda, S.; Pant, K.K.; Naik, S.; Kozinski, J.A.; Dalai, A.K. Evaluation of the physiochemical development of biochars obtained from pyrolysis of wheat straw, timothy grass and pinewood: Effects of heating rate. *J. Anal. Appl. Pyrol.* **2013**, *104*, 485–493. [CrossRef]
112. Filiberto, D.M.; Gaunt, J.L. Practicality of biochar additions to enhance soil and crop productivity. *Agriculture* **2013**, *3*, 715–725. [CrossRef]
113. Oguntunde, P.G.; Fosu, M.; Ajayi, A.E.; Van De Giesen, N. Effects of charcoal production on maize yield, chemical properties, and texture of soil. *Biol. Fertil Soils* **2004**, *39*, 295–299. [CrossRef]
114. Yao, Y.N.; Gao, B.; Chen, H.; Jiang, L.; Inyang, M.; Zimmerman, A.R. Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation. *J. Hazard. Mater.* **2012**, *209*, 408–413. [CrossRef]
115. Wu, F.; Jia, Z.; Wang, S.; Chang, S.X.; Startsev, A. Contrasting effects of wheat straw and its biochar on greenhouse gas emissions and enzyme activities in a Chernozemic soil. *Biol. Fert. Soils* **2013**, *49*, 555–565. [CrossRef]
116. Awad, Y.M.; Blagodatskaya, E.; Ok, Y.K.; Kuzyakov, Y. Effects of polyacrylamide, biopolymer, and biochar on decomposition of soil organic matter and plant residues as determined by C and enzyme activities. *Eur. J. Soil Biol.* **2012**, *48*, 1–10. [CrossRef]
117. Demisie, W.; Liu, Z.Y.; Zhang, M.K. Effect of biochar on carbon fractions and enzyme activity of red soil. *Catena* **2014**, *121*, 214–221. [CrossRef]
118. Akça, M.O.; Namli, A. Effects of poultry litter 1053 biochar on soil enzyme activities and tomato, pepper and lettuce plants growth. *Eur. J. Soil Sci.* **2014**, *4*, 161–168.
119. Shang, J.; Geng, Z.C.; Wang, Y.T.; Chen, X.X.; Zhao, J. Effect of biochar amendment on soil microbial biomass carbon and nitrogen and enzyme activity in tier soils. *Sci. Agric. Sin.* **2016**, *49*, 1142–1151.

120. Paz-Ferreiro, J.; Fu, S.; Mendez, A.; Gasco, G. Biochar modifies the thermodynamic parameters of soil enzyme activity in a tropical soil. *J. Soil Sediment.* **2015**, *15*, 578–583. [CrossRef]
121. Paz-Ferreiro, J.; Gascó, G.; Gutiérrez, B.; Méndez, A. Soil biochemical activities and the geometric mean of enzyme activities after application of sewage sludge and sewage sludge biochar to soil. *Biol. Fert. Soils* **2012**, *48*, 511–517. [CrossRef]
122. Zhang, M.; Cheng, G.; Feng, H.; Sun, B.; Zhao, Y.; Chen, H.; Chen, J.; Dyck, M.; Wang, X.; Zhang, J.; et al. Effects of straw and biochar amendments on aggregate stability, soil organic carbon, and enzyme activities in the Loess Plateau, China. *Environ. Sci. Pollut. Res.* **2017**, *24*, 10108–10120. [CrossRef] [PubMed]
123. Zhu, L.; Xiao, Q.; Chenga, H.; Shi, B.; Shen, Y.; Li, S. Seasonal dynamics of soil microbial activity after biochar addition in a dry land maize field in North-Western China. *Ecol. Eng.* **2017**, *104*, 141–149. [CrossRef]
124. Chen, J.; Li, S.; Lianga, C.; Xu, O.; Li, Y.; Qin, H.; Fuhrman, J.J. Response of microbial community structure and function to short-term biochar amendment in an intensively managed bamboo (Phyllostachys praecox) plantation soil: Effect of particle size and addition rate. *Sci. Total Environ.* **2017**, *574*, 24–33. [CrossRef]
125. Pokharel, P.; Kwak, J.H.; Ok, Y.S.; Chang, S.X. Pine sawdust biochar reduces GHG emission by decreasing microbial and enzyme activities in forest and grassland soils in a laboratory experiment. *Sci. Total Environ.* **2018**, *625*, 1247–1256. [CrossRef]
126. Li, S.; Liang, C.; Shangguan, Z. Effects of apple branch biochar on soil C mineralization and nutrient cycling under two levels of N. *Sci. Total Environ.* **2017**, *607–608*, 109–119. [CrossRef]
127. Mierzwa-Hersztek, M.; Gondek, K.; Klimkowicz-Pawlas, A.; Baran, A. Effect of wheat and Miscanthus straw biochars on soil enzymatic activity, ecotoxicity, and plant yield. *Int. Agrophys.* **2017**, *31*, 367–375. [CrossRef]
128. Pei, J.; Zhuang, S.; Cui, J.; Li, J.; Li, B.; Wu, J.; Fang, C. Biochar decreased the temperature sensitivity of soil carbon decomposition in a paddy field. *Agric. Ecosyst. Environ.* **2017**, *249*, 156–164. [CrossRef]
129. Bashir, S.; Hussain, Q.; Akmal, M.; Riaz, M.; Hu, H.; Ijaz, S.S.; Iqbal, M.; Abro, S.; Mehmood, S.; Ahmad, M. Sugarcane bagasse-derived biochar reduces the cadmium and chromium bioavailability to mash bean and enhances the microbial activity in contaminated soil. *J. Soil Sediment.* **2017**, *18*, 874–886. [CrossRef]
130. Wang, D.; Fonte, S.J.; Parikh, S.J.; Six, J.; Scow, K.M. Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. *Geoderma* **2017**, *303*, 110–117. [CrossRef] [PubMed]
131. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant. Soil* **2002**, *241*, 155–176. [CrossRef]
132. Zimmerman, A.R. Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environ. Sci. Technol.* **2010**, *44*, 1295–1301. [CrossRef] [PubMed]
133. Fang, Y.; Singh, B.; Singh, B.P. Effect of temperature on biochar priming effects and its stability in soils. *Soil Biol. Biochem.* **2015**, *80*, 136–145. [CrossRef]
134. Singh, B.P.; Cowie, A.L. Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil. *Sci. Rep.* **2014**, *4*, 3687. [CrossRef] [PubMed]
135. Jien, S.H.; Wang, C.S. Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena* **2013**, *110*, 225–233. [CrossRef]
136. Kimetu, J.M.; Lehmann, J. Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. *Soil Res.* **2010**, *48*, 577–585. [CrossRef]
137. Harvey, O.R.; Kuo, L.J.; Zimmerman, A.R.; Louchouarn, P.; Amonette, J.E.; Herbert, B.E. An index-based approach to assessing recalcitrance and soil carbon sequestration potential of engineered black carbons (biochars). *Environ. Sci. Technol.* **2012**, *46*, 1415–1421. [CrossRef]
138. Joseph, S.D.; Camps-Arbestain, M.; Lin, Y.; Munroe, P.; Chia, C.H.; Hook, J.; Lehmann, J. An investigation into the reactions of biochar in soil. *Soil Res.* **2010**, *48*, 501–515. [CrossRef]
139. Chan, K.Y.; Van Zwieten, L.; Meszaros, I.; Downie, A.; Joseph, S. Agronomic values of greenwaste biochar as a soil amendment. *Soil Res.* **2008**, *45*, 629–634. [CrossRef]
140. Asai, H.; Samson, B.K.; Stephan, H.M.; Songyikhangsuthor, K.; Homma, K.; Kiyono, Y.; Horie, T. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Res.* **2009**, *111*, 81–84. [CrossRef]
141. Wu, L.; Zhang, S.; Wang, J.; Ding, X. Phosphorus retention using iron (II/III) modified biochar in saline-alkaline soils: Adsorption, column, and field tests. *Environ. Pollut.* **2020**, *261*, 114223. [CrossRef]
142. Burrell, L.D.; Zehetner, F.; Rampazzo, N.; Wimmer, B.; Soja, G. Long-term effects of biochar on soil physical properties. *Geoderma* **2016**, *282*, 96–102. [CrossRef]
143. Glaser, B.; Lehr, V.I. Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Sci. Rep.* **2019**, *9*. [CrossRef]
144. Dharmakeerthi, R.S.; Kumaragamage, D.; Goltz, D.; Indraratne, S.P. Phosphorus release from unamended and gypsum-or biochar-amended soils under simulated snowmelt and summer flooding conditions. *J. Environ. Q.* **2019**, *48*, 822–830. [CrossRef] [PubMed]
145. Li, F.; Liang, X.; Niyungeko, C.; Sun, T.; Liu, F.; Arai, Y. Effects of biochar amendments on soil phosphorus transformation in agricultural soils. *Adv. Agron.* **2019**, *158*, 131–172.
146. Pottmaier, D.; Costa, M.; Farrow, T.; Oliveira, A.A.; Alarcon, O.; Snape, C. Comparison of rice husk and wheat straw: From slow and fast pyrolysis to char combustion. *Energy Fuels* **2013**, *27*, 7115–7125. [CrossRef]

147. Bourke, J.; Manley-Harris, M.; Fushimi, C.; Dowaki, K.; Nunoura, T.; Antal, M.J. Do all carbonized charcoals have the same chemical structure? 2. A model of the chemical structure of carbonized charcoal. *Ind. Eng. Chem. Res.* **2007**, *46*, 5954–5967. [CrossRef]
148. Kondo, Y.; Fukuzawa, Y.; Kawamitsu, Y.; Ueno, M.; Tsutsumi, J.; Takemoto, T.; Kawasaki, S. A new application of bagasse char as a solar energy absorption and accumulation material. *Earth Environ. Sci. Trans. Royal Soc. Edinburgh* **2012**, *103*, 31–38. [CrossRef]
149. Burhenne, L.; Damiani, M.; Aicher, T. Effect of feedstock water content and pyrolysis temperature on the structure and reactivity of spruce wood char produced in fixed bed pyrolysis. *Fuel* **2013**, *107*, 836–847. [CrossRef]
150. Zeng, K.; Minh, D.P.; Gauthier, D.; Weiss-Hortala, E.; Nzihou, A.; Flamant, G. The effect of temperature and heating rate on char properties obtained from solar pyrolysis of beech wood. *Bioresour. Technol.* **2015**, *182*, 114–119. [CrossRef] [PubMed]
151. Trubetskaya, A.; Jensen, P.A.; Jensen, A.D.; Steibel, M.; Spliethoff, H.; Glarborg, P. Influence of fast pyrolysis conditions on yield and structural transformation of biomass chars. *Fuel Proc. Technol.* **2015**, *140*, 205–214. [CrossRef]
152. Song, X.; Li, Y.; Yue, X.; Hussain, Q.; Zhang, J.; Liu, Q.; Cui, D. Effect of cotton straw-derived materials on native soil organic carbon. *Sci. Total Environ.* **2019**, *663*, 38–44. [CrossRef] [PubMed]
153. Giagnoni, L.; Maienza, A.; Baronti, S.; Vaccari, F.P.; Genesio, L.; Taiti, C.; Mancuso, S. Long-term soil biological fertility, volatile organic compounds and chemical properties in a vineyard soil after biochar amendment. *Geoderma* **2019**, *344*, 127–136. [CrossRef]
154. Awad, Y.M.; Wang, J.; Igalavithana, A.D.; Tsang, D.C.; Kim, K.H.; Lee, S.S.; Ok, Y.S. Biochar effects on rice paddy: Meta-analysis. *Adv. Agron.* **2018**, *148*, 1–32.
155. Abdelhafez, A.A.; Abbas, M.H.; Li, J. Biochar: The black diamond for soil sustainability, contamination control and agricultural production. *Eng. Appl. Biochar* **2017**, *2*. [CrossRef]
156. Elshony, M.; Farid, I.M.; Alkamar, F.; Abbas, M.H.; Abbas, H. Ameliorating a sandy soil using biochar and compost amendments and their implications as slow release fertilizers on plant growth. *Egypt. J. Soil Sci.* **2019**, *59*, 305–322. [CrossRef]
157. Rahman, G.M.; Rahman, M.M.; Alam, M.S.; Kamal, M.Z.; Mashuk, H.A.; Datta, R.; Meena, R.S. Biochar and organic amendments for sustainable soil carbon and soil health. In *Carbon and Nitrogen Cycling in Soil*; Springer: Singapore, 2020; pp. 45–85.
158. Zheng, H.; Wang, X.; Luo, X.; Wang, Z.; Xing, B. Biochar-induced negative carbon mineralization priming effects in a coastal wetland soil: Roles of soil aggregation and microbial modulation. *Sci. Total Environ.* **2018**, *610*, 951–960. [CrossRef]
159. Dai, Y.; Wang, W.; Lu, L.; Yan, L.; Yu, D. Utilization of biochar for the removal of nitrogen and phosphorus. *J. Clean. Prod.* **2020**, *257*, 120573. [CrossRef]
160. Brassard, P.; Godbout, S.; Raghavan, V. Soil biochar amendment as a climate change mitigation tool: Key parameters and mechanisms involved. *J. Environ. Manag.* **2016**, *181*, 484. [CrossRef]
161. Manolikaki, I.; Diamadopoulos, E. Agronomic potential of biochar prepared from brewery byproducts. *J. Environ. Manag.* **2020**, *255*, 109856. [CrossRef] [PubMed]
162. Wiersma, W.; van der Ploeg, M.J.; Sauren, I.J.; Stoof, C.R. No effect of pyrolysis temperature and feedstock type on hydraulic properties of biochar and amended sandy soil. *Geoderma* **2020**, *364*, 114209. [CrossRef]
163. Cooper, J.; Greenberg, I.; Ludwig, B.; Hippich, L.; Fischer, D.; Glaser, B.; Kaiser, M. Effect of Biochar and Compost on Soil Properties and Organic Matter in Aggregate Size Fractions under Field Conditions. *Agric. Ecosyst. Environ.* **2020**, *295*, 106882. [CrossRef]
164. Bruun, E.W.; Petersen, C.T.; Hansen, E.; Holm, J.K.; Hauggaard-Nielsen, H. Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. *Soil Use Manag.* **2014**, *30*, 109–118. [CrossRef]
165. Abel, S.; Peters, A.; Trinks, S.; Schonsky, H.; Facklam, M.; Wessolek, G. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma* **2013**, *202–203*, 183–191. [CrossRef]
166. Hardie, M.; Clothier, B.; Bound, S.; Oliver, G.; Close, D. Does biochar influence soil physical properties and soil water availability? *Plant. Soil* **2014**, 1–15. [CrossRef]
167. Hansen, V.; Hauggaard-Nielsen, H.; Petersen, C.T.; Mikkelsen, T.N.; Müller-Stöver, D. Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. *Soil Tillage Res.* **2016**, *161*, 1–9. [CrossRef]
168. Ebenezer, A.A.; Rainer, H.O.R.N. Biochar-induced changes in soil resilience: Effects of soil texture and biochar dosage. *Pedosphere* **2017**, *27*, 236–247.
169. Pituello, C.; Dal Ferro, N.; Francioso, O.; Simonetti, G.; Berti, A.; Piccoli, I.; Morari, F. Effects of biochar on the dynamics of aggregate stability in clay and sandy loam soils. *Eur. J. Soil Sci.* **2018**, *69*, 827–842. [CrossRef]
170. Ma, N.; Zhang, L.; Zhang, Y.; Yang, L.; Yu, C.; Yin, G.; Ma, X. Biochar improves soil aggregate stability and water availability in a mollisol after three years of field application. *PLoS ONE* **2016**, *11*. [CrossRef]
171. Fungo, B.; Lehmann, J.; Kalbitz, K.; Thionġo, M.; Okeyo, I.; Tenywa, M.; Neufeldt, H. Aggregate size distribution in a biochar-amended tropical Ultisol under conventional hand-hoe tillage. *Soil Tillage Res.* **2017**, *165*, 190–197. [CrossRef] [PubMed]
172. Atkinson, C.J.; Fitzgerald, J.D.; Hipps, N.A. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant. Soil* **2010**, *337*, 1–18. [CrossRef]
173. Glaser, B.; Lehmann, J.; Zech, W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–A review. *Biol. Fertile. Soils* **2002**, *35*, 219–230. [CrossRef]
174. Glaser, B.; Balashov, E.; Haumaier, L.; Guggenberger, G.; Zech, W. Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. *Organ. Geochem.* **2000**, *31*, 669–678. [CrossRef]

175. Liang, B.; Lehmann, J.; Solomon, D.; Sohi, S.; Thies, J.E.; Skjemstad, J.O.; Wirick, S. Stability of biomass-derived black carbon in soils. *Geochim. Cosmochim. Acta* **2008**, *72*, 6069–6078. [CrossRef]
176. Brodowski, S.; John, B.; Flessa, H.; Amelung, W. Aggregate-occluded black carbon in soil. *Eur. J. Soil Sci.* **2006**, *57*, 539–546. [CrossRef]
177. Piccolo, A.; Pietramellara, G.; Mbag Demisie, J.S.C. Use of humic substances as soil conditioners to increase aggregate stability. *Geoderma* **1997**, *75*, 267–277. [CrossRef]
178. Verheijen, F.; Jeffery, S.; Bastos, A.C.; Van der Velde, M.; Diafas, I. Biochar application to soils. A critical scientific review of effects on soil properties, processes, and functions. *EUR* **2010**, *24099*, 162.
179. Patel, J.S.; Singh, A.; Singh, H.B.; Sarma, B.K. Plant genotype, microbial recruitment and nutritional security. *Front. Plant. Sci.* **2015**, *6*, 1–3. [CrossRef]
180. Hamilton, C.E.; Bever, J.D.; Labbé, J.; Yang, X.; Yin, H. Mitigating Climate Change through Managing Constructed-Microbial Communities in Agriculture. *Agric. Ecosyst. Environ.* **2016**, *216*, 304–308. [CrossRef]
181. Srivastav, A.L. Chemical fertilizers and pesticides: Role in groundwater contamination. In: Agrochemicals detection, treatment, and remediation. *Butterworth-Heinemann* **2020**, 143–159. [CrossRef]
182. Ye, L.; Zhao, X.; Bao, E.; Li, J.; Zou, Z.; Cao, K. Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality. *Sci. Rep.* **2020**, *10*, 1–11. [CrossRef]
183. Mandal, S.; Sarkar, B.; Bolan, N.; Novak, J.; Ok, Y.S.; Van Zwieten, L.; Singh, B.P.; Kirkham, M.B.; Choppala, G.; Spokas, K.; et al. Designing advanced biochar products for maximizing greenhouse gas mitigation potential. *Crit. Rev. Environ. Sci. Technol.* **2016**, *46*, 1367–1401. [CrossRef]
184. El-Naggar, A.; Awad, Y.M.; Tang, X.Y.; Liu, C.; Niazi, N.K.; Jien, S.H.; Tsang, D.C.W.; Song, H.; Yong, S.O.; Sang, S.L. Biochar influences soil carbon pools and facilitates interactions with soil: A field investigation. *Land Degrad. Dev.* **2018**. [CrossRef]
185. Yu, K.L.; Show, P.L.; Ong, H.C.; Ling, T.C.; Chen, W.H.; Salleh, M.A.M. Biochar production from microalgae cultivation through pyrolysis as a sustainable carbon sequestration and biorefinery approach. *Clean. Technol. Environ. Policy* **2018**, *20*, 2047–2055. [CrossRef]
186. Panwar, N.L.; Pawar, A.; Salvi, B.L. Comprehensive review on production and utilization of biochar. *SN Appl. Sci.* **2019**, *1*, 168. [CrossRef]
187. Schiermeier, Q. Putting the carbon back: The hundred billion tonne challenge. *Nature* **2006**, *442*, 620–624. [CrossRef]
188. Lehmann, J.; Gaunt, J.; Rondon, M. Bio-char sequestration in terrestrial ecosystems—A review. *Mitig Adapt. Strat Glob. Chang.* **2006**, *11*, 403–427. [CrossRef]
189. Oguntunde, P.G.; Abiodun, B.J.; Ajayi, A.E.; van de Giesen, N. Effects of charcoal production on soil physical properties in Ghana. *J. Plant. Nutr. Soil Sci.* **2008**, *171*, 591–596. [CrossRef]
190. Dang, V.M.; Joseph, S.; Van, H.T.; Mai, T.L.A.; Duong, T.M.H.; Weldon, S.; Taherymoosavi, S. Immobilization of heavy metals in contaminated soil after mining activity by using biochar and other industrial by-products: The significant role of minerals on the biochar surfaces. *Environ. Technol.* **2019**, *40*, 3200–3215. [CrossRef]
191. Bolan, N.S.; Choppala, G.; Kunhikrishnan, A.; Park, J.; Naidu, R. Microbial transformation of trace elements in soils in relation to bioavailability and remediation. In *Reviews of Environmental Contamination and Toxicology*; Springer: New York, NY, USA, 2013; pp. 1–56.
192. Aziz, T.; Ullah, S.; Sattar, A.; Nasim, M.; Farooq, M.; Khan, M.M. Nutrient availability and maize (Zea mays. L) growth in soil amended with organic manures. *Int. J. Agric. Biol.* **2010**, *12*, 621–624.
193. Alshankiti, A.; Gill, S. Integrated plant nutrient management for sandy soil using chemical fertilizers, compost, biochar and biofertilizers. *J. Arid. Land Stud.* **2016**, *26*, 101–106.
194. Bohara, H.; Dodla, S.; Wang, J.J.; Darapuneni, M.; Acharya, B.S.; Magdi, S.; Pavuluri, K. Influence of poultry litter and biochar on soil water dynamics and nutrient leaching from a very fine sandy loam soil. *Soil Tillage Res.* **2019**, *189*, 44–51. [CrossRef]
195. Brockhoff, S.R.; Christians, N.E.; Killorn, R.J.; Horton, R.; Davis, D.D. Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar. *Agron. J.* **2010**, *102*, 1627–1631. [CrossRef]
196. Lehman, J.; Silva, J.P.D.; Steiner, C.; Nehls, T.; Zech, W.; Glaser, B. Nutrients availability and leaching in an archaeological Anthrosol and Ferralsol of the Central Amazon basin: Fertilizer, manure, and charcoal amendments. *J. Plant. Soil* **2003**, *249*, 343–357. [CrossRef]
197. Tian, X.; Li, C.; Zhang, M.; Wan, Y.; Xie, Z.; Chen, B.; Li, W. Biochar derived from corn straw affected availability and distribution of soil nutrients and cotton yield. *PLoS ONE* **2018**, *13*, e0189924. [CrossRef]
198. Yu, H.; Zou, W.; Chen, J.; Chen, H.; Yu, Z.; Huang, J.; Gao, B. Biochar amendment improves crop production in problem soils: A review. *J. Environ. Manag.* **2019**, *232*, 8–21. [CrossRef]
199. Nartey, O.D.; Zhao, B. Biochar Preparation, Characterization, and Adsorptive Capacity and Its Effect on Bioavailability of Contaminants: An Overview. *Adv. Mater. Sci. Eng.* **2014**. [CrossRef]
200. Poole, N. *Smallholder Agriculture and Market. Participation*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2017.
201. Buol, S.W.; Eswaran, H.O. *Advances in Agronomy*; Academic Press: Cambridge, MA, USA, 1999; Volume 68, pp. 151–195.
202. Safaei Khorram, M.; Fatemi, A.; Khan, M.A.; Kiefer, R.; Jafarnia, S. Potential risk of weed outbreak by increasing biochar's application rates in slow-growth legume, lentil (Lens culinaris Medik.). *J. Sci. Food Agric.* **2018**, *98*, 2080–2088. [CrossRef]

203. Kavitha, B.; Reddy, P.V.L.; Kim, B.; Lee, S.S.; Pandey, S.K.; Kim, K.H. Benefits and limitations of biochar amendment in agricultural soils: A review. *J. Environ. Manag.* **2018**, *227*, 146–154. [CrossRef]
204. Anyanwu, I.N.; Alo, M.N.; Onyekwere, A.M.; Crosse, J.D.; Nworie, O.; Chamba, E.B. Influence of biochar aged in acidic soil on ecosystem engineers and two tropical agricultural plants. *Ecotoxicol. Environ. Saf.* **2018**, *153*, 116–126. [CrossRef]
205. Hol, W.G.; Vestergård, M.; ten Hooven, F.; Duyts, H.; van de Voorde, T.F.; Bezemer, T.M. Transient negative biochar effects on plant growth are strongest after microbial species loss. *Soil Biol. Biochem.* **2017**, *115*, 442–451. [CrossRef]
206. Zhao, J.; Ren, T.; Zhang, Q.; Du, Z.; Wang, Y. Effects of biochar amendment on soil thermal properties in the North China Plain. *Soil Sci. Soc. Am. J.* **2016**, *80*, 1157–1166. [CrossRef]
207. Vaccari, F.P.; Maienza, A.; Miglietta, F.; Baronti, S.; Di Lonardo, S.; Giagnoni, L.; Valboa, G. Biochar stimulates plant growth but not fruit yield of processing tomato in a fertile soil. *Agric. Ecosyst. Environ.* **2015**, *207*, 163–170. [CrossRef]
208. Denyes, M.J.; Rutter, A.; Zeeb, B.A. Bioavailability assessments following biochar and activated carbon amendment in DDT-contaminated soil. *Chemosphere* **2016**, *144*, 1428–1434. [CrossRef]

Received: 4 May 2021 | Revised: 30 September 2021 | Accepted: 13 October 2021

DOI: 10.1111/sum.12773

RESEARCH PAPER

Soil Use and Management | WILEY

Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil

Muhammad Ayaz[1] | **Urte Stulpinaite**[1] | **Dalia Feiziene**[1] | **Vita Tilvikiene**[1] | **Kashif Akthar**[2] | **Edita Baltrėnaitė-Gedienė**[3] | **Nerijus Striugas**[4] | **Urooj Rehmani**[5] | **Sahib Alam**[5] | **Rashid Iqbal**[6] | **Monika Toleikiene**[1] | **Modupe Doyeni**[1]

[1]Institute of Agriculture, Lithuanian Research Center for Agriculture and Forestry, Kedainiai, Lithuania

[2]State Key Laboratory for Conservation and Utilization of Subtropical Agro-Bio-Resources, College of Life Science and Technology, Guangxi University, Nanning, China

[3]Vilnius Gediminas Technical University, Vilnius, Lithuania

[4]Lithuanian Energy Institute, Kaunas, Lithuania

[5]Department of Agronomy and Agricultural Chemistry, The Univeristy of Agriculture, Peshawar, Pakistan

[6]Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Punjab, Pakistan

Correspondence
Muhammad Ayaz, Institute of Agriculture, Lithuanian Research Center for Agriculture and Forestry, Kedainiai, Lithuania.
Email: muhammad.ayaz@lammc.lt

Funding information
The authors received no external funding

Abstract

Management of heavy metal-contaminated soil under drought and other harsh hydrological conditions is critical for protecting soil ecosystem services. In this study, we examined the effect of pig manure digestate-derived biochar as a soil amendment (15 t ha^{-1}) with N fertilizer (180 kg ha^{-1}) on soil and plant heavy metal levels and nutrient availability under various moisture regimes (optimal moisture ~15%, drought condition ≤5%, and flooded condition ≥35% wt.). It was observed that biochar applications significantly decreased heavy metals in the spring wheat plants, lowering Cr by 90%, Ni by 50%, Cd by 9% and Pb by 34% compared to non-biochar (control) treatments. However, the pig digestate-derived biochar increased heavy metals in soil under all moisture regimes, increasing soil Cr by 21%, Ni by 43%, Cu by 55%, Zn by 70%, and Pb by 12%. The availability of macroelements also increased with the biochar applications under the optimum moisture regimes in both soil and plants, increasing Mg^{2+} by 11%, P by 4%, K^+ by 50%, and Ca^{2+} by 56% in the soil, and Mg^{2+} by 13%, P by 69%, K^+ by 29, and Ca^{2+} by 39% in plants. Biochar addition also improved chlorophyll fluorescence (CF) levels in the crop for the entire season (12^{th} to 62^{nd} day) and the aboveground crop biomass and dry matter contents both increased. Consequently, the use of pig manure digestate-derived biochar with N fertilizer under normal moisture conditions was able to reduce heavy metal availability to plants and thus could be used in contaminated soils to maintain better crop growth and development.

KEYWORDS
biochar, crop yield, heavy metals, land degradation, soil moisture

1 | INTRODUCTION

Industrial and agricultural activities have detrimentally affected the natural environment (Kumar et al., 2021). The substantial amount of heavy metals (HMs) released to soils through anthropogenic activities has become a global concern because of their detrimental impact on food security and human health (Girault et al., 2016; Kumar et al., 2021; Salam, Shaheen, et al., 2019). If they are transmitted through the human agri-food continuum, HM exposure can cause diseases such as cancer (Rashmi et al., 2020). Therefore, adequate action must be taken to diminish the impact of HMs in polluted soils. The use of biochar as an organic amendment is an economical and efficient way to treat hazardous substances such as HMs by lowering their bioaccumulation and availability in contaminated soils (Zhou et al., 2021).

Biochar is a black, porous carbon product that is produced through pyrolysis of organic remains such as manures, animal digestates, forests and plants residues, and other wastes under limited oxygen conditions at 200–900°C (Kumar et al., 2021; Yan et al., 2020). It has the ability to stabilize HMs by processes such as surface adsorption, ion exchange and precipitation as a result of its multiple surface functional groups, high specific surface area, alkalinity and cation exchange capacity (CEC) (Bandara et al., 2020). It is particularly effective in lowering Pb and Cd availability in soil (Chen et al., 2018; Wang et al., 2021).

To assess the effectiveness of biochar to stabilize HMs in contaminated soils, researchers have used sequential leaching procedures and discharge kinetics (Kumar et al., 2021; Wang et al., 2020). For example, Ahmad et al., 2016 reported on soya bean stover and pine-needle-derived biochar (produced at 300 and 700°C) applied at a dosage rate of 10% wt. They found it lowered the exchangeable carbonate fraction up to 79% and bound fractions of HMs, for example Pb in an alkaline, contaminated loam soil, whereas the organic matter and residual HMs fractions increased by up to 41%. One study showed that sheep manure-derived biochar and vermicompost-derived biochar (300–500°C) substantially reduced heavy metal concentration in plants (Boostani et al., 2019). It was concluded that biochar amendments significantly lowered carbonate (10%–11%) and exchangeable (10%–20%) forms of soil HMs. Additionally, rice straw-derived and rapeseed residue-derived biochar amendment at 5% (wt.) substantially lowered the easily accessible fractions of HMs, for example Pb and Cu in polluted and partially acidic soils (Salam, Bashir, et al., 2019).

Soil moisture content influences the allocation of HMs among soil phases, with impacts on soil pH, soil redox potential, transition in Fe oxides, decomposition and conversation of soil organic matter (Qi et al., 2014; Shaheen et al., 2019). However, there is limited published literature regarding the impact of soil hydrothermal conditions on the chemical forms of HMs and their adsorption in contaminated soils. In one study, the influence of different soil field capacities (FC) on HM availability in a naturally contaminated soil was observed to be lowest at 40% and highest at 80% of soil FC (Salam, Shaheen, et al., 2019). A percentage of soil HMs was transfigured from an exchangeable fragment to a less labile fragment (iron oxide phase) after incubation with water. They reported that after 180 days of water incubation, the release of HMs was restrained and reduced leaching of Cu, Zn, Cd and Pb by as much as 2%–8% (Yang et al., 2016).

The high surface area, porous structure of biochar also impacts soil moisture and, therefore, H_2SO_4-modified biochar with higher surface area has emerged with improved performance in this area (Lau et al., 2017). Numerous field studies and pot experiments have identified biochar's ability to improve crop yields and build up C stocks in several soil types, especially in nutrient-poor soils (Ali et al., 2021; Khadem et al., 2021). It is reported that due to its porous structure, biochar increases microbial activity and nutrient supply in soil and decreases nutrient loss (Ayaz et al., 2021; Egamberdieva et al., 2016). As a result of a liming effect (Köster et al., 2021), biochar encourages the provision of major macro- and micronutrients needed for plant growth (Ahmed et al., 2016; El-Bassi et al., 2021; Mandal et al., 2020). For example, one study showed that the application of rice- and cowpea-derived biochar (68 t ha^{-1}) enhanced crop biomass by 20% and 50%, respectively (Ali et al., 2021; Ayaz et al., 2021; Egamberdieva et al., 2016).

Soil contamination and degradation is a serious global issue and a threat to the United Nations' sustainable development goals (SDGs) (Hou, 2021). The shared aim of the global scientific community is to overcome the challenges of hunger, poverty, inequality, etc. (SDG, U. N., 2019). Our current research work on biochar allies with SDGs 2, 12 and 13 to end hunger, responsible consumption and production, and climate action, respectively, through increased food security, improved nutrition and sustainable agriculture (Mancini et al., 2019).

We hypothesized that the biogeochemical reallocation of HMs, the degree of HMs discharge and thus bioaccumulation may differ after applying biochar under the different soil hydrological conditions. Therefore, the objective of this research was to investigate the influence of biochar derived from pig manure digestate applied at 15 t ha^{-1} under three types of soil moisture regimes—optimal moisture (W—water content ≥15%), drought condition ($W \leq 5\%$) and flooded condition ($W \geq 35\%$) and their interactions on soil HMs release in soil and plant uptake.

2 | MATERIALS AND METHODS

2.1 | Experimental site and design

Endocalcaric Epigleyic Cambisol soil (WRB-IUSS, 2014) was obtained from the top 0–20 cm layer of a field at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry (55°23′49″N 23°51′40″E). The soil was air-dried and passed through a 2-mm mesh sieve. Pig manure digestate-derived biochar was manually mixed with soil at the rate of 15 t ha^{-1} and synthetic nitrogen (N) fertilizer in form of ammonium nitrate applied at a rate of 160 kg ha^{-1} (applied on day 20 after sowing). Small-sized plastic pots 27 cm diameter and 25 cm height were filled with 10 kg of soil. The pots were installed with closed-loop irrigation control system to control irrigation and soil moisture regimes. A randomized complete block design (RCBD) experiment was designed with six treatments and three replications each, for example M1B1 = (Soil and Biochar + Normal moisture regime, $W \geq 15\%$), M2B1 = (Soil and Biochar + drought condition, $W \leq 5\%$), M3B1 = (Soil and biochar + excess of moisture, $W \geq 35\%$), M1B0 = (Soil and No biochar + Normal moisture regime, $W \geq 15\%$), M2B0 = (Soil and no biochar + drought, $W \leq 5\%$ condition), M3B0 = (Soil and no biochar with excess of moisture, $W \geq 35\%$ condition). Ten seeds of spring wheat crop were sown in each pot. After two weeks, each pot was thinned and six healthy plants were left in the pots.

2.2 | Production and characterization biochar and soil

Pig manure waste was collected from an active farm. The manure was air-dried for 48 h and manually ground. The feedstock was heated at 550°C in a cylindrical furnace for 5–6 h under anaerobic conditions to produce biochar (Boostani et al., 2019). Physiochemical properties of the biochar and soil were analysed by standard laboratory methods. Soil and biochar (pH) and EC analysis was analysed as a 1:5 (vol vol^{-1}) soil mixture in 1 M KCl solution (Buneviciene et al., 2020) and extracted to distilled water (Yang et al., 2016). Cation exchange capacity was determined by the updated ammonium-acetate method (Gaskin et al., 2008). Thermo analysis of the feedstock during thermal decomposition was tested at the Lithuanian Energy Institute with thermal analyser (Netzsch Jupiter STA 449 F3). The biochar pyrolysis process was applied with a 35°C min^{-1} heating rate at the temperature range 40–900°C. To create an inert atmosphere, N2 carrier gas (60 ml min^{-1}) was used. Specific surface area was measured using Sear's method (Sears, 1956).

2.3 | Heavy metals and major nutrient analysis in soil and biochar

Dried soil and biochar samples (1 g) were mixed with 25 ml 0.1 M $CaCl_2$ solution and shaken for 2 h on an orbital shaker before being centrifuged for 15 min. The final solution was filtered and HMs analysed (Ni, Cr, Cd, Pb, Cu, Zn) using an ICP-OES (Optima 2000, PerkinElmer Co.). Soil and biochar samples were dissolved with HF–$HClO_4$–HNO_3, filtered, and then analysed by ICP-OES (Carignan & Tessier, 1988) for heavy metal fractions. Extractable nutrients P, K, Ca and Mg were measure by ICP-OES after DTPA extraction (Zaccheo et al., 2017).

2.4 | Crop biomass and dry matter analysis

Plants were harvested after 2 months. The aboveground biomass fresh weight was determined. Plants were separated into leaves, stems, roots and ear and for weighing. The aboveground dry biomass was determined after drying in an oven at 70°C until constant weight. The final grain yield was calculated by as the total number of ears per pot, the number of grains per ear and the average grain weight (Vitkova et al., 2017).

2.5 | Statistical analysis

All data sets were normally distributed and were subsequently subjected to analysis of variance (ANOVA) followed by the least significant difference (LSD) test. All data analyses were carried out using Statistix 8.1 and GraphPad PRISM 8 software. The ranked coefficient analysis was performed using R-studio software.

3 | RESULTS

3.1 | Effect of biochar on soil heavy metals

Heavy metal (HM) contents varied in soil under different treatments and moisture regimes. The biochar amendment significantly enhanced Cr content in soil (by 12.35%, $p \leq .01$) compared to no biochar amendment (Figure 1a). Biochar application and optimal moisture significantly increased ($p \leq .01$) Ni by 59.67% and 80%, Cu by 19.90%, 38.90%, Zn by 18.93%, 41.01% and Pb by 16.02%, 38.8% in soil compared no biochar application and drought condition, respectively (Figure 1b,c,d,f). However, Cd content decreased in soil under drought conditions compared to 15% and 35% moisture regimes (Figure 1e), whereas no significance was recorded after biochar application. The factorial interaction of treatments also showed significant variation among all treatments.

