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Integrated Use of Bio-inoculants and Biochar as a Strategy for Improving Crop Production of Marginal Soils in Guyana's Savannah: A Review

Tracy Persaud[1,*], Gomathinayagam Subramanian[1], Danilo López-Hernández[2]

[1]University of Guyana, School of Graduate Studies and Research, Turkeyen Campus, Greater Georgetown, Guyana
[2]Institute of Zoology and Tropical Ecology, Central University of Venezuela, Caracas, Caracas 1041-A, Venezuela

Abstract The coastal belt continues to be the most active agricultural zone in Guyana, despite climate risks and environmental vulnerabilities. To build the resilience of Guyana's agriculture sector to the threats of sea level rise, salinization and flooding exacerbated by climate change, it is imperative that agricultural activities be decentralized through the development of Guyana's vast hinterland region. The hinterland soils have the capacity to fulfill their potential as Guyana's next agricultural frontier. This can be achieved, through the efforts to amend its marginal soils to enhance its agricultural productive capacity. This review found that the combined use of biochar and plant growth-promoting microorganisms (bio-inoculants), might be the most efficacious and sustainable interventions for marginal sandy soils. Biochar when applied to acidic and infertile sandy agricultural soils is a valuable amendment for improving soil fertility and productivity. Biochar application improves the physical properties of the soil, enhances its capacity for nutrient retention, and encourages microbial activity, thus, improving soil quality and crop yield. The combined use of biochar and bio-inoculant creates synergies, especially for the establishment and beneficial activities of rhizobia bacteria, which fix nitrogen, and arbuscular mycorrhizae fungi, which increases the availability of nutrients especially phosphorous for plant uptake. Nitrogen and phosphorous are two of the most limiting nutritive factors in crop production on marginal sandy soils, thus the supplementation of nitrogen and phosphorous, using the combination of beneficial microorganisms and biochar, would help to improve soil quality and crop productivity.

Keywords Biochar, Guyana, Marginal, Savannah, Mycorrhiza, Soil, Rhizobium, Review

1. Introduction and Overview

Agricultural strategies for shortening crop development cycles and increasing crop yields have included genetic engineering (Bailey-Serres et al., 2019), intense application of chemical fertilizers (Kauppinen et al., 2016), growth promoters (Thirumdas et al., 2018), pesticides, herbicides, and soil sterilizers (Bamdad et al., 2021). Several of these techniques have resulted in significant negative consequences for soil health and agro-ecosystem functioning, including decreased organic matter (Šimon & Czakó, 2018), and decreased microbial and mesofaunal activity, and in turn biodiversity loss (Cluzeau et al., 2012).

Over the last few years, there has been a noticeable increase in research on the use of organic materials in sustainable agriculture. Organic waste can be converted into various types of soil amendments, resulting in a win-win situation for a more environmentally friendly and productive agriculture (Rehrah et al., 2016; Santana et al., 2020). Certain ecologically friendly organic amendments have been shown to boost yields and resilience to biotic and abiotic challenges (Semida et al., 2019). Two of the most promising options are organo-mineral fertilizers (Abd El-Mageed et al., 2015; Semida et al., 2015; Rady et al., 2016) and biochar (Beesley et al., 2011; Calvo et al., 2014; Akhtar et al., 2015). While both approaches boost crop production and contribute to a variety of ecosystem services, biochar, in particular, is capable of enhancing soil fertility, stimulating plant development, and increasing plant tolerance to harsh environments. Biochar's structural properties can influence the total microbial biomass. In general, when biochar is added to the soil as an amendment, it can enhance microbial activities and lead to changes in the community structure. This, in turn, can have positive effects on soil nutrient cycling, carbon sequestration, and ultimately improve crop yield (Zhang et al., 2018).

The interaction between biochar and microbes is influenced by the physicochemical properties of biochar. This interaction leads to improved growth of beneficial

* Corresponding author:
tracypersaud9@gmail.com (Tracy Persaud)
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microbes and increased soil nutrients, ultimately resulting in enhanced plant growth (Tan et al., 2022). In comparison to other plant-microbe interactions, the legume-rhizobia symbiosis is the most researched and characterized. It promotes plant development via nitrogen fixation (Oldroyd, 2013), and is estimated to produce around 50% of biologically fixed nitrogen on the planet. The second most researched plant-microbe symbiosis is that of a group of plant-fungal interactions that encompasses over 90% of all plant species on Earth, i.e. plant-mycorrhiza symbiosis (Gough & Cullimore, 2011; Zifcakova, 2020). These interactions help plants by enhancing nutrient absorption, water uptake, and their ability to withstand a variety of abiotic and biotic stressors.

Therefore, the objectives of this literature review were to critically analyze, identify and elaborate on research done on sustainable soil management practices that uses soil amendments such as biochar and bio-inoculants (rhizobia bacteria and mycorrhizae fungi), to improve soil quality and crop productivity of marginal soil types. A systemic literature search was conducted via appropriate journals and search engines. Criteria for the most relevant literature was set up using a time period of five years and with key search terms: "marginal soils", "economic viability", "microbial inoculants", "rhizobium", "mycorrhizae" and "biochar". Discretion was exercised in the case of literature older than five years but contain results and findings pertinent to the knowledge base. These findings were also included in the review.

The Intermediate Savannahs of South America and Guyana

The neotropical savannahs of South America, encompass a substantial area of 269 million hectares, are distributed across the countries of Bolivia, Brazil, Colombia, Guyana, and Venezuela (López-Hernández et al., 2005). These expansive lands hold immense potential for agricultural productivity; serving as a pivotal solution to circumvent the need for agricultural expansion into more ecologically vulnerable regions. Due to their geographical proximity and shared soil characteristics, the technological advancements devised for the utilization of savannahs have exerted a discernible influence on the agronomic and land management practices implemented in these alternative ecosystems (Narro et al., 2004). Over the past sixty years these savannahs lands with the exception of Guyana have experienced significant transformation from the native vegetation. With the use of chemical fertilizers and calcium carbonate, it was possible to introduce annual and perennial crops along with pasture grass into these ecosystems (López-Hernández et al., 2005).