The flooded moisture condition with 15 t ha^{-1} of biochar (M3B1) significantly enhanced the Cr content by 21% ($p \leq .05$) in soil compared to non-biochar treatments under optimal moisture regime (Figure 1a). Ni content was substantially increased by 42.96%

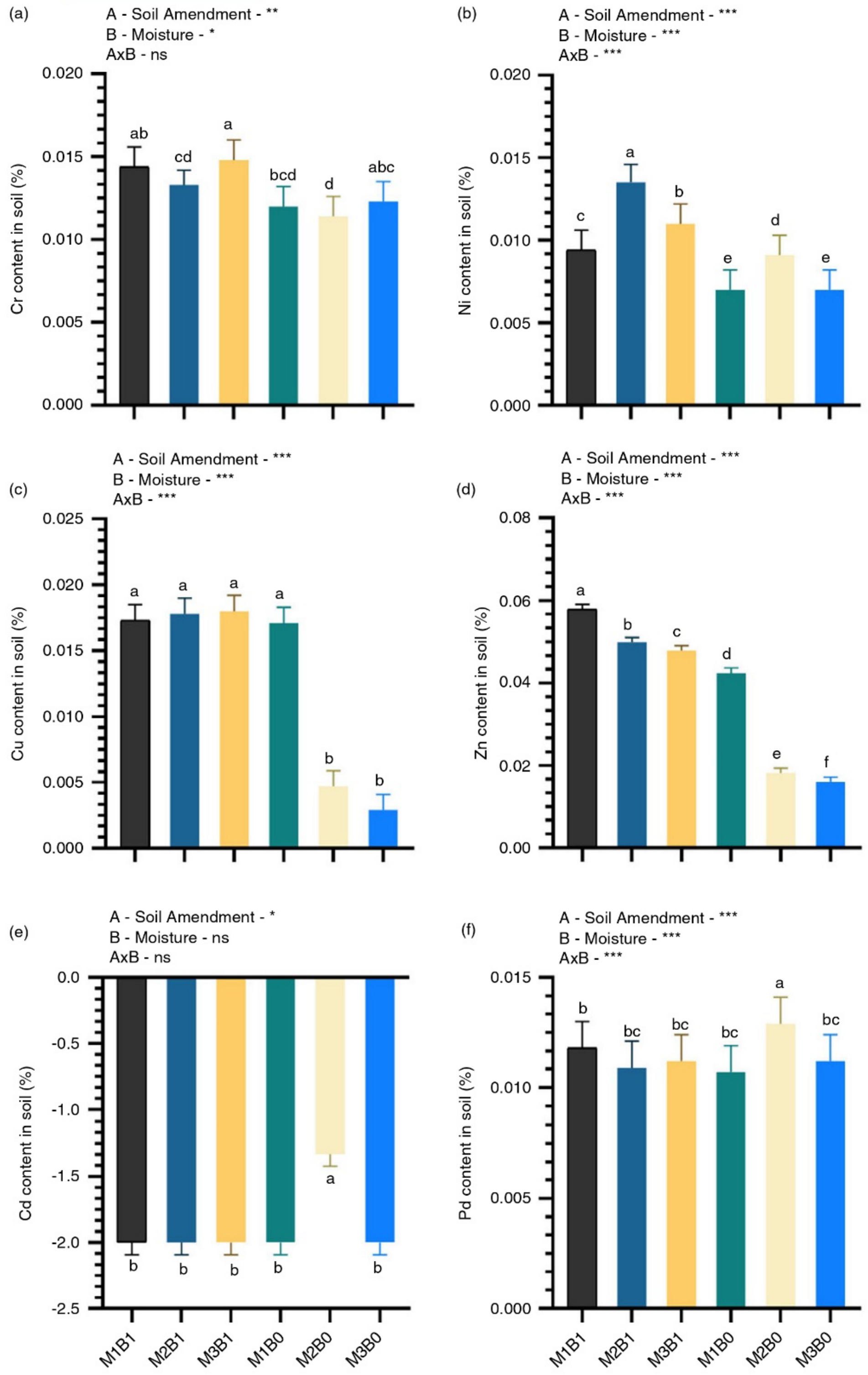
(a)
A - Soil Amendment - **
B - Moisture - *
AxB - ns
Cr content in soil (%)
(b)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Ni content in soil (%)
(c)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Cu content in soil (%)
(d)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Zn content in soil (%)
(e)
A - Soil Amendment - *
B - Moisture - ns
AxB - ns
Cd content in soil (%)
(f)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Pd content in soil (%)
M1B1
M2B1
M3B1
M1B0
M2B0
M3B0

FIGURE 1 The interactive effect of moisture and biochar on soil heavy metals, for example (a) Chromium, (b) Nickel, (c) Copper, (d) Zinc, (e) Cadmium and (f) Lead. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001), respectively

($p \leq .05$) with biochar amendment under drought condition (M2B1) compared to all no biochar treatments and M1B1 (Figure 1b). All biochar-treated soils under all types of moisture regimes significantly (by 55.36%, $p \leq .05$) enhanced Cu content in soil compared to non-biochar treatments (Figure 1c), except the M1B0 treatment where Cu content was similar to the biochar-amended treatments. Zn content in soil significantly increased by 70.46% ($p \leq .05$) in the biochar treatment under optimal moisture regime (M1B1) compared to non-biochar treatments with drought (M2B0) and flooded (M3B0) conditions (Figure 1d). However, soil Cd content decreased during the experiment period under different moisture regimes with biochar amendments compared to drought condition without biochar (M2B0) application (Figure 1e). Pb was the only heavy metal found to be significantly higher in soil (by 12.40%, $p \leq .05$) under drought condition without biochar (M2B0) application (Figure 1f). Overall, pig manure-derived biochar amendments with different moisture regimes enhanced the content of all heavy metals in soil, except Cd.

3.2 | Effect of biochar on plant heavy metals

The biochar amendment reduced Cd, Pb, Cr and Ni contents in crops; however, the strength of this influence depended on the moisture regime (Figure 2). Biochar application under optimal moisture conditions (M1B1) caused 88.9% lower Cr content than under drought (M2B1) or moisture excess (M3B1) conditions. Biochar application reduced Ni content in crops under all moisture regimes, especially in drought conditions. Biochar amendment was most beneficial for Cd and Pb content reduction in crops under optimal and excess moisture conditions. An effect of biochar over no-biochar was registered only for reduction of Ni and Pb accumulation in crops. Whereas in treatments with biochar application, Cu and Zn accumulation in crop tended to rise compared to no-biochar treatments. Figure 2 reflects that biochar significantly immobilized Cr, Ni and Pb content in plants under different moisture regimes and enhanced Cu and Zn content in biochar-treated plants under drought condition (M2B1).

3.3 | Effect of biochar on major elements in soil

Biochar application affected major elements, although this was dependent on soil moisture content. On average, P and Ca content was substantially higher (46.63% and 13.38%, respectively, $p \leq .01$) with biochar amendment compared to non-biochar application. However, the effect of biochar on soil K and Mg content was not so high (5.81% and 3.34%, respectively). Drought and moisture excess decreased biochar contribution for accumulation of soil elements. Biochar application under optimal moisture had a significant ($p \leq .001$) effect on increasing P, K, Mg and Ca content (by 37.34%, 9.39%, 12.68% and 11.10%, respectively), compared to drought and flooded conditions without biochar application (Figure 3). The factorial interaction of treatments revealed substantial effect on soil major elements. Optimum moisture regime at 15 t ha^{-1} of biochar application significantly ($p \leq .001$) enhanced soil P, K, Mg and Ca content (by 49.79%, 13.29%, 10.53% and Ca 29.11%, respectively), compared to no biochar under optimum moisture condition. These results indicate that the interaction of biochar and optimal moisture (15%) in treatment M1B1 could be a good strategy to improve soil major element accumulation.

3.4 | Effect of biochar on major elements in plants

Biochar as soil amendment increased crop nutrient accumulation. Data averaged across soil moisture regimes revealed that biochar caused significantly higher P content in plants (36.60%, $p \leq .01$) compared to non-biochar treatments. Mean data showed that moisture had no significant influence on plant P content (Figure 4a). The rest of the major elements, that is K, Mg and Ca were significantly ($p \leq .01$) affected by both factors (biochar and moisture). Plant K, Mg and Ca content in treatments M1B1, M2B1 and M3B1 were higher by 18.13% + 3.91%, 3.71% + 14.28% and 17.29% + 27.17%, respectively, compared to treatments M1B0, M2B0 and M3B0 (Figure 4b–d). The best results were obtained after biochar amendment under optimum moisture regimes (M1B1). In this treatment, P, K, Mg and Ca contents were higher by 55.62%, 68.95%, 3.80% and 38.52%, respectively, compared to the same moisture

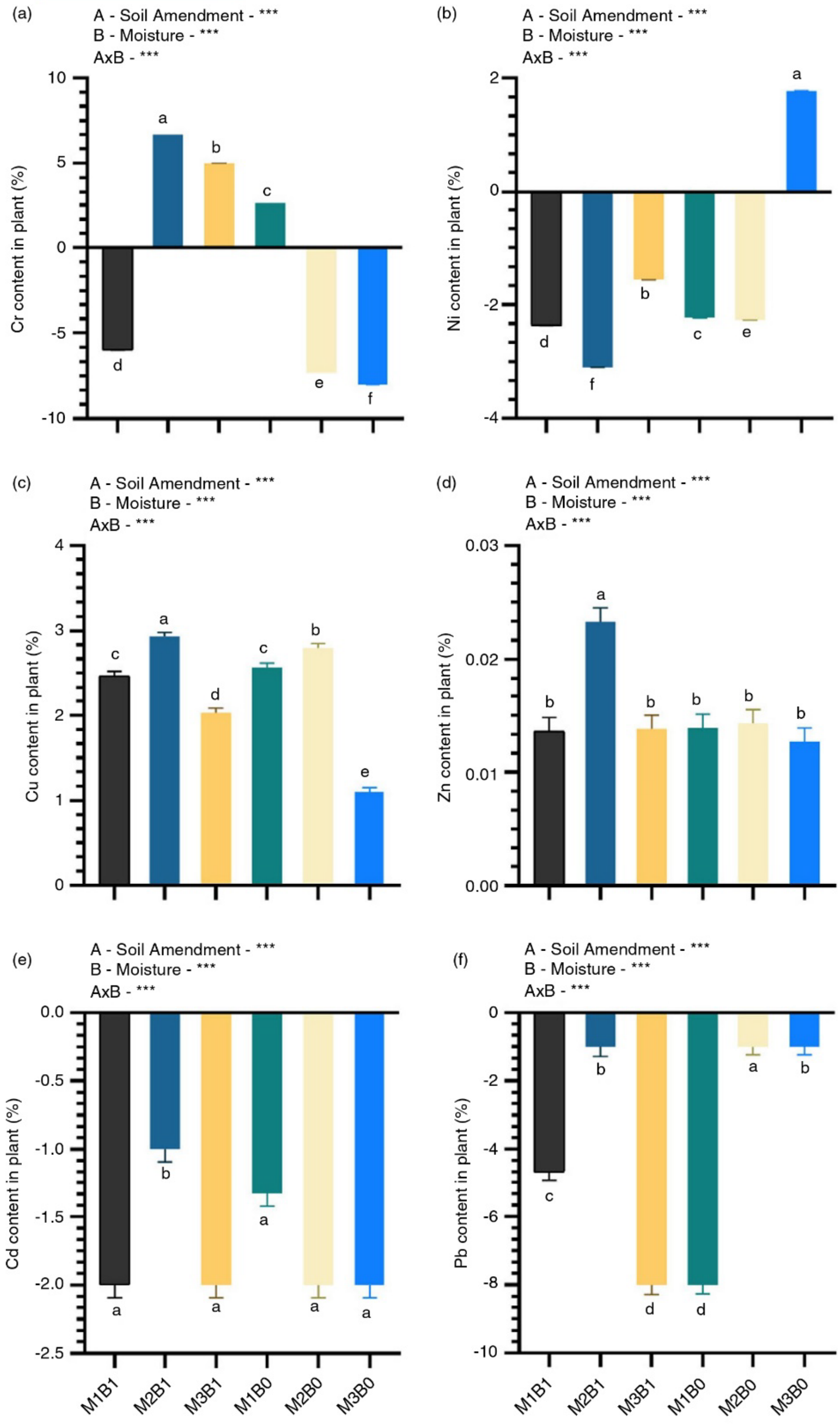
(a)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Cr content in plant (%)
10
5
0
-5
-10
a
b
c
d
e
f
(b)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Ni content in plant (%)
2
0
-2
-4
a
b
c
d
e
f
(c)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Cu content in plant (%)
4
3
2
1
0
a
b
c
c
d
e
(d)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Zn content in plant (%)
0.03
0.02
0.01
0.00
a
b
b
b
b
b
(e)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Cd content in plant (%)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
a
b
a
a
a
a
(f)
A - Soil Amendment - ***
B - Moisture - ***
AxB - ***
Pb content in plant (%)
0
-2
-4
-6
-8
-10
c
b
d
d
a
b
M1B1
M2B1
M3B1
M1B0
M2B0
M3B0

FIGURE 2 The interactive effect of moisture and biochar on plants heavy metals, for example (a) Chromium, (b) Nickel, (c) Copper, (d) Zinc, (e) Cadmium and (f) Lead. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001), respectively

condition with no biochar application (Figure 4a–d). It is concluded that biochar application under moisture ≤5% and 15% (treatments M1B1 and M2B1) could improve major element accumulation in plants compared to non-biochar treatments.

3.5 | Impact of biochar on chlorophyll fluorescence and chlorophyll index

The influence of different moisture regimes on chlorophyll fluorescence (CF) during the whole season was insignificant; however, biochar substantially ($p \le .01$) increased CF throughout the season, for example on day 12^{th}, 20^{th}, 27^{th}, 34^{th}, 47^{th} and 62^{nd} (i.e. by 21.29%, 20.21%, 23.95%, 10.44%, 14.52% and 9.28%, respectively) compared to non-biochar treatments (Figure 5a). Moisture regimes did not highlight significant differences under biochar application (Figure 5a).

Similarly, the effect of different moisture regimes on chlorophyll index (CI) was non-significant; however, biochar amendment substantially ($p \le .01$) increased CI on day 12^{th}, 20^{th}, 27^{th}, 34^{th}, 47^{th} and 62^{nd} (by 21.50%, 9.20%, 21.56%, 6.64%, 13.96%, and 20.35%, respectively), compared to non-biochar treatments (Figure 5b). These results reflect that biochar application irrespective of moisture regimes can impact both CF and CI.

3.6 | Impact of biochar on aboveground biomass and dry matter content

Biochar application to the soil as an amendment significantly ($p \le .001$) enhanced aboveground biomass

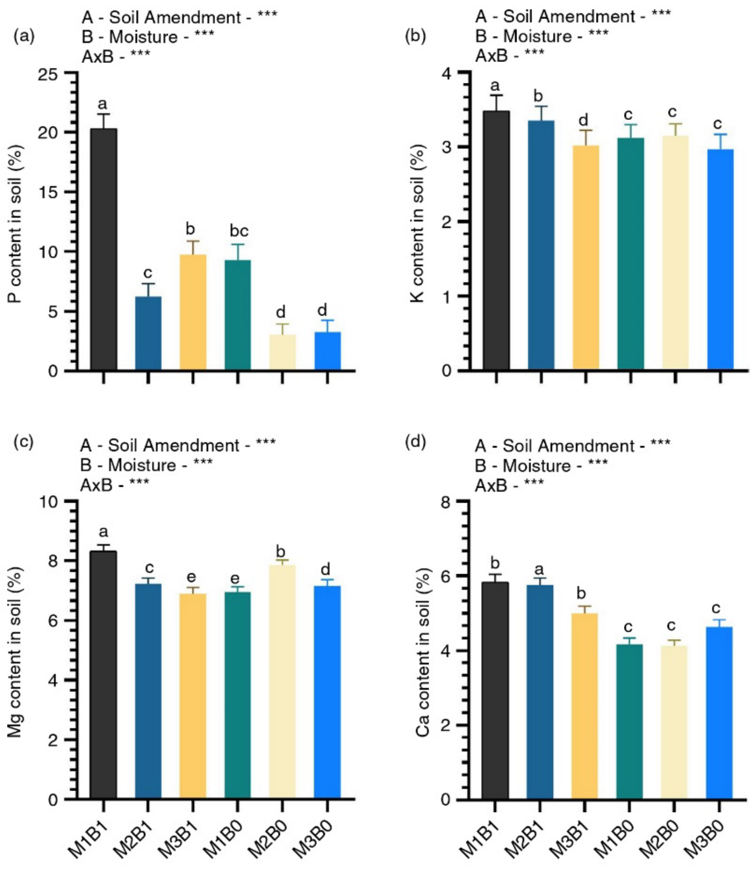

FIGURE 3 The interactive effect of moisture and biochar on major elements in soil, for example (a) Phosphorus, (b) Potassium, (c) Magnesium and (d) Calcium. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

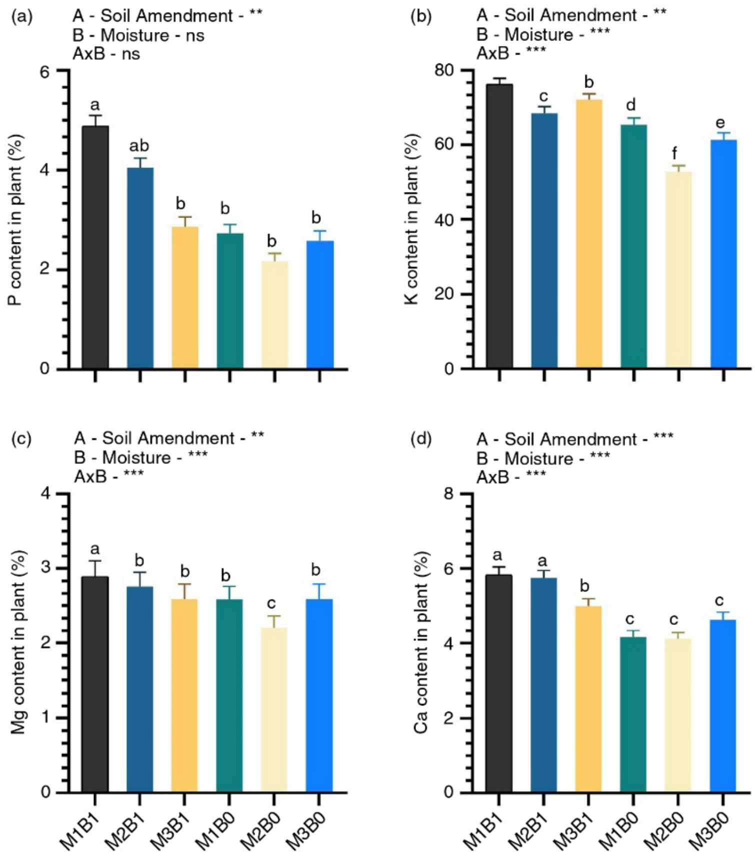

FIGURE 4 The interactive effect of moisture and biochar on major elements in plants, for example (a) Phosphorus, (b) Potassium, (c) Magnesium and (d) Calcium. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

(AGB) and dry matter content (DMC) irrespective of different moisture regimes. Factorial interaction in treatments M1B1, M2B1 and M3B1 significantly ($p \leq .05$) enhanced AGB compared with that in M1B0, M2B0 and M3B0 (by 71.87%, 66.66% and 68.64%), respectively (Figure 6). Similarly, the combination of biochar and moisture (M1B1, M2B1 and M3B1) caused significantly ($p \leq .05$) higher DMC (by 45.83%, 55.17% and 40.90%, respectively) compared with that in M1B0, M2B0 and M3B0 (Figure 3b). Thus, it indicates that biochar amendment under different moisture conditions could improve biomass, compared to no biochar applications.

3.7 | Relationship among heavy metals and major elements of soil and plant

A ranked coefficient analysis was performed among the heavy metals and major elements of soil and plants (Figure 7). All variables were significantly and positively correlated with each other. An exception was Pb, which showed negative relationship with Ca contents in plants. While Cr content in soil showed positive significant correlation with soil Cu, Zn, K and P content. Similarly, Cr content in plants showed significant positive correlation with soil Cr, Cu, Zn, Ni, Cr, K and P contents and plant K contents.

4 | DISCUSSION

4.1 | Response of biochar on heavy metals in soil and plants

The pig manure digestate-derived biochar used was rich in heavy metals (Table 1) which has also influenced heavy metal content in soil (Figure 1). Previously, it was reported that traditionally weaned pigs were fed pharmacological heavy metals (Hill et al., 1996; Smith et al., 1997), which may have led to higher heavy metal content in biochar and thereby biochar treatments significantly increased heavy metal content in the soil (Figure 1). Beesley et al. (2015)

reported that refurbishing of heavy metal–contaminated bases may be considered appropriate for soil amendment, particularly where the impact is the accessibility of certain metals. The evident case is Zn, Ca, Cu, etc. a vital plant nutrient and essential element to strengthen fodder but, in large, a toxin.

Our results showed that Cd content in soil was lowered (Figure 1). The exchangeable Cd content response to pH is essential to understand the influence of biochar on the bioavailability of Cd. It is reported that increase in soil pH causes hydrolysis of heavy metal cations to form oxides, which lowers the soil exchangeable Cd content (Chen et al., 2020). Furthermore, several studies have documented that biochar amendment can substantially affect the absorption and reabsorption of heavy metals in soil (Wang & Zhou, 2003; Yuan et al., 2011). Biochar application adds large amount of organic matter into soil which has active groups, thus facilitating chelation and complexation with Cd as ligands, which consequently reduces the Cd availability in soil (Zhu et al., 2008).

Biochar reduced heavy metals in plants (Figure 2) which was confirmed by Liu, Huang et al. (2021) where sewage sludge biochar (500–550°C) and broiler litter-derived biochar (700°C) substantially reduced heavy metals in plants due to the fact of splitting of metals from exchangeable form to less bioavailable organic bond proportion. The positive side that biochar immobilize heavy metals was attributed to enhancing the absorptive capacity of soil by altering the physical and chemical characteristics, as well by means of dynamoelectric attraction, cation and anion exchange, and physical absorptivity (He et al., 2019). Other sorption factors influenced by biochar include soil organic and mineral matter content, soil pH and CEC.

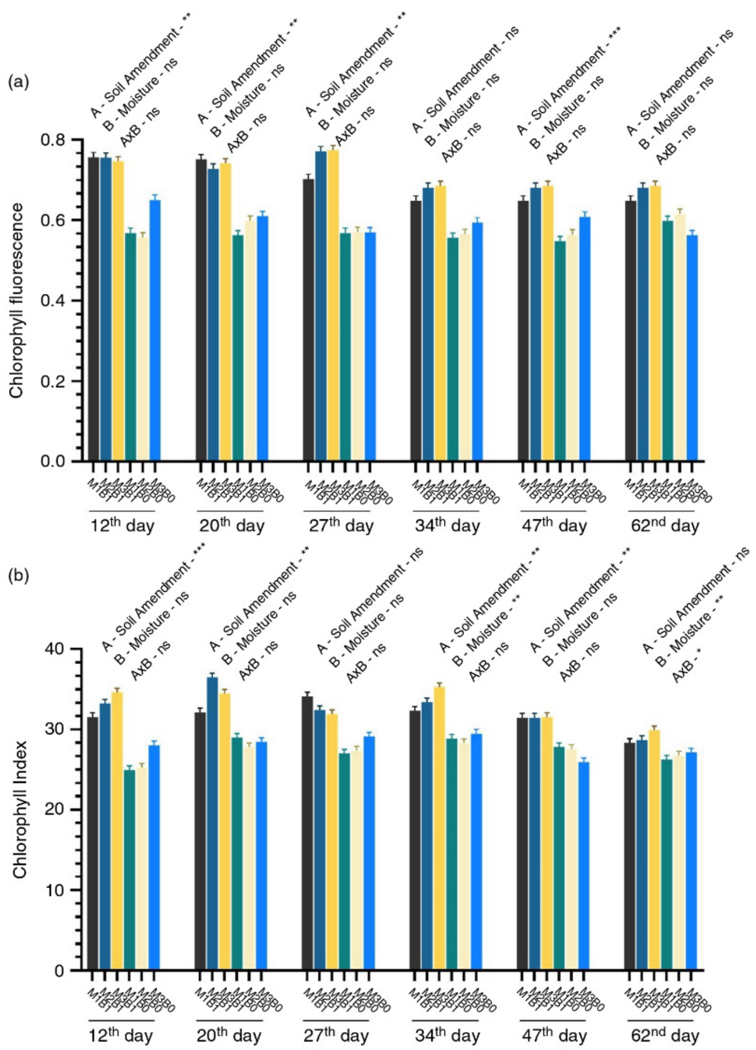

FIGURE 5 The interactive effect of moisture and biochar on (a) chlorophyll fluorescence and (b) SPAD chlorophyll index. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

4.2 | Effect of biochar on major elements in soil and plants

Several studies have documented that moisture conditions can significantly impact the soil nutrients and plant, morphological properties and biological variables (Ghanbary et al., 2018; Jafarnia et al., 2018). The current research indicates that major elements in soil and plants were positively affected under biochar treatment (M2B1) compared to non-biochar treatments under the same moisture regimes (Figures 3 and 4). Consequently, the negative effects of comparative moisture regimes are bounded by biochar application. Various reasons were reported for the ameliorative behaviour of biochar, that is application of biochar enhances fine pore structure, improves surface area (Kalus et al., 2019) and increases soil aeration and porosity which leads to strengthening the soil bulk density (Bd) and water holding capacity (WHC) (Chang et al., 2021; Guo et al., 2021; Xie et al., 2021).

Plant nutrient uptake and soil nutrient absorption (Mg, P and K) was substantially improved via biochar amendment under optimal moisture regimes (Figure 4). This is because of the biochar's richness in major nutrients which were released into soil after mineralization (Farhangi-Abriz & Ghassemi-Golezani, 2021; Plaimart et al., 2021); improvement in soil microbial density and WHC and reduction in nutrient lost could be attributed as the secondary impacts of biochar amendment (Kanthle et al., 2016; Tian et al., 2018). Similar results were reported by Farrar et al. (2021) where bamboo-derived biochar remarkably increased trace elements in plants and soil. Our results were also in line with those of Ref. (Liu et al., 2020; Zhang et al., 2020) who indicated that biochar application enhanced trace elements Mg, P and K in soil and plants.

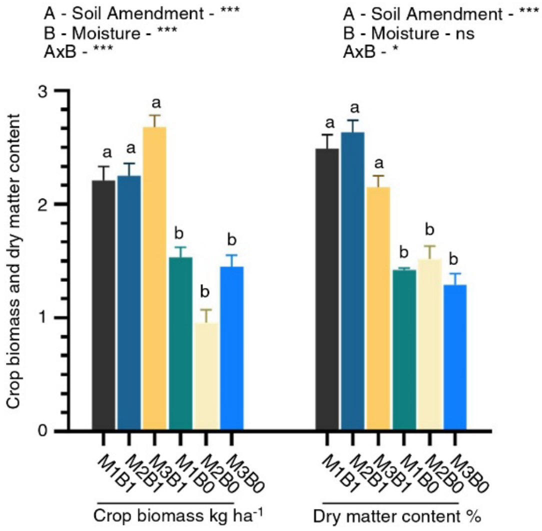

FIGURE 6 Response of moisture regimes and biochar on crop biomass and dry matter content under different moisture regimes. M1B1 = Optimum moisture (15%) with biochar (25 t ha^{-1}), M2B1 = drought condition (≤5) with biochar (25 t ha^{-1}), M3B1 = flooded condition (≥35) with biochar (25 t ha^{-1}), M1B0 = Optimum moisture (15%) with no biochar, M2B0 = drought condition (≤5) with no biochar, M3B0 = flooded condition (≥35) with no biochar. Different stars *, ** and *** represents statistical significance (>0.05, 0.01 and 0.001) respectively

4.3 | Impact of biochar on chlorophyll fluorescence and chlorophyll index

The effects of soil moisture condition on plants depends on its severity and plant genotypic condition (Vijayaraghavareddy et al., 2020). In the current research, physiological properties such as chlorophyll fluorescence and chlorophyll index significantly increased with each time interval under biochar treatments M1B1, M2B1 and M3B1, thus lowering the adverse effect of drought stress compared to non-biochar treatment (Figure 5). When a plant is subjected to drought conditions, it closes the stomata to maintain homeostasis and consequently lowering leaf transpiration. Stomata closure could provoke a deterioration in the photosynthetic rate under drought conditions (Hereme et al., 2020).

Major elements (P, K and Mg) can induce the transformation of photosynthetic electrons (Saccon et al., 2020) and regulate osmotic potential (Hafeez et al., 2017; Walter & Rajashekhar Rao, 2015). Biochar application could substantially enhance nutrient fraction in leaves (Hafez et al., 2020; Tanazawa et al., 2021); therefore, biochar application can mitigate these adverse consequences and ameliorate the chlorophyll fluorescence and chlorophyll index (Paneque et al., 2016; Subhan et al., 2014). Furthermore, photosynthetic activity can be severely influenced by soil hydrological condition and stress injury (Lyu et al., 2016). Previously, it was indicated that biochar amendment altered soil hydrological condition for plants by improving WHC and increasing the leaf water condition (Gao et al., 2020; Liu, Wei et al., 2021). Consequently, in this work, it was recorded that biochar application to soil could lower the adverse impact of waster stress on the photosynthesis.

4.4 | Influence of biochar on aboveground biomass and dry matter content

Biochar has been proposed as a potential soil amendment to improve soil quality and increase aboveground biomass (Banik

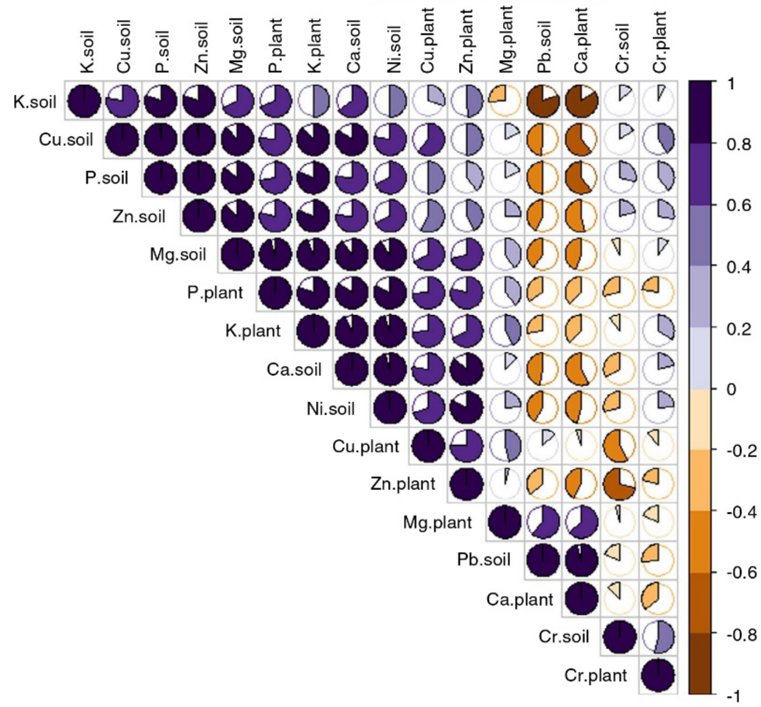

FIGURE 7 Correlation rank coefficient among major elements and heavy metals in soil and plant

TABLE 1 Physiochemical properties of soil and biochar prior to experiment

Physiochemical properties	Soil	Biochar
pH	7.5	9.1
Ash content (%)	–	32.21
Moisture wt. (%)	–	2.52
Volatiles wt. (%)	–	56.73
Residual mass (char formed) wt. (%)	–	40.75
Cr (%)	0.0113	0.0112
Ni (%)	0.010	0.014
Cu (%)	0.003	0.216
Zn (%)	0.020	0.444
Cd (%)	0.0001	0.0001
Pb (%)	0.011	0.002
Mg (%)	7.33	13.07
P (%)	0.31	18.11
K (%)	3.21	14.27
Ca (%)	10.12	75.51

et al., 2021; Elias et al., 2020) and dry matter content (Yakubu et al., 2020) particularly on degraded or highly weathered tropical soils. In the current study, pig manure digestate-derived biochar treatments (M1B1, M2B1 and M3B1) significantly enhanced aboveground biomass and dry matter compared to non-biochar treatments (Figure 6). These results were in line with Feng et al. (2021) ; Gupta et al. (2020) who applied corn straw-derived biochar and rice straw-derived biochar (5 Mg ha^{-1}) enhance crop biomass, respectively.

When biochar is applied, there is mutually reinforcement among the soil pH and ions released from biochar, which ultimately improve crop yields (Feng et al., 2021; Pulka et al., 2020). Simply put, it has ability to strengthen deteriorated soil and enhance crop production by upgrading soil quality (Zahra et al., 2021). Numerous studies have reported that biochar amendment to soil lowers soil bulk density (Chang et al., 2021; Liang et al., 2021), enhances and retains soil nutrients and organic matter content, and significantly improves soil microbiota plant growth and fruit quality (Arif et al., 2021; Jin et al., 2021; You et al., 2021).

5 | CONCLUSION AND RECOMMENDATION

The conclusions of this study are as follows:

1. Pig manure digestate-derived biochar could be a potential soil amendment for soil and plant quality improvement. At the first growing stages of spring

wheat, it significantly decreased heavy metal concentration in plants, lowering Cr by 90%, Ni by 50%, Cd by 9% and Pb by 34% compared to non-biochar treatments. However, the pig manure digestate biochar also increased heavy metals in soil under all moisture regimes, for example (Cr 21%, Ni 43%, Cu 55%, Zn 70% and Pb 12% content, respectively).
2. Biochar application significantly improved major elements (P, K, Mg and Ca) in both soil and plants under different moisture regimes. The highest concentration of those elements was found under the optimal soil humidity, while drought and flooded regimes may be the reason of loss of those elements, especially flooded soils which have high risk for leaching.
3. Plant vitality may be described by their chlorophyll fluorescence and chlorophyll index. After adding biochar to the soil, these improved throughout the growing interval (from day 12 to 62), which led to enhanced aboveground biomass and dry matter content.

For future work, we hypothesize that using different dosses of biochar as a soil amendment could have more significant results in highly contaminated and degraded soils. Further experiments are needed to analyse the long-term effect on soil and on crop quality and productivity.

ACKNOWLEDGEMENTS

I owe my deepest gratitude to my supervisor Dalia Feizienė and Co-Supervisor Dr. Vita Tilvikienė, for their valuable guidance, ideas and support during this research. I would like to extend my thanks to Lithuanian Energy Institute for providing their services and also all of my laboratory assistants and fellows for their support.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

All authors contributed to this research paper. Muhammad Ayaz had the idea for the article; performed practical and the literature search, data preparation, analyses and figures; and wrote the first draft. Dalia Feizienė and Vita Tilvikienė critically revised the work and contributed to writing and editing; Urte Stulpinaitė performed laboratory work; and Kashif Akhtar, Edita Baltrėnaitė-Gedienė, Monika Toleikienė, Modupe Doyeni, Nerijus Striug, Sahib Alam and Rashid Iqbal helped in biochar preparation and contributed to article conception, critical revision and editing of drafts. All authors read and approved the final version of the manuscript.

ORCID

Muhammad Ayaz https://orcid.org/0000-0002-8539-1017
Monika Toleikiene https://orcid.org/0000-0003-2176-4096

REFERENCES

Ahmad, M., Ok, Y. S., Rajapaksha, A. U., Lim, J. E., Kim, B. Y., Ahn, J. H., Lee, Y. H., Al-Wabel, M. I., Lee, S. E., & Lee, S. S. (2016). Lead and copper immobilization in a shooting range soil using soybean stover- and pine needle-derived biochars: Chemical, microbial and spectroscopic assessments. *Journal of Hazardous Materials*, *301*, 179–186. https://doi.org/10.1016/j.jhazmat.2015.08.029

Ahmed, A., Kurian, J., & Raghavan, V. (2016). Biochar influences on agricultural soils, crop production, and the environment: A review. *Environmental Reviews*, *24*(4), 495–502. https://doi.org/10.1139/er-2016-0008

Ali, E. F., Al-Yasi, H. M., Kheir, A. M. S., & Eissa, M. A. (2021). Effect of biochar on CO 2 sequestration and productivity of pearl millet plants grown in saline sodic soils. *Journal of Soil Science and Plant Nutrition*, *21*, 897–907. https://doi.org/10.1007/s42729-021-00409-z

Arif, M., Ikramullah, Jan, T., Riaz, M., Akhtar, K., Ali, S., Shah, S., Jalal, F., Mian, I. A., Dawar, K. M., & Wang, H. (2021). Biochar and leguminous cover crops as an alternative to summer fallowing for soil organic carbon and nutrient management in the wheat-maize-wheat cropping system under semiarid climate. *Journal of Soils and Sediments*, *21*(3), 1395–1407.

Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., & Iqbal, R. (2021). Biochar role in the sustainability of agriculture and environment. *Sustainability*, *13*(3), 1330. https://doi.org/10.3390/su13031330

Bandara, T., Franks, A., Jianming, X. U., Bolan, N., Wang, H., & Tang, C. (2020). Chemical and biological immobilization mechanisms of potentially toxic elements in biochar-amended soils. *Critical Reviews in Environmental Science and Technology*, *50*(9), 903–978. https://doi.org/10.1080/10643389.2019.1642832

Banik, C., Koziel, J. A., De, M., Bonds, D., Chen, B., Singh, A., & Licht, M. A. (2021). Biochar-swine manure impact on soil nutrients and carbon under controlled leaching experiment using a midwestern mollisols. *Frontiers in Environmental Science*, *9*, 1–11. https://doi.org/10.3389/fenvs.2021.609621

Beesley, L., Moreno-Jimenez, E., Fellet, G., Carrijo, L., & Sizmur, T. (2015). Biochar and heavy metals. In J. Lehmann, & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (2nd ed., pp. 563–594). Earthscan.

Boostani, H. R., Najafi-Ghiri, M., Hardie, A. G., & Khalili, D. (2019). Comparison of Pb stabilization in a contaminated calcareous soil by application of vermicompost and sheep manure and their biochars produced at two temperatures. *Applied Geochemistry*, *102*, 121–128. https://doi.org/10.1016/j.apgeochem.2019.01.013

Buneviciene, K., Drapanauskaite, D., Mazeika, R., Tilvikiene, V., & Baltrusaitis, J. (2020). Granulated biofuel ash as a sustainable source of plant nutrients. *Waste Management & Research*, *39*, 806–817. https://doi.org/10.1177/0734242X20948952

Carignan, R., & Tessier, A. (1988). The Co-diagenesis of sulfur and iron in acid lake sediments of Southwestern Quebec. *Geochimica et Cosmochimica Acta*, *52*(5), 1179–1188.