The Intermediate Savannahs of Guyana are located some 160 km behind the Atlantic coastal strip and occupy a land mass of approximately 2,980,836 ha (14.1%). This area represents soils that are now rarely farmed due to severe fertility limitations, but have the potential for agricultural development if access and inputs are improved. These soils are predominantly deep, poorly to well-drained sands, loams, and clays (Guyana Lands and Surveys Commission, 2013). With proper management, soil amelioration, and bio-inoculants, these regions could become profitable for arable crops. However, these soils represent a fragile ecosystem that requires careful and expert management for the growing of crops and improved pastures (TAMS Agricultural Development Group, 1976). Thirty-eight soil types have been identified; they range in texture from coarse sands to medium sandy clays. The white sands are classified as Entisols and the brown sands as Ultisols and Oxisols (Ahmad, 1989). The most common soil types are Ebini sandy loam, Kasarama loamy sand, Bukurana loamy sand, Tabela sand, and Tiwiwid white sand, which occur in small pockets (TAMS Agricultural Development Group, 1976). For these soils clay and organic matter levels are crucial to their agricultural potential, as they have low water holding capacity and are hence extremely droughty during the dry season (Paul et al., 1997).

The lessons learnt from work done in the Brazilian cerrados' indicates that the utilization of crop monocultures and pastures is not conducive to long-term sustainability within the framework of existing methodologies. Novel production systems that integrate enhanced production technologies and the preservation of natural resources are currently being devised and put into practice. The commencement of the cerrados for the purpose of cultivating crops and raising livestock has undeniably demonstrated that even marginal soils can be effectively integrated into production through the implementation of suitable management practices and advanced technology (Lopes et al., 2004).

Several recommendations were made that are essential for agricultural production systems to be sustainable in the Intermediate Savannahs of Guyana. The main recommendations include: crop rotation, crop residue management, weed control, legumes in inter-cropping systems, soil and water conservation, organic matter enhancement and maintenance, use of bio-inoculants, soil amelioration (liming, crop residue, animal manures, green manure), nutrient cycling and chemical and organic fertilizers (Paul et al., 1997). Sustainable agriculture on savannah lands must prioritize approaches that preserve the delicate ecosystem's integrity and biodiversity. The path to development is dependent on research that yields crop varieties and innovative production systems that efficiently and sustainably utilize the natural resource base.

Cereals, grain legumes, and pasture forages can produce high yields in the Intermediate Savannahs with proper management and technology (Paul et al., 1997; Narro et al., 2004). Legumes are one of the most abundant sources of proteins, minerals, and fibers for both animals and humans. Through biological nitrogen symbiosis (BNS), they play an important role in preserving soil fertility. Legumes help to increase soil microbial activity; they also have a weed-suppressing impact. As a result of their beneficial effects on soil health and exceptional adaptation to marginal environments, legumes are currently regarded as one of the most vital components of a cropping system. Importantly is the retention of nitrogen (N) produced from legume grain during crop senescence or in an inter-cropping system for the next crop. The importance of grain legumes to soil health necessitates the use of these crops in marginal soils. Thus, the optimization of nitrogenous fertilizer use in modern agriculture is crucial not only for maintaining and restoring soil organic carbon (SOC), but also for minimizing nitrate pollution from agricultural sources (Singh, 2018).

2. Use of Marginal Soils for Agricultural Purposes

On a global scale, marginal lands, also known as less favored areas (LFAs), cover significant areas with large human populations; however, they are not given priority in policy making due to the fact that their agricultural value is perceived to be low, and there is a lack of information about the other ecosystem services (ES) that they may provide (Wells et al., 2018). These marginal soils are significantly important globally since they support large poor rural populations (Barbier, 2010). Despite this, they are typically disregarded by natural resource management policymakers because of the historically low agricultural productivity of these soils. This exclusion has sometimes led to a lack of knowledge of the usage and function of marginal soils, which has resulted in relatively unrestricted development, poor land management, degradation of land, and a loss of biodiversity (Lipper et al., 2007). Marginal soils can be found in any ecosystem where agricultural productivity is severely constrained by low soil fertility (biophysical) or market access (socioeconomic). Given the high levels of poverty in LFAs globally, regionally and locally, the need for improved land management is critical not just for preventing environmental degradation but also for combating poverty (Wells et al., 2018). In such regions, policymakers would require greater understanding and approaches for balancing agricultural expansion and environmental conservation.

Marginal land is described as soil that has a low profit margin as a result of low cost-effective production, which takes into account environmental circumstances, methods of cultivation, agriculture regulations, as well as macroeconomic and legal constraints (Dauber et al., 2012; Lewandowski, 2015). The term includes area that is currently unsuitable for agricultural production as a result of natural limits such as low soil fertility, unfavorable weather conditions, or steep slopes (Terres et al., 2014). The rising demand for food on a global scale is driving the conversion of marginal soil types for agriculture and livestock activities (López-Hernández et al., 1997; Lamin & Meyfroit, 2011; Antolleni et al., 2015).

By 2050, the world's population will surpassed 9 billion, and temperatures globally will have risen to the point that the world will be confronted with extended droughts periods and decreased water supply (Schröder et al., 2022). Given the exponential growth of the global population and the subsequent surge in agricultural demands, it is becoming increasingly imperative to address the escalating necessity for expansive agricultural lands (Yu et al., 2013). The necessity for an increased land area to fulfill the demand for an increasing world's population may potentially give rise to conflicts with lands of significant ecological value, characterized by their abundant biodiversity (López-Hernández et al., 1997; Fernando et al., 2018). However, the cultivation of agricultural crops on marginal soils is being regarded as a viable strategy to support and increase crop productivity and rural development.

Current solutions for the management of marginal soils rely heavily on inorganic chemical fertilizers, which are expensive and that pose a serious threat to human health and the environment. In addition, the constant release of these chemical inputs allows hazardous chemicals, such as metals, to remain in the soil and be transferred to the plants with prolonged exposure, ultimately affecting human health. In order to increase agricultural yields on marginal soils, it is therefore vital to develop alternatives to chemical fertilizers and pesticides (Vishwakarma et al., 2020).