Chang, Y., Rossi, L., Zotarelli, L., Gao, B., Shahid, M. A., & Sarkhosh, A. (2021). Biochar improves soil physical characteristics and strengthens root architecture in muscadine grape (*Vitis rotundifolia* L.). *Chemical and Biological Technologies in Agriculture*, *8*(1), 1–11.

Chen, D. E., Liu, X., Bian, R., Cheng, K., Zhang, X., Zheng, J., Joseph, S., Crowley, D., Pan, G., & Li, L. (2018). Effects of biochar on availability and plant uptake of heavy metals – A meta-analysis. *Journal of Environmental Management*, *222*, 76–85. https://doi.org/10.1016/j.jenvman.2018.05.004

Chen, X., He, H.-Z., Chen, G.-K., & Li, H.-S. (2020). Effects of biochar and crop straws on the bioavailability of cadmium in contaminated soil. *Scientific Reports*, *10*(1), 1–12.

Egamberdieva, D., Wirth, S., Behrendt, U., Abd_Allah, E. F., & Berg, G. (2016). Biochar treatment resulted in a combined effect on soybean growth promotion and a shift in plant growth promoting rhizobacteria. *Frontiers in Microbiology*, *7*, 209. https://doi.org/10.3389/fmicb.2016.00209

El-Bassi, L., Azzaz, A. A., Jellali, S., Akrout, H., Marks, E. A. N., Ghimbeu, C. M., & Jeguirim, M. (2021). Application of olive mill waste-based biochars in agriculture: Impact on soil properties, enzymatic activities and tomato growth. *Science of the Total Environment*, *755*, 142531.

Elias, D. M. O., Ooi, G. T., Razi, M. F. A., Robinson, S., Whitaker, J., & McNamara, N. P. (2020). Effects of leucaena biochar addition on crop productivity in degraded tropical soils. *Biomass and Bioenergy*, *142*, 105710. https://doi.org/10.1016/j.biombioe.2020.105710

Farhangi-Abriz, S., & Ghassemi-Golezani, K. (2021). Changes in soil properties and salt tolerance of safflower in response to biochar-based metal oxide nanocomposites of magnesium and manganese. *Ecotoxicology and Environmental Safety*, *211*, 111904. https://doi.org/10.1016/j.ecoenv.2021.111904

Farrar, M. B., Wallace, H. M., Cheng Yuan, X. U., Joseph, S., Dunn, P. K., Nguyen, T. T. N., & Bai, S. H. (2021). Biochar co-applied with organic amendments increased soil-plant potassium and root biomass but not crop yield. *Journal of Soils and Sediments*, *21*, 784–798. https://doi.org/10.1007/s11368-020-02846-2

Feng, W., Yang, F., Cen, R., Liu, J., Zhongyi, Q. U., Miao, Q., & Chen, H. (2021). Effects of straw biochar application on soil temperature, available nitrogen and growth of corn. *Journal of Environmental Management*, *277*, 111331.

Gao, Y. U., Li, T., Qiang, F. U., Li, H., Liu, D., Ji, Y. I., Li, Q., & Cai, Y. (2020). Biochar application for the improvement of water-soil environments and carbon emissions under freeze-thaw conditions: An in-situ field trial. *Science of the Total Environment*, *723*, 138007. https://doi.org/10.1016/j.scitotenv.2020.138007

Gaskin, J. W., Steiner, C., Harris, K., Das, K. C., & Bibens, B. (2008). 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

Ghanbary, E., Kouchaksaraei, M. T., Guidi, L., Mirabolfathy, M., Etemad, V., Sanavi, S. A. M. M., & Struve, D. (2018). Change in biochemical parameters of Persian Oak (*Quercus brantii* Lindl.) seedlings inoculated by pathogens of charcoal disease under water deficit conditions. *Trees*, *32*(6), 1595–1608. https://doi.org/10.1007/s00468-018-1736-6

Girault, F., Perrier, F., Poitou, C., Isambert, A., Théveniaut, H., Laperche, V., Clozel-Leloup, B., & Douay, F. (2016). Effective Radium Concentration in Topsoils Contaminated by Lead and Zinc Smelters. *Science of the Total Environment*, *566–567*, 865–876. https://doi.org/10.1016/j.scitotenv.2016.05.007.

Guo, X.-X., Shu-biao, W. U., Wang, X.-Q., & Liu, H.-T. (2021). Impact of biochar addition on three-dimensional structural changes in aggregates associated with humus during swine manure composting. *Journal of Cleaner Production*, *280*, 124380. https://doi.org/10.1016/j.jclepro.2020.124380

Gupta, R. K., Hussain, A., Yadvinder-Singh, Sooch, S. S., Kang, J. S., Sharma, S., & Dheri, G. S. (2020). Rice straw biochar improves soil fertility, growth, and yield of rice-wheat system on a sandy loam soil. *Experimental Agriculture*, *56*(1), 118–131. https://doi.org/10.1017/S0014479719000218

Hafeez, Y., Iqbal, S., Jabeen, K., Shahzad, S., Jahan, S., & Rasul, F. (2017). Effect of biochar application on seed germination and seedling growth of glycine max (l.) merr. under drought stress. *Pakistan Journal of Botany*, *49*(51), 7–13.

Hafez, Y., Attia, K., Alamery, S., Ghazy, A., Al-Doss, A., Ibrahim, E., Rashwan, E., El-Maghraby, L., Awad, A., & Abdelaal, K. (2020). Beneficial effects of biochar and chitosan on antioxidative capacity, osmolytes accumulation, and anatomical characters of water-stressed barley plants. *Agronomy*, *10*(5), 630. https://doi.org/10.3390/agronomy10050630

He, L., Zhong, H., Liu, G., Dai, Z., Brookes, P. C., & Jianming, X. U. (2019). Remediation of heavy metal contaminated soils by biochar: Mechanisms, potential risks and applications in China. *Environmental Pollution*, *252*, 846–855. https://doi.org/10.1016/j.envpol.2019.05.151

Hereme, R., Morales-Navarro, S., Ballesteros, G., Barrera, A., Ramos, P., Gundel, P. E., & Molina-Montenegro, M. A. (2020). Fungal endophytes exert positive effects on *Colobanthus quitensis* under water stress but neutral under a projected climate change scenario in Antarctica. *Frontiers in Microbiology*, *11*, 264. https://doi.org/10.3389/fmicb.2020.00264

Hill, G. M., Cromwell, G. L., Crenshaw, T. D., Ewan, R. C., Knabe, D. A., Lewis, A. J., Mahan, D. C., Shurson, G. C., Southern, L. L., & Veum, T. L. (1996). Impact of pharmacological intakes of zinc and (or) copper on performance of weanling pigs. *Journal of Animal Science*, *74*(Suppl 1), 181.

Hou, D. (2021). Biochar for sustainable soil management. *Soil Use and Management*, *37*(1), 2–6. https://doi.org/10.1111/sum.12693

Jafarnia, S., Akbarinia, M., Hosseinpour, B., Sanavi, S. A. M. M., & Salami, S. A. (2018). Effect of drought stress on some growth, morphological, physiological, and biochemical parameters of two different populations of *Quercus brantii*. *IForest-Biogeosciences and Forestry*, *11*(2), 212. https://doi.org/10.3832/ifor2496-010

Jin, Z., Zhang, X., Chen, X., Zhenjie, D. U., Ping, L., Han, Z., & Tao, P. (2021). Dynamics of soil organic carbon mineralization and enzyme activities after two months and six years of biochar addition. *Biomass Conversion and Biorefinery*, 1–10. https://doi.org/10.1007/s13399-021-01301-7

Kalus, K., Koziel, J. A., & Opaliński, S. (2019). A review of biochar properties and their utilization in crop agriculture and livestock production. *Applied Sciences (Switzerland)*, *9*(17), 3494. https://doi.org/10.3390/app9173494

Kanthle, A. K., Lenka, N. K., Lenka, S., & Tedia, K. (2016). Biochar impact on nitrate leaching as influenced by native soil organic carbon in an inceptisol of central India. *Soil and Tillage Research*, *157*, 65–72. https://doi.org/10.1016/j.still.2015.11.009

Khadem, A., Raiesi, F., Besharati, H., & Khalaj, M. A. (2021). The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. *Biochar*, *3*, 105–116.

Köster, E., Pumpanen, J., Palviainen, M., Zhou, X., & Köster, K. (2021). Effect of biochar amendment on the properties of growing media and growth of containerized Norway spruce, scots pine, and silver birch seedlings. *Canadian Journal of Forest Research*, *51*(999), 1–10.

Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P. L., Sawarkar, A. D., Singh, L., & Tsang, D. C. W. (2021). A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. *Journal of Cleaner Production*, *305*, 127143. https://doi.org/10.1016/j.jclepro.2021.127143

Lau, A. Y. T., Tsang, D. C. W., Graham, N. J. D., Ok, Y. S., Yang, X., & Li, X.-D. (2017). Surface-modified biochar in a bioretention system for *Escherichia coli* removal from stormwater. *Chemosphere*, *169*, 89–98. https://doi.org/10.1016/j.chemosphere.2016.11.048

Liang, J., Li, Y. I., Si, B., Wang, Y., Chen, X., Wang, X., Chen, H., Wang, H., Zhang, F., Bai, Y., & Biswas, A. (2021). Optimizing biochar application to improve soil physical and hydraulic properties in saline-alkali soils. *Science of the Total Environment*, *771*, 144802.

Liu, C., Sun, B., Zhang, X., Liu, X., Drosos, M., Li, L., & Pan, G. (2020). The water-soluble pool in biochar dominates maize plant growth promotion under biochar amendment. *Journal of Plant Growth Regulation*, *40*, 1466–1476. https://doi.org/10.1007/s00344-020-10203-3

Liu, L., Huang, L., Huang, R., Lin, H., & Wang, D. (2021). Immobilization of heavy metals in biochar derived from co-pyrolysis of sewage sludge and calcium sulfate. *Journal of Hazardous Materials*, *403*, 123648. https://doi.org/10.1016/j.jhazmat.2020.123648

Liu, X., Wei, Z., Ma, Y., Liu, J., & Liu, F. (2021). Effects of biochar amendment and reduced irrigation on growth, physiology, water-use efficiency and nutrients uptake of tobacco (*Nicotiana tabacum* L.) on two different soil types. *Science of the Total Environment*, *770*, 144769.

Lyu, S., Guodong, D. U., Liu, Z., Zhao, L., & Lyu, D. (2016). Effects of biochar on photosystem function and activities of protective enzymes in *Pyrus ussuriensis* Maxim. under drought stress. *Acta Physiologiae Plantarum*, *38*(9), 1–10. https://doi.org/10.1007/s11738-016-2236-1

Mancini, L., Vidal Legaz, B., Vizzarri, M., Wittmer, D., Grassi, G., & Pennington, D. (2019). Mapping the role of raw materials in sustainable development goals. Joint Research Centre (JRC), the European Commission's Science and Knowledge Service. 1–70.

Mandal, S., Shengyan, P. U., Adhikari, S., Ma, H., Kim, D.-H., Bai, Y., & Hou, D. (2020). Progress and future prospects in biochar composites: Application and reflection in the soil environment. *Critical Reviews in Environmental Science and Technology*, *51*, 219–271. https://doi.org/10.1080/10643389.2020.1713030

Paneque, M., José, M., Franco-Navarro, J. D., Colmenero-Flores, J. M., & Knicker, H. (2016). Effect of biochar amendment on morphology, productivity and water relations of sunflower plants under non-irrigation conditions. *Catena*, *147*, 280–287 https://doi.org/10.1016/j.catena.2016.07.037

Plaimart, J., Acharya, K., Mrozik, W., Davenport, R. J., Vinitnantharat, S., & Werner, D. (2021). Coconut husk biochar amendment enhances nutrient retention by suppressing nitrification in agricultural soil following anaerobic digestate application. *Environmental Pollution*, *268*, 115684. https://doi.org/10.1016/j.envpol.2020.115684

Pulka, J., Manczarski, P., Stepien, P., Styczyńska, M., Koziel, J. A., & Białowiec, A. (2020). Waste-to-carbon: Is the torrefied sewage sludge with high ash content a better fuel or fertilizer? *Materials*, *13*(4), 954. https://doi.org/10.3390/ma13040954

Qi, Y., Huang, B., & Darilek, J. L. (2014). Effect of drying on heavy metal fraction distribution in rice paddy soil. *PLoS One*, *9*(5), 3–10. https://doi.org/10.1371/journal.pone.0097327

Rashmi, I., Roy, T., Kartika, K. S., Pal, R., Coumar, V., Kala, S., & Shinoji, K. C. (2020). Organic and inorganic fertilizer contaminants in agriculture: Impact on soil and water resources. In *Contaminants in agriculture* (pp. 3–41). Springer. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Organic+and+inorganic+fertilizer+contaminants+in+agriculture%3A+Impact+on+soil+and+water+resources&btnG=

Saccon, F., Giovagnetti, V., Shukla, M. K., & Ruban, A. V. (2020). Rapid regulation of photosynthetic light harvesting in the absence of minor antenna and reaction centre complexes. *Journal of Experimental Botany*, *71*(12), 3626–3637. https://doi.org/10.1093/jxb/eraa126

Salam, A., Bashir, S., Khan, I., Hussain, Q., Gao, R., & Hongqing, H. U. (2019). Biochar induced Pb and Cu immobilization, phytoavailability attenuation in Chinese cabbage, and improved biochemical properties in naturally co-contaminated soil. *Journal of Soils and Sediments*, *19*(5), 2381–2392. https://doi.org/10.1007/s11368-019-02250-5

Salam, A., Shaheen, S. M., Bashir, S., Khan, I., Wang, J., Rinklebe, J., Rehman, F. U., & Hongqing, H. U. (2019). Rice straw- and rapeseed residue-derived biochars affect the geochemical fractions and phytoavailability of Cu and Pb to maize in a contaminated soil under different moisture content. *Journal of Environmental Management*, *237*, 5–14. https://doi.org/10.1016/j.jenvman.2019.02.047

Sears, G. W. (1956). Determination of specific surface area of colloidal silica by titration with sodium hydroxide. *Analytical Chemistry*, *28*, 1981–1983. https://doi.org/10.1021/ac60120a048

Shaheen, S. M., Niazi, N. K., Hassan, N. E. E., Bibi, I., Wang, H., Tsang, D. C. W., Ok, Y. S., Bolan, N., & Rinklebe, J. (2019). Wood-based biochar for the removal of potentially toxic elements in water and wastewater: A critical review. *International Materials Reviews*, *64*(4), 216–247. https://doi.org/10.1080/09506608.2018.1473096

Smith, J. W., Tokach, M. D., Goodband, R. D., Nelssen, J. L., & Richert, B. T. (1997). Effects of the interrelationship between zinc oxide and copper sulfate on growth performance of early-weaned pigs. *Journal of Animal Science*, *75*(7), 1861–1866. https://doi.org/10.2527/1997.7571861x

Subhan, D., Ameer Adeel, T. I., Qureshi, Y. U., Hina, M., Amal, S., & Muhammad, E. (2014). Influence of biochar on growth and photosynthetic attributes of *Triticum aestivum* L. under half and full irrigation. *International Journal of Biosciences (IJB)*, *5*(7), 101–108.

Tanazawa, Y., Tomotsune, M., Suzuki, T., Koizumi, H., & Yoshitake, S. (2021). Photosynthetic response of young oaks to biochar amendment in field conditions over 3 years. *Journal of Forest Research*, *26*, 116–126. https://doi.org/10.1080/13416979.2020.1866231

Tian, X., Li, C., Zhang, M., Wan, Y., Xie, Z., Chen, B., & Li, W. (2018). Biochar derived from corn straw affected availability and distribution of soil nutrients and cotton yield. *PLoS One*, *13*(1), e0189924. https://doi.org/10.1371/journal.pone.0189924

SDG, U. N. (2019). Sustainable Development Goals. The Energy Progress Report. Tracking SDG 7.

Vijayaraghavareddy, P., Xinyou, Y. I. N., Struik, P. C., Makarla, U., & Sreeman, S. (2020). Responses of lowland, upland and aerobic rice genotypes to water limitation during different phases. *Rice Science*, *27*(4), 345–354. https://doi.org/10.1016/j.rsci.2020.05.009

Vitkova, J., Kondrlova, E., Rodny, M., Surda, P., & Horak, J. (2017). Analysis of soil water content and crop yield after biochar application in field conditions. *Plant, Soil and Environment*, *63*(12), 569–573. https://doi.org/10.17221/564/2017-PSE

Walter, R., & Rajashekhar Rao, B. K. (2015). Biochars influence sweet-potato yield and nutrient uptake in tropical Papua New Guinea. *Journal of Plant Nutrition and Soil Science*, *178*(3), 393–400. https://doi.org/10.1002/jpln.201400405

Wang, G. M., & Zhou, L. X. (2003). The dynamics of dissolved organic matter and associated water-soluble cu in two cu-contaminated soils amended with various organic matters. *Acta Scientiae Circumstantiae*, *23*(4), 452–457.

Wang, J., Shi, L., Zhai, L., Zhang, H., Wang, S., Zou, J., Shen, Z., Lian, C., & Chen, Y. (2021). Analysis of the long-term effectiveness of biochar immobilization remediation on heavy metal contaminated soil and the potential environmental factors weakening the remediation effect: A review. *Ecotoxicology and Environmental Safety*, *207*, 111261. https://doi.org/10.1016/j.ecoenv.2020.111261

Wang, L., Ok, Y. S., Tsang, D. C. W., Alessi, D. S., Rinklebe, J., Wang, H., Mašek, O., Hou, R., O'Connor, D., & Hou, D. (2020). New trends in biochar pyrolysis and modification strategies: Feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment. *Soil Use and Management*, *36*(3), 358–386. https://doi.org/10.1111/sum.12592

WRB-IUSS (2014). World Reference Base for Soil Resources. World Soil Resources Reports 106.

Xie, Y., Dong, C., Chen, Z., Liu, Y., Zhang, Y., Gou, P., Zhao, X. U., Ma, D., Kang, G., Wang, C., Zhu, Y., & Guo, T. (2021). Successive biochar amendment affected crop yield by regulating soil nitrogen functional microbes in wheat-maize rotation farmland. *Environmental Research*, *194*, 110671. https://doi.org/10.1016/j.envres.2020.110671

Yakubu, A., Danso, E. O., Arthur, E., Kugblenu-Darrah, Y. O., Sabi, E. B., Abenney-Mickson, S., Ofori, K., & Andersen, M. N. (2020). Rice straw biochar and irrigation effect on yield and water productivity of okra. *Agronomy Journal*, *112*(4), 3012–3023. https://doi.org/10.1002/agj2.20230

Yan, F. L., Wang, Y. I., Wang, W. H., Zhao, J. X., Feng, L. L., Li, J. J., & Zhao, J. C. (2020). Application of biochars obtained through the pyrolysis of *Lemna minor* in the treatment of Ni-electroplating wastewater. *Journal of Water Process Engineering*, *37*(13), 101464. https://doi.org/10.1016/j.jwpe.2020.101464

Yang, X., Liu, J., McGrouther, K., Huang, H., Kouping, L. U., Guo, X. I., He, L., Lin, X., Che, L., Ye, Z., & Wang, H. (2016). Effect of biochar on the extractability of heavy metals (Cd, Cu, Pb, and Zn) and enzyme activity in soil. *Environmental Science and Pollution Research*, *23*(2), 974–984. https://doi.org/10.1007/s11356-015-4233-0

You, X., Yin, S., Suo, F., Zongchang, X. U., Chu, D., Kong, Q., Zhang, C., Li, Y., & Liu, L. (2021). Biochar and fertilizer improved the growth and quality of the ice plant (*Mesembryanthemum crystallinum* L.) shoots in a coastal soil of Yellow River Delta, China. *Science of the Total Environment*, *775*, 144893.

Yuan, J.-H., Ren-Kou, X. U., Qian, W., & Wang, R.-H. (2011). Comparison of the ameliorating effects on an acidic ultisol between four crop straws and their biochars. *Journal of Soils and Sediments*, *11*(5), 741–750. https://doi.org/10.1007/s11368-011-0365-0

Zaccheo, P., Crippa, L., & Bedussi, F. (2017). Biochar Can Enhance Potassium Availability during Cyclamen Cultivation. in International Symposium on Growing Media, Soilless Cultivation, and Compost Utilization in Horticulture 1266. (35–42).

Zahra, M. B., Aftab, Z.-E.-H., Akhter, A., & Haider, M. S. (2021). Cumulative effect of biochar and compost on nutritional profile of soil and maize productivity. *Journal of Plant Nutrition*, *44*(11), 1664–1676. https://doi.org/10.1080/01904167.2021.1871743

Zhang, Q., Song, Y., Zhen, W. U., Yan, X., Gunina, A., Kuzyakov, Y., & Xiong, Z. (2020). Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. *Journal of Cleaner Production*, *242*, 118435.

Zhou, Y., Qin, S., Verma, S., Sar, T., Sarsaiya, S., Ravindran, B., Liu, T., Sindhu, R., Patel, A. K., Binod, P., Varjani, S., Rani Singhnia, R., Zhang, Z., & Awasthi, M. K. (2021). Production and beneficial impact of biochar for environmental application: A comprehensive review. *Bioresource Technology*, *337*, 125451.

Zhu, L., Wu, J., Zhou, J. M., Chen, H. L., & Tang, D. M. (2008). Effect of dissolved organic matter on sorption-desorption behavior of copper in soil. *Journal of Agro-Environment Science*, *27*(5), 1779–1785.

How to cite this article: Ayaz, M., Stulpinaite, U., Feiziene, D., Tilvikiene, V., Akthar, K., Baltrėnaitė-Gedienė, E., Striugas, N., Rehmani, U., Alam, S., Iqbal, R., Toleikiene, M., & Doyeni, M. (2021). Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil. *Soil Use and Management*, 00, 1–15. https://doi.org/10.1111/sum.12773 *plants*

MDPI

Article

The Impact of Swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils

Muhammad Ayaz [1,*], Dalia Feizienė [1], Virginijus Feiza [1], Vita Tilvikienė [1], Edita Baltrėnaitė-Gedienė [2] and Attaullah Khan [3]

[1] Lithuanian Research Center for Agriculture and Forestry, Institute of Agriculture, Instituto al. 1, LT-58344 Kėdainiai, Lithuania; dalia.feiziene@lammc.lt (D.F.); virginijus.feize@lammc.lt (V.F.); vita.tilvikiene@lammc.lt (V.T.)

[2] Institute of Environmental Protection, Vilnius Gediminas Technical University, LT-10223 Vilnius, Lithuania; edita.baltrenaite-gediene@vilniustech.lt

[3] School of Forestry, Northeast Forestry University, Harbin 150040, China; khan52@aup.edu.pk

* Correspondence: muhammad.ayaz@lammc.lt; Tel.: +370-654-22-196

Abstract: Biochar has been proven to influence soil hydro-physical properties, as well as the abundance and diversity of microbial communities. However, the relationship between the hydro-physical properties of soils and the diversity of microbial communities is not well studied in the context of biochar application. The soil analyzed in this study was collected from an ongoing field experiment (2019–2024) with six treatments and three replications each of biochar (B1 = 25 t·ha^{-1} and B0 = no biochar) and nitrogen fertilizer (N1 = 160, N2 = 120 kg·ha^{-1}, and N0 = no fertilizer). The results show that biochar treatments (B1N0, B1N1, and B1N2) significantly improved the soil bulk density and total soil porosity at different depths. The B1N1 treatment substantially enhanced the volumetric water content (VMC) by 5–7% at −4 to −100 hPa suction at 5–10 cm depth. All three biochar treatments strengthened macropores by 33%, 37%, and 41%, respectively, at 5–10 cm depth and by 40%, 45%, and 54%, respectively, at 15–20 cm depth. However, biochar application significantly lowered hydraulic conductivity (HC) and enhanced carbon source utilization and soil indices at different hours. Additionally, a positive correlation was recorded among carbon sources, indices, and soil hydro-physical properties under biochar applications. We can summarize that biochar has the potential to improve soil hydro-physical properties and soil carbon source utilization; these changes tend to elevate fertility and the sustainability of Cambisol.

Keywords: biochar; carbon source utilization; soil indices; soil hydraulic conductivity; soil porosity

check for updates

Citation: Ayaz, M.; Feizienė, D.; Feiza, V.; Tilvikienė, V.; Baltrėnaitė-Gedienė, E.; Khan, A. The Impact of Swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils. *Plants* **2022**, *11*, 1729. https://doi.org/10.3390/plants11131729

Academic Editor: Adriano Sofo

Received: 30 May 2022
Accepted: 24 June 2022
Published: 29 June 2022

1. Introduction

In recent years, biochar has been used extensively as a soil conditioner to improve soil quality [1]. Soil physical conditions directly influence soil fertility by determining water retention capacity, aeration, and soil permeability, which tend to improve soil productivity [2]. Several studies indicated that good soil structure, porosity, hydraulic conductivity, and specific gravity created favorable conditions for essential soil microbial growth and enabled the more efficient use of water and nutrients in the soil profile [3,4].

Moreover, the addition of biochar improved nutrient and water retention and increased root growth substantially compared to degraded soils with poor physical properties [5]. Biochar amendment improved soil hydraulic conductivity by decreasing soil bulk density and increasing soil porosity [6]. However, some studies found that biochar has little effect or even negative effects on soil physical properties. Previously, there was no proof to support the claim that biochar amendment influenced soil porosity by direct pore contribution, the creation of accommodation pores, or ameliorations in aggregate stability [7]. The application of biochar lowered pore connectivity and the number of macropores in a wheat–rice rotation system [8]. Such variations signify that the effects of biochar on soil structure and hydraulic properties are unclear.

Numerous reports have stated that biochar application substantially enhances microbial activity in soil [9,10]. In theory, the application of almost antiseptic biochar would dilute the diversity of soil microorganisms [11]. Macropores and the large surface area of biochar tend to contribute to the loss of volatiles during pyrolysis, which creates favorable conditions for soil microbiota in the long term [12]. Previous reports have also indicated a decline in microbial abundance and mycorrhizal diversity with the addition of biochar; these studies specified conditions that depended upon the nitrogen (N) and phosphorus (P) levels in soil [13], due to a lower adverse effect caused by the extreme content of mineral elements in biochar [14,15]. Certainly, microbial abundance is very sensitive to ecological factors such as the physicochemical characteristics of soil [16]. Gul (2016) reported that biochar particles could intervene as an unconventional niche for soil microbes in relation to soil water content, pH, aeration, and other physicochemical properties [17]. Furthermore, it was added that biochar-absorbed organic carbon from the contiguous soil might be directly consumed as an energy source by soil microorganisms [18]. In addressing all these elements, it is necessary to measure the effect of biochar on soil microbial activities with respect to biochar type and soil properties. However, data regarding the mechanisms of how biochar affects microbial diversity and abundance are still lacking. Soil microbes are considered as executors in the soil environment [19], and their distribution, abundance, and diversity are vital to ecosystem resources and soil function [20]. The plate-counting procedure can be employed to count only a low percentage of the entire soil microbial abundance; however, it has also been frequently used and reflects microbial biomass reliably. This is a legitimate procedure for counting the bacteria and organisms with specific functions that can live in artificial media. The diversity of soil microorganisms is another point of interest in the soil ecology context and is considered an indicator of soil health [21].

There are several methods for studying the phylogenetic diversity and abundance of soil microbial communities, which relate to the phospholipid fatty acids of the microbial membranes [22]. Additionally, the correlation between the fingerprint [23] and the environmental factors of the denaturing gradient gel electrophoresis profile can be established by redundancy analysis. Generally, microbial syndicates with high genetic variability have the capacity to consume more diverse carbon (C) sources; this can be evaluated by their community-level physiological profile, which leads to their C metabolic potential. The complex correlation of different soil functions makes analyses difficult [24]. The relationships between the chemical and physical properties of soils amended with biochar and their effects on soil biota are poorly understood. Soil microbial functions and the soil pore structure influence some soil physical properties and determine the retention, transport, and supply of soil moisture and, therefore, crop yield through their interactions [25].

Thus, we hypothesized that a swine-digestate-derived biochar amendment could influence soil microbial diversity and abundance and also the utilization of soil carbon source (SCS) (28 substrates) by influencing the hydro-physical properties of soil. Furthermore, the microbial potential of SCSs may vary in the presence of biochar carbon sources. To test the above hypotheses, we examined the hydro-physical soil properties, microbial abundance, and SCS utilization of biochar-amended loamy Cambisol (sand (2.0–0.05 mm), 50.1%; silt (0.05–0.002 mm), 31.1%; and clay (<0.002 mm), 18.8%) under moderate climatic conditions.

2. Materials and Methods

2.1. Biochar and Soil

Swine manure digestate was collected from an active animal farm. The manure digestate was air-dried for 48 h and manually ground. The feedstocks were pyrolyzed at 550 °C in a cylindrical furnace for 5–6 h under anaerobic conditions to produce biochar [26]. The performance of the feedstock during thermal decomposition was tested through thermo-gravity analysis (TGA) with a thermal analyzer, namely the Netzsch Jupiter STA 449 F3, at the Lithuanian Energy Institute [27]. During the TGA process, the pyrolysis process was applied, with a 35 °C/min heating rate in the temperature range 40–900 °C with 9.6 ± 0.32 of the feedstock sample. To create an inert atmosphere, N_2 carrier gas (60 mL/min) was used. *Endocalcari-epihypogleyic* Cambisol soil (WRB, 2014) was used in this study; it was obtained from 0 to 20 cm depth in a farmland field of the Institute of Agriculture (55°23′49″ N and 23°51′40″ E) at the Lithuanian Research Centre for Agriculture and Forestry. The soil samples were air-dried, homogenized, and meshed through a 2 mm sieve before use, and the physicochemical properties of the soil and biochar are given in Table 1.

Table 1. Physicochemical characteristics of the soil and biochar under experimental trial.

Physicochemical Properties	Soil	Biochar
pH_{KCl}	7.5	9.1
Ash content (%)	-	32.21
Moisture wt. (%)	-	2.52
Volatiles wt. (%)	-	56.73
Residual mass (char formed) wt. (%)	-	40.75
Total N (g/kg)	0.01	19.18
Ammonium N (mg/kg)	1.21	-
Mineral N (mg/kg)	11.21	-
Available P (g/kg)	0.145	-
Available K (g/kg)	0.213	-
Total Mg (g/kg)	-	10.50
Organic C (%)	1.10	62.33

2.2. Experimental Design

A three-factorial randomized complete block design (RCBD) field experiment was designed with six treatments and three replications each. The combination of the treatments was as follows: B0N0 (no biochar + no Nitrogen fertilizer), B0N1 (no biochar + 160 kg·ha^{-1} Nitrogen fertilizer), B0N2 (no biochar + 120 kg·ha^{-1} Nitrogen fertilizer), B1N1 (25 t·ha 25 t·ha^{-1} biochar + 160 kg·ha^{-1} Nitrogen fertilizer), B1N2 (25 t·ha 25 t·ha^{-1} biochar + 120 kg·ha^{-1} Nitrogen fertilizer), and B1N0 (25 t·ha^{-1} biochar + no Nitrogen fertilizer). Ammonium nitrate was used as an N fertilizer. The biochar was broadcast and shallowly incorporated into the soil surface during pre-sowing tillage. The main crop was spring barley (*Hordeum vulgare* L.), which was sown in April 2020 and harvested in August 2020. The weather conditions at the experimental site are given in Figure 1 and were obtained from a meteorological station located 0.5 km away from the experimental site.

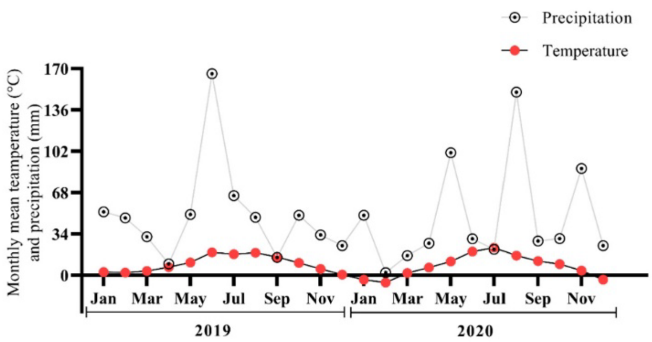

Figure 1. Monthly mean temperature and precipitation at the experimental site during the period 2019–2020.

2.3. Chemical Analysis

The physicochemical properties of the biochar and soil were analyzed by standard laboratory methods. Soil and biochar (pH) and EC analyses were performed using a 1:5 (vol vol^{-1}) soil mixture in a 1 M KCl solution [28] and an extract to distilled water [29], respectively. Cation exchange capacity was determined with an updated ammonium-acetate method [30]. Inductively coupled plasma atomic emission spectrometry (Perkin Elmer ICP-OES, Waltham, MA, USA) was used for measuring the DTPA extractable nutrients P, K, Ca, and Mg [31]. The contents of total nitrogen (TN), available phosphorus (PA-L), and potassium (KA-L) were measured using a reference method [32]. The data for biochar ash content, moisture, volatiles, and residual mass were obtained from TGA.

2.4. Hydro-Physical Soil Analysis

For the analysis of soil water retention characteristics and pore-size distribution, undisturbed soil samples were taken in stainless steel cylinders (51 mm high and 53 mm in diameter) from each treatment. Water retention properties were studied at −4, −10, −30, and −100 hPa (in a sand box) and at −300 hPa (in a sand–kaolin box). Water content was determined at −15,500 hPa of suction using sieved soil samples [33]. The water content levels at −100 hPa and at −15,500 hPa were considered the field capacity (FC) and the permanent wilting point (WP), respectively. The amount of water between these two suctions was regarded as plant-available water (PAW) content. Soil cores were stored in the refrigerator at a constant temperature (2 °C). The same samples were used for the analysis of soil bulk density (BD), total air-filled porosity, and saturated hydraulic conductivity. HC was determined with a laboratory permeameter (Eijkelkamp, The Netherlands) by the constant head method [34].

2.5. Microorganism Community-Level Substrate Utilization Pattern Analysis Using Biolog® Ecoplate

The Biolog system and the Biolog® EcoPlate procedure were used to determine 31 types of carbon and the metabolic functional diversity of soil microorganisms; this system was particularly meant for community analysis and microbial environmental research [35]. For this purpose, fresh soil samples were collected from each plot. Samples were air-dried, ground, and meshed through a 2 mm sieve. A 10 g dried soil sample was collected from each treatment and mixed with 90 mL of distilled water in a 250 mL flask at 250 rpm for 30 min in the rotary shaker. From each 10–3 diluted suspension, 150 µL was added into a 96-well Biolog® EcoPlate (Biolog, Hayward, CA, USA); these samples comprise three replications of 31 widely useful carbon sources, and one was regarded as a control treatment (without a C source). Data for the absorbance-incubated plates were recorded at 590 nm (dual-wavelength data: OD590–OD750) every 24 h at 25 °C for periods of 24, 48, 72, and 96 h [36]. The resulting data of each well, i.e., the color changes from the carbon utilization of the soil microbes, were investigated in Microlog 4.01. For the estimation of the integral fingerprinting of carbon source utilization, the average well color development (AWCD) was used for each microplate well per reading time [37]. The EcoPlate readings at 15 d were used to analyze the Shannon index (H), richness (S), Simpson index (D), and McIntosh index (U), which evaluated the diversity, richness, number, and evenness of the soil microbes, respectively [38].

2.6. Calculation of the Species Diversity Indices

Species richness is regarded as the number of species in a sample, whereas the distribution of individuals among the recorded species is considered species evenness. The information needed to describe every species of the community is known as Shannon's index; it is calculated using the following Equation (1):

$$H = \sum_{i}^{s} = 1\ P_i\ \log_{pi} \quad (1)$$

where s is the total number of species and P_i is the proportion of all individuals in the sample that belongs to species i.

Simpson's index (D) assesses the contingency that two species randomly chosen from a sample belong to the same species. See Equation (2):

$$\text{Simpson's index (D)} = \sum(n/N)^2 \quad (2)$$

where n represents the total number of organisms of a specific species and N is the total number of organisms of all species.

Species richness (R) is regarded as the number of species in a particular area and is calculated using the following Equation (3):

$$(\text{R}) = \text{S} - 1/\text{Iog}(N) \quad (3)$$

where N = the total number of individuals in the sample and S = the number of species recorded, and U is represented by Expression 4, also known as the Mclntosh index:

$$\text{U} = \sqrt{\sum n_i^2} \quad (4)$$

where n (i) represents the number of individuals in the ith species, the sum is that of all the species, and U is the Euclidean distance of the community from the origin [39].

Species evenness, described by Magurran (1988) [40] as another index of diversity, is calculated using the diversity index, as in Equation (5):

$$\text{Species Evenness} = \text{H}/\text{H}_{max} \quad (5)$$

where H′ = Shannon's index and H_{max} = lnS, where S is the number of species present in the community.

2.7. Statistical Analysis

Three-way analysis of variance (ANOVA) was used to compare the effects of factors A (25 t·ha 25 t·ha^{-1} biochar and without biochar), B (160 kg·ha^{-1}, 120 kg·ha^{-1}, and without N fertilizer), and C (depths 5–10 and 15–20 cm; timing 24, 48, 72, and 90 h) and their interactions on the soil hydro-physical properties, carbon sources, and indices. The homogeneity of variances was tested with Levene's test. Normality was assessed with the Shapiro—Wilk and Durbin—Watson tests. A post-hoc Tukey HSD test was used to analyze the differences between treatments. Pearson's correlation coefficients were calculated to explore the interrelations between and within the hydro-physical properties and soil microbial abundance and also between B0 and B1 under N0, N1, and N2 conditions. The Pearson's correlation analysis was performed using the corrplot package in R [41]. Redundancy analysis (RDA) was used to compare the interrelations between the carbon sources and soil physical properties. RDA analysis was performed with the vegan package in R [42]. The Pearson's correlation analysis (PCA) was performed with the PCA package in R [43]. All statistical analyses were performed using SPSS v. 25.0 (IBM Inc., Armonk, NY, USA). Sigma Plot v. 12.2 (Systat Software Inc., San Jose, CA, USA) was used for graphical representation.