These alternatives may include the use of various forms of high carbon amendments such as biochar, and plant growth promoting microorganisms in the form of bio-inoculants to increase crop performance and quality, and the modification of the soil microbiome in a specific manner. Due to their potential significance in food safety and sustainable crop production, the use of beneficial microorganisms as a bio-inoculant or microbial inoculants has assumed utmost importance in the agricultural industry. Bio-inoculants are preparations that contain specific living microorganisms that can fix, mobilize, or breakdown sources of nutrients. Bio-inoculant may be applied via soil or seed to improve the uptake of nutrients by plants (Mohanram & Kumar, 2019). The environmentally friendly approaches of using plant growth promoting microorganisms such as plant growth promoting rhizobacteria (PGPRs), endomycorrhizal and ectomycorrhizal fungi (Arbuscular Mycorrhizal Fungi), cyanobacteria, and numerous other beneficial microorganisms has led to improved plant productivity through enhanced nutrient uptake and tolerance to biotic and abiotic stress (Bhardwaj et al., 2014; Backer et al., 2018; Cabrales et al. 2019; Mora et al. 2019).

A balanced use of organic, bio-inoculants and inorganic fertilizers as sources of plant nutrients is necessary to increase and maintain soil fertility and productivity for the purpose of sustaining food production on marginal land. The variable responses of bio-inoculants in field research and crops, however, have created a fundamental barrier that impedes its wider implementation. The interactions between various rhizosphere components, such as plant roots and soil microorganisms, are researched to provide better knowledge of the intricate rhizospheric intercommunication. Having knowledge of the rhizosphere microbiome is crucial for the development of methods to shape the rhizosphere for the benefit of the plants (Mohanram & Kumar, 2019).

3. The Use of Biochar in Farming Systems

Biochar is primarily recognized for its application as a soil amendment, which has garnered significant interest due to its potential to enhance agricultural productivity and soil quality (Gelardi & Parikh, 2021). Biochar is defined as a product that is high in carbon and is created by the pyrolysis (heating with a restricted supply of oxygen) of organic materials at temperatures ranging from 250 to 700 degrees Celsius (Rajakumar & Sankar, 2016). It is often referred to as the "black gold" of the agricultural industry. The use of biochar is nothing new. One of the most renowned instances of agricultural biochar utilization can be observed in the pre-Columbian Terra Preta soils located within the Amazon River basin.

The indigenous inhabitants of the Amazonian region ingeniously developed the Terra Preta by incorporating substantial quantities of charcoal into the soil, thereby enhancing the nutrient deficient composition of the rainforest's soil (Taylor, 2010). The soils found in these areas display qualities that are diametrically different to the majority of the soils in that location (Glaser & Birk, 2012). These biochar amended soils are widespread throughout the Amazon region and are distinguished by their high nutrient content, which includes phosphorus (P), carbon (C), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn), and organic matter (Barbosa et al., 2020). Its organic component does not derive solely from the buildup of vegetal cover; rather, it developed as a result of ancestral human actions as a means of utilizing plant and animal bone remains, cooking coal, and waste from fires used to replace forests with cultivated areas (Ogawa & Okimori, 2010).

The utilization of charcoal as a means to enhance the quality of marginal soils was once considered obsolete subsequent to the advent of chemical fertilizers during the era of industrialization. Nevertheless, given the detrimental impacts of chemical fertilizers on contemporary agricultural soils and the environment, as well as the growing apprehension regarding the rise in atmospheric carbon levels, there has been a resurgence of attention towards the use of charcoal-based soil amendment (Chia et al., 2010). This renewed interest primarily centers around the application of biochar.

Biochar is a material that is considered environmentally friendly and cost-effective, for the removal of a wide variety of contaminants because it possesses various features that are unique to it (Oliveira et al., 2017). Modern thermochemical processes, such as pyrolysis, are utilized to produce biochar from residual biomass. Biochar is a fine-grained, porous substance that resembles the appearance of naturally-produced charcoal. The sole distinction between biochar and charcoal is biochar's utilitarian intent (Kapoor et al., 2022).

In the Intermediate Savannahs of Guyana, low soil fertility and acidity are two of the most significant limitations affecting agricultural productivity. Acidic infertile soils, such as Kasarama Loamy Sand (Oxisol), can be restored sustainably by adding organic amendments such as biochar, one of the most important and readily available methods for considerably raising soil pH. According to Agegnehu et al. (2016), there are numerous methods for restoring nutrient deficiencies in acid soils. These methods include liming, the addition of organic amendments, bio-inoculants, and inorganic fertilization.

Biochar and biochar bio-inoculants combinations derived from a variety of alternative organic sources have been proposed as a way to improve soil fertility, restore degraded soil and mitigate greenhouse gas emissions connected with agriculture. Additionally, biochar has the ability to retain water and nutrients, which could potentially mitigate the leaching issue of highly weathered tropical acid soils such as Oxisols that are present in the Intermediate Savannahs of Guyana, as well as serve as plant-growth nutrients.

Research done by Persaud et al. (2018), on marginal sandy soil (Tabela Sand – Oxisols), using application rates of 0, 5 t/ha 25 t/ha and 50 t/ha of rice husk biochar found that the application rate of 25 t/ha of rice husk biochar improved soil quality and crop yield. Results showed that in each cycle the lowest crop biomass was from the unamended soil (control), and the highest crop biomass was from the application of biochar at 25 t/ha. There was a 32.81% increase in plant biomass between the application of biochar at 25 t/ha and the control. These results suggest an upper limit to the application of biochar on crop productivity. These findings confirm the information presented in a review done by Liu et al. (2013), on published data from 21 countries, which found that benefits were achieved with biochar application rates of typically below 30 t/ha.

It should be noted, that over the course of two decades, extensive research has revealed that the anticipated advantages of biochar application are not consistently realized. This inconsistency can be attributed to various factors, including variations in biochar properties, soil characteristics, climatic conditions, and agricultural practices. Although biochar has the potential to enhance agronomic conditions in marginal soils, its effectiveness in temperate climates and fertile soils is comparatively limited (Gelardi & Parikh, 2021). The existence of various challenges hinders the ability to draw comparisons among different biochar studies and develop cohesive recommendations for the efficient and sustainable utilization of biochar. Despite these challenges, the concept of incorporating biochar into agricultural landscapes is attracting considerable interest within the realm of policy. The Intergovernmental Panel on Climate Change (IPCC) designated biochar as a prominent natural climate solution in 2018 (De Coninck et al., 2018). In the year 2020, the National Resource Conservation Service made the decision to incorporate biochar into their Soil Carbon Amendment program, alongside compost and whole orchard recycling. This decision was based on the recognition that biochar has the potential to provide a range of beneficial outcomes in both agricultural and environmental contexts.

3.1. The Effects of Biochar on Physical and Chemical Soil Properties

The maintenance of healthy soil and the implementation of sustainable agriculture practices promotes biodiversity, which contributes to the improvement of crucial ecological services (Kremen & Merenlender, 2018). Tropical soils that have undergone significant weathering have inherent deficiencies in soil fertility due to a multitude of physical, chemical, and microbiological limitations, which consequently restrict agricultural productivity. The existing findings regarding the positive impact of biochar application to soils, particularly in terms of improving nutrient relations (such as enhancing phosphorus availability and reducing nutrient leaching), enhancing soil aeration and water retention capacity, and promoting beneficial microbiological activities (such as symbiotic nitrogen symbiosis and mycorrhizal associations), indicate the potential benefits of biochar in tropical farming systems (Nair et al., 2017). Several other experts are in agreement that incorporating biochar into farmland can have numerous positive effects on the physicochemical properties of the soil (Jeffery et al., 2015; Gelardi & Parikh, 2021; Knoblauch et al., 2021). Biochar holds great potential since it can be produced using a simple kiln on the farm. The production of biochar using these simple techniques can benefit small and large-scale farmers globally, regionally and locally as in the case of farmers in the Intermediate Savannahs of Guyana.

A global meta-analysis done by Jeffery et al. (2017), revealed that increasing agricultural productivity in tropical regions through the application of biochar was more successful than the application of limestone and fertilizers to acidic marginal soils. The most significant projected positive effects of adding biochar to acid soils are an increase in pH, a reduction in the toxicity of aluminum and, to a lesser extent, either manganese or iron, and reducing the soil's ability to fix phosphorus. Srivastava (2017), also reported soil quality has improved significantly, with improvements in pH, organic carbon, exchangeable cations, and nitrogen fertilizer use efficiency following the application of biochar.

The impact of biochar on acidic soils is likely a result of their alkaline nature and strong buffering capacity (Juriga & Šimanský, 2019). The basic cations (e.g., K, Ca, Na and Mg), found in biochar as carbonates or oxides can help reduce acidity by increasing the exchangeable cation reaction. This reaction occurs when the functional groups on the surface of biochar, such as COO^- and O^-, react with the H^+ or Al^{+3} ions in the soil, resulting in an increase in the soil pH (Hansen et al., 2016; Dai et al., 2017; Zong et al., 2018). Shetty & Prakash. (2020), also shared the view that certain characteristics of biochar, such as a high surface charge density, internal porosity, a large surface area and the presence of polar and non-polar surface sites, all contribute significantly to its liming effect.

Since biochar is derived from biomass containing numerous nutrient elements, including nitrogen, phosphorus, sulphur, and potassium, these elements can be converted into bioavailable inorganic forms through pyrolysis and/or mineralization processes. The use of biochar as a nutrient enhancer or alternative nutrient provider has been the subject of a significant amount of research. A recent meta-analysis done by Ye et al. (2020), reported that using biochar on its own does not increase crop yield; however, using biochar in conjunction with inorganic fertilizers has the potential to increase crop yield by 15% when compared to using inorganic fertilizers alone. Numerous studies have demonstrated that biochar's physical and chemical qualities encourage adsorption due to its higher specific surface area than other organic materials, hence increasing the soil's nutrient availability (Bonanomi et al., 2017; Yadav et al., 2019).

Biochar is also an excellent habitat for microbes to colonize, develop, and reproduce, especially rhizobia bacteria, arbuscular mycorrhizal fungi and actinomycetes, and, due to its porous structure, which contains a large number of pores of varying sizes. Several researchers have proposed that the biochar pores may serve as a microhabitat for microorganisms that colonize it, protecting them from their natural predator (Warnock et al., 2007; Kapoor et al., 2022). The application of biochar also improves the structure, porosity and aggregation of the soil, facilitating tillage, and promoting nutrient retention (Karimi et al., 2020). As a result, it effectively reduces nutrient leaching and ultimately improves the overall soil quality index (Jeffery et al., 2017; Oladele et al., 2019). The low density of biochar results in a reduction of soil bulk density, (Grunwald et al., 2017), leading to decreased soil resistance during plowing and other field operations. This, in turn, translates to notable cost savings on fuel consumption.

Biochar's CEC is largely determined by the temperature conditions under which it is produced (Tan et al., 2017; Leng & Huang, 2018). The carboxylic groups formed in the bridges of the aromatic nuclei of biochar are responsible for the increase of the CEC and reactivity (Zhang et al, 2018). When biochar is added to the soil, its functional groups have a generally positive charge (Tan et al., 2020). However, over time, the functional groups on the surface oxidize and generate more negative charges than positive charges, increasing the CEC. Another process that affects CEC is the adsorption of highly oxidized organic matter onto biochar surfaces (Tomczyk et al., 2020). When exposed to oxygen and water, biochar can generate more functional groups on the surface through oxidation, resulting in an increase in CEC. However, Hailegnaw et al. (2019), cautioned that CEC is highly variable and tends to change over time as a result of interactions with the environment once the biochar is incorporated. These processes may have an effect on the improvement of other physical and chemical soil properties, either directly or indirectly (Karimi et al., 2020).

Several studies showed that the application of biochar to soils have a positive effects on the productivity of crops (Jin et al., 2016; He et al., 2017; Masud et al., 2020). However, Diatta et al. (2020), reported that most noticeable changes have been noted in acidic soils, which implies that its yield effect is comparable to that of liming, with the added benefit of improved water retention. Other authors, Ahmed et al. (2016) and Batista et al. (2018), agreed that the water retention capacity as previously stated is primarily due to two factors: the large internal surface area and the high number of residual pores in the biochar, which retain water via capillarity, thereby improving soil aggregation and structure. This increases the soil's overall porosity and water content, reducing water mobility and alleviating plant water stress. As a result, biochar does not exert a single effect. It has an effect on a variety of interconnected soil physicochemical and biological properties (Riascos & Herrera, 2020). According to Kolton et al. (2011) and Li et al. (2018), the effect of biochar on soil biota exhibits a highly variable response, with increases, decreases, or no significant effect reported. These interactions between microorganisms and biochar are also influenced by a variety of environmental factors, including the type and rate of biochar amendment, the type of soil, the type of land use, and the type of vegetation (Gorovtsov et al., 2020).