3. Results

3.1. Soil Bulk Density and Total Porosity

Dry soil bulk density and total soil porosity in the investigated treatments during the month of May and August are summarized in Figure 2. The application of 25 t·ha^{-1} of biochar alone (B1N0) and biochar with 120 kg·ha^{-1} of N fertilizer (B1N2) significantly (p = $\leq$0.05) enhanced soil BD by 10–12% at 5–10 cm soil depth in the month of May (Figure 2A); in August, biochar alone and biochar with 160 kg·ha^{-1} of N fertilizer (B1N1) significantly ($\leq$0.05) enhanced soil BD by 8–10% compared to non-biochar treatments (Figure 1B). Similarly, treatments B1N0 and B1N1 substantially ($p = \leq 0.05$) increased soil BD at 15–20 cm depth by 9–10% in May compared to non-biochar treatments, whereas, in August, treatment B1N0 at 15–20 cm soil depth significantly ($p = \leq 0.05$) increased soil BD compared to other treatments (Figure 2A). Soil porosity was recorded as being substantially ($p = \leq 0.05$) higher in non-biochar treatments at 5–10 cm depth in May (Figure 2C); however, in August, 25 t·ha 25 t·ha^{-1} of biochar with 120 kg·ha^{-1} of N fertilizer significantly ($p = \leq 0.05$) increased soil porosity at both 5–10 cm and 15–20 cm depths by 17% and 15%, respectively, compared to non-biochar treatments (Figure 2D). Factors A, B, and A*B showed significant ($p = \leq 0.05$) impacts on soil BD and TP, whereas factor A*B*C recorded non-substantial results. Thus, the overall effect of biochar with and without N fertilizer was positive with respect to BD and TP.

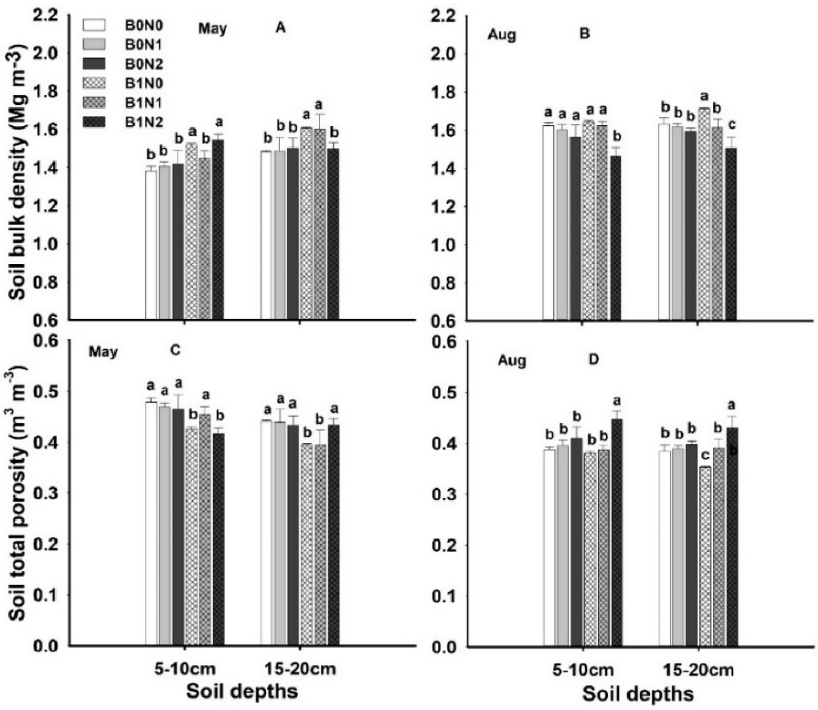

Figure 2. Effect of different treatments onsoil bulk density (**B**,**D**), (**A**) in May at 5–10 cm and 15–20 cm depth, (**B**) in August at 5–10 cm and 15–20 cm depth, and total soil porosity (**C**) in May at 5–10 cm and 15–20 cm depth, (**D**) in August at 5–10 cm and 15–20 cm depth. The letters a, b, c indicate statistically significant difference at $p < 0.05$.

3.2. Volumetric Soil Water Content

In our current study, the volumetric soil water content (VWC) at −4 to −100 hPa suction at 5–10 cm depth was recorded as being higher (5–7%) under the application of 25 t·ha 25 t·ha^{-1} of biochar and 160 kg·ha^{-1} of N fertilizer (B1N1) compared to other treatments. Field capacity (FC) and wilting point (WP) at −100 hPa to −15,500 hPa suction at 5–10 cm and 15–20 cm depths under biochar treatments were enhanced by 9–11% compared to non-biochar treatments (Figure 3A,B). However, soil FC and WP at 5–10 cm and 15–20 cm depths were significantly ($p \leq 0.05$) higher (12–15%) after treatments B1N2 and B1N1 compared to the other treatments (Figure 3C,D). The factorial interactions (A*B and A*B*C) showed non-significant variations among all the treatments; only factors A and

B significantly ($p \leq 0.05$) enhanced VWC. This reflects the fact that biochar application has the potential to enhance VWC in soil.

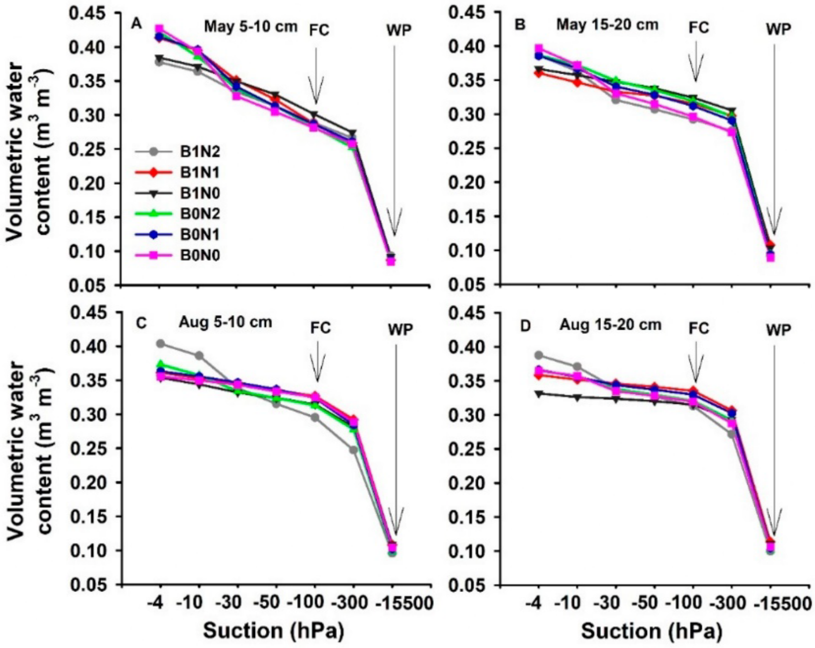

Figure 3. Effect of different treatments on VWC (volumetric water content), FC (field capacity), and WP (plant wilting point) (**A**) in May at 5–10 cm depth, (**B**) in May at 15–20 cm depth, (**C**) in August at 5–10 cm depth, (**D**) in August at 15–20 cm depth.

The application of biochar increased the soil macropores at both the 5–10 cm and 15–20 cm depths. Three applications, namely 25 t·ha 25 t·ha^{-1} of biochar with 120 kg·ha^{-1} of N fertilizer (B1N2), 25 t·ha 25 t·ha^{-1} biochar alone (B1N0), and 25 t·ha 25 t·ha^{-1} of biochar with 160 kg·ha^{-1} of N fertilizer (B1N1), substantially ($p = \leq 0.05$) enhanced macropores by 33.33%, 37.5%, and 41.17%, respectively, at the 5–10 cm depth. The same trend was recorded at the 15–20 cm soil depth, where the above treatments enhanced soil macropores by 40%, 45.45%, and 53.84%, respectively. However, no significant effect was recorded on mesopores or micropores (Figure 4A).

Biochar application had no substantial impact on soil pore distribution at either the 5–10 or 15–20 cm depths (Figure 4B). However, 120 kg·ha^{-1} of N fertilizer application significantly ($p \leq 0.05$) enhanced soil macropores compared to all other treatments at both the 5–10 and 15–20 cm depths. Factors A, B, A*B, and A*B*C substantially ($p \leq 0.05$) enhanced soil macropores by 30–40%, and the results recorded were non-significant for the rest factors. Thus, swine-digestate-derived biochar with and without N fertilizer application had a positive effect on soil macropores.

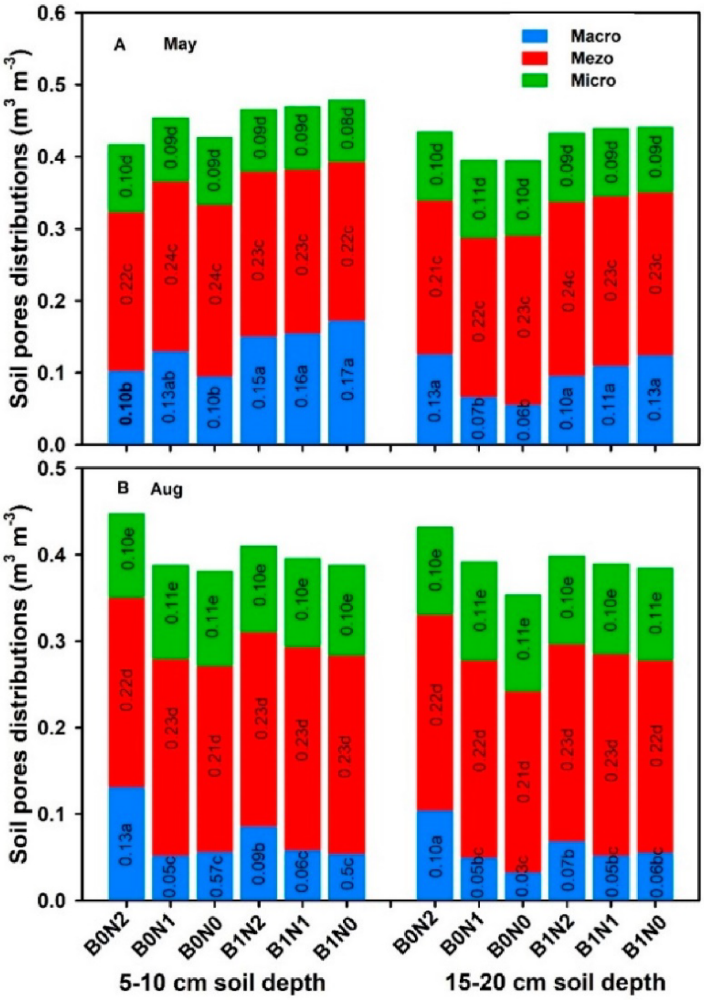

Figure 4. Effect of different treatments on pore size distribution (macropores, mesopores, and micropores) (**A**) in May, at 5–10 cm and 15–20 cm depths, (**B**) in August at 5–10 cm and 15–20 cm depths for B0N0 (without biochar or N fertilization); B0N1 (without biochar and with 160 kg·ha^{-1} N); B0N2 (without biochar and with 120 kg·ha^{-1} N); B1N0 (biochar 25 t·ha 25 t·ha^{-1} only); B1N1 (biochar 25 t·ha^{-1} and 160 kg·ha^{-1} N); and B1N2 (biochar 25 t·ha^{-1} and 120 kg·ha^{-1} N. The letters a–e indicate statistically significant difference at $p < 0.05$.

Biochar application significantly ($p \leq 0.05$) reduced the HC of soil by 35–40% at the 5–10 cm soil depth compared to the non-biochar treatments. However, biochar did not affect HC at the 15–20 cm soil depth (Figure 5). The antilog of K of the soil varied during the entire season and ranged from 2.5 to 3.3% in May and from 2.6 to 4.7% in August. However, certain factorial interactions (B and A*B*C) recorded non-significant variations. Thus, among all the treatments, factors A and A*B showed substantial ($p \leq 0.05$) effects on soil HC.

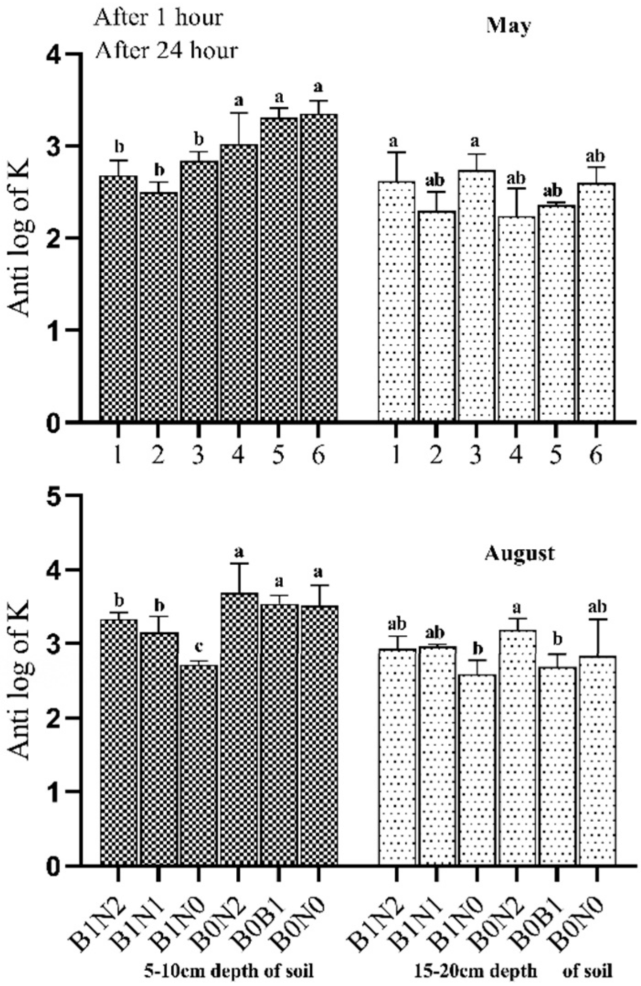

Figure 5. Effect of different treatments on soil hydraulic conductivity. B0N0 (without biochar or N fertilization); B0N1 (without biochar and with 160 kg·ha^{-1} N); B0N2 (without biochar and with 120 kg·ha^{-1} N); B1N0 (biochar 25 t·ha^{-1} only); B1N1 (biochar 25 t·ha^{-1} and 160 kg·ha^{-1} N); and B1N2 (biochar 25 t·ha^{-1} and 120 kg·ha^{-1} N) at two different depths (5–10 cm and 15–20 cm) and times (May and August). The letters a, b, c indicate statistically significant difference at $p < 0.05$.

3.3. Soil Carbon Sources

The results suggest that the SCS utilization rate was significant and directly proportional to microbial growth (Figure 5). Carboxylic acid was the leading SCS utilized, and amines were the least-utilized carbon source. The overall utilization of all the SCSs was increased in biochar-treated soil compared to non-biochar treatments, e.g., B1N1 enhanced carbohydrates by 24.1%, B1N0 enhanced carboxylic acid by 32.8%, B1N0 enhanced amino acids by 23.2%, and B1N1 enhanced amines by 6.5% (Figure 6). Among the factorial interactions, factors A, B, and A*B showed significantly ($p \leq 0.05$) enhanced SCS utilization.

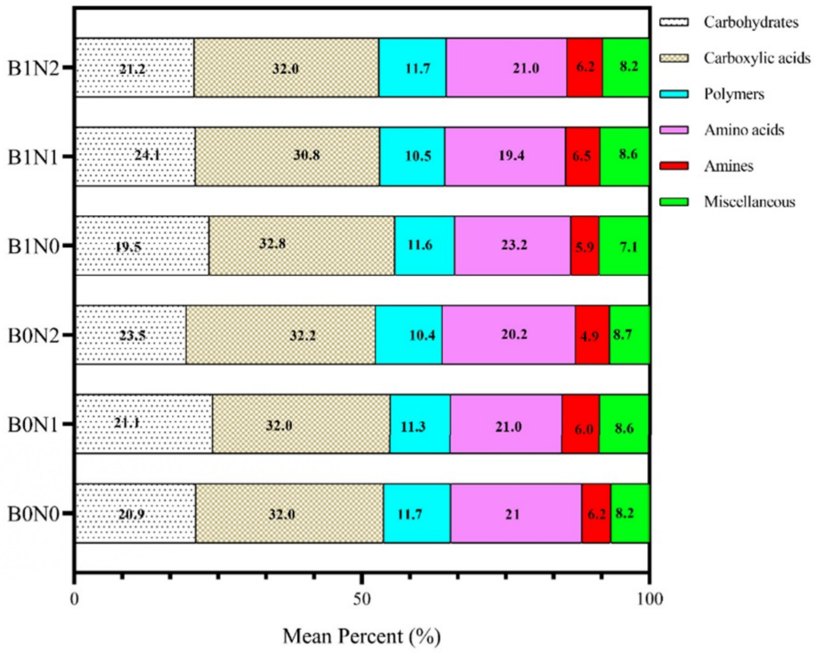

Figure 6. Effect of different treatments on the average mean of soil carbon sources. B0N0 (without biochar or N fertilization); B0N1 (without biochar and with 160 kg·ha^{-1} N); B0N2 (without biochar and with 120 kg·ha^{-1} N); B1N0 (biochar 25 t·ha^{-1} only); B1N1 (biochar 25 t·ha^{-1} and 160 kg·ha^{-1} N); and B1N2 (biochar 25 t·ha^{-1} and 120 kg·ha^{-1} N).

3.4. Soil Microbiological Activity

According to all of the diversity indices (average well color development (AWCD), richness (R), and the McIntosh Index (U)) analyzed for the samples incubated in the Biolog EcoPlate for 96 h, higher biodiversity rates were recorded in biochar-treated soil (Figure 7). However, treatment with B0N1 also significantly ($p \leq 0.05$) enhanced soil biodiversity. Soil biodiversity was characterized by high metabolic activity. Initially, at 24 and 48 h, treatment with B0N1 and B1N0 substantially ($p \leq 0.05$) enhanced the AWCD rate by 50 and 59%, respectively, compared to the control treatment. Later on, at 72 and 96 h, treatment with B0N1 and B1N2 also significantly ($p \leq 0.05$) enhanced AWCD by 55–60% compared to the control treatment (Figure 6). Similarly, the R index rate was significantly ($p \leq 0.05$) enhanced from 24–96 h for the treatments B0N1, B1N0, B1N1, and B1N2; the rate increased by 20–35% compared to the control treatment. The *U* index recorded was significantly ($p \leq 0.05$) lower from 24 to 96 h for treatment B1N2; it was 20–30% lower compared to the control treatment (Figure 6). Carbohydrates, amines, and miscellaneous (MS) followed the same trend as that of the R index and were significantly influenced under biochar application. Factorial interactions (A, B, and A*B) significantly ($p \leq 0.05$) increased soil microbial activity, whereas factor A*B*C recorded non-significant results.

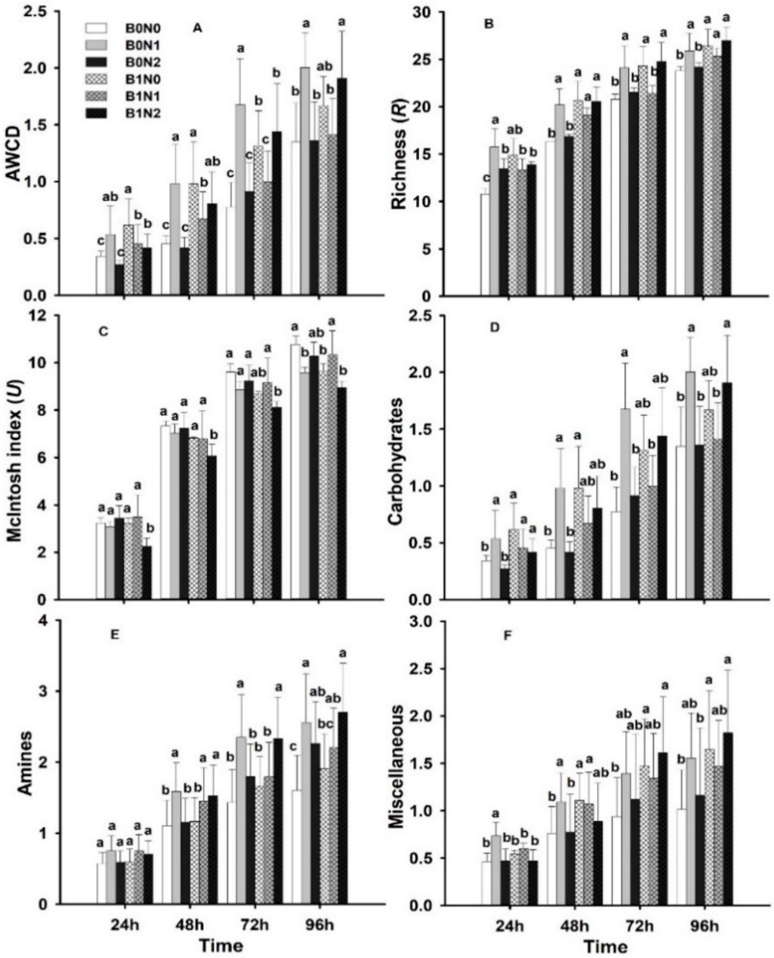

Figure 7. Effect of different treatments on soil carbon sources (**A**) Average well color development (AWCD), (**B**) Richness (R), (**C**) Mclntosh index (*U*), (**D**) Carbohydrates, (**E**) Amines, (**F**) Miscellaneous; B0N0 (without biochar or N fertilization); B0N1 (without biochar and with 160 kg·ha^{-1} N); B0N2 (without biochar and with 120 kg·ha^{-1} N); B1N0 (biochar 25 t·ha^{-1} only); B1N1 (biochar 25 t·ha^{-1} and 160 kg·ha^{-1} N); B1N2 (biochar 25 t·ha^{-1} and 120 kg·ha^{-1} N) at different times (24, 48, 72, and 96 h). The letters a, b, c, indicate statistically significant difference at $p < 0.05$.

3.5. Correlation between Soil Physical Properties and Carbon Sources

Looking at the trait interrelations between N0 (Figure 8A), N1 (Figure 8B), and N2 (Figure 8C) under B0 conditions, BD was found to be significantly positively correlated, while TP was significantly negatively correlated to amino acids under B0N0 conditions and had no correlation recorded under B0N1 or B0N2. Similarly, BD was substantially positively correlated, and TP was significantly negatively correlated, to amines under B0N1. In contrast, BD was significantly negatively correlated, and TP was significantly positively correlated, to the antilog of K under B0N0 and B0N1 conditions. FC was substantially positively correlated to R and H under B0N0 and B0N2 conditions and significantly positively correlated to amino acids under B0N0 conditions and to amines under B0N1 conditions. PAW was significantly positively correlated to CH and amino acids under B0N0 conditions and significantly positively correlated to amines under B0N1 conditions and to U under B0N2 conditions. Macropores were found to be significantly negatively correlated to amino acids under B0N0 conditions and to amines under B0N1 conditions. Micropores were found to be significantly positively correlated to amino acids under B0N0 conditions and to amines under B0N1 conditions. AWCD was found to be significantly positively correlated to polymers and amino acids and significantly negatively correlated to the antilog of K under B0N1 conditions.

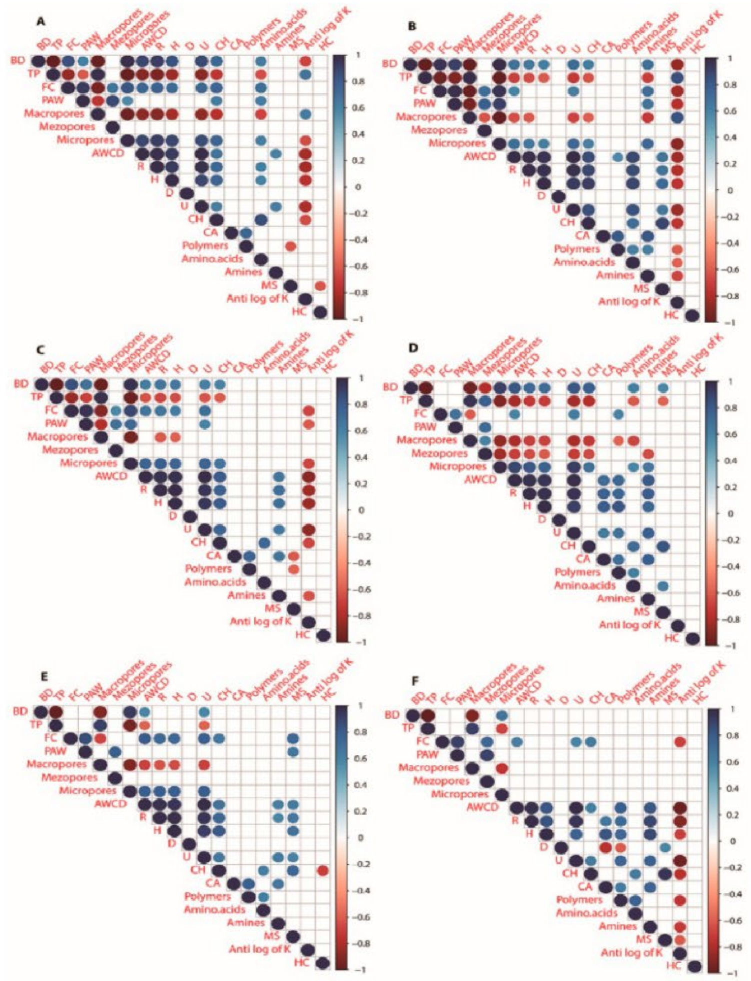

Figure 8. Heatmap correlations under different treatments (**A**) B0N0 (without biochar and N fertilization); (**B**) B0N1 (Without Biochar and 160 kg·ha^{-1} N); (**C**) B0N2 (Without Biochar and 120 kg·ha^{-1} N fertilization); (**D**) B1N0 (Biochar 25 t·ha^{-1} only); (**E**) B1N1 (Biochar 25 t·ha^{-1} and 120 kg·ha^{-1} N); (**F**) B1N2 (Biochar 25 t·ha^{-1}, 160 kg·ha^{-1} N) for bulk density (BD), total porosity (TP), field capacity (FC), plant-available water (PAW), average well color development (AWCD), richness (R), the Shannon index (H), the Simpson index (D), the McIntosh index (U), carbohydrates (CH), carboxylic acid (CA), miscellaneous (MS), hydraulic conductivity (HC). Note: Significant ($p < 0.05$) negative (red color) and positive (blue color) correlations between different soil carbon sources and soil physical properties are identified by color (−1.0 to +1.0); non-significant correlations are omitted.

With the addition of biochar treatments, the trait interrelations between N0 (Figure 8D), N1 (Figure 8E), and N2 (Figure 8F) revealed that BD was significantly positively correlated, while TP was significantly negatively correlated, to R, H, amino acids, and MS under B1N0 conditions. FC was significantly positively correlated to R and H under B1N0 conditions. PAW was significantly positively correlated to MS under B1N1 conditions. Macropores were found to be significantly negatively correlated to R and H under B1N0 and B1N1 conditions, while under B1N0 conditions, they were significantly positively correlated to mesopores and significantly negatively correlated to CH, polymers, and amino acids. Mesopores were found to be significantly negatively correlated to micropores, AWCD, R, H, U, CH, and amines under B1N0 conditions. Macropores were found to be significantly positively correlated to CH, amino acids, and amines under B1N0 conditions. AWCD, R, and H were found to be significantly positively correlated to MS under B1N1 conditions and significantly negatively correlated to the antilog of K under B1N2 conditions. D was found to be significantly negatively correlated to CA and polymers and significantly positively correlated to MS under B1N2 conditions. U and CH were significantly negatively correlated to the antilog of K under B1N2 conditions. CH was significantly negatively correlated to HC under B1N1 conditions. Polymers, amino acids, amines, and MS were found to be significantly negatively correlated to the antilog of K under B1N2 conditions. Amino acids were significantly positively correlated to MS under B1N0 conditions.

3.6. Principal Component Analysis

The purpose of employing principal component analysis (PCA) was to compare biochar and characterize the associations between the hydro-physical properties, SCSs, and indices. According to PCA, the two axes of PCA explained 90.4% and 4.3% of the total variations, respectively. MS, CH, amino acids, U, R, micropores, AWCD, and H were relatively clustered together. Likewise, polymers, amines, and CA were relatively clustered together. TP and macropores clustered together (Figure 9).

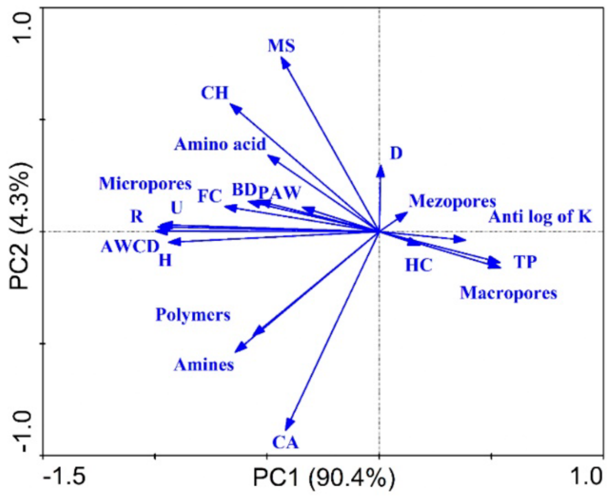

Figure 9. Pearson's correlations for bulk density (BD), total porosity (TP), field capacity (FC), plant-available water (PAW), average well color development (AWCD), richness (R), the Shannon index (H), the Simpson index (D), the McIntosh index (U), carbohydrates (CH), carboxylic acid (CA), miscellaneous (MS), and hydraulic conductivity (HC) under different treatments, i.e., B0N0 (without biochar or N fertilization); B0N1 (without biochar and with 160 kg·ha^{-1} N); B0N2 (without biochar and with 120 kg·ha^{-1} N); B1N0 (biochar 25 t·ha^{-1} only); B1N1 (biochar 25 t·ha^{-1} and 160 kg·ha^{-1} N); and B1N2 (biochar 25 t·ha^{-1} and 120 kg·ha^{-1} N).

4. Discussion

4.1. Biochar Effect on Soil Hydro-Physical Properties

Current results revealed a significant decrease in BD under 25 t·ha^{-1} of biochar with fertilizer application (Figure 1). There were several reasons for the soil BD reduction that are associated with biochar properties such as active large surface area, particle size, porosity, as well as soil properties [44]. Additionally, biochar has the ability to form soil pores in combination with soil particles, which results in a decrease in BD [45]. Šimanský et al. (2018) [46] reported that a 20 t·ha^{-1} biochar application significantly improved the soil structure compared to the control treatment, even though no significant improvement in the soil structure was recorded for a low-dose biochar application (10 t·ha^{-1}). Biochar and other organic matter have the potential to improve the physical condition of the soil [47,48]. Figure 2 shows the significant improvement in TP. Biochar particles contain hydroxyl and carboxyl groups on their surfaces that enable soil organic particles and minerals to form a soil structure [49,50]. Biochar acts as a substrate for soil fauna that, when mixed with the soil particles in earthworms' digestive tracts, produce coprolites that improve soil porosity and ultimately lead to lower BD [45,51].

The results indicated that the soil water content varied significantly and was substantially enhanced under biochar application with hPa suction at different depths (Figure 2). The reason for such variation could be rainfall and drought conditions [52]. In another study, it was reported that the soil water potential under biochar application tended to increase during the wheat-growing period [53]. They attributed this to biochar, which enhanced soil evaporation and tended to increase the soil temperature. Additionally, biochar significantly increased the soil's water-holding capacity due to the fact that its large surface area tended to enhance the volumetric water content of soil [45]. In line with the results of our study, Claire L. Phillips reported that 9−36 Mg ha^{-1} of conifer-wood- and wheat-straw-derived biochar both significantly enhanced soil porosity, which tended to substantially enhance soil volumetric water content and soil field capacity [54].

In the current study, swine-digestate manure-derived biochar significantly increased soil macropores but had no effect on meso- or micro-porosity at both of the depths recorded (Figure 3). Biochar amendment had a direct effect on soil porosity due to the high porosity of biochar and its other physical properties [55,56]. Additionally, the increase in soil microporosity could be attributed to the higher rate of biochar amendment. However, an increase in a certain level of biochar restricts the rate, affecting the soil pore size distribution [57,58]. Due to various amounts of soil organic carbon (SOC) in aggregate fractions, macropores are richer in SOC content [59]. Biochar substantially enhanced soil porosity, but the mechanisms still remain unknown. It was reported in a study that biochar application indirectly enhanced the macropore fraction, but the soil contained <3% of biochar internally, which could not explain the increase in porosity [60].

Soil hydraulic conductivity allows soil to transmit water and influences every soil, depending upon soil type and the amount of mineral and organic content in the soil [61]. In this study, soil HC increased in biochar-treated soil by 35–40% compared to non-biochar treatments (Figure 5). The increase in soil HC was influenced by the particle sizes of biochar and the soil [62]; thus, it could be attributed to biochar amendment due to the fact that the particle sizes of biochar were larger than those of the soil at the experimental site [45]. Similarly, in another study, it was stated that soil HC might be influenced by improved soil structure and by biochar having greater particle sizes than the soil, and vice versa [63,64]. However, several factors were involved in measuring the value of the antilog of K, e.g., soil pores, aeration within soil pores, etc. [45], due to which some of the values of the antilog of K 15–20 cm depths were non-significant.

4.2. Biochar Effect on Soil Carbon Sources and Indices

Figures 6 and 7 reveal the utilization trends of six major kinds of substrate guilds. The carbohydrate consumption capacity in the soil was recorded as being higher. Moreover, amino acids, carboxylic acids, polymers, amines, etc., were consumed much more extensively, and there was a significant SCS utilization trend recorded. These results imply that biochar with organic N fertilizer can increase the utilization of SCS, which tends to increase soil microbial diversity [65]. Higher diversity often increases the consumption of different substrates compared to deep soil, where microbial diversity is restricted [66,67]. Additionally, it is indicated that the soil depth gradient reduced both nutrient availability and the oxygen rate, which had a negative effect on soil bacteria and the regulation of their metabolic process [68,69]. The average well color development (AWCD) is a vital index of soil microbiota usage of carbon sources and reflects the physiological functions of soil microbial diversity [69,70]. Thus, it may be proposed that some of the selected C-source consumption may have a positive influence on microbial functional diversity and their metabolic activity in soil.

Under non-biochar treatments, the following correlations were found to be negative; TP and macropores to amino acids and amines under B0N0 and B0N1 conditions, respectively. BD and AWCD to HC under B0N0 and B0N1 conditions (Figure 8A–C). These negative correlations may be attributed to the lack of organic matter and carbon concentration [71,72]. In contrast, under biochar-treated soil, the following correlations were recorded as positive: macropores, FC, and BD to R, H, CH, amino acids, amines, and MS under B1N0 conditions. Amino acids were significantly and positively correlated to MS under B1N0 conditions (Figure 7D–F). Several studies reported that biochar application exerted positive priming effects by stimulating the soil's organic carbon content, which built a strong correlation with soil physicochemical properties [73,74].

5. Conclusions

The conclusions of this study are as follows:

1. Biochar alone and applied with 160 kg·ha^{-1} and 120 kg·ha^{-1} of N fertilizer significantly reduced soil BD and enhanced TP, as well as substantially enhanced soil macropores at both studied depths during August. Thus, swine-digestate manure-derived biochar may be a useful amendment to soil facing the problem of high BD and low TP, as well as in compacted soil with lower soil porosity.
2. Biochar with 160 kg·ha^{-1} of N fertilizer substantially increased VWC at the 5–10 cm depth at −4 to −100 hPa suction, whereas at higher suction (−100 hPa to −15,500 hPa), both field capacity and the wilting point of soil were recorded as being higher at both the 5–10 and 15–20 cm depths. Thus, biochar application may be helpful in drought conditions to enhance soil water content.
3. Biochar with and without N fertilizer application significantly lowered soil hydraulic conductivity by 35–40% at the 5–10 cm depth compared only to the non-biochar treatments. Thus, swine-digestate manure-derived biochar may substantially improve water transmission within the topsoil layer.
4. Biochar amendment may substantially enhance carbon source utilization, which tends to enhance soil microbial activity and was positively correlated in this study. Carboxylic acid was the leading SCS utilized, and amines were the least-utilized carbon source. The overall utilization of all SCSs was increased in biochar-treated soil compared to non-biochar treatments. According to all of the diversity indices (e.g., average well color development (AWCD) and richness (S)) analyzed in the Biolog EcoPlate incubated for 96 h, with the exception of the Mclntosh Index (U), higher biodiversity rates were recorded in biochar-treated soil and with the B0N1 treatment. However, the U index was recorded as being significantly lower from 24 to 96 h under treatment with B1N2; it was 20–30% lower compared to the control treatment. This study summarized that swine-digestate manure-derived biochar, both with and without N fertilizer, may be a useful amendment; depending upon the type of soil and the environmental factors, it may be useful in improving hydro-physical properties and microbial abundance.