The expanding body of knowledge indicates that biochar applications could be a critical input for sustaining production while lowering pollution and reliance on fertilizers (Beesley et al., 2011; Stavi & Lal, 2013). Numerous studies have demonstrated that amending soils with biochar can boost agricultural yields and decrease plant stress caused by salinity, drought, and heavy metals (Akhtar et al., 2015; Dugdug et al., 2018; Karunanayake et al., 2018; Rizwan et al., 2018; Riascos & Herrera, 2020; Jatav et al., 2021 & Kocsis et al., 2022). However, Purakayastha et al. (2019), contends that the composition and availability of nutrients in biochar are dependent on the raw material used and the pyrolysis conditions. Wang et al. (2020) and Yu et al. (2019), also shared the view that biochar has unquestionably emerged as a significant potential tool for environmental applications; however, to facilitate additional biochar applications, it is necessary to investigate a number of issues. These issues include the nutrient status of biochar-treated soils, including the type of soil and feedstock used, the pyrolysis temperature, and the rate of application and economic viability of adding biochar to large scale cropping systems.

4. Use of Bio-Inoculants in Sustainable Agriculture

The South American savannahs contains soils that have variable levels of total phosphorous and low levels of available nitrogen and phosphorous. The long-term sustainability of agricultural production systems in savannah soils are contingent upon the preservation or enhancement of the physical and chemical attributes, as well as the biological composition, of the soil. (Lopez-Hernandez et al., 2005). Sustainable agriculture focuses primarily on reducing plants' dependence on chemical fertilizers and enhancing their adaptability to marginal soil types. The utilization of eco-friendly bio-inoculants derived from indigenous strains has been observed to yield beneficial outcomes in savannah ecosystems (Lopes et al., 1999; Cabrales et al. 2019; Mora et al. 2019). Microorganisms used to promote plant growth have primarily focused on facilitating plant growth and development by enhancing the plant's acquisition of nutrient resources from the environment, such as fixed nitrogen, and phosphate, or by modulating plant growth by altering plant hormone levels (Hayat et al., 2010).

Although the benefits of bio-inoculants are numerous, it must be noted that there are some constraints to its usage. The lack of consistent responses in various soils and environmental conditions, the difficulty of application, the short shelf life, and the slow action of bio-inoculants prevent their widespread commercialization. It should be recognized that bio-inoculants are highly specific to crops and soil types, and that their sustainability in soils is primarily dependent on pH, native microorganisms, soil organic matter content and soil moisture and temperature regime. Extensive research and development are required to enhance our understanding of the efficacy of specific strains in connection to crop, soil, and climate conditions (Debnath et al., 2019).

4.1. Rhizobia Bacteria: Potential for Increasing Crop Yield

Rhizobia are a diverse group of gram-negative bacteria that live in soil either as saprophytes or in connection with plants as endophytes of internal plant tissues. When these bacteria are positioned within the nodule, they have an incredible ability to fix atmospheric nitrogen and convert it to accessible nitrogen compounds that may be utilized directly by the legumes; these characteristics have been widely studied for decades (Ferguson et al., 2019). Due to the ability of rhizobia to fix atmospheric nitrogen, rhizobial inoculants are frequently used in agriculture to reduce nitrogen fertilizer applications on legume crops (Volpiano et al., 2019). Recent research has identified the orders Rhizobiales (α-rhizobia) and Burkholderiales (ß-rhizobia) as keystone axa due to their constant presence in plants' core microbiomes. The genera Rhizobium and Bradyrhizobium, are the ones most known for their roles in increasing plant productivity and preserving community evenness (Yeoh et al., 2017).

According to Egamberdieva et al. (2018), research done using biochar as a carrier for the rhizobia bacteria, reported a high survival rate of the bacteria that were introduced and significantly increased the amount of colonization that occurred in the rhizosphere of the plant. The author further stated that in pot and field experiments, biochar based inoculants were also effective at boosting plant growth and grain yield. Biochar based rhizobial inoculants can substantially enhance the symbiotic performance of legumes with rhizobia, thereby reducing the need for N fertilizer and enhancing the sustainability of crop production.

4.1.1. The Use of Biochar with Arbuscular Mycorrhizal Fungi

The availability of phosphorus (P) is one of the most significant yield limiting variables in acidic marginal soils. Arbuscular mycorrhizal fungi have been shown to boost the availability of P to plants when they are stressed. Mycorrhizal fungi are commonly utilized as soil inoculants to increase the availability of phosphorus, soil characteristics and crop yields. There is mounting evidence that biochar can increase mycorrhizal fungi in soil, hence improving the soil's quality (Malik et al., 2019). When biochar is applied to soil, it frequently results in considerable improvements in soil characteristics, plant development and mycorrhizal fungi. Increased nutrient availability in soil via biochar application can benefit host plants' performance, which may aid in the colonization of AM fungus.

At the community level, it also creates a microhabitat in the soil that allows mycorrhizal fungi to extend their hyphae in search of nutrients to benefit nearby plants (Warnock et al., 2007). Additionally, biochar boosted mycorrhizal fungal colonization, which aided in the improvement of water supply and other resources for plants in drought prone areas. This theory was supported by a meta-analysis conducted by Gao et al. (2020), which used 284 data pairs from 43 studies and found an average increase of 18.8% in plant water use efficiency (PWUE) and 20% increase in leaf water use efficieny (LWUE) after biochar was applied to the soil. The greatest positive effect in PWUE was found in the biochar application rates of less than 20t/ha. However, the author warned that the increases were dependent on specific soil properties and the type of biochar used. Additionally, the findings justified the application of biochar to improve PWUE and LWUE. However, the increased water use efficiencies in the study were not permanent.

While there is significant evidence that the rhizosphere microbial community works together with their mycorrhizal partners to mobilize nutrients from soil minerals, cycle nitrogen and protect plants from root diseases, such bidirectional synergy is not always present. There have been findings that bacterial communities have suppressive effects on mycorrhizal function and vice versa (Ray et al., 2020). While one study indicated that soil with more Acidobacteria restricts the normal functioning of extra-radical mycelium in arbuscular mycorrhizae (Svenningsen et al., 2018), another study discovered that *Rhizophagus irregularis* and *Glomus mosseae* reduced the majority of the associated soil microbial population (Welc et al., 2018). Not withstanding these exceptions, several other studies have reported positive crop responses with dual inoculation of arbuscular mycorrhizal fungus with plant growth promoting bacteria (Fatnassi et al., 2015; Priyadharsini & Muthukumar, 2016; del Barrio-Duque et al., 2019; Yadav et al., 2020; Dabral et al., 2020).

4.1.2. Effects of Biochar and Bio-Inoculants on Crop Yield

The use of bio-inoculants with biochar could enhances soil health and decreases the need for extensive chemical fertilizer application. Increasing the population and beneficial activities of soil microorganisms through the use of bio-inoculants provides plants with essential nutrient elements such as nitrogen and phosphorus, thereby enhancing plant growth and crop production (Hosseini et al., 2021). According to Van Zwieten et al. (2010), biochar does not contain a significant amount of plant nutrients but improves the efficiency of inorganic fertilizers and enhance the capabilities of mycorrhizae fungi and rhizobia bacteria in the soil.

As Ren et al. (2020), demonstrated the application of biochar and bio-inoculants will substantially enhance nitrogen symbiosis, inorganic nitrogen, potassium content, and soil moisture. Hosseini et al. (2021), further reported an increase in grain yield of barley when biochar was used in combination with co-inoculation (rhizobia and mycorrhizae), when compared to separate application of the bio-inoculant. Several other researchers reported increase in yield following the use of biochar and bio-inoculants (Stewart & Cromey, 2011; Asouli-Sadaghiani et al., 2021; Sher & Mishra, 2023; Rasouli-Sadaghiani et al., 2021). The beneficial effects of applying biochar to soil are believed to increase over time (Rajakumar & Sankar, 2016).

5. Potential Research Gaps

To improve crop production (yield) on marginal soils, the use of bio-inoculants alone may not be able to sustain plant growth and could be used in combination with biochar. However, the use of bio-inoculants such as rhizobia bacteria and mycorrhizae fungi in combination with biochar in open field experiments is understudied and powerfully needed. A review by Agegnehu et al. (2017), on 634 research publications in the past ten years on the use of biochar as soil amendments for improving soil health and production on marginal soils found that the vast majority of studies were conducted in developed countries, which have soils that are significantly less marginal or degraded in terms of their capacity to produce crops than many developing countries. Additionally, most of the research done using soil amendments and bio-inoculants were short term studies conducted in either green houses or in the laboratory under controlled environment. In a broader context, a review of the literature by Marazza et al. (2022), revealed that around 80% of the available data pertaining to the effects of biochar are derived from pot trials. Wang et al. (2020), also shared the view that there is limited field research on biochar. The author further stated that prior to the application of biochar on a large scale, more in situ or field experiments should be conducted over an extended period of time to simulate the actual environment and investigate the true impact of biochar.

Due to the paucity of field study data, researchers are unable to determine conclusively the positive and negative effects of biochar on soil physical properties. The performance of biochar on broad fields with varied soil and environmental conditions may differ from small greenhouse or laboratory pots. For instance, field experiments are necessary for obtaining representative measurements of compaction characteristics (bulk density), water holding capacity, water erosion, and soil temperature changes after the application of biochar. Soil reactions to biochar application, particularly responses of soil physical qualities, might be gradual. The entire range of biochar's effects may not be realized until long term biochar soil interactions occur (Canqui, 2017). Palansooriya et al. (2019), also agreed that the next major step of biochar research should focus on determining the long-term effects of biochar application on soil biota and soil health.

Our current understanding of biochar's potential to improve crop production and mitigate climate change is hindered by a general lack of long-term, well-designed field studies on the efficacy of biochar and bio-inoculants on various soil types and agro-climatic zones (Agegnehu et al., 2017).

Limited research has been conducted as it relates to the benefits of biochar in degraded or problem soils (low fertility, eroded, low organic matter, compacted, saline, saline-sodic, and sodic soils). The application of biochar may have a greater impact on the physical features of such soils than on those of highly fertile or productive soils. To validate this hypothesis, field tests are necessary. The utilization of biochar derived from various sources may not consistently yield identical outcomes for a given soil characteristic in less productive soils. Hence, it is important to take into account the use of appropriate biochar in the suitable soil type when aiming to improve a specific soil function. Therefore, it is crucial to accurately evaluate and document the climatic conditions, soil types, soil pH levels, soil nutrient composition, and biochar properties that are specific to different crops and their corresponding yield variations resulting from changes in these factors (Vijay et al., 2021). Importantly, the application of biochar may have a positive impact on soil quality and productivity; nevertheless, the economics of biochar application and use on large scales should also be studied and fully explored in order to make recommendations that are applicable in real life. This information is needed to evaluate the economic viability of this technology. Wang et al. (2020), also shared the same view that there is need for research to evaluate the viability and practicality of using biochar in combination with other sustainable strategies in order to improve its usefulness and make it economical to farmers.

Frequently, biochar is used as a soil amendment by itself. In fact, biochar contains a distinct, highly porous structure with varying pore diameters. Prior to use, biochar can be inoculated with various soil microorganisms, such as bacteria and fungi. It not only increases the colonization rate of desirable groups of soil microorganisms, but also accelerates the presence of their beneficial effects in biochar amended soils, particularly for decontaminating polluted soils. The utility of biochar as a microbial carrier in crop production systems in order to improve soil health and productivity must thus be investigated. Long term research elucidating these microorganisms is strongly required especially on marginal sandy soil types.