Author Contributions: All authors contributed to this research paper. M.A. conceived the article; performed the practical research and the literature search; handled data preparation, analyses, and figures; and wrote the first draft. D.F., V.F., and V.T. critically revised the work and contributed to writing and editing; E.B.-G. and A.K. helped with biochar preparation and contributed to the article's conception, critical revision, and editing of drafts. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All datasets generated for this study are included in the article.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

References

1. Abdullah, R.; Osman, N.; Yusoff, S.; Mohd Yusof, H.; Halim, A.; Sa'adah, N.; Mohd Rosli, N.S. Effects of palm kernel biochar and food waste compost on the growth of palm lily (*Cordyline fruticosa*), coleus (*Coleus* sp.), and boat lily (*Rhoeo discolor*). *Appl. Ecol. Environ. Res.* **2021**, *19*, 205–218. [CrossRef]
2. Page, K.L.; Dang, Y.P.; Dalal, R.C. The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. *Front. Sustain. Food Syst.* **2020**, *4*, 31. [CrossRef]
3. Rostami, S.; Jafari, S.; Moeini, Z.; Jaskulak, M.; Keshtgar, L.; Badeenezhad, A.; Azhdarpoor, A.; Rostami, M.; Zorena, K.; Dehghani, M. Current methods and technologies for degradation of atrazine in contaminated soil and water: A review. *Environ. Technol. Innov.* **2021**, *24*, 102019. [CrossRef]
4. Singh, Y.; Choudhary, R.L.; Chaudhary, A.; More, N.; Singh, N.P. Impact of Conservation Agriculture and Residue Management on Soil Properties Under Sugarcane-Based Cropping Systems. In *Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 239–266.
5. Adekiya, A.O.; Olayanju, T.M.A.; Ejue, S.W.; Alori, E.T.; Adegbite, K.A. Contribution of Biochar in Improving Soil Health. In *Soil Health*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 99–113.
6. Zhou, H.; Fang, H.; Zhang, Q.; Wang, Q.; Chen, C.; Mooney, S.J.; Peng, X.; Du, Z. Biochar enhances soil hydraulic function but not soil aggregation in a sandy loam. *Eur. J. Soil Sci.* **2019**, *70*, 291–300. [CrossRef]
7. Hardie, M.; Clothier, B.; Bound, S.; Oliver, G.; Close, D. Does biochar influence soil physical properties and soil water availability? *Plant Soil* **2014**, *376*, 347–361. [CrossRef]
8. Fan, R.; Zhang, B.; Li, J.; Zhang, Z.; Liang, A. Straw-derived biochar mitigates CO_2 emission through changes in soil pore structure in a wheat-rice rotation system. *Chemosphere* **2020**, *243*, 125329. [CrossRef]
9. Jabborova, D.; Wirth, S.; Halwani, M.; Ibrahim, M.F.M.; El Azab, I.H.; El-Mogy, M.M.; Elkelish, A. Growth response of Ginger (*Zingiber officinale*), its physiological properties and soil enzyme activities after biochar application under greenhouse conditions. *Horticulturae* **2021**, *7*, 250. [CrossRef]
10. Zhang, Q.; Li, S.; Saleem, M.; Ali, M.Y.; Xiang, J. Biochar and earthworms synergistically improve soil structure, microbial abundance, activities and pyraclostrobin degradation. *Appl. Soil Ecol.* **2021**, *168*, 104154. [CrossRef]
11. Yin, D.; Li, H.; Wang, H.; Guo, X.; Wang, Z.; Lv, Y.; Ding, G.; Jin, L.; Lan, Y. Impact of Different Biochars on Microbial Community Structure in the Rhizospheric Soil of Rice Grown in Albic Soil. *Molecules* **2021**, *26*, 4783. [CrossRef]
12. Leng, L.; Xiong, Q.; Yang, L.; Li, H.; Zhou, Y.; Zhang, W.; Jiang, S.; Li, H.; Huang, H. An overview on engineering the surface area and porosity of biochar. *Sci. Total Environ.* **2021**, *763*, 144204. [CrossRef]
13. Warnock, D.D.; Mummey, D.L.; McBride, B.; Major, J.; Lehmann, J.; Rillig, M.C. Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: Results from growth-chamber and field experiments. *Appl. Soil Ecol.* **2010**, *46*, 450–456. [CrossRef]
14. Jiang, L.; Han, G.; Yu, L.A.N.; Liu, S.; Gao, J.; Xu, Y.; Jun, M.; Chen, W. Corn cob biochar increases soil culturable bacterial abundance without enhancing their capacities in utilizing carbon sources in Biolog Eco-plates. *J. Integr. Agric.* **2017**, *16*, 713–724. [CrossRef]
15. Ayaz, M.; Feizien, D.; Tilvikien, V.; Akhtar, K.; Stulpinait, U. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. [CrossRef]
16. Quilliam, R.S.; Glanville, H.C.; Wade, S.C.; Jones, D.L. Life in the 'charosphere'–Does biochar in agricultural soil provide a significant habitat for microorganisms? *Soil Biol. Biochem.* **2013**, *65*, 287–293. [CrossRef]
17. Gul, S.; Whalen, J.K. Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biol. Biochem.* **2016**, *103*, 1–15. [CrossRef]
18. Thies, J.E.; Rillig, M.C.; Graber, E.R. Biochar effects on the abundance, activity and diversity of the soil biota. *Biochar Environ. Manag. Sci. Technol. Implement.* **2015**, *2*, 327–389.

19. Hou, Q.; Zuo, T.; Wang, J.; Huang, S.; Wang, X.; Yao, L.; Ni, W. Responses of nitrification and bacterial community in three size aggregates of paddy soil to both of initial fertility and biochar addition. *Appl. Soil Ecol.* **2021**, *166*, 104004. [CrossRef]
20. Mujeeb Rahman, P.; Varma, R.V.; Sileshi, G.W. Abundance and diversity of soil invertebrates in annual crops, agroforestry and forest ecosystems in the Nilgiri biosphere reserve of Western Ghats, India. *Agrofor. Syst.* **2012**, *85*, 165–177. [CrossRef]
21. Kirchman, D.; Sigda, J.; Kapuscinski, R.; Mitchell, R. Statistical analysis of the direct count method for enumerating bacteria. *Appl. Environ. Microbiol.* **1982**, *44*, 376–382. [CrossRef]
22. Hale, L.; Curtis, D.; Leon, N.; McGiffen, M., Jr.; Wang, D. Organic amendments, deficit irrigation, and microbial communities impact extracellular polysaccharide content in agricultural soils. *Soil Biol. Biochem.* **2021**, *162*, 108428. [CrossRef]
23. Vos, M.; Wolf, A.B.; Jennings, S.J.; Kowalchuk, G.A. Micro-scale determinants of bacterial diversity in soil. *FEMS Microbiol. Rev.* **2013**, *37*, 936–954. [CrossRef] [PubMed]
24. Fierer, N.; Wood, S.A.; de Mesquita, C.P.B. How microbes can, and cannot, be used to assess soil health. *Soil Biol. Biochem.* **2021**, *153*, 108111. [CrossRef]
25. Waqas, M.; Asam, Z.; Rehan, M.; Anwar, M.N.; Khattak, R.A.; Ismail, I.M.I.; Tabatabaei, M.; Nizami, A.S. Development of biomass-derived biochar for agronomic and environmental remediation applications. *Biomass Convers. Biorefinery* **2021**, *11*, 339–361. [CrossRef]
26. Boostani, H.R.; Najafi-Ghiri, M.; Hardie, A.G.; Khalili, D. Comparison of Pb stabilization in a contaminated calcareous soil by application of vermicompost and sheep manure and their biochars produced at two temperatures. *Appl. Geochemistry* **2019**, *102*, 121–128. [CrossRef]
27. Ayaz, M.; Stulpinaite, U.; Feiziene, D.; Tilvikiene, V.; Akthar, K.; Baltrėnaite-Gediene, E.; Striugas, N.; Rehmani, U.; Alam, S.; Iqbal, R. Pig manure digestate derived biochar for soil management and crop cultivation in heavy metal contaminated soil. *Soil Use Manag.* **2021**, *38*, 1307–1321. [CrossRef]
28. Buneviciene, K.; Drapanauskaite, D.; Mazeika, R.; Tilvikiene, V.; Baltrusaitis, J. Granulated biofuel ash as a sustainable source of plant nutrients. *Waste Manag. Res.* **2021**, *39*, 806–817. [CrossRef]
29. Egene, C.E.; Sigurnjak, I.; Regelink, I.C.; Schoumans, O.F.; Adani, F.; Michels, E.; Sleutel, S.; Tack, F.M.G.; Meers, E. Solid fraction of separated digestate as soil improver: Implications for soil fertility and carbon sequestration. *J. Soils Sediments* **2021**, *21*, 678–688. [CrossRef]
30. Razzaghi, F.; Arthur, E.; Moosavi, A.A. Evaluating models to estimate cation exchange capacity of calcareous soils. *Geoderma* **2021**, *400*, 115221. [CrossRef]
31. *SIST EN 13651:2002*; Soil Improvers and Growing Media-Extraction of Calcium Chloride/DTPA (CAT) Soluble Nutrients. European Committee for Standardization: Brussels, Belgium, 2001.
32. Egner, H.; Riehm, H.; Domingo, W.R. Chemische Extraktionsmethoden zur Phosphor und Kaliumbestimmung, und Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nahrstoffzustandes der Böden. *K. Lantbrukshögskolans Ann.* **1960**, *26*, 199–215.
33. Klute, A.; Dirksen, C. Hydraulic conductivity and diffusivity: Laboratory methods. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*; American Society of Agronomy—Soil Science Society of America: Madison, WI, USA, 1986; Volume 5, pp. 687–734.
34. Luo, M.; Lin, H.; He, Y.; Zhang, Y. The influence of corncob-based biochar on remediation of arsenic and cadmium in yellow soil and cinnamon soil. *Sci. Total Environ.* **2020**, *717*, 137014. [CrossRef]
35. Wang, L.; Lin, H.; Dong, Y.; Li, B.; He, Y. Effects of endophytes inoculation on rhizosphere and endosphere microecology of Indian mustard (Brassica juncea) grown in vanadium-contaminated soil and its enhancement on phytoremediation. *Chemosphere* **2020**, *240*, 124891. [CrossRef] [PubMed]
36. Manjunath, M.; Kumar, U.; Yadava, R.B.; Rai, A.B.; Singh, B. Influence of organic and inorganic sources of nutrients on the functional diversity of microbial communities in the vegetable cropping system of the Indo-Gangetic plains. *C. R. Biol.* **2018**, *341*, 349–357. [CrossRef] [PubMed]
37. Garau, G.; Morillas, L.; Roales, J.; Castaldi, P.; Mangia, N.P.; Spano, D.; Mereu, S. Effect of monospecific and mixed Mediterranean tree plantations on soil microbial community and biochemical functioning. *Appl. Soil Ecol.* **2019**, *140*, 78–88. [CrossRef]
38. Rajpar, M.N.; Ozturk, M.; Altay, V.; Ullah, S.; Ullah, A.; Martin, C.O.; Gücel, S.; Zakaria, M. Species composition of dry-temperate forest as an important habitat for wildlife fauna species. *J. Environ. Biol.* **2020**, *41*, 328–336. [CrossRef]
39. Henderson, P.A.; Seaby, R.M.H. *Community Analysis Package 4.0*; Pisces Conservation Ltd.: Lymington, UK, 2007. Available online: http//www.pisces-conservation.com (accessed on 1 January 2020).
40. Magurran, A.E. *Ecological Diversity and Its Measurement*; Princeton University Press: Ryde, Australia, 1988.
41. Wei, T.; Simko, V. *R Package "Corrplot": Visualization of a Correlation Matrix*, Version 0.84; 2017. Available online: https://githubcom/taiyun/corrplot (accessed on 1 January 2020).
42. Oksanen, J.; Blanchet, F.G.; Kindt, R.; Legendre, P.; Minchin, P.R.; O'hara, R.B.; Simpson, G.L.; Solymos, P.; Stevens, M.H.; Wagner, H. Community ecology package: Ordination, diversity and dissimilarities. *Version* **2013**, *2*, 1–295.
43. Thioulouse, J.; Renaud, S.; Dufour, A.-B.; Dray, S. Overcoming the Spurious Groups Problem in Between-Group PCA. *Evol. Biol.* **2021**, *48*, 458–471. [CrossRef]
44. Tokovà, L.; Igaz, D.; Horák, J.; Aydin, E. Effect of biochar application and re-application on soil bulk density, porosity, saturated hydraulic conductivity, water content and soil water availability in a silty loam Haplic Luvisol. *Agronomy* **2020**, *10*, 1005. [CrossRef]

45. Šimanský, V.; Horák, J.; Igaz, D.; Jonczak, J.; Markiewicz, M.; Felber, R.; Rizhiya, E.Y.; Lukac, M. How dose of biochar and biochar with nitrogen can improve the parameters of soil organic matter and soil structure? *Biologia* **2016**, *71*, 989–995. [CrossRef]
46. Šimanský, V.; Horák, J.; Igaz, D.; Balashov, E.; Jonczak, J. Biochar and biochar with N fertilizer as a potential tool for improving soil sorption of nutrients. *J. Soils Sediments* **2018**, *18*, 1432–1440. [CrossRef]
47. Igaz, D.; Šimanský, V.; Horák, J.; Kondrlová, E.; Domanová, J.; Rodný, M.; Buchkina, N.P. Can a single dose of biochar affect selected soil physical and chemical characteristics? *J. Hydrol. Hydromech.* **2018**, *66*, 421–428. [CrossRef]
48. Šrank, D.; Šimanský, V. Physical Properties of Texturally Different Soils after Application of Biochar Substrates. *Agriculture (Pol'nohospodárstvo)* **2020**, *66*, 45–55. [CrossRef]
49. Jien, S.-H.; Wang, C.-S. Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena* **2013**, *110*, 225–233. [CrossRef]
50. Agbede, T.M.; Adekiya, A.O. Influence of Biochar on Soil Physicochemical Properties, Erosion Potential, and Maize (*Zea mays* L.) Grain Yield under Sandy Soil Condition. *Commun. Soil Sci. Plant Anal.* **2020**, *51*, 2559–2568. [CrossRef]
51. Šimanský, V.; Šrank, D.; Jonczak, J.; Juriga, M. Fertilization and application of different biochar types and their mutual interactions influencing changes of soil characteristics in soils of different textures. *J. Ecol. Eng.* **2019**, *20*, 149–164. [CrossRef]
52. Zhao, J.; Ren, T.; Zhang, Q.; Du, Z.; Wang, Y. Effects of biochar amendment on soil thermal properties in the North China Plain. *Soil Sci. Soc. Am. J.* **2016**, *80*, 1157–1166. [CrossRef]
53. Zhang, Q.; Wang, Y.; Wu, Y.; Wang, X.; Du, Z.; Liu, X.; Song, J. Effects of biochar amendment on soil thermal conductivity, reflectance, and temperature. *Soil Sci. Soc. Am. J.* **2013**, *77*, 1478–1487. [CrossRef]
54. Atkinson, C.J. How good is the evidence that soil-applied biochar improves water-holding capacity? *Soil Use Manag.* **2018**, *34*, 177–186. [CrossRef]
55. Phillips, C.L.; Light, S.E.; Gollany, H.T.; Chiu, S.; Wanzek, T.; Meyer, K.; Trippe, K.M. Can biochar conserve water in Oregon agricultural soils? *Soil Tillage Res.* **2020**, *198*, 104525. [CrossRef]
56. Sun, Q.; Meng, J.; Lan, Y.; Shi, G.; Yang, X.; Cao, D.; Chen, W.; Han, X. Long-term effects of biochar amendment on soil aggregate stability and biological binding agents in brown earth. *Catena* **2021**, *205*, 105460. [CrossRef]
57. Lu, H.; Bian, R.; Xia, X.; Cheng, K.; Liu, X.; Liu, Y.; Wang, P.; Li, Z.; Zheng, J.; Zhang, X. Legacy of soil health improvement with carbon increase following one time amendment of biochar in a paddy soil–A rice farm trial. *Geoderma* **2020**, *376*, 114567. [CrossRef]
58. Xiu, L.; Zhang, W.; Sun, Y.; Wu, D.; Meng, J.; Chen, W. Effects of biochar and straw returning on the key cultivation limitations of Albic soil and soybean growth over 2 years. *Catena* **2019**, *173*, 481–493. [CrossRef]
59. Liu, Z.; Chen, X.; Jing, Y.; Li, Q.; Zhang, J.; Huang, Q. Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. *Catena* **2014**, *123*, 45–51. [CrossRef]
60. Gupta, V.; Germida, J.J. Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. *Soil Biol. Biochem.* **1988**, *20*, 777–786. [CrossRef]
61. Sun, Z.; Zhang, Z.; Zhu, K.; Wang, Z.; Zhao, X.; Lin, Q.; Li, G. Biochar altered native soil organic carbon by changing soil aggregate size distribution and native SOC in aggregates based on an 8-year field experiment. *Sci. Total Environ.* **2020**, *708*, 134829. [CrossRef]
62. Benson, C.H.; Trast, J.M. Hydraulic conductivity of thirteen compacted clays. *Clays Clay Miner.* **1995**, *43*, 669–681. [CrossRef]
63. Lehmann, J.; Stephen, J. Biochar effect on soil hydrology. *Biochar Environ. Manag. Sci. Technol. Implement.* **2015**, 543–563.
64. Lim, T.J.; Spokas, K.A.; Feyereisen, G.; Novak, J.M. Predicting the impact of biochar additions on soil hydraulic properties. *Chemosphere* **2016**, *142*, 136–144. [CrossRef]
65. Esmaeelnejad, L.; Shorafa, M.; Gorji, M.; Hosseini, S. mossa Impacts of woody biochar particle size on porosity and hydraulic conductivity of biochar-soil mixtures: An incubation study. *Commun. Soil Sci. Plant Anal.* **2017**, *48*, 1710–1718. [CrossRef]
66. Duan, Y.; Yang, J.; Song, Y.; Chen, F.; Li, X.; Awasthi, M.K.; Li, H.; Zhang, L. Clean technology for biochar and organic waste recycling, and utilization in apple orchard. *Chemosphere* **2021**, *274*, 129914. [CrossRef]
67. Wolińska, A.; Włodarczyk, K.; Kuźniar, A.; Marzec-Grządziel, A.; Grządziel, J.; Gałązka, A.; Uzarowicz, Ł. Soil microbial community profiling and bacterial metabolic activity of technosols as an effect of soil properties following land reclamation: A case study from the abandoned iron sulphide and uranium mine in Rudki (South-Central Poland). *Agronomy* **2020**, *10*, 1795. [CrossRef]
68. Koner, S.; Chen, J.-S.; Hsu, B.-M.; Rathod, J.; Huang, S.-W.; Chien, H.-Y.; Hussain, B.; Chan, M.W.Y. Depth-resolved microbial diversity and functional profiles of trichloroethylene-contaminated soils for Biolog EcoPlate-based biostimulation strategy. *J. Hazard. Mater.* **2021**, 127266. [CrossRef]
69. Sandén, T.; Zavattaro, L.; Spiegel, H.; Grignani, C.; Sandén, H.; Baumgarten, A.; Tiirola, M.; Mikkonen, A. Out of sight: Profiling soil characteristics, nutrients and bacterial communities affected by organic amendments down to one meter in a long-term maize experiment. *Appl. Soil Ecol.* **2019**, *134*, 54–63. [CrossRef]
70. Xun, W.; Zhao, J.; Xue, C.; Zhang, G.; Ran, W.; Wang, B.; Shen, Q.; Zhang, R. Significant alteration of soil bacterial communities and organic carbon decomposition by different long-term fertilization management conditions of extremely low-productivity arable soil in South China. *Environ. Microbiol.* **2016**, *18*, 1907–1917. [CrossRef] [PubMed]
71. Li, Y.; Li, Z.; Cui, S.; Zhang, Q. Trade-off between soil pH, bulk density and other soil physical properties under global no-tillage agriculture. *Geoderma* **2020**, *361*, 114099. [CrossRef]

72. Knorr, M.; Frey, S.D.; Curtis, P.S. Nitrogen additions and litter decomposition: A meta-analysis. *Ecology* **2005**, *86*, 3252–3257. [CrossRef]
73. Peng, X.; Tong, X.; Hao, L.; Wu, F. Applicability of biochar for limiting interrill erosion and organic carbon export of sloping cropland in a semi-arid area of China. *Agric. Ecosyst. Environ.* **2019**, *280*, 68–76. [CrossRef]
74. Pan, S.-Y.; Dong, C.-D.; Su, J.-F.; Wang, P.-Y.; Chen, C.-W.; Chang, J.-S.; Kim, H.; Huang, C.-P.; Hung, C.-M. The Role of Biochar in Regulating the Carbon, Phosphorus, and Nitrogen Cycles Exemplified by Soil Systems. *Sustainability* **2021**, *13*, 5612. [CrossRef]

plants

MDPI

Article

Biochar with Inorganic Nitrogen Fertilizer Reduces Direct Greenhouse Gas Emission Flux from Soil

Muhammad Ayaz [1,*], Dalia Feizienė [1], Vita Tilvikienė [1], Virginijus Feiza [1], Edita Baltrėnaitė-Gedienė [2] and Sana Ullah [1]

1 Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry, Instituto al. 1, Akademija, LT-58344 Kėdainiai, Lithuania
2 Institute of Environmental Protection, Vilnius Gediminas Technical University, LT-10223 Vilnius, Lithuania
* Correspondence: muhammad.ayaz@lammc.lt; Tel.: +370-6542-2196

Abstract: Agricultural waste can have a catastrophic impact on climate change, as it contributes significantly to greenhouse gas (GHG) emissions if not managed sustainably. Swine-digestate-manure-derived biochar may be one sustainable way to manage waste and tackle GHG emissions in temperate climatic conditions. The purpose of this study was to ascertain how such biochar could be used to reduce soil GHG emissions. Spring barley (*Hordeum vulgare* L.) and pea crops in 2020 and 2021, respectively, were treated with 25 t ha^{-1} of swine-digestate-manure-derived biochar (B_1) and 120 kg ha^{-1} (N_1) and 160 kg ha^{-1} (N_2) of synthetic nitrogen fertilizer (ammonium nitrate). Biochar with or without nitrogen fertilizer substantially lowered GHG emissions compared to the control treatment (without any treatment) or treatments without biochar application. Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions were directly measured using static chamber technology. Cumulative emissions and global warming potential (GWP) followed the same trend and were significantly lowered in biochar-treated soils. The influences of soil and environmental parameters on GHG emissions were, therefore, investigated. A positive correlation was found between both moisture and temperature and GHG emissions. Thus, biochar made from swine digestate manure may be an effective organic amendment to reduce GHG emissions and address climate change challenges.

Keywords: biochar; CO_2; N_2O; CH_4 emissions; cumulative emissions; global warming potential; soil moisture; soil temperature

check for updates

Citation: Ayaz, M.; Feizienė, D.; Tilvikienė, V.; Feiza, V.; Baltrėnaitė-Gedienė, E.; Ullah, S. Biochar with Inorganic Nitrogen Fertilizer Reduces Direct Greenhouse Gas Emission Flux from Soil. *Plants* **2023**, *12*, 1002. https://doi.org/10.3390/plants12051002

Academic Editors: Giedrė Samuolienė, Gražina Kadžienė, Darius Kviklys and Neringa Rasiukeviciute

Received: 9 February 2023
Revised: 20 February 2023
Accepted: 21 February 2023
Published: 22 February 2023

1. Introduction

In recent decades, the increase in human population has caused serious challenges to the agriculture sector and to the agronomist in ensuring food security, causing minimum soil and environmental pollution [1]. Inorganic nitrogen fertilizer consumption in the agricultural sector of the European Union has increased by around 2% over the past ten years to 10.2 million tons [2]. This considerable share of synthesized fertilizer application is due to inefficient use, which causes financial harm, environmental damage, and health risks [3–5]. Inorganic fertilizer amendment and soil tillage practices have increased greenhouse gas (GHG) emissions [6–8]. By 2030, it is anticipated that the agricultural sector's nitric oxide (N_2O) emissions may rise by 35–60%. This increase is linked to higher nitrogen content due to fertilizer use and higher production of animal waste [9,10]. Moreover, the increase in the number of livestock is directly proportional to methane (CH_4) emissions that, between 1990 and 2030, are anticipated to increase by 60% [11]. The predicted rise in agrofarming emissions is 8–8.4%, with a mean increase of 8.3 Pg CO_2-eq by 2030, assuming the aforesaid rates of rising emissions (10–15%) for the 2020–2030 period. Anthropogenic emissions of GHGs (CO_2, CH_4, and N_2O), have become a substantial contributor to global climate change [12,13]. GHG emissions are highly dependent on soil temperature and moisture, which are instantaneously affected by biochar application [14–16]. The use of biochar is a farming method that improves soil temperature and moisture retention. There are two ways to best manage increase in soil moisture: (1) to increase the amount of organic matter in the soil (because the stability and porosity of aggregates are improved by the direct addition of biochar [17,18]) and (2) to increase physical barriers on the surface, which reduces soil surface runoff and evaporation [19]. Thus, soil moisture and temperature improvements appear to balance the emission of GHGs. Biochar application enhances soil organic carbon and, consequently, results in carbon sequestration [20,21]. Biochar amendment boosts crop productivity and reduces the overuse of synthetic chemical fertilizers while simultaneously increasing soil organic carbon (SOC) stock, moisture retention, and temperature [22–24]. By reducing the usage of synthetic fertilizers, this strategy can enhance both environmental and human health [25,26].

One of the main economic drivers is agriculture, and according to EEA Report No. 17, the sector's overall GHG emissions, which amount a 4.4 Mt CO_2 equivalent, are slightly lower than those of the transportation sector [27]. According to the long-term commitment EU panel, which was initiated in 2014 by Fertilizers Europe, the EU mineral fertilizer industry promotes fertilizer use efficiency to improve agricultural production and a sustainable environment (EU Nitrogen Expert Panel). Moreover, the addition of biochar improves the efficiency of the bacteria involved in carbon and nitrogen metabolism, considerably enhancing CO_2, CH_4, and N_2O outputs [28,29]. However, using biochar in conjunction with inorganic nitrogen fertilizer lowers GHG emissions without reducing crop output [30,31]. The impact of adding swine-digestate-derived biochar as an organic amendment with nitrogen fertilizer on GHG emissions from the soil in spring barley and pea cropping systems in the EU has not yet been reported. The use of biochar made from swine digestate is, therefore, hypothesized to minimize GHG emissions, either with or without using 70% of the recommended dose of synthetic nitrogen fertilizer. Therefore, two-year experiments on the mitigation of GHGs coupled with reduced synthetic nitrogen fertilizer are carried out at the research fields of the Lithuanian Research Center for Agriculture and Forestry, Lithuania. This study's primary goals are to decrease the excessive use of inorganic synthetic nitrogen fertilizer, improve environmental quality by lowering GHG emissions, and evaluate the usage of biochar made from swine digestate as a potential substitute source of fertilizer.

2. Materials and Methods

2.1. Experimental Site

The experimental study was conducted during the growing seasons of 2020 and 2021 at the fields of the Lithuania Research Center for Agriculture and Forestry (55°40′ N, 23°87′ E). The chemical compositions at depths of 0–10, 0–20, and 0–60 cm for the Endocalcari-Epihypogleyic Cambisol soil used in the experimental fields is shown in Table 1. Biochar was prepared from swine manure digestate at 550 °C. Both biochar and N fertilizer were applied to the soil one week prior to sowing of the crop and were manually applied to each plot (1.5 m^2). The experiment was carried out using the spring barley (*Hordeum vulgare* L.) "Luoke cultivar" and the pea (*Pisum sativum*) "Respect cultivar" in 2020 and 2021, respectively. The period of growth was from April to August 2020 for spring barley and from April to July 2021 for the pea crop. Data were recorded at each growth stage from seedling until maturity. Lithuanian Hydrometeorological Service-Dotnuva data under the Ministry of Environment data were used (http://www.meteo.lt/, accessed on 12 January 2020) (Figure 1). The chemical changes over two years in the fields studied are given in Table 1.

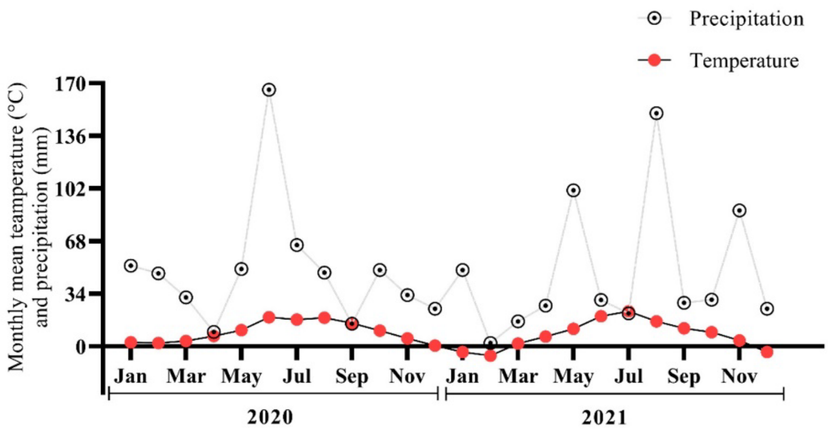

Figure 1. Mean monthly precipitation (mm) and air temperature (°C) during 2020 and 2021.

Table 1. Physiochemical properties of soil and biochar and soil chemical changes during two years.

				Soil				
Depth (cm)	pH	Total N (%)	P_2O_5 (mg/kg)	K_2O (mg/kg)	Organic carbon (%)	Mineral nitrogen (mg/kg)	NH_4-N (mg/kg)	NO_3-N+N_2O-N (mg/kg)
0–10	6.8	0.14	13.90	228.22	1.02	-	-	-
0–20	6.9	0.14	24.03	230.11	0.98	-	-	-
0–60	-	-	-		-	11.21	1.21	10
				Soil Chemical Changes				
Before sowing	6.8	0.14	142	230.17	1.03	6.78	1.25	9.39
After harvesting	6.9	0.13	254	232.08	0.99	9.20	2.09	7.11
Difference	−0.1	0.01	−112	−1.91	0.04	−2.42	−0.84	−1.58
				Biochar				
-	pH	Ash content (%)	Moisture wt. (%)	Volatile wt. (%)	Residual mass (char formed) wt. (%)	Total Mg (g/kg)	Organic C (%)	
	9.1	32.21	2.52	56.73	40.75	10.50	62.33	

P_2O_5—phosphorus pentoxide; NH_4-N—ammonium nitrogen; NO_3-N+N_2O-N—nitrate plus nitrite.

2.2. Soil Physicochemical Properties

Laboratory-based, standardized techniques were used to examine the physicochemical characteristics of both the soil and the biochar. A 1:5 (vol:vol^{-1}) soil combination in 1 M KCl solution was used for the electrical conductivity and pH analysis of the soil and biochar [32,33], as well as an extract in distilled water [34]. Soil and biochar organic matter contents were measured using a spectrophotometer at a wave length of 590 nm [35]. A revised ammonium-acetate technique was used to measure cation exchange capacity [36]. Inductively coupled plasma atomic emission spectrometry (Perkin Elmer ICP-OES, Waltham, MA, USA) was used to assess the extractable Mg from DTPA [37]. Using a reference approach, total nitrogen (TN) and accessible phosphorus concentrations were determined [38]. A TGA provided information on biochar ash content, moisture, volatiles, and residual mass.

2.3. Experimental Design

The field study used a three-factorial randomized full-block design with six treatments and three replications. No biochar plus no nitrogen fertilizer (control), no biochar plus 160 kg ha^{-1} nitrogen fertilizer (N_1), no biochar plus 120 kg ha^{-1} nitrogen fertilizer (N_2), 25 t ha^{-1} biochar plus 160 kg ha^{-1} nitrogen fertilizer (N_1B), 25 t ha^{-1} biochar plus 120 kg ha^{-1} nitrogen fertilizer (N_2B), and 25 t ha^{-1} biochar plus no nitrogen fertilizer (N_2B) were the experimental treatments (B).

2.4. Gas Sampling and Flux Calculation

Gas chromatography was used to measure the gas flux, and a static chamber gas [13,39] method was modified only slightly for the analysis. A U-shaped groove (50 mm wide and 50 mm deep) was present on the top edge of the chamber base box (frame) to retain a detachable chamber box. Stainless-steel frames were permanently buried 10 cm beneath the surface of the soil. A frame's perimeter covered 0.36 m^2. The chamber was sealed for 3 min before each flux measurement, and 20 mL of gas sample was drawn using a 20 cm^3 syringe. To increase the consistency of gaseous flux estimates, the gas samples were collected between the hours of 9:00 and 10:00 in the morning. Glass vials with rubber tubing used as a lid were used to collect the gas samples. From the beginning of the cultivating season (one week before the application of biochar) to one month after harvest, the fluxes of CO_2, N_2O, and CH_4 were measured at 2-week intervals. Three replicates of each treatment were used; thus, gas samples were collected from each plot. The samples were examined using a gas chromatograph (HP 6890 Series, GC System, Hewlett-Packard, Analytical system Management, Denver, USA) that had nickel catalysts for converting CO_2 to CH_4 and flame ionization and electron capture detectors. The corresponding temperatures were 70, 300, and 350 °C, respectively. The techniques for gas chromatography were explained by [40]. Equations (1) and (2) were used, respectively, to compute the cumulative and GHG flow rates and global warming potential for the growing seasons of 2020 and 2021 (from April to August). Based on the rate of change in GHG concentration within the chamber, which was determined as the slope of the linear regression between the GHG concentration and the gas-sampling time, the flow rate of each GHG was derived.

$$R_a = \left[\frac{R_i + R_i + 1}{2}\right] \times n \quad (1)$$

$$GWP = (CO_2 * 1) + (N_2O * 298) + (CH_4 * 25) \quad (2)$$

2.5. Calculation of Cumulative Soil GHG Emissions

Between various growth stages, cumulative CO_2, CH_4, and N_2O emissions for each treatment were estimated as indicated by [5,41].

The total cumulative emissions of soil CO_2, CH_4, and N_2O (mgha^{-1}h^{-1}) are represented by the symbol R_a, where the initial emissions of soil CO_2, CH_4, and N_2O are represented by R_i; the subsequent emissions of soil CO_2, CH_4, and N_2O are represented by R_i + 1 after the subsequent time i; and n is the number of interval days for the emissions of soil CO_2, CH_4, and N_2O.

2.6. Global Warming Potential (GWP)

The following equation was used to determine the global warming potential (GWP) of soils treated with biochar and N fertilizer in 2020–2021 (IPCC, 2007).

2.7. Soil Temperature and Moisture Measurements

In each growth stage, the soil temperature was measured using a squarely buried thermometer at a depth of 5 cm over the years 2020–21 [5]. Additionally, using an oven-drying method for 24 h at 105 °C, soil samples were taken from 0 to 10 cm deep using a soil auger in order to quantify soil moisture (in mass percent) at each growth stage. The link between soil temperature, moisture content, and CO_2, N_2O, and CH_4 emissions was examined using a linear regression.

2.8. Statistical Analysis

An analysis of variance (ANOVA) was performed on annual data gathered for each parameter during the 2-year period. The statistical differences were examined using Statistix 8. The Tukey Test was used to assess mean values at a *0.05* probability level. GraphPad Prism 9 was used to plot the data.

3. Results

3.1. Soil CO_2 Emission Flux

Periodic variation was recorded between the seasons of the spring barley crop of 2020 and the pea crop of 2021. The emission of CO_2 during the 2020 spring barley crop was recorded as higher throughout the season, except during jointing stage. During 2021 of the pea crop season, CO_2 emissions were found significantly ($\leq$0.05) lowered under biochar-treated soils compares to the spring barley of 2020 (Figure 2). All biochar-treated soils showed substantially ($\leq$0.05) lowered CO_2 emissions (by 57%, 55%, and 59%, respectively, for B, N_1B, and N_2B) compared to non-biochar-treated soils during all stages of the pea crop. The N_2B treatment significantly ($\leq$0.05) lowered CO_2 emissions during the tillering stage (by 58%) compared to the control treatment. Similarly, the B treatment substantially ($\leq$0.05) lowered CO_2 emissions during the jointing, flowering, and maturity stages by 50%, 51%, and 50%, respectively (Figure 2).

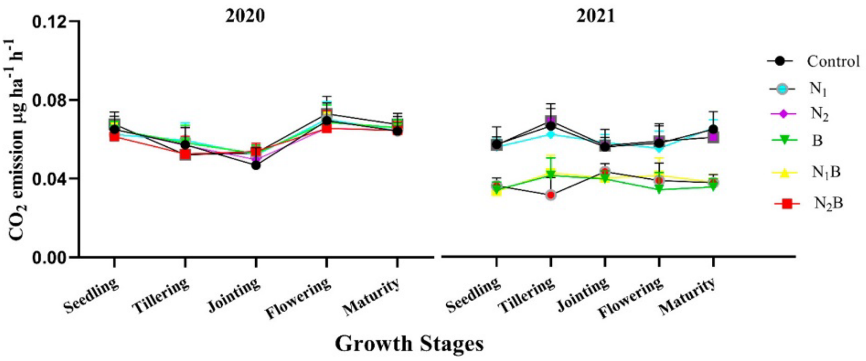

Figure 2. Direct effect of biochar on CO_2 emissions at different growth stages of spring barley (2020) and after effects on pea crop (2021). Treatments: control-without amendments; N_1-160 kg ha^{-1} nitrogen fertilizer; N_2-120 kg ha^{-1} nitrogen fertilizer; B-25 t ha^{-1} biochar; N_1B-160 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar; N_2B-120 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar.

3.2. Soil N_2O Emission Flux

Biochar treatments had no effect on N_2O emissions during the spring barley crop of 2020 throughout all the growth stages. However, there was significant variation recorded during different growth stages of both cropping seasons regarding N_2O emissions (Figure 3). Following the above trend, the biochar-treated soils of B, N_1B, and N_2B showed substantially ($\leq$0.05) lowered N_2O emissions by 48%, 49%, and 48%, respectively, throughout the growth stages of the pea crop compared to non-biochar treatments (Figure 3). In 2021, during the pea crop season, the N_2 treatment (100% nitrogen fertilizer alone) tended to enhance N_2O emission, specifically during the seedling and tillering stages.

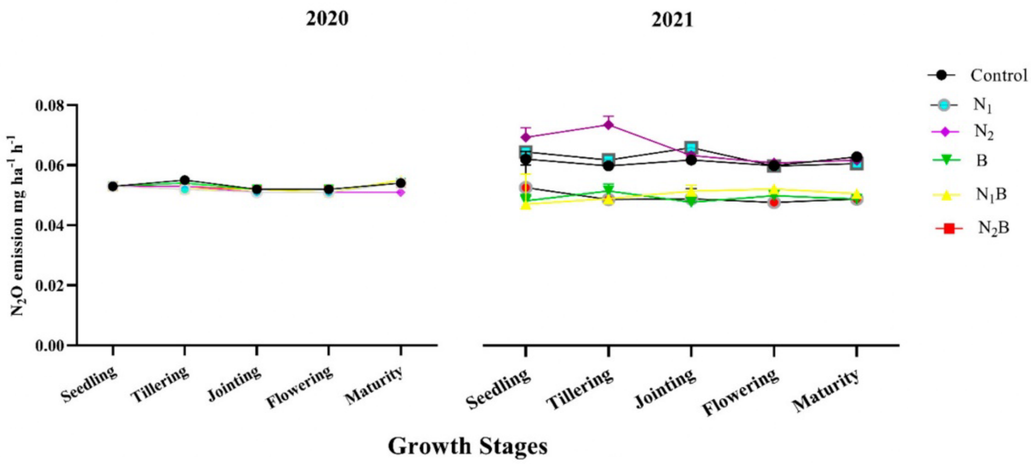

Figure 3. Direct effect of biochar on N_2O emissions at different growth stages of spring barley (2020) and after effects on pea crop (2021). Treatments: control-without amendments; N_1-160 kg ha^{-1} nitrogen fertilizer; N_2-120 kg ha^{-1} nitrogen fertilizer; B-25 t ha^{-1} biochar; N_1B-160 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar; N_2B-120 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar.