6. Economic Viability of Biochar

Oliveira et al. (2017), suggested that biochar is a material that is considered environmentally friendly and cost-effective. However, Jatav et al. (2020), reported that the variable application rates, unclear feedstock impacts and initial status of the soil all contribute to a wide range of costs associated with marginally enhanced yields from biochar additions, which is frequently economically impractical. On the other hand, McHenry (2009), and Fytili & Zabaniotou (2018), suggested that the economic feasibility of biochar farming has not been extensively studied in the literature. The majority of studies conducted on the utilization of biochar have been in controlled laboratory settings or in small-scale field experiments that only offer limited insights into its long-term commercial viability. However, Grycová et al. (2016), reported that the pyrolysis of biowaste, such as food waste, is becoming more profitable as gate fees enable production costs to be reduced to US$50/ ton from US$2,2 000/ ton for conventional feed stock (Vochozka et al., 2016).

Ha et al. (2010), suggested that one way to decrease the cost of production of biochar is by utilizing mobile pyrolysis units and making logistic improvements. Bruckman et al. (2016), also agreed that in order to minimize logistical costs, biochar should be produced close to the source of the feedstock or at the site of its use, while also incorporating energy recovery, can significantly reduce production costs, potentially even to zero. Efforts to further reduce its price are, therefore, unnecessary. Instead, more profitable methods of biochar application must be researched (Maroušek et al., 2019). Although biochar does contain nutrients relative to the feedstock, it should not be evaluated based on traditional nutrient perspectives as a fertilizer or biofuel. The price of the product should reflect its ability to improve soil quality and crop yield.

7. Conclusions

Biochar is derived from biomass waste and has the potential to address agricultural waste management issues while also improving soil quality and promoting beneficial microbial diversity. Research has demonstrated that utilizing biochar in a combination with bio-inoculants in soil has significant potential to improve soil fertility and crop yield by enhancing soil properties and increasing the availability of plant nutrients. In order to utilize marginal sandy soils for agricultural purposes, it is imperative that a sustainable management strategy is developed for these soils and ecosystems. After critically reviewing journal articles and research papers, it can be concluded that the application of biochar and bio-inoculant creates synergies that modifies soil physical, chemical and biological properties and encourages the activity of soil microorganisms, which impact soil quality and crop production. Soil microorganisms have been shown to play a crucial role in soil ecosystem functions and services which includes maintaining soil quality and health, driving biogeochemical cycles and suppressing pathogens, thus the next major step of biochar research should focus on determining the long term effects of biochar application and bio-inoculant on soil biota and soil health and its economic viability for large scale application. The use of biochar and bio-inoculant is an environmentally friendly and sustainable option to improve soil quality and crop yields of marginal sandy soils.

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REFERENCES

[1] Agegnehu, G., Srivastava, A.K., & Bird, M.I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Applied Soil Ecology, 119, 156-170. DOI:10.1016/J.APSOIL.2017.06.008.

[2] Ahmad, N. (1989). Farming systems for low fertility acid soils. CTA Seminar Proceedings, Keytone Address, (pp. 12-31).

[3] Ahmad, N. (2011). Soils of the Caribbean. Kingston: Ian Randle Publishers.

[4] Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., & Chen, M. (2016). Progress in the preparation and application of modified biochar for improved contaminant removal from water and wastewater. Bioresource technology, 214, 836-851. https://doi.org/10.1016/j.biortech.2016.05.057.

[5] Ajeng, A. A., Abdullah, R., Ling, T. C., Ismail, S., Lau, B. F., Ong, H. C., Chew, K. W., Show, P. L., & Chang, J. S. (2020). Bioformulation of biochar as a potential inoculant carrier for sustainable agriculture. Opus.lib.uts.edu.au. https://opus.lib.uts.edu.au/handle/10453/144061.

[6] Akhtar, S.S., Andersen, M.N & Liu, F. (2015). Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. Agricultural Water Management, 158, 61–68. https://doi.org/10.1016/j.agwat.2015.04.010.

[7] Antolleni, M., Siciliano, G., Turvani, M. E., & Rulli, M. C. (2015). Global investments in agricultural land and the role of the EU: Drivers, scope and potential impacts. Elsevier Land Use Policy, 98-111 https://doi.org/10.1016/j.landusepol.2015.04.007.

[8] Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J. R., Praslickova, D., Ricci, E., Subramanian, S., & Smith, D. L. (2018). Plant Growth-Promoting Rhizobacteria: Context, Mechanisms of Action, and Roadmap to Commercialization of Biostimulants for Sustainable Agriculture. Front. Plant Sci. 9:1473, 9. https://doi.org/10.3389/fpls.2018.01473.

[9] Bailey-Serres, J., Parker, J. E., Ainsworth, E. A., Oldroyd, G.E.D., & Schroeder, J. I. (2019). Genetic strategies for improving crop yields. 575(7781), 109–118. https://doi.org/10.1038/s41586-019-1679-0.

[10] Bamdad, H., Papari, S., MacQuarrie, S., & Hawboldt, K. (2021). Study of surface heterogeneity and nitrogen functionalizing of biochars: Molecular modeling approach. Carbon, 171, 161–170. https://doi.org/10.1016/j.carbon.2020.08.062.

[11] Barbier, E. B. (2010). Poverty, development, and environment. Scopus Review, 635-660.Barbier, E. B. (2010). Poverty, development, and environment. Scopus Review, 635-660.

[12] Barbosa, J. Z., Motta, A. C. V., Corrêa, R. S., Muniz, A. W., Martins, G. C., Silva, L. D. C. R., ... & Broadley, M. R. (2020). Elemental signatures of an Amazonian Dark Earth as result of its formation process. Geoderma, 361, 114085.

[13] Batista, E. M., Shultz, J., Matos, T. T., Fornari, M. R., Ferreira, T. M., Szpoganicz, B., & Mangrich, A. S. (2018). Effect of surface and porosity of biochar on water holding capacity aiming indirectly at preservation of the Amazon biome. Scientific Reports, 8(1), 1-9. DOI:10.1038/s41598-018-28794-z.

[14] Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. 159(12), 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023.

[15] Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microbial cell factories, 13, 1-10. https://doi.org/10.1186/1475-2859-13-66.

[16] Bonanomi, G., Ippolito, F., Cesarano, G., Nanni, B., Lombardi, N., Rita, A., Saracino, A., & Scala, F. (2017). Biochar As Plant Growth Promoter: Better Off Alone or Mixed with Organic Amendments? Frontiers in Plant Science, 8. https://doi.org/10.3389/fpls.2017.01570.