3.3. Soil CH_4 Emission Flux

There was no substantial variation recorded for methane gas (CH_4) emissions during the spring barley crop of 2020. However, the results indicated significant fluctuation in CH_4 emissions during the pea crop growing stages of 2021 (Figure 4). The N_1B treatment significantly ($\leq$0.05) lowered CH_4 emissions by 17%, and 19% during the flowering and maturity stages, respectively (Figure 4). However, biochar did not affect CH_4 emissions the way it effected CO_2 and N_2O emissions.

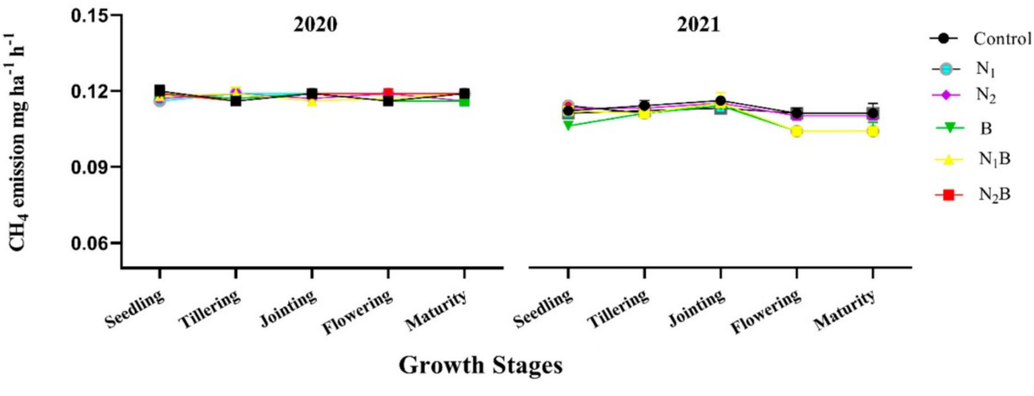

Figure 4. Direct effect of biochar on CH_4 emissions at different growth stages of spring barley (2020) and after effects on pea crop (2021). Treatments: control-without amendments; N_1-160 kg ha^{-1} nitrogen fertilizer; N_2-120 kg ha^{-1} nitrogen fertilizer; B-25 t ha^{-1} biochar; N_1B-160 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar; N_2B-120 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar.

Biochar application did not affect the cumulative emissions of CO_2, N_2O, and CH_4 during the growth stages of the spring barley crop of 2020 (Table 1). However, there was big variation recorded during the growth stages of the pea crop of 2021. The biochar treatments of B, N_1B, and N_2B significantly ($\leq$0.05) lowered cumulative CO_2 emissions by 16%, 19%, and 17%, respectively, compared to the control treatment. However, the cumulative emission of N_2O was significantly ($\leq$0.05) lowered by 6% only in the B treatment compared to the control treatment (Table 2). Similarly, the cumulative emission of CH_4 was significantly lowered by 7% in the B and N_1B treatments compared to the control treatment (Table 2).

Table 2. Cumulative CO_2–C, N_2O–N, and CH_4 (mg ha^{-1} hr^{-1}) emissions under different treatments over the two-year study.

Treatment	Cumulative CO_2	Cumulative N_2O	Cumulative CH_4
	2020		
Control	13262 ± 81.71a	10.09 ± 0.17a	20.18 ± 0.20ab
N_1	12393 ± 79.03ab	9.66 ± 0.19ab	19.78 ± 0.17ab
N_2	12487 ± 110.1ab	9.66 ± 0.15ab	21.13 ± 0.21a
B	13685 ± 99.21a	9.66 ± 0.17ab	20.68 ± 0.13ab
N_1B	13972 ± 83.52a	9.93 ± 0.19ab	20.77 ± 0.18ab
N_2B	12385 ± 91.33ab	10.04 ± 0.15a	21.20 ± 0.19a
	2021		
Control	8374 ± 91.01a	7.05 ± 0.11a	14.26 ± 0.20a
N_1	8093 ± 91.26a	7.96 ± 0.11a	14.18 ± 0.18a
N_2	8264 ± 83.21a	7.84 ± 0.13a	14.08 ± 0.20a
B	6907 ± 74.32b	6.64 ± 0.12b	13.06 ± 0.16b
N_1B	6716 ± 63.41b	7.00 ± 0.14a	13.05 ± 0.15b
N_2B	6833 ± 78.51b	6.97 ± 0.12a	14.16 ± 0.19a

Treatments: control-without amendments; N_1-160 kg ha^{-1} nitrogen fertilizer; N_2-120 kg ha^{-1} nitrogen fertilizer; B-25 t ha^{-1} biochar; N_1B-160 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar; N_2B-120 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar. Letters (a, b, and ab) show significant differences among treatments for spring barley (2020) and pea crops (2021) at $p \leq 0.05$ (LSD).

The global warming potential (GWP) of CO_2, N_2O, and CH_4 emissions followed the same trend as that of cumulative emissions. There was no significant fluctuation recorded for GWP during the growth stages of spring barley in 2020. However, the GWP caused by CO_2 was recorded as substantially ($\leq$0.05) lower in the biochar treatments of B, N_1B, and N_2B by 39%, 35%, and 39%, respectively, compared to other treatments during the growth stages of the pea crop of 2021 (Table 3). The GWPs caused by CH_4 and N_2O were significantly lowered in treatment B by 19% and 34% compared to the control treatment, respectively (Table 3).

The substantial changes under biochar and N fertilizer rates for soil moisture and temperature are presented in (Figure 5). During 2020–2021, no significant effects of the treatments were recorded for lower soil temperature during the vegetative growth stages of both crops. Furthermore, soil moisture contents were 9.5%, 8.3%, and 7.6% higher in the N_2B, N_1B, and B treatments, respectively, during flowering and maturity stages of spring barley. A similar trend was recorded during different growth stages of the pea crop (Figure 5).

Table 3. Effect of biochar on global warming potential (GWP) (mg ha hr^{-1}) during the years of 2020 and 2021.

Treatment	GWP of CO_2	GWP of CH_4	GWP of N_2O	Cumulative GWP
		2020		
Control	60.59 ± 0.117a	2.95 ± 0.05a	15.85 ± 0.15a	79.39 ± 0.112a
N_1	61.68 ± 0.132a	2.96 ± 0.06a	15.56 ± 0.19a	80.20 ± 0.132a
N_2	60.38 ± 0.126a	2.94 ± 0.04a	15.44 ± 0.12ab	78.76 ± 0.144ab
B	62.09 ± 0.137a	2.94 ± 0.05a	15.79 ± 0.20a	80.82 ± 0.141a
N_1B	62.66 ± 0.118a	2.95 ± 0.02a	15.67 ± 0.14 a	81.28 ± 0.152a
N_2B	59.58 ± 0.127a	2.96 ± 0.07a	15.73 ± 0.17a	78.27 ± 0.143ab
		2021		
Control	60.81 ± 0.281a	2.82 ± 0.09a	16.29 ± 0.27ab	79.92 ± 0.138a
N_1	59.76 ± 0.256ab	2.79 ± 0.08a	16.60 ± 0.14a	79.15 ± 0.163a
N_2	60.77 ± 0.242ab	2.81 ± 0.07a	17.46 ± 0.21a	81.04 ± 0.140a
B	37.17 ± 0.271b	2.70 ± 0.09b	13.08 ± 0.17b	52.95 ± 0.145b
N_1B	39.33 ± 0.229b	2.74 ± 0.02ab	15.29 ± 0.19a	57.36 ± 0.134b
N_2B	37.70 ± 0.217b	2.75 ± 0.10ab	15.11 ± 0.21a	55.53 ± 0.122b

Treatments: control-without amendments; N_1-160 kg ha^{-1} nitrogen fertilizer; N_2-120 kg ha^{-1} nitrogen fertilizer; B-25 t ha^{-1} biochar; N_1B-160 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar; N_2B-120 kg ha^{-1} nitrogen fertilizer plus 25 t ha^{-1} biochar. Letters (a, b, and ab) show significant differences among treatments for spring barley (2020) and pea crops (2021) at $p \leq 0.05$ (LSD).

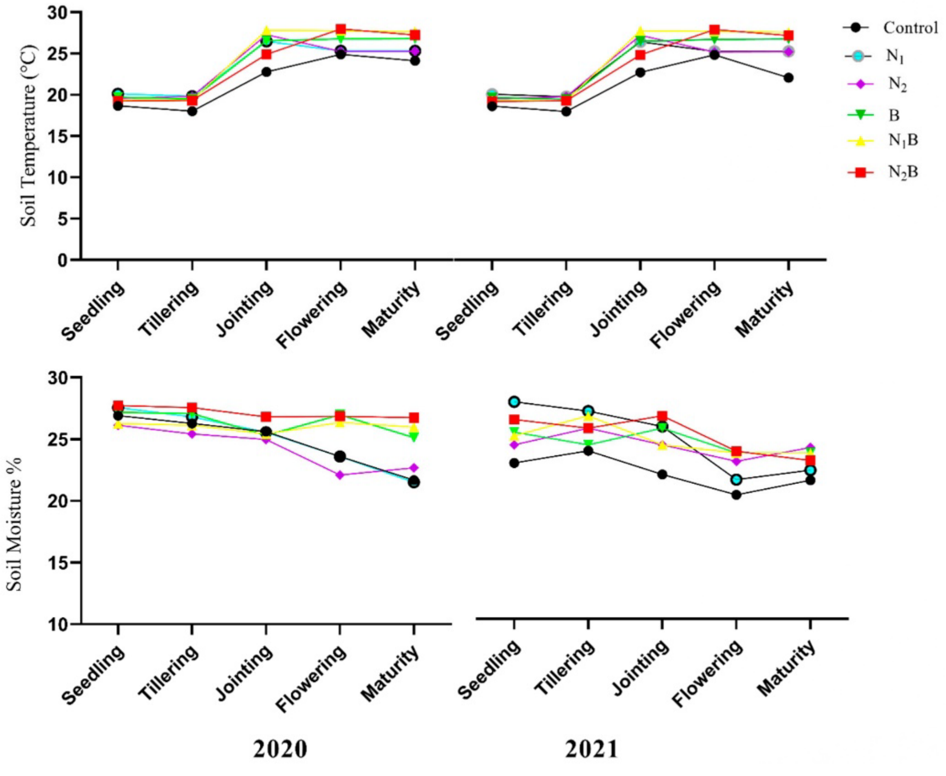

Figure 5. Changes in soil moisture content (%) and soil temperature (°C) in different growth stages of spring barley (2020) and pea crops (2021).

4. Discussion

4.1. CO_2 Emission

The decomposition of organic materials is caused by CO_2, N_2O, and CH_4 emissions [42,43]. Biochar provides additional environmental advantages since it improves soil fertility through decomposition [44,45]. Biochar is a significant source of carbon and helps in increasing SOC buildup [46,47] that, even at low soil temperatures, resulted in higher average CO_2 emissions in biochar-amended soil compared to non-biochar treatments in 2020. This result showed that soil C has a greater potential for soil CO_2 emission variability [48,49] and, hence, increases soil fertility. However, on the other hand, biochar has the potential to mitigate CO_2 emission [50,51]. The seasonal changes in soil CO_2 were dramatically impacted by biochar applications in 2021. Similar fluctuations in soil temperature and moisture were visible for the biochar treatments during the field trial. The agricultural fields′ consistent results demonstrate that biochar decomposition initially boosted soil CO_2 emission and soil carbon and nitrogen availability [52,53]. However, there was also substantially lowered soil CO_2 after biochar decomposition compared to non-biochar treatments. Unnecessary agronomic practices may influence soil moisture, which can affect soil CO_2 emission [54,55]. For instance, it was reported that different tillage operations lead to GHG emissions [56]. According to the current study, the higher precipitation (Figure 1) in the first year (2020) compared with that of the second year (2021) could mean that, due to favorable conditions for the decomposition of biochar, the soil CO_2 emission increased [57,58].

4.2. N_2O Emission

The overusage of N fertilizer increases GHG emissions and has negative effects on the ecosystem [59,60]. The current findings showed that, during the growth seasons, the N fertilizer treatments of N_1, N_2, and N_3 alone considerably boosted soil N_2O emissions. (2021). Based on the N used and the emission variables, soil amendment with biochar and synthetic fertilizers can reduce N_2O emissions [61]. It is challenging to anticipate the emission factors because of the complex chemical compositions of organic fertilizers [5,62]. It is known that N fertilization and mulching treatments together boost N_2O flux by 71–123% [63–65].

Nevertheless, biochar on a field might help to reduce N_2O emissions [66,67]. Additionally, it was determined from these outcomes that N application with biochar could decrease N_2O emissions, as observed in the biochar-treated plots compares to non-biochar-treated plots. Moreover, it was also reported that N fertilization could influence degradable N and C, which resulted in improving the intricate microbial interaction between N and C, thus enhancing N_2O emissions [68,69].

As a comparison to applying N fertilizer alone, using biochar with N fertilizer reduces N_2O emissions by 25–35% [70,71]. Higher nitrogen fertilizer application rates result in higher GHG emissions, which has an immediate impact on soil N_2O emissions [5,72,73]. The present study suggested that the N_1, N_2, and N_3 treatments are more environmentally unfriendly due to N_2O emissions, while the B treatment with N fertilizer is ecofriendly.

4.3. CH_4 Emission

Compared to CO_2 and N_2O emissions, only the N_1B treatment decreased CH_4 emissions during 2021. It was reported that the organic piles′ structure was improved with biochar application anaerobically, and biochar could alter the oxidation–reduction potential by enhancing absorptivity, which lowered the mechanism of methanogens and increased that of methanotrophs to mitigate CH_4 emissions [74]. Several of the literature findings have indicated that the interaction between applying biochar to soil and CH_4 flux is not well-known [75,76]. The soil applications of biochar have been shown to enhance [77], lower [77–79], or have no substantial influence on CH_4 emission flux [80]. It was reported that biochar addition to soil also promoted methanotrophic CH_4 intake at the oxic–anoxic junction in anaerobic environments. Moreover, the addition of biochar improved the oxidation of CH_4 by methanotrophic organisms at the oxic–anoxic root interface, which lowered the concentration of CH_4 that could enter a plant's aerenchyma and escape [79].

4.4. Global Warming Potential (GWP)

The overall impact of the main greenhouse gases (i.e., CO_2, CH_4, and N_2O) is driven by GWP [81]. The plots with applied biochar had a much lower net GWP during 2021. However, no substantial difference was reported in 2020, which is in line with the following reports. The non-significant difference in GWP might be due to the non-decomposition of biochar in the first year [82]; however, the decomposition of biochar might be enhanced in the second year, which led to GWP reduction [51]. Overall, studies report that biochar application can significantly mitigate global warming. The biochar C:N ratio may be an important factor that drives GWP under biochar applications [83].

4.5. Soil Moisture and Temperature

The incorporation of biochar into soil is treated as sustainable waste. It was reported that the inappropriate management of different wastes (food, agriculture, etc.) creates a global environmental challenge [84]. Thus, biochar addition provides a multitude of advantages in terms of sustainable environment and agriculture aspects [85]. Furthermore, the current study reported that biochar applications significantly ($p \leq 0.05$) elevated soil moisture content in the years of 2020–2021. Greater soil moisture content as a result of surface area and porous structure has been observed [22,86]. However, changes in soil temperature could be attributed to weather conditions.

4.6. Correlation between Soil Moisture, Temperature, and CO_2 and N_2O Emissions

According to the current study, CO_2, N_2O, and CH_4 emissions were considerably positively associated with soil temperature and moisture. According to a report, the primary variables affecting soil gas emission fluxes are its thermal characteristics [87,88]. Soil CO_2 and CH_4 emissions increase due to fact that higher soil temperature and moisture cause higher biochar decomposition and higher methane oxidation rates [89–91]. The reason for higher N_2O emissions with higher temperatures could be attributed to N fertilization, which releases mineralized N upon decomposition [92]. It was observed that soil temperature and soil moisture had a positive, two-parameter linear association with CO_2, N_2O, and CH_4 emissions (Figure 6). The findings of this study, therefore, show that agricultural management techniques under humid climate conditions affected the rate of soil GHG emission.

For the spring barley and pea crops in 2020–2021, the linear relationship between soil CO_2, N_2O, and CH_4 emissions and soil moisture and soil temperature was studied. Figure 6 demonstrates a positive correlation between soil temperature and moisture and soil GHG CO_2, N_2O, and CH_4 emissions. The linear CO_2, N_2O, and CH_4 R^2 values during 2020 and 2021 were 0.2171 and 0.1353, 0.5550 and 0.3355, and 0.7611 and 0.1981, respectively. According to Figure 6, soil CO_2, N_2O, and CH_4 emissions significantly increased when soil temperature and wetness rose.

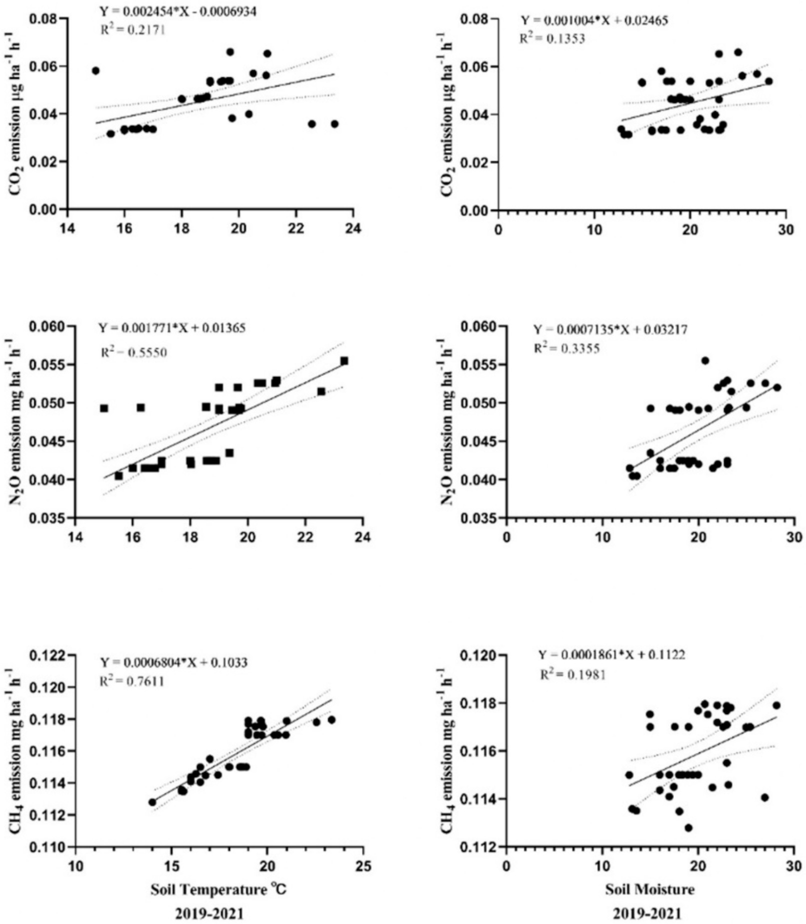

Figure 6. Linear relationship of soil CO_2, N_2O, and CH_4 emissions with soil temperature and soil moisture at different growth stages of spring barley (2020) and pea crops (2021).

5. Conclusions

Biochar application substantially lowered direct CO_2, N_2O, and CH_4 emissions from soil in the second year compared to first year for non-biochar-treated plots. Thus, the lower CO_2, N_2O, and CH_4 emissions from the agricultural fields confirmed that swine manure digestate biochar could be a suitable remedy for agriculture fields with higher GHG emissions, especially in temperate climatic conditions. Likewise, the cumulative emissions and global warming potential were substantially influenced by biochar during the second year of the experiment. A positive correlation was recorded between GHG emissions and soil moisture and temperature. No negative environmental issues were recorded during the two years of field research. More research is required to explore the long-term implication of swine-digestate-manure-derived biochar.

Author Contributions: All authors contributed to this research paper. M.A. conceived the idea for the article; performed the practical and the literature searches, data preparation, analyses, and figures; and wrote the first draft. D.F., V.F. and V.T. critically revised the work and contributed to writing and editing. E.B.-G. and S.U. helped in biochar preparation and contributed to article conception, critical revision, and editing drafts. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Muhammad Ayaz, upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, X. Managing Land Carrying Capacity: Key to Achieving Sustainable Production Systems for Food Security. *Land* **2022**, *11*, 484. [CrossRef]
2. Martinho, V.J.P.D. Direct and indirect energy consumption in farming: Impacts from fertilizer use. *Energy* **2021**, *236*, 121504. [CrossRef]
3. Yu, Y.; Hu, Y.; Gu, B.; Reis, S.; Yang, L. Reforming smallholder farms to mitigate agricultural pollution. *Environ. Sci. Pollut. Res.* **2021**, *29*, 13869–13880. [CrossRef]
4. Ghafoor, I.; Habib-Ur-Rahman, M.; Ali, M.; Afzal, M.; Ahmed, W.; Gaiser, T.; Ghaffar, A. Slow-release nitrogen fertilizers enhance growth, yield, NUE in wheat crop and reduce nitrogen losses under an arid environment. *Environ. Sci. Pollut. Res.* **2021**, *28*, 43528–43543. [CrossRef]
5. Akhtar, K.; Wang, W.; Ren, G.; Khan, A.; Enguang, N.; Khan, A.; Feng, Y.; Yang, G.; Wang, H. Straw mulching with inorganic nitrogen fertilizer reduces soil CO_2 and N_2O emissions and improves wheat yield. *Sci. Total Environ.* **2020**, *741*, 140488. [CrossRef]
6. Huang, Q.; Zhang, G.; Ma, J.; Song, K.; Zhu, X.; Shen, W.; Xu, H. Dynamic interactions of nitrogen fertilizer and straw application on greenhouse gas emissions and sequestration of soil carbon and nitrogen: A 13-year field study. *Agric. Ecosyst. Environ.* **2021**, *325*, 107753. [CrossRef]
7. Islam, S.M.; Gaihre, Y.K.; Islam, R.; Ahmed, N.; Akter, M.; Singh, U.; Sander, B.O. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. *J. Environ. Manag.* **2022**, *307*, 114520. [CrossRef]
8. Han, Z.; Lin, H.; Xu, P.; Li, Z.; Wang, J.; Zou, J. Impact of organic fertilizer substitution and biochar amendment on net greenhouse gas budget in a tea plantation. *Agric. Ecosyst. Environ.* **2021**, *326*, 107779. [CrossRef]
9. Lamb, W.F.; Grubb, M.; Diluiso, F.; Minx, J.C. Countries with sustained greenhouse gas emissions reductions: An analysis of trends and progress by sector. *Clim. Policy* **2021**, *22*, 1–17. [CrossRef]
10. Bruinsma, J. *World Agriculture: Towards 2015/2030: An FAO Perspective*; Routledge: Abingdon, UK, 2017.
11. Tsujimoto, S.; Takagi, T.; Osada, T.; Ogino, A. Greenhouse gas reduction and improved sustainability of animal husbandry using amino acids in swine, poultry feeds. *Anim. Sci. J.* **2013**, *84*, 409–415. [CrossRef]
12. Sonwani, S.; Saxena, P. Introduction to Greenhouse Gases: Sources, Sinks and Mitigation. In *Greenhouse Gases: Sources, Sinks and Mitigation*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 1–7.
13. Doyeni, M.O.; Stulpinaite, U.; Baksinskaite, A.; Suproniene, S.; Tilvikiene, V. Greenhouse gas emissions in agricultural cultivated soils using animal waste-based digestates for crop fertilization. *J. Agric. Sci.* **2021**, *159*, 23–30. [CrossRef]
14. Kumar, A.; Mishra, S.; Pandey, R.; Yu, Z.G.; Kumar, M.; Khoo, K.S.; Thakur, T.K.; Show, P.L. Microplastics in terrestrial ecosystems: Un-ignorable impacts on soil characterises, nutrient storage and its cycling. *TrAC Trends Anal. Chem.* **2023**, *158*, 116869. [CrossRef]
15. Raza, S.; Jiang, Y.; Elrys, A.S.; Tao, J.; Liu, Z.; Li, Z.; Chen, Z.; Zhou, J. Dicyandiamide efficacy of inhibiting nitrification and carbon dioxide emission from calcareous soil depends on temperature and moisture contents. *Arch. Agron. Soil Sci.* **2021**, *68*, 1413–1429. [CrossRef]
16. Sereni, L.; Guenet, B.; Blasi, C.; Crouzet, O.; Lata, J.-C.; Lamy, I. To what extend can soil moisture and soil contamination stresses affect greenhouse gas emissions? An attempt to calibrate a nitrification/denitrification model. *Biogeosci. Discuss.* **2021**, 1–27.
17. Goyal, R.; Kahlon, M.S. Soil physico-chemical properties and water productivity of maize as affected by biochar application under different irrigation regimes in northwest India. *Commun. Soil Sci. Plant Anal.* **2022**, *53*, 1068–1084. [CrossRef]
18. Wu, L.; Zheng, H.; Wang, X. Effects of soil amendments on fractions and stability of soil organic matter in saline-alkaline paddy. *J. Environ. Manag.* **2021**, *294*, 112993. [CrossRef]
19. Huang, Y.; Tao, B.; Xiaochen, Z.; Yang, Y.; Liang, L.; Wang, L.; Jacinthe, P.-A.; Tian, H.; Wen, R. Conservation tillage increases corn and soybean water produc-tivity across the Ohio River Basin. *Agric Water Manag.* **2021**, *254*, 106962. [CrossRef]
20. Liu, Q.; Li, Y.; Liu, S.; Gao, W.; Shen, J.; Zhang, G.; Xu, H.; Zhu, Z.; Ge, T.; Wu, J. Anaerobic primed CO_2 and CH_4 in paddy soil are driven by Fe reduction and stimulated by biochar. *Sci. Total Environ.* **2022**, *808*, 151911. [CrossRef]
21. Li, X.; Wang, R.; Shao, C.; Li, D.; Bai, S.; Hou, N.; Zhao, X. Biochar and Hydrochar from Agricultural Residues for Soil Conditioning: Life Cycle Assessment and Microbially Mediated C and N Cycles. *ACS Sustain. Chem. Eng.* **2022**, *10*, 3574–3583. [CrossRef]
22. Ayaz, M.; Feizien, D.; Tilvikien, V.; Akhtar, K.; Stulpinait, U. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. [CrossRef]
23. An, N.; Zhang, L.; Liu, Y.; Shen, S.; Li, N.; Wu, Z.; Yang, J.; Han, W.; Han, X. Biochar application with reduced chemical fertilizers improves soil pore structure and rice productivity. *Chemosphere* **2022**, *298*, 134304. [CrossRef]

24. Shi, Y.; Liu, X.; Zhang, Q.; Li, G.; Wang, P. Biochar rather than organic fertilizer mitigated the global warming potential in a sa-line-alkali farmland. *Soil Tillage Res.* **2022**, *219*, 105337. [CrossRef]
25. Babu, S.; Singh, R.; Yadav, D.; Rathore, S.S.; Raj, R.; Avasthe, R.; Yadav, S.; Das, A.; Yadav, V.; Yadav, B.; et al. Nanofertilizers for agricultural and environmental sustainability. *Chemosphere* **2021**, *292*, 133451. [CrossRef]
26. Wang, J.; Qin, L.; Cheng, J.; Shang, C.; Li, B.; Dang, Y.; He, H. Suitable chemical fertilizer reduction mitigates the water footprint of maize production: Evidence from Northeast China. *Environ. Sci. Pollut. Res.* **2021**, *29*, 22589–22601. [CrossRef]
27. Klusáčková, M. *Approximated EU Greenhouse Gas Inventory*; Flemish Institute for Technological Research: Mol, Belgium, 2021.
28. Nguyen, M.K.; Lin, C.; Hoang, H.G.; Sanderson, P.; Dang, B.T.; Bui, X.T.; Nguyen, N.S.H.; Vo, D.-V.N.; Tran, H.T. Evaluate the role of biochar during the organic waste composting process: A critical review. *Chemosphere* **2022**, *299*, 134488. [CrossRef]
29. Ji, B.; Chen, J.; Li, W.; Mei, J.; Yang, Y.; Chang, J. Greenhouse gas emissions from constructed wetlands are mitigated by biochar substrates and distinctly affected by tidal flow and intermittent aeration modes. *Environ. Pollut.* **2020**, *271*, 116328. [CrossRef]
30. He, Y.; Zhou, X.; Jiang, L.; Li, M.; Du, Z.; Zhou, G.; Shao, J.; Wang, X.; Xu, Z.; Bai, S.H.; et al. Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy* **2016**, *9*, 743–755. [CrossRef]
31. Lai, L.; Ismail, M.R.; Yusof, M.M.; Ismail, R. Rice straw biochar and different urea rates on rice yield and CH_4 and CO_2 gases emissions. *Chil. J. Agric. Res.* **2021**, *81*, 448–455. [CrossRef]
32. Buneviciene, K.; Drapanauskaite, D.; Mazeika, R.; Tilvikiene, V.; Baltrusaitis, J. Granulated biofuel ash as a sustainable source of plant nutrients. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2020**, *39*, 806–817. [CrossRef]
33. Ayaz, M.; Feizienė, D.; Feiza, V.; Tilvikienė, V.; Baltr, E. The Impact of Swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils. *Plants* **2022**, *11*, 1729. [CrossRef]
34. Egene, C.E.; Sigurnjak, I.; Regelink, I.C.; Schoumans, O.F.; Adani, F.; Michels, E.; Sleutel, S.; Tack, F.M.G.; Meers, E. Solid fraction of separated digestate as soil improver: Implications for soil fertility and carbon sequestration. *J. Soils Sediments* **2021**, *21*, 678–688. [CrossRef]
35. Nikitin, B. A Method for humus determination. *Agrokhimiia* **1999**, 91–93.
36. Razzaghi, F.; Arthur, E.; Moosavi, A.A. Evaluating models to estimate cation exchange capacity of calcareous soils. *Geoderma* **2021**, *400*, 115221. [CrossRef]
37. Prasad, M.; Tzortzakis, N. Critical review of chemical properties of biochar as a component of growing media. *Acta Hortic.* **2021**, 115–124. [CrossRef]
38. Egnér, H.; Riehm, H.; Domingo, W.R. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II. *Chem. Extraktionsmethoden Phosphor Kaliumbestimmung K. Lantbr. Ann.* **1960**, *26*, 199–215.
39. Zhang, J.; Li, Y.; Chang, S.X.; Qin, H.; Fu, S.; Jiang, P. Understory management and fertilization affected soil greenhouse gas emissions and labile organic carbon pools in a Chinese chestnut plantation. *For. Ecol. Manag.* **2015**, *337*, 126–134. [CrossRef]
40. Kanerva, T.; Regina, K.; Rämö, K.; Ojanperä, K.; Manninen, S. Fluxes of N_2O, CH_4 and CO_2 in a meadow ecosystem exposed to elevated ozone and carbon dioxide for three years. *Environ. Pollut.* **2007**, *145*, 818–828. [CrossRef]
41. Zhai, L.-M.; Liu, H.-B.; Zhang, J.-Z.; Huang, J.; Wang, B.-R. Long-Term Application of Organic Manure and Mineral Fertilizer on N_2O and CO_2 Emissions in a Red Soil from Cultivated Maize-Wheat Rotation in China. *Agric. Sci. China* **2011**, *10*, 1748–1757. [CrossRef]
42. Araújo, M.D.; de Souza, H.A.; Signor, D.; Muniz, L.C.; Costa, J.B.; de Souza, I.M.; Ribeiro Reis, V.R.; Pereira Brasil, E.; Pompeu, R.E.C.C. Integrated production systems in a Plinthosol: Greenhouse gas emissions and soil quality. *Aust. J. Crop Sci.* **2022**, *16*, 184–191. [CrossRef]
43. Shaaban, M.; Khalid, M.S.; Hu, R.; Zhou, M. Effects of water regimes on soil N_2O, CH_4 and CO_2 emissions following addition of dicyandiamide and N fertilizer. *Environ. Res.* **2022**, *212*, 113544. [CrossRef]
44. Liao, C.-S.; Xie, Z.-H.; Jien, S.-H. Decomposition and Nutrient Releasing of Biochar Compound Materials in Soil with Different Textures. *Processes* **2021**, *9*, 1521. [CrossRef]
45. Ferry, Y.; Herman, M.; Tarigan, E.B.; Pranowo, D. Improvements of soil quality and cocoa productivity with agricultural waste biochar. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *974*, 012045. [CrossRef]
46. Neogi, S.; Sharma, V.; Khan, N.; Chaurasia, D.; Ahmad, A.; Chauhan, S.; Singh, A.; You, S.; Pandey, A.; Bhargava, P.C. Sustainable biochar: A facile strategy for soil and environmental restoration, energy generation, mitigation of global climate change and circular bioeconomy. *Chemosphere* **2022**, *293*, 133474. [CrossRef]
47. Lu, T.; Wang, X.; Du, Z.; Wu, L. Impacts of continuous biochar application on major carbon fractions in soil profile of North China Plain's cropland: In comparison with straw incorporation. *Agric. Ecosyst. Environ.* **2021**, *315*, 107445. [CrossRef]
48. Zhang, S.; Fang, Y.; Luo, Y.; Li, Y.; Ge, T.; Wang, Y.; Wang, H.; Yu, B.; Song, X.; Chen, J.; et al. Linking soil carbon availability, microbial community composition and enzyme activities to organic carbon mineralization of a bamboo forest soil amended with pyrogenic and fresh organic matter. *Sci. Total Environ.* **2021**, *801*, 149717. [CrossRef]
49. Ahirwal, J.; Kumari, S.; Singh, A.K.; Kumar, A.; Maiti, S.K. Changes in soil properties and carbon fluxes following afforestation and agriculture in tropical forest. *Ecol. Indic.* **2021**, *123*, 107354. [CrossRef]
50. Shakoor, A.; Arif, M.S.; Shahzad, S.M.; Farooq, T.H.; Ashraf, F.; Altaf, M.M.; Ahmed, W.; Tufail, M.A.; Ashraf, M. Does biochar accelerate the mitigation of greenhouse gaseous emissions from agricultural soil?—A global meta-analysis. *Environ. Res.* **2021**, *202*, 111789. [CrossRef]

51. Lehmann, J.; Cowie, A.; Masiello, C.A.; Kammann, C.; Woolf, D.; Amonette, J.E.; Cayuela, M.L.; Camps-Arbestain, M.; Whitman, T. Biochar in climate change mitigation. *Nat. Geosci.* **2021**, *14*, 883–892. [CrossRef]
52. Bolan, N.; Hoang, S.A.; Beiyuan, J.; Gupta, S.; Hou, D.; Karakoti, A.; Joseph, S.; Jung, S.; Kim, K.-H.; Kirkham, M.; et al. Multifunctional applications of biochar beyond carbon storage. *Int. Mater. Rev.* **2021**, *67*, 150–200. [CrossRef]
53. Grau-Andrés, R.; Pingree, M.R.; Öquist, M.G.; Wardle, D.A.; Nilsson, M.-C.; Gundale, M.J. Biochar increases tree biomass in a managed boreal forest, but does not alter N_2O, CH_4, and CO_2 emissions. *GCB Bioenergy* **2021**, *13*, 1329–1342. [CrossRef]
54. Alskaf, K.; Mooney, S.J.; Sparkes, D.L.; Wilson, P.; Sjögersten, S. Short-term impacts of different tillage practices and plant residue retention on soil physical properties and greenhouse gas emissions. *Soil Till. Res.* **2021**, *206*, 104803. [CrossRef]
55. Li, Z.; Zhang, Q.; Qiao, Y.; Du, K.; Li, Z.; Tian, C.; Zhu, N.; Leng, P.; Yue, Z.; Cheng, H.; et al. Influence of straw mulch and no-tillage on soil respiration, its components and economic benefit in a Chinese wheat–maize cropping system. *Glob. Ecol. Conserv.* **2022**, *34*, e02013. [CrossRef]
56. Reicosky, D. Tillage-induced CO_2 emission from soil. *Nutr. Cycl. Agroecosyst.* **1997**, *49*, 273–285. [CrossRef]
57. Kumar, A.; Bhattacharya, T.; Mukherjee, S.; Sarkar, B. A perspective on biochar for repairing damages in the soil–plant system caused by climate change-driven extreme weather events. *Biochar* **2022**, *4*, 22. [CrossRef]
58. Abagandura, G.O.; Bansal, S.; Karsteter, A.; Kumar, S. Soil greenhouse gas emissions, organic carbon and crop yield following pinewood biochar and biochar–manure applications at eroded and depositional landscape positions: A field trial in South Dakota, USA. *Soil Use Manag.* **2022**, *38*, 487–502. [CrossRef]
59. Zhang, L.; Zhang, W.; Cui, Z.; Hu, Y.; Schmidhalter, U.; Chen, X. Environmental, human health, and ecosystem economic perfor-mance of long-term optimizing nitrogen management for wheat production. *J. Clean. Prod.* **2021**, *311*, 127620. [CrossRef]
60. Jamali, M.; Soufizadeh, S.; Yeganeh, B.; Emam, Y. A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110704. [CrossRef]
61. Han, Z.; Wang, J.; Xu, P.; Li, Z.; Liu, S.; Zou, J. Differential responses of soil nitrogen-oxide emissions to organic substitution for synthetic fertilizer and biochar amendment in a subtropical tea plantation. *GCB Bioenergy* **2021**, *13*, 1260–1274. [CrossRef]
62. Novoa, R.S.A.; Tejeda, H.R. Evaluation of the N_2O emissions from N in plant residues as affected by environmental and man-agement factors. *Nutr. Cycl. Agroecosyst.* **2006**, *75*, 29–46. [CrossRef]
63. Kim, G.W.; Kim, P.J.; Khan, M.I.; Lee, S.-J. Effect of Rice Planting on Nitrous Oxide (N_2O) Emission under Different Levels of Nitrogen Fertilization. *Agronomy* **2021**, *11*, 217. [CrossRef]
64. Ma, R.; Yu, K.; Xiao, S.; Liu, S.; Ciais, P.; Zou, J. Data-driven estimates of fertilizer-induced soil NH_3, NO and N_2O emissions from croplands in China and their climate change impacts. *Glob. Chang. Biol.* **2022**, *28*, 1008–1022. [CrossRef]
65. Garcia-Ruiz, R.; Baggs, E.M. N_2O emission from soil following combined application of fertiliser-N and ground weed residues. *Plant Soil.* **2007**, *299*, 263–274. [CrossRef]
66. Nelissen, V.; Saha, B.K.; Ruysschaert, G.; Boeckx, P. Effect of different biochar and fertilizer types on N_2O and NO emissions. *Soil Biol. Biochem.* **2014**, *70*, 244–255. [CrossRef]
67. Van Zwieten, L.; Kimber, S.; Morris, S.; Downie, A.; Berger, E.; Rust, J.; Scheer, C. Influence of biochars on flux of N_2O and CO_2 from *Ferrosol*. *Soil Res.* **2010**, *48*, 555–568. [CrossRef]
68. Montes, F.; Meinen, R.; Dell, C.; Rotz, A.; Hristov, A.N.; Oh, J.; Waghorn, G.; Gerber, P.J.; Henderson, B.; Makkar, H.P.S.; et al. SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *J. Anim. Sci.* **2013**, *91*, 5070–5094. [CrossRef]
69. Helgason, B.L.; Janzen, H.H.; Chantigny, M.H.; Drury, C.F.; Ellert, B.H.; Gregorich, E.G.; Lemke, L.R.; Pattey, E.; Rochette, P.; Wagner-Riddle, C. Toward improved coefficients for pre-dicting direct N2O emissions from soil in Canadian agroecosystems. *Nutr. Cycl. Agroecosyst.* **2005**, *72*, 87–99. [CrossRef]
70. González-Cencerrado, A.; Ranz, J.P.; Jiménez, M.T.L.-F.; Gajardo, B.R. Assessing the environmental benefit of a new fertilizer based on activated biochar applied to cereal crops. *Sci. Total Environ.* **2019**, *711*, 134668. [CrossRef]
71. Dawar, K.; Fahad, S.; Jahangir, M.M.R.; Munir, I.; Alam, S.S.; Alam Khan, S.; Mian, I.A.; Datta, R.; Saud, S.; Banout, J.; et al. Biochar and urease inhibitor mitigate NH3 and N2O emissions and improve wheat yield in a urea fertilized alkaline soil. *Sci. Rep.* **2021**, *11*, 17413. [CrossRef]
72. Smith, K.A.; Conen, F. Impacts of land management on fluxes of trace greenhouse gases. *Soil Use Manag.* **2004**, *20*, 255–263. [CrossRef]
73. Shcherbak, I.; Millar, N.; Robertson, G.P. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 9199–9204. [CrossRef]
74. Sonoki, T.; Furukawa, T.; Jindo, K.; Suto, K.; Aoyama, M.; Sánchez-Monedero, M.Á. Influence of biochar addition on methane me-tabolism during thermophilic phase of composting. *J. Basic Microbiol.* **2013**, *53*, 617–621. [CrossRef]
75. Kammann, C.; Ippolito, J.; Hagemann, N.; Borchard, N.; Cayuela, M.L.; Estavillo, J.M.; Fuertes-Mendizabal, T.; Jeffery, S.; Kern, J.; Novak, J.; et al. Biochar as a tool to reduce the agricultural greenhouse-gas burden–knowns, unknowns and future research needs. *J. Environ. Eng. Landsc. Manag.* **2017**, *25*, 114–139. [CrossRef]
76. Jeffery, S.; Verheijen, F.G.; Kammann, C.; Abalos, D. Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biol. Biochem.* **2016**, *101*, 251–258. [CrossRef]

77. Yu, L.; Tang, J.; Zhang, R.; Wu, Q.; Gong, M. Effects of biochar application on soil methane emission at different soil moisture levels. *Biol. Fertil. Soils* **2013**, *49*, 119–128. [CrossRef]
78. Lin, X.W.; Xie, Z.B.; Zheng, J.Y.; Liu, Q.; Bei, Q.C.; Zhu, J.G. Effects of biochar application on greenhouse gas emissions, carbon seques-tration and crop growth in coastal saline soil. *Eur. J. Soil Sci.* **2015**, *66*, 329–338. [CrossRef]
79. Feng, Y.; Xu, Y.; Yu, Y.; Xie, Z.; Lin, X. Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biol. Biochem.* **2011**, *46*, 80–88. [CrossRef]
80. Xie, Z.; Xu, Y.; Liu, G.; Liu, Q.; Zhu, J.; Tu, C.; Amonette, J.E.; Cadisch, G.; Yong, J.W.H.; Hu, S. Impact of biochar application on nitrogen nutrition of rice, greenhouse-gas emissions and soil organic carbon dynamics in two paddy soils of China. *Plant Soil* **2013**, *370*, 527–540. [CrossRef]
81. IPCC CWT. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2007; p. 104.
82. Mukherjee, A.; Lal, R. Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. *Agronomy* **2013**, *3*, 313–339. [CrossRef]
83. Xu, H.; Cai, A.; Wu, D.; Liang, G.; Xiao, J.; Xu, M.; Colinet, G.; Zhang, W. Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C: N ratio and soil pH: A global meta-analysis. *Soil Tillage Res.* **2021**, *213*, 105125. [CrossRef]
84. Giwa, A.S.; Xu, H.; Chang, F.; Wu, J.; Li, Y.; Ali, N.; Ding, S.; Wang, K. Effect of biochar on reactor performance and methane generation during the anaerobic digestion of food waste treatment at long-run operations. *J. Environ. Chem. Eng.* **2019**, *7*, 103067. [CrossRef]
85. Parmar, A.; Nema, P.K.; Agarwal, T. Biochar production from agro-food industry residues: A sustainable approach for soil and environmental management. *Curr. Sci.* **2014**, *107*, 1673–1682.
86. Tao, Z.; Li, C.; Li, J.; Ding, Z.; Xu, J.; Sun, X.; Zhou, P.; Zhao, M. Tillage and straw mulching impacts on grain yield and water use efficiency of spring maize in Northern Huang–Huai–Hai Valley. *Crop J.* **2015**, *3*, 445–450. [CrossRef]
87. Zhang, D.; Pan, G.; Wu, G.; Kibue, G.W.; Li, L.; Zhang, X.; Zheng, J.; Zheng, J.; Cheng, K.; Joseph, S.; et al. Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. *Chemosphere* **2016**, *142*, 106–113. [CrossRef]
88. Khan, R.; Abbas, A.; Farooque, A.A.; Abbas, F.; Wang, X. Mitigation of Greenhouse Gas Emissions from Agricultural Fields through Bioresource Management. *Sustainability* **2022**, *14*, 5666. [CrossRef]
89. Schaufler, G.; Kitzler, B.; Schindlbacher, A.; Skiba, U.; Sutton, M.A.; Zechmeister-Boltenstern, S. Greenhouse gas emissions from European soils under different land use: Effects of soil moisture and temperature. *Eur. J. Soil Sci.* **2010**, *61*, 683–696. [CrossRef]
90. Sänger, A.; Geisseler, D.; Ludwig, B. Effects of moisture and temperature on greenhouse gas emissions and C and N leaching losses in soil treated with biogas slurry. *Biol. Fertil. Soils* **2011**, *47*, 249–259. [CrossRef]
91. Yuan, H.; Lu, T.; Wang, Y.; Huang, H.; Chen, Y. Influence of pyrolysis temperature and holding time on properties of biochar derived from medicinal herb (radix isatidis) residue and its effect on soil CO_2 emission. *J. Anal. Appl. Pyrolysis* **2014**, *110*, 277–284. [CrossRef]
92. Chen, C.; Chen, D.; Lam, S.K. Simulation of Nitrous Oxide Emission and Mineralized Nitrogen under Different Straw Retention Conditions Using a Denitrification-Decomposition Model. *CLEAN Soil Air Water* **2014**, *43*, 577–583. [CrossRef]

SANTRAUKA

Bioanglies ir mineralinių azoto trąšų naudojimo perspektyvumas dirvožemio tvarumo ir augalų derlingumo gerinimui Nemoralinėje klimatinėje zonoje

ĮVADAS

Žmonių populiacija vis didėja, o civilizacija vis dar labai priklausoma nuo iškastinio kuro, todėl būtina rasti kūrybiškus, veiksmingus, ilgalaikius ir finansiškai patrauklius šių problemų sprendimus (Zhang *ir kt.,* 2019). Žemės ūkis šiuo metu susiduria su didele problema - neužtikrintumu maistu. Jei gamyba didinama tokiomis priemonėmis, kaip perteklinis žemės dirbimas ar didelių mineralinių trąšų dozių naudojimas, gali kilti neigiamų pasekmių aplinkai, pavyzdžiui, gali būti sutrikdyti pagrindiniai dirvožemio procesai (Tripathi *ir kt.,* 2020). Efektyviai, saugiai ir kokybiškai maisto produktų gamybai reikia labai rūpintis aplinka, teigia Tvaraus žemės ūkio taryba (Council on Sustainable Agriculture) (Council, 2010). Dėl gebėjimo išsaugoti ar net pagerinti dirvožemio derlingumą geriausi agronominiai metodai ir toliau išlieka labai paklausūs (Ullah *ir kt.,* 2019). Žemdirbystės sistemų technologijų taikymas leido kai kuriuose pasaulio regionuose patenkinti maisto poreikius. Tai apima, be kita ko, įvairias ūkininkavimo sistemas, tokias kaip agrarinė miškininkystė, agroekologija, tvarioji žemdirbystė, ekologinė žemdirbystė ir kitos (Nair *ir kt.,* 2017). Visų šių metodų tikslas - didinti derlių, mažinti taršą, kurti ekologiškai tvarų žemės ūkį ir buveines (Lehmann ir Joseph, 2015). Ši strategija nukreipė mokslininkų ir ūkininkų dėmesį nuo pramoniniu būdu apdorotų prekių į natūralius likučius ir organines medžiagas (Paas *ir kt.,* 2019). Bioanglis - tai mokslinis atradimas, kuris labai padeda siekti aplinkosaugos ir žemės ūkio tvarumo (K. Khan *ir kt.,* 2022). Dirvožemio fizikinės savybės turi įtakos pralaidumui, aeracijai ir gebėjimui sulaikyti vandenį, o tai savo ruožtu daro įtaką dirvožemio derlingumui (Oladosu *ir kt.,* 2022). Keliuose tyrimuose nustatyta, kad dirvožemio profilis geriau panaudoja vandenį ir maisto medžiagas, kai jo struktūra, poringumas, hidraulinis laidumas ir savitasis svoris yra optimalūs (Rostami *ir kt.,* 2021; Singh *ir kt.,* 2021). Šaknų augimas ir maisto medžiagų sulaikymas taip pat labai pagerėjo apdorojus bioangliu, palyginti su prastos fizinės būklės dirvožemiais (A O Adekiya *ir kt.,* 2020). Dirvožemio hidraulinis laidumas pagerėjo pridėjus bioanglies, nes sumažėjo dirvožemio tūrinis tankis ir pagerėjo dirvožemio poringumas (Zhou *ir kt.,* 2019). Nepaisant to, daugelyje tyrimų padaryta išvada, kad bioanglis reikšmingai nekeičia dirvožemio fizikinių savybių. Naudojant bioanglies sumažėjo makroporų ir porų jungiamumas (Fan *ir kt.,* 2020). Bioanglies poveikis dirvožemio hidrologiniams veiksniams vis dar nėra gerai ištirtas.

Šiltnamio efektą sukeliančios dujos (ŠESD), tokios kaip anglies dioksidas (CO_2), metanas (CH_4) ir azoto oksidas (N_2O), kurios į atmosferą patenka dėl žmogaus veiklos, yra pagrindinis planetos atšilimo veiksnys (Doyeni *ir kt.,* 2021; Sonwani ir Saxena, 2022). Vieną akimirką panaudojus bioanglies galima pakeisti dirvožemio temperatūrą ir drėgmę (Li *ir kt.,* 2023). Buvo iškelta hipotezė, kad Nemoralės klimato zonoje ŠESD emisijų atsako rodikliai bus mažiausi ir kad šie rodikliai laikui bėgant mažės dėl vėsios temperatūros; kontroliuojamomis sąlygomis tai gali būti sėkmingiau nei lauko bandymuose dėl dirvožemio drėgmės kiekio ir mikrobų aktyvumo (Lehtinen *ir kt.,* 2014).

Bioanglies naudojimas yra žemės ūkio technika, gerinanti drėgmės išsaugojimą ir reguliuojanti dirvožemio temperatūrą. Esant drėgnoms sąlygoms, organinės medžiagos skaidosi lėčiau, nes deguonies prieinamumas yra ribotas, todėl sumažėja mikrobų, atsakingų už organinių medžiagų skaidymą, aktyvumas Todėl esant drėgnoms sąlygoms, dirvožemyje sumažėja CO_2 emisija (Bot ir Benites, 2005). Sausame dirvožemyje skaidymas gali paspartėti dėl padidėjusio mikrobų aktyvumo laikotarpiais, kai yra daugiau drėgmės. Tačiau jei dėl užsitęsusios sausros plačiai sumažėja dirvožemio organinės medžiagos kiekis, ši nauda gali būti laikina (Gao *ir kt.,* 2016). Dirvožemio drėgmės lygis turi didelę įtaką metano emisijai iš dirvožemio. Sąlygos, kai trūksta deguonies, pavyzdžiui, tokios, kokios būdingos užliejamiems ar užtvindytiems dirvožemiams, yra idealios metano susidarymui (Conrad, 2020). Dirvožemio drėgmė atlieka svarbų vaidmenį mikrobiologiniuose nitrifikacijos ir denitrifikacijos procesuose, kurie savo ruožtu prisideda prie azoto oksido emisijos (Butterbach-Bahl *ir kt.,* 2013). Nitrifikacija (procesas, kurio metu amonis paverčiamas nitratais) paprastai slopinama esant drėgnoms arba prisotintoms sąlygoms, todėl sumažėja N_2O emisija (Reddy, Patrick ir Broadbent, 1984).

Bioanglis gali daryti didelį poveikį dirvožemio pralaidumui ir metalų judrumui, visų pirma dėl proceso, vadinamo "sorbcija", kai sunkiųjų metalų jonai prisijungia prie bioanglio dalelių paviršiaus. Dėl daugybės surišimo vietų bioanglies paviršiuje ji gerokai sumažina sunkiųjų metalų judrumą dirvožemyje. Dėl teigiamai įkrautų katijonų bioanglis labai artimas švinui (Pb), kadmiui (Cd), variui (Cu) ir cinkui (Zn). Šiuos metalus bioanglis absorbuoja ir sulaiko dėl neigiamo jo funkcinių grupių krūvio (Shahrokhi-Shahraki *ir kt.,* 2021). Daugeliu tyrimų (Bandara *ir kt.,* 2021; Jabborova *ir kt.,* 2021; Q. Zhang *ir kt.,* 2021) įrodyta, kad bioanglis gerokai padidina dirvožemio mikrobų aktyvumą. Teoriškai naudojant bioanglies, kuri praktiškai yra antiseptinė medžiaga, gali sumažėti dirvožemyje esančių mikrobų skaičius (Yin *ir kt.,* 2021). Ilgalaikė nauda dirvožemio mikrobiotai sukuriama dėl bioanglies makroporų ir plataus paviršiaus ploto (Wang, K. Zhang *ir kt.,* 2021) (parodyta 4 straipsnyje) prarandamų lakiųjų medžiagų pirolizės metu (parodyta 4 straipsnyje). Nustatyta, kad bioanglis daro neigiamą poveikį dirvožemio mikrobams ir mikorizės grybams, panašų į tą, kuris pastebimas naudojant didelį azoto ir fosforo kiekį (Warnock *ir kt.,* 2010), tačiau dėl mažesnio mineralinių elementų kiekio bioanglyje neigiamas poveikis yra mažesnis (Jiang *ir kt.,* 2017). Pavyzdžiui, dirvožemio fizikinės ir cheminės savybės gali turėti didelės įtakos mikrobų gausumui (Quilliam *ir kt.,* 2013). Dirvožemio vandens kiekis, pH, aeracija ir kitos fizikinės-cheminės savybės priklauso nuo bioanglies dalelių, kurios gali veikti kaip neįprasta niša dirvožemio bakterijoms (Bruun *ir kt.,* 2014). Dirvožemio bakterijos taip pat gali tiesiogiai naudoti organinę anglį, kurią bioanglis atgavo iš šalia esančio dirvožemio, kaip energijos šaltinį. Nagrinėjant visus šiuos veiksnius būtina atsižvelgti į bioanglies poveikį dirvožemio mikrobų veiklai, atsižvelgiant į bioanglies rūšį ir dirvožemio parametrus (Thies ir Rillig, 2012). Tačiau kaip tiksliai bioanglis veikia mikrobų gausą ir įvairovę, vis dar lieka paslaptis. Ekosistemų ištekliai ir dirvožemio funkcijos kritiškai priklauso nuo dirvožemio mikroorganizmų pasiskirstymo, kiekio (Wang, W. Zhang *ir kt.,* 2021) ir įvairovės (Rahman, 2012). Plokštelių skaičiavimo metodu galima suskaičiuoti tik nedidelę dalį visos dirvožemio mikrobų įvairovės, tačiau jis plačiai taikomas ir įrodyta, kad teisingai atspindi mikrobų rūšių biomasę. Dirbtinėje terpėje pritaikytoms bakterijų rūšims, pasižyminčioms ypatingu aktyvumu, tai yra formali procedūra. Dirvožemio mikrobų įvairovė yra svarbi, nes ji laikoma dirvožemio kokybės rodikliu (Kirchman *ir kt.,* 1982).

Nagrinėjamas bioanglies, kaip filtravimo terpės, naudojimas nuotekoms valyti, taip pat jos potencialus panaudojimas aplinkos atkūrimui ir teršalų judrumo mažinimui užterštame dirvožemyje bei rizikingų elementų pokyčių žemės ūkio produktuose mažinimui (Chen *ir kt.,* 2022). Bioanglis paprastai gaminamas iš žemės ūkio šalutinių produktų, gyvulių mėšlo ir medienos atliekų (Van Nguyen *ir kt.,* 2022). Atliekas galima paversti vertingu produktu, naudojant šias žaliavas bioanglies gamybai (Brewer *ir kt.,* 2014). Jo, kaip dirvožemio priedo, poveikis gerina dirvožemio būklę ir augalų vystymąsi, todėl didėja derlius. Tačiau jo veiksmingumui įtakos gali turėti tokie veiksniai kaip bioanglies ištekliai, gamybos procesas, dirvožemio būklė ir tipas bei auginamų augalų rūšis (Yasser Mahmoud Awad *ir kt.,* 2018; Arif *ir kt.,* 2021) (Parodyta 1 straipsnyje).

Įvairių sričių mokslininkai, įskaitant agronomus ir dirvožemininkus, iš šių tyrimų gali pasimokyti apie bioanglies, kaip organinės pataisos, naudą dirvožemio sveikatai stiprinti, taip užtikrinant ilgalaikį žemės ūkio ir gamtinės aplinkos gyvybingumą.

Tyrimo hipotezė

Bioanglis apibūdinamas kaip potencialus dirvožemio papildas, todėl darome prielaidą, kad naudojant iš kiaulių virškinamojo trakto gautą bioanglį būtų galima sumažinti sunkiųjų metalų patekimą į augalus esant skirtingiems drėgmės režimams, sumažinti šiltnamio efektą sukeliančių dujų (CO_2, N_2O ir CH_4) išmetimą, pagerinti dirvožemio funkcinę įvairovę ir augalų derlių.

Tyrimų tikslas - įvertinti bioanglies, pagamintos iš kiaulių mėšlo digestato, poveikį dirvožemio sunkiųjų metalų pasisavinimui augalais, šiltnamio efektą sukeliančių dujų emisijos mažinimui, dirvožemio hidrofizikinėms savybėms, mikrobų gausai ir įvairovei bei pasėlių produktyvumui.

Tyrimo uždaviniai

1. Ištirti kiaulių mėšlo digestato bioanglies poveikį sunkiųjų metalų pasisavinimui augaluose, esant skirtingiems drėgmės režimams.
2. Nustatyti iš kiaulių mėšlo digestato gautos bioanglies poveikį šiltnamio efektą sukeliančių dujų (CO_2, N_2O ir CH_4) emisijai.
3. Įvertinti iš kiaulių mėšlo digestato gauto bioanglies priedo poveikį dirvožemio anglies šaltinių panaudojimui, dirvožemio mikrobiologiniams rodikliams (Shannon, Simpson, Richness, Mclntosh ir rūšių tolygumas).
4. Ištirti kiaulių mėšlo digestatu gauto bioanglies tręšimo įtaką dirvožemio fizikiniams-cheminiams parametrams ir fotosintezės rodikliams (chlorofilo fluorescencijai ir SPAD chlorofilui) bei vasarinių kviečių, vasarinių miežių ir žirnių derliui.

Ginamieji teiginiai

1. Kiaulių mėšlo digestato bioanglies naudojimas sumažina sunkiųjų metalų įsisavinimą augaluose esant skirtingiems drėgmės režimams (optimalios drėgmės, sausros ir užliejimo sąlygomis).
2. Bioanglies panaudojimas padeda mažinti atskirų, suminių išmetamų šiltnamio efektą sukeliančių dujų (CO_2, N_2O ir CH_4) kiekį ir globalinio atšilimo potencialą.
3. Iš kiaulių mėšlo digestato gauta bioanglis pagerina dirvožemio fizikinius ir cheminius parametrus, augalų fotosintezės reakciją ir derlių.
4. Iš kiaulių mėšlo digestato gautas bioanglis daro įtaką dirvožemio mikrobų gausai ir įvairovei bei gerina dirvožemio hidrofizikines savybes.

Tyrimo naujumas

Tyrimas parodė, kad iš kiaulių mėšlo digestato gautos bioanglies naudojimas gali gerokai sumažinti sintetinių trąšų naudojimą žemės ūkyje. Dėl savo savybių jis padėjo sumažinti šiltnamio efektą sukeliančių dujų (anglies dioksido, azoto oksido ir metano) emisiją, sumažinti sunkiųjų metalų patekimą į augalus. Be to, bioanglies naudojimas padidino augalų biomasę ir produktyvumą, pagerino dirvožemio funkcinę įvairovę (anglies šaltinių panaudojimą, dirvožemio mikrobiologinius rodiklius) ir dirvožemio fizikines bei fizikines savybes (dirvožemio poringumą, tūrinį tankį, tūrinį vandens kiekį ir hidraulinį laidumą).

1. TYRIMO METODIKA

1.1. Eksperimentų įrengimas

Eksperimentas atliktas ir lauko, ir kontroliuojamomis (laboratorinėmis) sąlygomis. Lauko eksperimentiniai tyrimai buvo atliekami Lietuvos agrarinių ir miškų mokslų centro laukuose (55°40′ šiaurės platumos, 23°87′ rytų ilgumos). Eksperimentinio lauko dirvožemis buvo endokalcari-epihipoglinis kambisolis (WRB dirvožemių klasifikavimo sistema 2015). Lauko eksperimentai buvo atliekami trimis pakartojimais pagal pilną atsitiktinių imčių planą su 6 apdorojimo būdais (2 pav.). Kiekvieno apdorojimo laukelis buvo 1,5 m2 (1,5 m × 1,0 m). Eksperimentinius bandymus sudarė kontrolė, N0B0 (be trąšų + be bioanglies), N1 (100% rekomenduojamų azoto trąšų dozių, t. y. 160 kg ha^{-1} vasariniams miežiams , N2 (75% rekomenduojamų azoto trąšų dozių, t. y. 120 kg ha^{-1} vasariniams miežiams, N1B (100% rekomenduojamų azoto trąšų dozių + 25 ton ha^{-1} bioanglies), N2B (75% rekomenduojamų azoto trąšų dozių + 25 ton ha-1 bioanglies), B (25 ton ha^{-1} bioanglies). N trąšomis buvo tręšti tik vasariniai miežiai. Naudota bioanglis, gautas iš kiaulių mėšlo digestato, kurio temperatūra 550 °C, ir trąšos bei bioanglis buvo įterpti į dirvą prieš sėją.

2020 ir 2021 m. dviejuose eksperimentiniuose laukeliuose buvo pasėta vasarinių miežių (Hordeum vulgare L.) veislė 'Luoke', o 2021 ir 2022 m. - žirnių veislė 'Respect'. Pasėliai buvo sėjami kiekvienais tyrimo metais balandžio mėnesį, sėjos norma atitinkamai 280 kg ha^{-1} (žirnių pasėlis), 180 kg ha^{-1} (vasariniai miežiai). Visais eksperimento metais laukai buvo tręšti fosforo (54 kg ha^{-1}) ir kalio (78 kg ha^{-1}) trąšomis. Abiejuose bandymų laukeliuose buvo taikoma ta pati procedūra, taikant tą patį eksperimento planą, sėjomainą, sėjos normą ir auginimo laikotarpį. Tačiau eksperimento metai buvo 2020-2022 metai. Laboratorinis eksperimentas atliktas 2020 m. (sausio-balandžio mėn.) Lietuvos agrarinių ir miškų mokslų centro Žemdirbystės institute (Augalų mitybos ir agroekologijos skyriuje). Endokarstinio epiglacialinio kambrolio dirvožemis (WRB dirvožemių klasifikavimo sistema 2015 m.) buvo paimtas iš Žemės ūkio instituto lauko (55°23′49″N 23°51′40″E) viršutinio 0-20 cm sluoksnio. Dirvožemis buvo išdžiovintas ore ir perkoštas per 2 mm akučių sietą. Kiaulių mėšlo digestato pagrindu gauta bioanglies buvo rankiniu būdu sumaišyta su dirvožemiu 15 ton ha^{-1}, o sintetinės azoto (N) trąšos amonio salietros pavidalu išbertos 160 kg ha^{-1} (išberta 20 dieną po sėjos). Į nedidelius 27 cm skersmens ir 25 cm aukščio plastikinius vazonus buvo pripilta 10 kg dirvožemio. Vazonuose buvo sumontuota uždaro ciklo drėkinimo valdymo sistema, skirta kontroliuoti drėkinimo ir dirvožemio drėgmės režimą. Eksperimentas, kuriame naudotas atsitiktinės imties pilno bloko planas (RCBD), buvo sudarytas iš šešių apdorojimų ir trijų pakartojimų: M1B1 = (Dirvožemis ir bioanglis + normalus drėgmės režimas, W ≤ 15%), M2B1 = (Dirvožemis ir bioanglis + sausros sąlygos, W ≤ 5%), M3B1 =

(Dirvožemis ir bioanglis + drėgmės perteklius, W ≥ 35%), M1B0 = (Dirvožemis ir be bioanglies + normalus drėgmės režimas, W ≤ 15%), M2B0 = (Dirvožemis ir be bioanglies + sausra, W ≤ 5%), M3B0 = (Dirvožemis ir be bioanglies su drėgmės pertekliumi, W ≥ 35%). Į kiekvieną vazonėlį buvo pasėta po dešimt vasarinių kviečių 'Collada' veislės augalų sėklų. Po dviejų savaičių kiekvienas vazonas buvo praretinamas, o vazonuose buvo paliekami šeši sveiki augalai.

1.2. Dirvožemio ir bioanglies mėginių ėmimas ir cheminė analizė

Prieš pradedant ūkininkauti kiekvienais metais iš eksperimentinių laukelių buvo paimti dirvožemio mėginiai iš dviejų gylių (0-10 ir 0-20 cm). Dirvožemio pH buvo matuojamas 1:5 dirvožemio suspensiją ištirpinant 1M KCl. Naudojant amonio laktato ir acto rūgšties ekstrakciją, trimis egzemplioriais (Egnér, Riehm ir Domingo, 1960) buvo ištirtas dirvožemyje esantis judrusis kalis (K2O), judrusis fosforas (P2O5), judrusis kalcis (Ca) ir judrusis magnis (Mg) (1, 2 ir 3 dokumentai) (Ayaz *ir kt.,* 2021; Ayaz *ir kt.,* 2022; Ayaz *ir kt.,* 2023) pateikiama išsami dirvožemio cheminė analizė tiek lauko, tiek kontroliuojamų laboratorinių tyrimų metu. Kiaulių išmatos buvo paimtos iš realaus ūkio. Po 48 valandų džiovinimo ore žaliava (mėšlas) buvo susmulkinta rankomis. Bioanglis buvo gaminamas kaitinant žaliavą anaerobinėje cilindrinėje krosnyje 550 °C temperatūroje 5-6 valandas (Boostani *ir kt.,* 2019). Bioanglies fizikinės ir cheminės savybės buvo ištirtos naudojant įprastus laboratorinius metodus (2 lentelė). Bioanglies pH nustatyti naudotas praskiedimas 1:5 (tūrio tūrio-1) (Bunevičienė *ir kt.,* 2021). Dietilentriamino pentaacetato (DTPA) ekstrahuojamos maistingosios medžiagos buvo nustatomos induktyviai surištos plazmos optinės emisijos spektroskopijos (ICP-OES) metodu (Perkin Emer ICP-OES,Waltham, MA, JAV) (Prasad, Tzortzakis ir McDaniel, 2018)Naudojant standartinį protokolą (Flisch *ir kt.,* 2017), nustatyta bendrojo azoto (TN) ir magnio (Mg) koncentracija. TGA (4 dokumentas) (Ayaz *ir kt.,* 2021) suteikė informacijos apie bioanglies pelenų kiekį, drėgmę, lakiąsias medžiagas ir likutinę masę. 2 lentelėje apžvelgiama dirvožemio ir bioanglies fitocheminė sudėtis; daugiau informacijos pateikiama 2 ir 3 dokumentuose (Ayaz *ir kt.,* 2022; Ayaz *ir kt.,* 2023).

1.3. Dirvožemio ir bioanglies sunkiųjų metalų analizė

Eksperimento metu iš kiekvieno indo buvo paimti dirvožemio mėginiai sunkiųjų metalų kiekiui nustatyti. Išdžiovinti dirvožemio ir bioanglies mėginiai (1 g) buvo sumaišyti su 25 ml 0,1 M CaCl2 tirpalo ir 2 val. kratomi orbitinėje kratyklėje, po to 15 min. centrifuguojami. Galiausiai ICP-OES (Optima 2000, PerkinElmer Co.) buvo naudojamas filtruojant ir analizuojant tirpalą dėl HM (Ni, Cr, Cd, Pb, Cu, Zn). Sunkiųjų metalų frakcijos buvo nustatomos ištirpinant dirvožemio ir bioanglies mėginius HF-$HClO_4$-HNO_3, filtruojant tirpalą ir analizuojant jį ICP-OES (Carignan ir Tessier, 1988). Po DTPA ekstrakcijos P, K, Ca ir Mg kiekiai nustatyti ICP-OES metodu (Zaccheo, Crippa ir Bedussi, 2017). 2 dokumente (Ayaz *ir kt.,* 2021).pateikiami konkretūs duomenys.

1.4. Pasėlių biomasės ir sausųjų medžiagų analizė

Augalai iš visų vazonų buvo nuimti po 2 mėnesių. Nustatyta antžeminės biomasės šviežia masė. Augalai buvo suskirstyti į lapus, stiebus, šaknis ir varpas. Po džiovinimo 105 °C temperatūroje (pramoninio dydžio džiovyklė Thermolab) iki pastovaus svorio buvo apskaičiuota sausoji antžeminės dalies biomasė.

1.5. Chlorofilo ir grūdų derliaus nustatymas

Visuose mažuose eksperimentiniuose laukeliuose augalai buvo skinami rankomis. Nustatytas grūdų derlius ir 1000 grūdų masė. Visos analizės buvo atliekamos dviem egzemplioriais, o procedūros atliktos pagal pirmajame tyrime (Ayaz *ir kt.,* 2021) aprašytas procedūras. Augalų fiziologiniams parametrams nustatyti chlorofilo indeksas ir fluorescencija buvo matuojami kartu kas 2 savaites, atliekant penkis SPAD ir fluorescencijos matavimus vienam augalui ir juos išvedant vidurkį. Chlorofilo indeksas buvo matuojamas prietaisu MINOLTA SPAD 502 (Ling, Huang ir Jarvis, 2011) pagal chlorofilo gebėjimą sugerti mėlyną (400-500 nm) ir raudoną (600-700 nm) bangas. Chlorofilo fluorescencijos II indeksai (Fmin, Fmax, Fv/ Fm,) nustatyti in vivo chlorofilo fluorimetru OS-30p (OptiScience, JAV), o jų reikšmės nustatytos pagal OJIP testo lygtis (Strasser *ir kt.,* 2004), 2 straipsniuose (Ayaz *ir kt.,* 2022).

1.6. Dirvožemio hidrofizikinis tyrimas

Vandens sulaikymo savybėms ir porų dydžio pasiskirstymui tirti iš kiekvienos procedūros buvo paimti nepažeisto dirvožemio mėginiai ir sudėti į nerūdijančio plieno cilindrus (51 mm aukščio ir 53 mm skersmens). Vandens sulaikymo savybės buvo tiriamos esant -4, -10, -30, -50, -100 ir 300 hPa įsiurbimo slėgiui smėlio dėžėje ir smėlio-kaolino dėžėje. Apskaičiuota, kad slėgis, reikalingas nuolatiniam sudžiūvimui sukelti, yra apie -15 500 hPa (Klute, 1986). Apskaičiuota, kad 100 ir -15 500 hPa vandens kiekio vertės yra atitinkamai lauko talpa (FC) ir nuolatinio vytimo taškas (WP). Augalams prieinamo vandens kiekis, arba augalams prieinamas vanduo (angl. plant-available water, PAW), buvo apibūdintas kaip šių dviejų įsiurbimo taškų skirtumas. Dirvožemio šerdys buvo laikomos šaldytuve pastovioje 2 laipsnių Celsijaus temperatūroje. Su visomis kruvinomis detalėmis galite susipažinti antrojoje publikacijoje (Ayaz *ir kt.,* 2022 m.)

1.7. Substrato panaudojimas naudojant Biolog®Ecoplate

Specialiai bendruomenių analizei ir mikrobų aplinkos tyrimams sukurta sistema "Biology" ir metodas *"Biolog-EcoPlate"* buvo naudojami siekiant nustatyti 31 anglies šaltinį ir dirvožemio mikroorganizmų metabolinę funkcinę įvairovę (Luo *ir kt.,* 2020). Tai buvo atlikta renkant naujausius dirvožemio mėginius iš kiekvieno apdorojimo būdo. Dirvožemio mėginiai buvo sijojami ir smulkinami naudojant 2 mm sietą. Kiekvienam apdorojimui naudota 250 ml kolba su 90 ml distiliuoto vandens ir 10 g sauso dirvožemio. Mišinys 30 min. buvo purtomas 250 sūkių per minutę greičiu. Kiekviena kultūra buvo praskiesta 10-3 kartus ir 150 l buvo perkelta į 96 duobučių "Biolog® EcoPlate" (Biolog, Hayward, CA, JAV), kad būtų galima ištirti 31 skirtingo anglies šaltinio ir kontrolinio apdorojimo (be C šaltinio) poveikį. 24 valandų absorbcijos rodmenys, esant 590 nm bangos ilgiui (dvigubo bangos ilgio duomenys: OD590-OD750), buvo matuojami esant 25 laipsniams Celsijaus 24, 48, 72 ir 96 valandoms (L. Wang *ir kt.,* 2020). Antrajame tyrime (Ayaz *ir kt.,* 2022) metodai pateikiami išsamiau.

1.8. Rūšių įvairovės indeksų apskaičiavimas

Vienas iš rūšių gausos rodiklių yra tam tikroje imtyje aptinkamų rūšių skaičius; kitas - tolygus rūšių individų pasiskirstymas. Šenono indeksas yra informacijos, reikalingos kiekvienai bendrijos rūšiai apibūdinti, matas, ir jį galima nustatyti naudojant knygoje pateiktą lygtį (Ayaz, Feizienė *ir kt.,* 2022). Simpsono indeksas (D) kiekybiškai nusako tikimybę, kad dvi atsitiktinai iš imties atrinktos rūšys priklauso tai pačiai rūšiai. Rūšių gausumas (R), apibrėžiamas kaip bendras tam tikroje teritorijoje esančių rūšių skaičius. Mclntosh indeksas taip pat buvo apskaičiuotas kartu su rūšių tolygumu, kaip teigia Magurranas (1988). Visos lygtys apibendrintos 2 straipsnyje (Ayaz, Feizienė *ir kt.,* 2022).

1.9. Šiltnamio efektą sukeliančių dujų (ŠESD) matavimai

Eksperimento vietoje dujų mėginiams rinkti buvo naudojama statinė dujų kamera, o mėginiai buvo analizuojami naudojant dujų chromatografiją pagal ankstesnius tyrimus (Kanerva *ir kt.,* 2007; Zhang *ir kt.,* 2015). Statinės dujų kameros specifikacijas sudarė 50 cm pločio ir 50 cm ilgio pagrindo dėžė (rėmas) su □ formos grioveliu. Nerūdijančio plieno rėmai buvo stacionariai įstatyti 10 cm po paviršiumi ir užima 0,25 m2 plotą. Uždarius kamerą, kiekvienam dujų matavimui buvo taikomas 3 minučių intervalas. Dujų mėginiams paimti naudotas gerai užsandarintas 20 cm3 talpos švirkštas, po to jie buvo supilti į gerai užsandarintus stiklinius buteliukus. 4 dokumente pateikiami išsamūs metodai (Ayaz *ir kt.,* 2023).

1.10. Šiltnamio efektą sukeliančių dujų kiekio apskaičiavimas

Kaip teigiama (Zhai *ir kt.,* 2011; Akhtar *ir kt.,* 2020), apskaičiavome bendrą CO_2, CH_4 ir N_2O emisiją kiekvienu apdorojimo būdu per kelis augimo etapus. Naudodami šią lygtį (IPCC, 2007), nustatėme medžio anglimi ir N trąšomis apdorotų dirvožemių GWP 2020-2022 m. ir yra pateiktas (Ayaz *ir kt.,* 2023).

1.11. Dirvožemio temperatūros ir drėgmės matavimai

2020 m. ir 2021 m. visuose vystymosi etapuose 5 cm gylyje buvo matuojama prie paviršiaus esanti dirvožemio temperatūra (Akhtar *ir kt.,* 2020). Be to, dirvožemio mėginiai buvo paimti iš 0-10 cm sluoksnio dirvožemio grąžtu ir 24 valandas džiovinti džiovykloje 105 °C temperatūroje, kad būtų galima nustatyti dirvožemio drėgmę (masės procentais) kiekviename vystymosi etape. Siekiant išanalizuoti CO_2, N_2O ir CH_4 emisijos priklausomybę nuo drėgmės kiekio ir temperatūros, naudota tiesinė regresija.

1.12. Meteorologinės sąlygos

Buvo naudojami Lietuvos hidrometeorologijos tarnybos prie Lietuvos Respublikos aplinkos ministerijos Dotnuvos meteorologijos stoties duomenys, kurie suteikė duomenis apie vidutinę metinę temperatūrą ir vidutinį metinį kritulių kiekį per trejus tyrimo metus eksperimento vietoje. Vidutinė oro temperatūra 2020, 2021 ir 2022 m. sausio-gruodžio mėnesiais buvo atitinkamai 9,3 °C, 7,4 °C ir 8,0 °C. Suminė metinė kritulių vertė buvo atitinkamai 591,8 mm, 573,0 mm ir 627,9 mm (3 pav.). 2021 ir 2022 m. pastebimai padažnėjo sausringi orai, kai vasarą iškrenta nedaug kritulių.

1.13. Statistinė analizė

Visi duomenų rinkiniai buvo tiriami taikant dispersinę analizę (ANOVA) ir mažiausio reikšmingo skirtumo (LSD) testą, nes jie visi buvo normaliai pasiskirstę. Visoms statistinėms analizėms atlikti naudotos programos Statistix 8.1 ir GraphPad PRISM 8. Rangavimo koeficientų analizei atlikti naudota R-studio.

2. TYRIMO REZULTATAI

2.1. Sunkiųjų metalų tyrimas

Iš kiaulių mėšlo digestato pagamintas bioanglis, kaip dirvožemio papildas, eksperimentų metu pasirodė esąs perspektyvus ir gali turėti teigiamą poveikį tiek dirvožemio, tiek augalų sveikatai. Sunkiųjų metalų kiekis augaluose sumažėjo 90% Cr, 50% Ni, 9% Cd ir 34% Pb, kai ankstyvaisiais augimo tarpsniais jais buvo tręšti vasariniai kviečiai, palyginti su augalais be bioanglies *($p \geq 0.01$).* Nuotekų dumblo bioanglies (naudotos 500-550 °C temperatūroje) ir broilerių kraiko bioanglies (naudotos 700 °C temperatūroje) naudojimas labai sumažino sunkiųjų metalų kiekį augaluose dėl metalų skilimo iš mainų formos į mažiau prieinamą organinių ryšių dalį (Liu *ir kt.,* 2021). Bioanglis dėl savo gebėjimo sulaikyti vandenį gerokai sumažina sunkiųjų metalų prieinamumą augalams esant užliejamam, optimaliam ir drėgnam drėgmės režimui (Chen *ir kt.,* 2023). Panašiai iš ryžių šiaudų pagaminta bioanglis gerokai sumažino augalams prieinamo Cd kiekį (Akca *ir kt.,* 2022). Bioanglies gebėjimas imobilizuoti sunkiuosius metalus siejamas su dirvožemio absorbcinės gebos padidėjimu, kurį lemia dirvožemio fizikinių ir cheminių savybių modifikacijos, įskaitant dinamoelektrinę trauką, katijonų ir anijonų mainus ir fizikinį absorbcinį pajėgumą. Tačiau sunkiųjų metalų koncentraciją dirvožemyje padidino ir kiaulių mėšlo digestato bioanglis visais drėgmės režimais (21% Cr, 43% Ni, 55% Cu, 70% Zn ir 12% Pb). Dėl bioanglies naudojimo dirvožemyje ir augaluose labai padidėjo pagrindinių elementų (P, K, Mg ir Ca) kiekis įvairiomis drėgmės sąlygomis. Paaiškėjo, kad optimalios drėgmės (15-20%) dirvožemyje šių komponentų koncentracija buvo didžiausia, o sausros ir užliejimo režimai gali lemti jų praradimą, o užliejamame dirvožemyje ypač didelė išplovimo rizika. Bioanglies teigiamas poveikis siejamas su keliais veiksniais, įskaitant jos gebėjimą didinti dirvožemio aeraciją ir poringumą (Kalus, Koziel ir Opaliński, 2019), o tai savo ruožtu mažina dirvožemio tūrinį tankį (Bd) ir didina vandens sulaikymo gebą (WHC) (Chang *ir kt.,* 2021; Guo *ir kt.,* 2021); ir gebėjimą didinti paviršiaus plotą (Kalus, Koziel ir Opaliski, 2019). Viso pranešimo šaltinis (Ayaz, Stulpinaitė *ir kt.,* 2022).

2.2. Pasėlių derliaus analizė

Chlorofilo fluorescencija ir chlorofilo indeksas gali būti naudojami kaip augalų gyvybingumo rodikliai atliekant eksperimentą vazonuose. Antžeminės biomasės ir sausųjų medžiagų kiekio padidėjimas pasireiškė į dirvožemį įterpus bioanglies ir išliko per augimo tarpsnį (nuo 12-os iki 62-os dienos). Antžeminės biomasės ir sausųjų medžiagų kiekis gerokai *($p \leq 0.05$)*padidėjo, kai bioanglies buvo įterpta į dirvožemį kaip priedas. Apdorojimas M1B1, M2B1 ir M3B1 su faktorine sąveika padidino antžeminės dalies biomasę atitinkamai 71,87%, 66,66%ir 68,64 % *($p \leq 0.05$)*, palyginti su M1B0, M2B0 ir M3B0. Sausųjų medžiagų kiekis mišiniuose su bioanglimi ir vandeniu (M1B1, M2B1 ir M3B1) buvo atitinkamai 45,83%, 55,17% ir 40,90% didesnis nei M1B0, M2B0 ir M3B0. Tai rodo, kad, palyginti su tuo, kad biomasė nebuvo apdorota bioanglimi, biomasės papildymas bioanglimi gali būti naudingas esant įvairioms drėgmės sąlygoms. Panašiai ir 2020-2022 m. lauko bandyme apdorojimas bioanglimi reikšmingai padidino vasarinių miežių ir žirnių grūdų derlių. Skirtingai nuo kontrolinio apdorojimo (CK), vasarinių miežių N1B, N2B, B ir N1 apdorojimai 2021 m. reikšmingai padidino 1000 grūdų derlių atitinkamai 9, 3, 15, 2, 8 ir 16 proc. Grūdų derlius padidėjo 46, 09, 42, 84 ir 32 proc. Tuo tarpu žirnių pasėlių 1000 grūdų derlius smarkiai padidėjo ir 2021, ir 2022 metais. Dirvožemio pH ir iš bioanglies susidarantys jonai veikia kartu ir padidina augalų derlių, kai naudojama bioanglis (Pulka *ir kt.,* 2020). Yra pranešimų, kad naudojant iš šiaudų pagamintą bioanglę (5 Mg ha^{-1} norma) galima padidinti derlių (Gupta *ir kt.,* 2020; Feng *ir kt.,* 2021). Dirvožemio kokybė gali būti pagerinta, o tai savo ruožtu padidina žemės ūkio derlių dėl jo atgaivinančio poveikio (Zahra *ir kt.,* 2021). Daugiau informacijos pateikiama 1 dokumente (Ayaz *ir kt.,* 2021).

2.3 Kiaulių mėšlo bioanglies poveikis dirvožemio fizikinėms savybėms ir mikrobiologinei funkcinei įvairovei

2.3.1. Dirvožemio bendrasis poringumas ir tūrinis tankis

Dirvožemio hidrofizikiniai tyrimai atlikti I eksperimento (vasariniai miežiai) pradžioje ir pabaigoje. Taigi eksperimento pradžioje 5-10 cm gylyje, panaudojus 25 ton ha^{-1} vien tik bioanglies (B1N0) ir 25 ton ha^{-1} bioanglies, sumaišytos su 120 kg ha^{-1} azoto trąšų (B1N2), dirvožemio tūrinis tankis (BD) reikšmingai padidėjo *($p \geq 0.05$)* 10-12%. Panašiai nustatėme, kad naudojant tik bioanglies ir bioanglies kartu su 160 kg ha^{-1} azoto trąšų (B1N1) dirvožemio BD padidėjo 8-10%, palyginti su apdorojimais be bioanglies, ir tai buvo statistiškai reikšmingai *($p \geq 0.05$).* Po derliaus nuėmimo bioanglies tiek atskirai, tiek kartu su N trąšomis, kurių kiekis buvo 160 kg ha^{-1} ir 120 kg ha^{-1}, gerokai sumažino dirvožemio BD ir padidino bendrąjį poringumą (TP). Abiejuose tirtuose gyliuose taip pat reikšmingai pagerėjo dirvožemio makroporos. Todėl bioanglies, pagamintos iš kiaulių digestato, naudojimas gali būti laikomas naudingu dirvožemio priedu sprendžiant tokius sunkumus, kaip didelis BD, mažas TP ir sutankintas dirvožemis su ribotu poringumu. Aktyvus didžiulis bioanglies paviršiaus plotas, dalelių dydis ir poringumas, taip pat dirvožemiui būdingos savybės - visa tai prisideda prie jos gebėjimo mažinti BD kiekį dirvožemyje (Toková *ir kt.,* 2020). Bioanglis taip pat gali sumažinti BD, nes susimaišęs su dirvožemio dalelėmis jis formuoja dirvožemio poras (Šimanský *ir kt.,* 2016). Antrajame tyrime (Ayaz *ir kt.,* 2022) pateikiama daugiau informacijos.

2.3.2. Bioanglies poveikis dirvožemio hidrologijai

Apibendrinome, kad bioanglies papildymas 160 kg ha^{-1} azoto trąšų 5-10 cm gylyje, esant -4 iki -100 hPa įsiurbimo slėgiui, labai padidino vandens sulaikymą, o 5-10 ir 15-20 cm gylyje buvo nustatytas didesnis įsiurbimas ir slėgis (atitinkamai -100 hPa ir -15,5 tūkst. hPa), kartu padidinant lauko talpą ir dirvožemio vytimo tašką. Bioanglies panaudojimas gali pagerinti sausros sąlygas didindamas dirvožemio vandens kiekį. Dirvožemio hidraulinis laidumas sumažėjo

35-40%, palyginti su 5-10 cm gylyje taikytais be bioanglies ir su bioanglimi. Taigi bioanglis nepagreitina vandens judėjimo greičio per viršutinį dirvožemio sluoksnį. Kadangi bioanglis padidino dirvožemio garavimą, o kartu ir dirvožemio temperatūrą, tai ir įvyko. Nustatyta, kad dėl didžiulio bioanglies paviršiaus ploto dirvožemio vandens sulaikymas gerokai pagerėjo, kai buvo įdėta bioanglies (Šimanský *ir kt.,* 2016). Su šiomis išvadomis sutampa ir Claire L. Phillips darbas, kuri nustatė, kad pridėjus bioanglies, pagamintos iš spygliuočių medienos ir kviečių šiaudų, labai padidėjo dirvožemio poringumas (nuo 9 iki 36 Mg ha^{-1}), o kartu ir dirvožemio tūrinis vandens kiekis bei dirvožemio lauko talpa (Atkinson, 2018). Bioanglis ir kiti organiniai junginiai gali pagerinti dirvožemio fizinę būklę (Igaz *ir kt.,* 2018; Šrank ir Šimanský, 2020).

2.3.3. Bioanglies poveikis dirvožemio anglies šaltinių panaudojimui ir dirvožemio biologiniams rodikliams

Remiantis šio tyrimo rezultatais, iš kiaulių digestato pagaminta bioanglis, tręšiant azoto trąšomis arba be jų, gali būti naudingas dirvožemio papildymas. Priklausomai nuo dirvožemio rūšies ir kitų aplinkos parametrų, jis gali padėti pagerinti hidrofizikines savybes ir mikrobų gausumą. Nustatyta, kad bioanglis gerina dirvožemio mikrobų aktyvumą (4 pav.) ir šiame tyrime buvo nustatytas teigiamas jo ryšys su anglies šaltinių naudojimu. Buvo naudojami įvairūs dirvožemio anglies šaltiniai - nuo karboksirūgščių iki aminų, o aminų naudota mažiausiai. Lyginant su dirvožemiu, apdorotu be bioanglies, bendras visų SCS suvartojimas buvo didesnis dirvožemyje, apdorotame bioanglimi. Visi įvairovės rodikliai (pvz. vidutinis šulinio spalvos išsivystymas (AWCD) ir turtingumas (S), tirti Biolog EcoPlate, inkubuoti 96 valandas) parodė, kad bioanglies apdorotame dirvožemyje ir apdorojant B0N1 padidėjo biologinės įvairovės rodikliai. terapija su B1N2 gerokai sumažino U indeksą nuo 24 iki 96 valandų; jis buvo 20-30 proc. mažesnis nei kontrolinės terapijos (2 darbas) (Ayaz, Feizienė *ir kt.,* 2022).

Šie rezultatai rodo, kad bioanglies derinimas su organinėmis N trąšomis gali pagerinti SKS suvartojimą, o tai savo ruožtu turi tendenciją didinti dirvožemio mikrobų įvairovę (Esmaeelnejad *ir kt.,* 2017). Platesnės substratų įvairovės suvartojimas paprastai stebimas sekliame dirvožemyje, kur mikrobiologinė įvairovė yra didesnė (Wolińska *ir kt.,* 2020; Duan *ir kt.,* 2021). Nustatyta, kad dėl dirvožemio gylio gradiento sumažėjęs tiek maisto medžiagų prieinamumas, tiek deguonies kiekis daro žalingą poveikį dirvožemio bakterijoms ir jų medžiagų apykaitos proceso reguliavimui (Sandén *ir kt.,* 2019; Koner *ir kt.,* 2021). Dirvožemio mikrobų įvairovė atsispindi fiziologinėse funkcijose, kurias atspindi vidutinis šulinio spalvos išsivystymas (AWCD) (Xun *ir kt.,* 2016; Koner *ir kt.,* 2021). Dėl to galima prognozuoti, kad kai kurių pasirinktų C šaltinių suvartojimas gali būti naudingas dirvožemio mikrobų funkcinei įvairovei ir jų metaboliniam aktyvumui.

2.4 Bioanglies poveikis išmetamų ŠESD kiekiui

2.4.1. Atskirų CO_2, CH_4 ir N_2O emisijų kiekis

Per trejus šiltnamio efektą sukeliančių dujų emisijos eksperimento metus buvo stebimi periodiniai svyravimai tarp 2020-2022 m. vasarinių miežių ir žirnių pasėlių. CO_2 emisijos 2020 m. vasarinių miežių pasėlyje buvo didesnės viso sezono metu, išskyrus jungimosi tarpsnį (žirnių pasėlyje - žiedynų pasirodymo tarpsnį) viso eksperimento metu, palyginti su 2021 ir 2022 m. eksperimentais. Pastebėta, kad CO_2 emisija buvo reikšmingai mažesnė *($p \geq 0.05$)* po bioanglies apdorotu dirvožemiu per visus 2021, 2022 metus, palyginti su 2020 metais. Visuose žirnių pasėlių augimo tarpsniuose (B, N1B ir N2B) visuose bioanglies apdorotuose dirvožemiuose CO_2 emisija sumažėjo atitinkamai 57%, 55% ir 59%, palyginti su bioanglies neapdorotais dirvožemiais *($p \geq 0.05$)*. N2B apdorojimas gerokai *($p \geq 0.05$)* sumažino CO_2 emisiją 58%, palyginti su kontroliniu apdorojimu krūmijimosi tarpsniu. Panašiai, palyginti su apdorojimais be biokuro, CO_2 emisijos sumažėjo 50%, 51% ir 50% atitinkamai per visą krūmijimosi, žydėjimo ir brandos etapus *($p \geq 0.05$)*. Teigiama, kad dirvožemio CO_2 emisijos kintamumas yra didesnis anglies turtingame dirvožemyje (Ahirwal *ir kt.,* 2021; S. Zhang *ir kt.,* 2021). Nors CO_2 emisijos kelia didelį susirūpinimą, bioanglis gali padėti jas sumažinti (Lehmann *ir kt.,* 2021; Shakoor *ir kt.,* 2021). Bioanglies panaudojimas 2021 m. turėjo didelį poveikį sezoniniams dirvožemio CO_2 svyravimams.

Nepaisant to, buvo pastebėti dideli N_2O emisijos svyravimai įvairiais abiejų pasėlių augimo tarpsniais. Remiantis minėtu dėsningumu, bioanglimi (B, N1B ir N2B) apdorotuose dirvožemiuose (B, N1B ir N2B) N_2O emisija reikšmingai *($p \geq 0.05$)* sumažėjo atitinkamai 48%, 49% ir 48% per visus žirnių pasėlių augimo tarpsnius, palyginti su bioanglimi neapdorotais dirvožemiais. N2 apdorojimas turi tendenciją didinti N_2O emisiją žirnių derliaus sezono metu, ypač žiedynų pasirodymo ir brandos tarpsniu. Neigiamas poveikis aplinkai ir šiltnamio efektą sukeliančių dujų emisijos didėjimas siejamas su per didelio azoto trąšų kiekio naudojimu (Jamali *ir kt.,* 2021; L. Zhang *ir kt.,* 2021). Tyrimų rezultatuose pabrėžiama, kad 2021 m. azoto trąšų (N1, N2 ir N3) tręšimo būdai reikšmingai padidino N_2O emisiją dirvožemyje vegetacijos metu. Dirvožemio papildymas bioanglimi ir sintetinėmis trąšomis gali sumažinti N_2O emisiją, priklausomai nuo panaudoto N ir emisijos faktorių (Han *ir kt.,* 2021). Organinių trąšų cheminė sudėtis yra sudėtinga, todėl sunku prognozuoti jų išmetamų teršalų komponentus (Singh, 2010; Akhtar *ir kt.,* 2020). Nustatyta, kad tręšimas N trąšomis ir mulčiavimas kartu padidina N_2O srautą 71-123% (Novoa ir Tejeda, 2006; Kim *ir kt.,* 2021; Ma *ir kt.,* 2022).

Metano dujų (CH_4) emisija vasarinių miežių sezono metu reikšmingai nesiskyrė. Tačiau rezultatai parodė, kad 2021, 2022 ir 2023 m. CH_4 emisijos reikšmingai kito vegetacijos tarpsniais.

Žydėjimo ir brandos tarpsniais apdorojimas N1B reikšmingai *($p \geq 0.05$)* sumažino CH_4 emisiją atitinkamai 17% ir 19%. Tačiau bioanglis neturėjo tokio poveikio CH_4 emisijai, kokį turėjo CO_2 ir N_2O emisijai. Keliuose tyrimuose nustatyta, kad ryšys tarp bioanglies įterpimo į dirvožemį ir CH_4 srauto yra menkai suprantamas (Jeffery *ir kt.,* 2016; Kammann *ir kt.,* 2017). Pastebėta, kad bioanglies panaudojimas dirvožemyje didina CH_4 emisijos srautą (Yu *ir kt.,* 2013), mažina CH_4 emisijos srautą (Feng *ir kt.,* 2012; Lin *ir kt.,* 2015) arba visai neturi reikšmingo poveikio CH_4 emisijos srautui (Xie *ir kt.,* 2013). Buvo teigiama, kad anaerobinėje aplinkoje metanotrofinės CH_4 sąnaudos didėja dėl dirvožemyje esančios bioanglies. CH_4 kiekis, kuris galėjo patekti į augalo aerenchimą ir išeiti iš jos, taip pat sumažėjo, nes bioanglies priedas sustiprino metanotrofinių organizmų atliekamą CH_4 oksidaciją oksikanoksinėje šaknų sąsajoje (Feng *ir kt.,* 2012). 3 straipsnyje (Ayaz *ir kt.,* 2023) pateikiama papildomos informacijos.

2.4.2 Bendras išmetamo CO_2, CH_4 ir N_2O kiekis

Naudojant bioanglį buvo paveiktas bendras CO_2, N_2O ir CH_4 emisijų kiekis vasarinių miežių pasėlių augimo etapais. Nepaisant to, žirnių pasėlių augimo etapuose pastebėtas didelis nevienodumas. Bioanglies apdorojimo būdai (B, N1B ir N2B) gerokai *($p \geq 0.05$)* sumažino bendrą CO_2 emisiją (atitinkamai 16%, 19% ir 17%), palyginti su kontroliniu apdorojimu. Tačiau tik B apdorojimas reikšmingai *($p \geq 0.05$)* sumažino bendrą N_2O emisiją 6%, palyginti su kontroliniu apdorojimu. Panašiai kaip ir apdorojimas B, apdorojimas N1B labai sumažino bendrą CH_4 emisiją 7%, palyginti su kontroliniu apdorojimu.

2.4.3 Globalinio atšilimo potencialas (GWP)

Bendro išmetamo CO_2, N_2O ir CH_4 kiekio ir GWP tendencijos buvo panašios. Remiantis duomenimis, GWP pavasarinių miežių augimo tarpsniais reikšmingai nekito. Tačiau apdorojant bioanglimi (B, N1B ir N2B) 2021 ir 2022 m. žirnių pasėlių augimo etapais užfiksuotas reikšmingai *($p \geq 0.05$)* mažesnis (atitinkamai 39%, 35% ir 39%) CO_2 sukeltas GWP nei apdorojant kitais būdais. Šiltnamio efektą sukeliančių dujų emisijos duomenys (Li *ir kt.,* 2015) patvirtino teiginį, kad bioanglies priedas reikšmingai sumažino GWP. B apdorojimas gerokai sumažino CH_4 ir N_2O susidarantį GWP - atitinkamai 19% ir 34%, palyginti su kontroliniu apdorojimu. GWP yra pagrindinis veiksnys, lemiantis trijų svarbiausių šiltnamio efektą sukeliančių dujų (CO_2, CH_4 ir N_2O) poveikį pasauliui ((Team, 2007). Grynasis GWP 2021 ir 2022 m. apdorotuose bioanglies laukeliuose buvo gerokai mažesnis. Tačiau, remiantis šiomis ataskaitomis, 2020 m. didelių pokyčių nebus. Bioanglies nesuardymas pirmaisiais metais gali paaiškinti statistiškai reikšmingo GWP skirtumo nebuvimą (Mukherjee ir Lal, 2013); tačiau didesnis bioanglies suardymas antraisiais ir trečiaisiais metais gali paaiškinti GWP sumažėjimą (Lehmann *ir kt.,* 2021). Pranešama, kad anglies dioksido sekvestracija dirvožemyje yra didesnė, kai GWP yra mažesnis (Yao *ir kt.,* 2021). Apskritai tyrimai rodo, kad bioanglies naudojimas dėl jos struktūrinės elgsenos gali labai sumažinti visuotinį atšilimą. Taikant bioanglį, bioanglies C:N santykis gali būti pagrindinis elementas, lemiantis GWP (Xu *ir kt.,* 2021). 3 straipsnyje (Ayaz *ir kt.,* 2023) pateikiama papildomos informacijos.

IŠVADOS

1. Kontrolinėje aplinkoje bioanglies apdorotame dirvožemyje vasarinių kviečių vidutinis antžeminės biomasės ir sausųjų medžiagų kiekis reikšmingai $(p \leq 0.05)$ padidėjo, palyginti su dirvožemiu, kuriame bioanglies nebuvo. Tuo tarpu lauko sąlygomis bioanglies su N trąšomis (160 ir 120 kg ha^{-1}) apdoroti dirvožemiai 2021 m. reikšmingai padidino vasarinių miežių 1000 grūdų masę ir grūdų derlių atitinkamai 46,09% ir 42,54%, palyginti su kontroliniu apdorojimu (CK). Tuo tarpu žirnių pasėlyje 1000 grūdų masė ir grūdų derlius reikšmingai padidėjo tiek 2021, tiek 2022 metais. Taigi, bioanglies naudojimas gali būti naudingas didinant pasėlių derlingumą.
2. Kontrolinėje aplinkoje bioanglies naudojimas gerokai sumažino sunkiųjų metalų patekimą į augalus, palyginti su dirvožemiu be bioanglies naudojimo. Dirvožemio ir augalų P, K, Mg ir Ca koncentracijos po bioanglies panaudojimo padidėjo, nepriklausomai nuo drėgmės sąlygų. Iš kiaulių mėšlo digestato pagaminta bioanglis galėtų būti potenciali priemonė dirvožemio ir augalų kokybei gerinti.
3. Vien bioanglies ir bioanglies su 160 kg ha^{-1} bei 120 kg ha^{-1} mineralinių azoto trąšų naudojimas labai sumažino dirvožemio tūrinį tankį ir padidino bendrąjį poringumą, taip pat labai padidino dirvožemio makroporingumą 5-10 ir 15-20 cm dirvožemio sluoksniuose. Todėl galima teigti, kad iš kiaulių mėšlo digestato pagaminta bioanglis gali būti naudingas dirvožemį gerinantis veiksnys didelio tankio (BD) ir mažo poringumo (TP) suslėgtuose dirvožemiuose.
4. Bioanglis kartu su 160 kg ha^{-1} mineralinių N trąšų norma gerokai padidino vandens sulaikymą 5-10 cm sluoksnyje, esant -4-100 hPa siurbimo jėgai. Esant didesnei pumpavimo jėgai (-100 hPa) ir slėgiui (-15 500 hPa), nustatyta, kad ir lauko talpa, ir augalų vytimo taškas buvo didesni 5-10 ir 15-20 cm gylyje. Bioanglis su mineralinėmis N trąšomis ir be jų 5-10 cm gylyje sumažino dirvožemio hidraulinį laidumą (35-40%), palyginti su dirvožemiu be bioanglio. Sausros sąlygomis gali būti naudinga naudoti bioanglį, kad padidėtų dirvožemio vandens sulaikymas.

5. Kontrolinėmis sąlygomis bioanglies įterpus į dirvožemį, pagerėjo chlorofilo fluorescencija (Fmin, Fmax, Fv/ Fm) ir chlorofilo indeksas per visą augalų augimo laikotarpį (nuo 12 iki 62 dienų), dėl to padidėjo antžeminės biomasės ir sausųjų medžiagų kiekis. Be to, lauko eksperimento metu bioanglies naudojimas gerokai padidino chlorofilo fluorescenciją (Fmin, Fmax, Fv/Fm) ir chlorofilo indeksą, palyginti su kontroliniu apdorojimu.
6. Anglies šaltinių panaudojimas dirvožemyje padidėjo sekliai įterpus bioanglies į dirvožemį, o tai taip pat pagerino dirvožemio mikrobų funkcinę įvairovę. Bendras visų SCS panaudojimas buvo didesnis naudojant bioanglies, palyginti su bioanglies nenaudojimu. Nuo 24 iki 96 valandos bandymų laikotarpiu indeksas U gerokai sumažėjo įterpus bioanglies (B1N2), palyginti su kontroliniu apdorojimu.
7. Naudojant bioanglies, antraisiais ir trečiaisiais lauko eksperimento metais, palyginti su pirmaisiais metais, iš dirvožemio išmetamo CO_2, N_2O ir CH_4 kiekis labai sumažėjo. Be to, bioanglis turėjo didelį poveikį bendram išmetamųjų teršalų kiekiui, išreikštam visuotinio atšilimo potencialu, antraisiais ir trečiaisiais eksperimento metais. Nustatyta, kad ŠESD emisijos ir dirvožemio drėgmės bei temperatūros ryšys buvo teigiamas. Vidutinio klimato zonose seklus anglies, susidariusios iš kiaulių mėšlo digestato, įsisavinimas dirvožemyje gali būti tinkamas būdas mažinti išmetamų ŠESD kiekį.Iš kiaulių mėšlo digestato pagamintos anglies seklus įterpimas į dirvą gali būti tinkama priemonė ŠESD emisijoms mažinti borealinio klimato sąlygomis. Antraisiais ir trečiaisiais metais po bioanglies įterpimo į dirvožemį, CO_2, N_2O ir CH_4 emisijos iš dirvožemio žymiai sumažėjo, palyginus su pirmaisiais tyrimo metais ir variantais, kur į dirvožemį nebuvo įterpta bioanglis. Be to, antraisiais ir trečiaisiais eksperimento vykdymo metais bioanglis taip pat labai paveikė suminę emisiją, kaip visuotinio atšilimo potencialą. Buvo užfiksuota teigiama koreliacija tarp ŠESD emisijų ir dirvos drėgmės bei temperatūros. Per dvejus lauko eksperimento vykdymo metus, neigiamų aplinkosaugos problemų dėl bioanglies įterpimo į dirvą, nebuvo neužfiksuota.

Praktinė nauda / rekomendacija

Remdamiesi šiais eksperimentais, rekomenduojame, kad iš kiaulių mėšlo digestato pagaminta bioanglis kartu su mineralinėmis N trąšomis ir be jų galėtų būti naudinga priemonė žemės ūkyje, gerinanti dirvožemio būklę, fizikines ir chemines savybes bei mikroorganizmų gausą. Bioanglis taip pat galėtų būti naudojamas siekiant sumažinti šiltnamio efektą sukeliančių dujų išmetimą iš dirbamų dirvožemių. Dirvožemiuose, kurie yra smarkiai užteršti ir nualinti cheminių komponentų, patartume naudoti skirtingas bioanglies dozes kaip dirvožemio gerinimo priemonę, kad rezultatai būtų reikšmingesni. Reikalingi papildomi tyrimai, kad būtų galima išanalizuoti ilgalaikį bioanglies, pagamintos iš kiaulių mėšlo digestato, poveikį dirvožemio ir augalų kokybei bei produktyvumui.

ABOUT THE AUTHOR

Full Name: Muhammad Ayaz

Email: muhammad.ayaz@lammc.lt

Address: Department of Plant Nutrition and Agroecology, Institute of Agriculture, Instituto Al. 1, Akedemija

Certificates	Year	Name of Institution/Board/University
PhD. Plant Nutrition and agroecology	2019-2023	Lithuanian Research Center for Agriculture and Forestry
M.sc (Hons) Soil and Plant Nutrition	2016-2019	Northwest A&F University China
B.S. (Hons) Soil & Environmental Sciences	2014	The University of Agriculture-Peshawar Pakistan
Intermediate (Pre-Medical)	2010	Cadet College Jajja,Disst. Rawalpindi
Chinese language Course	2015-2016	Northwest A&F University China

Professional Experience		
Junior Researcher	Institute of Agriculture, LAMMC	2019-to date

Publications referenced and indexed in the Clarivate Analytics Web of Science database
1. **Ayaz, Muhammad**, Dalia Feizienė, Virginijus Feiza, Vita Tilvikienė, Edita Baltrėnaitė-Gedienė, and Attaullah Khan. "The Impact of Swine Manure Biochar on the Physical Properties and Microbial Activity of Loamy Soils." *Plants* 11, no. 13 **(2022)**: 1729.
2. **Ayaz, Muhammad**, Urte Stulpinaite, Dalia Feiziene, Vita Tilvikiene, Kashif Akthar, Edita Baltrėnaitė-Gedienė, Nerijus Striugas et al. "Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil." *Soil Use and Management* 38, no. 2 **(2022)**: 1307-1321.
3. **Ayaz, Muhammad**, Dalia Feizienė, Vita Tilvikienė, Kashif Akhtar, Urte Stulpinaitė, and Rashid Iqbal. "Biochar role in the sustainability of agriculture and environment." *Sustainability* 13, no. 3 **(2021)**: 1330.
4. Iqbal, Rashid, Muhammad Habib-ur-Rahman, Muhammad Aown Sammar Raza, Muhammad Waqas, Rao Muhammad Ikram, **Muhammad Ayaz**, Monika Toleikiene et al. "Assessing the potential of partial root zone drying and mulching for improving the productivity of cotton under arid climate." *Environmental Science and Pollution Research* 28, no. 46 **(2021)**: 66223-66241.
5. Azeem, Imran, Muhammad Adeel, Muhammad Arslan Ahmad, Noman Shakoor, Gama Dingba Jiangcuo, Kamran Azeem, **Muhammad Ayaz**. "Uptake and accumulation of nano/microplastics in plants: a critical review." *Nanomaterials* 11, no. 11 **(2021)**: 2935.
6. Iqbal, Rashid, Muhammad Aown Sammar Raza, Muhammad Adil Rashid, Monika Toleikiene, **Muhammad Ayaz**, Farhan Mustafa, Muhammad Zeshan Ahmed et al. "Partial Root Zone Drying Irrigation Improves Water Use Efficiency but Compromise the Yield and Quality of Cotton Crop." *Communications in Soil Science and Plant Analysis* 52, no. 13 **(2021)**: 1558-1573.
7. Ali, Muhammad, Yasir Niaz, Ghulam Hassan Abbasi, Salman Ahmad, Zaffar Malik, Muhammad Kamran, Rashid Iqbal, **Ayaz Muhammad** et al. "Exogenous zinc induced NaCl tolerance in okra (Abelmoschus esculentus) by ameliorating osmotic stress and oxidative metabolism." *Communications in Soil Science and Plant Analysis* 52, no. 7 **(2021)**: 743-755.
8. Iqbal, Rashid, Muhammad Aown Sammar Raza, Monika Toleikiene, **Muhammad Ayaz**, Fatemeh Hashemi, Muhammad Habib-ur-Rahman, Muhammad Saqlain Zaheer

et al. “Partial root-zone drying (PRD), its effects and agricultural significance: a review.” *Bulletin of the National Research Centre* 44, no. 1 **(2020)**: 1-15.

9. Liu, Lin, Shan Yao, Hongtao Zhang, **Ayaz Muhammed**, Jiaxing Xu, Ruonan Li, Dongjie Zhang, Shulan Zhang, and Xueyun Yang. “Soil nitrate nitrogen buffer capacity and environmentally safe nitrogen rate for winter wheat-summer maize cropping in Northern China.” *Agricultural Water Management* 213 **(2019)**: 445-453.
10. LÜ, Feng-lian, Miao-miao HOU, Hong-tao ZHANG, Asif Khan, **Muhammad Ayaz**, Ciren QIANGJIU, Chang-lu HU, Xue-yun YANG, Ben-hua SUN, and Shu-lan ZHANG. “Closing the nitrogen use efficiency gap and reducing the environmental impact of wheat-maize cropping on smallholder farms in the Guanzhong Plain, Northwest China.” *Journal of integrative agriculture* 18, no. 1 **(2019)**: 169-178.
11. Khan, Asif, Guoyan Lu, **Muhammed Ayaz**, Hongtao Zhang, Renjie Wang, Fenglian Lv, Xueyun Yang, Benhua Sun, and Shulan Zhang. “Phosphorus efficiency, soil phosphorus dynamics and critical phosphorus level under long-term fertilization for single and double cropping systems.” *Agriculture, Ecosystems & Environment* 256 **(2018)**: 1-11.

NON SCI-PUBLICATIONS

1. **Ayaz M**., Sharif M., Ayesha B, Tahir N., Ali S.;. Determination of Water Quality of Rawal Dam, Islamabad, **2016**; 4, 113–117. doi: 10.15413 / ajar.2016.0209.
2. Ahmad M., Ali M., **Ayaz M**. , Khan A., Hamid A., Amin B., MORPHOLOGICAL AND BIOCHEMICAL STUDY OF EXOTIC PEPPER (Capsicum annuum L.). GERMPLASM; Science intern. lahr; **2017**. 29: 245–255.
3. Muhammad R., Asghar A., **Ayaz M**. , Ijaz SS, Ali M., Sharif M., Nadeem M., Ali S., Ayesha B. Wheat Response To Soil Water Retention And Dynamics Under Conservation Tillage In Dryland Pothwar, Pakistan 29, **2017**; 1283–1289.
4. Tahir N., Khan MJ, **Ayaz M**., Ali M., Fatima A., Ali S., Ayesha B.; Analysis of soil fertility and mapping using geostatistical information system. *Pure Appl. Biol*., **2016**; 5 (3): 446-452. http://dx.doi.org/10.19045/bspab.2016.50057
5. B. Amin, Yaqubi A., M. Ali, Mr Ullah, A. Khan, Muhammad T., A. Khan, **Ayaz M**. Response of potato genotypes to different levels of nitrogen. *Pure Appl. Biol*. **2016**. http://dx.doi.org/10.19045/bspab.2016.50048

Projects

1. 2022 year – Participation in project "Soil Ecosystem services and soil threats modelling and mapping" (SERENA) in accordance to the proposal which was submitted in the frame of the EJP SOIL.
2. Project funded by the Ministry of Agriculture of the Republic of Lithuania "Evaluation and preparation of fibre hemp products as organic carbon accumulators in long-term products and soil for their application according to IPCC, 2020–2022 methodology in GHG inventory".

ACKNOWLEDGEMENTS

My deepest appreciation is to Almighty Allah, HE is the most merciful and gracious to me in every facet of my life. Durood o salam upon the last Prophet (Khatim e Nabieen) Muhmmad ﷺ.

It is great pleasure to acknowledge my deepest thanks and gratitude to Lithuania Research Centre for Agriculture and Forestry (LAMMC), which provided the needed environment to thrive and excel during my doctoral studies. I would like to appreciate the immense contributions of my supervisor, (Dr. Dalia Feizienė) a very patient and calm loving lady, and consultant supervisor, (Dr. Vita Tilvikienė), a young energetic lady of LAMMC. They gave me the necessary support and tools needed to succeed in the pursuit of my career and scientific goals. It was such a worthwhile journey- teaching, supporting, mentoring, and advising me over the past four years. I must not fail to mention my excellent team members in the Department of Plant Nutrition and Agrobiology and the field technicians who all contributed in no small measure to the success of my academic journey. Lastly but not the least, I want to thank my family, my mother and father (late), lovely siblings and mumu Jan (Mir Ehsan Uddin), and especially my lovely wife Ayesha Ayaz for being so supportive during this entire journey.

To all my teachers since school till today, and all my friends and loved ones who supported me and provided the emotional support to lean on, I am sincerely grateful.

Muhammad AYAZ

PERSPECTIVES OF BIOCHAR WITH MINERAL NITROGEN FERTILIZERS FOR IMPROVEMENT OF SOIL SUSTAINABILITY AND CROP PRODUCTION IN NEMORAL CLIMATIC ZONE

Doctoral Dissertation

Edited by Author

Spausdino – Vytauto Didžiojo universitetas
K. Donelaičio g. 58, LT-44248 Kaunas
Užsakymo Nr. 23-126. Tiražas 15 egz. 2023 08 31.
Nemokamai