[17] Bruckman, V. J., Varol, E. A., & Uzun, B. B. (Eds.). (2016). Biochar. Cambridge University Press.

[18] Cabrales H, E., López-Hernández, D & Toro, M. 2019. Effects of the inoculation with native Glomeromycota fungi and fertilization in the yield of maize in acid soils. In: Zúñiga D, Ormeño E and González-Andrés F (Eds.) Microbial probiotics for agricultural systems. Advances in agronomic use. Springer. 205-212. ISBN: 978-3-030-17596-2.

[19] Calvo, P., Nelson, L. M., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. Plant and Soil, 383(1-2), 3–41. https://doi.org/10.1007/s11104-014-2131-8.

[20] Chia, C., Munroe, P., Joseph, S., & Lin, Y. (2010). Microscopic characterisation of synthetic Terra Preta. 48(7), 593–593. https://doi.org/10.1071/sr10012.

[21] Cluzeau, D., Guernion, M., Chaussod, R., Martin-Laurent, F., Villenave, C., Cortet, J., Ruiz-Camacho, N., Pernin, C., Mateille, T., Philippot, L., Bellido, A., Rougé, L., Arrouays, D., Bispo, A., & Pérès, G. (2012). Integration of biodiversity

in soil quality monitoring: Baselines for microbial and soil fauna parameters for different land-use types. 49, 63–72. https://doi.org/10.1016/j.ejsobi.2011.11.003.

[22] Dabral, S. N., Saxena, S. C., Choudhary, D.K; Bandyopadhyay, P., Sahoo, R.K; Tuteja, N; & Nath, M. (2020). Synergistic inoculation of Azotobacter vinelandii and Serendipita indica augmented rice growth. Symbiosis, 81(2), 139–148. https://doi.org/10.1007/s13199-020-00689-6.

[23] Dai, L., Tan, F., Li, H., Zhu, N., He, M., Qili, Z; Hu, G., Wang, L., & Zhao, J. (2017). Calcium-rich biochar from the pyrolysis of crab shell for phosphorus removal. 198, 70–74. https://doi.org/10.1016/j.jenvman.2017.04.057.

[24] Dauber, J., Brown, C. P., Luísa, A., Finnan, J., Krasuska, E., Jens Ponitka, Styles, D., Thrän, D., Jan, Weih, M., & Zah, R. (2012). Bioenergy from "surplus" land: environmental and socio-economic implications. BioRisk, 7, 5–50. https://doi.org/10.3897/biorisk.7.3036.

[25] De Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J. C., Ley, D., Mechler, R., Newman, P., Revokatova, A., Schultz, S., Steg, L., & Sugiyama, T. (2018). Strengthening and Implementing the Global Response. In *Global warming of 1.5°C: Summary for policy makers* (pp. 313-443). IPCC - The Intergovernmental Panel on Climate Change.

[26] Debnath, S., Rawat, D., Mukherjee, A.K; Adhikary, S; & Kundu, R. (2020). Applications and Constraints of Plant Beneficial Microorganisms in Agriculture. IntechOpen EBooks. https://doi.org/10.5772/intechopen.89190.

[27] Diatta, A. A., Fike, J. H., Battaglia, M. L., & Baig; M.B. (2020). Effects of biochar on soil fertility and crop productivity in arid regions: a review. Arabian Journal of Geosciences 13(14).DOI:10.1007/s12517-020-05586-2.

[28] Ducey, T. F., Novak, J. M., & Johnson, M. H. (2015). Effects of Biochar Blends on Microbial Community Composition in Two Coastal Plain Soils. 5(4), 1060–1075. https://doi.org/10.3390/agriculture5041060.

[29] Duque, D. B., Ley, J., Samad, A., Antonielli, L., Sessitsch, A., & Compant, S. (2019). Beneficial Endophytic Bacteria-Serendipita indica Interaction for Crop Enhancement and Resistance to Phytopathogens. Frontiers in Microbiology, 10. https://doi.org/10.3389/fmicb.2019.02888.

[30] El-Mageed, Taia A.; Semida, Wael M. (2015). Organo mineral fertilizer can mitigate water stress for cucumber production (Cucumis sativus L.). Agricultural Water Management, 159(C), 1–10. https://ideas.repec.org/a/eee/agiwat/v159y2015icp1-10.html.

[31] Fatnassi, I.C., Chiboub, M., Saadani, O., Jebara, M., & Jebara, S.H. (2015). Impact of dual inoculation with Rhizobium and PGPR on growth and antioxidant status of Vicia faba L. under copper stress. Competes Rendus Biologies, 338(4), 241-254. https://doi.org/10.1016/j.crvi.2015.02.001.

[32] Ferguson, B. J., Mens, C., Hastwell, A. H., Zhang, M., Su, H., Jones, C. H., Chu, X., & Gresshoff, P. M. (2018). Legume nodulation: The host controls the party. Plant Cell and Environment, 42(1), 41–51. https://doi.org/10.1111/pce.13348.

[33] Fernando A.L; Costa, J., Barbosa, B., Monti, A., & Rettenmaier, N. (2018). Environmental impact assessment of perennial crops cultivation on marginal soils in the Mediterranean Region. *Biomass & Bioenergy*, *111*, 174–186. https://doi.org/10.1016/j.biombioe.2017.04.005.

[34] Fytili D, Zabaniotou A. (2018). Circular economy synergistic opportunities of decentralized thermochemical systems for bioenergy and biochar production fueled with agro-industrial wastes with environmental sustainability and social acceptance: a review. Curr Sustain Renew Energy Rep. https://doi.org/10.1007/s4051 8-018-0109-5.

[35] Gao, X., Guo, H., Zhang, Q., Guo, H., Zhang, L., Zhang, C., Gou, Z., Liu, Y., Wei, J., Chen, A., Zhang, C., & Zeng, F. (2020). Arbuscular mycorrhizal fungi (AMF) enhanced the growth, yield, fiber quality and phosphorus regulation in upland cotton (Gossypium hirsutum L.). Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-59180-3.

[36] Gelardi, D. L., & Parikh, S. J. (2021). Soils and Beyond: Optimizing Sustainability Opportunities for Biochar. Sustainability, 13(18), 10079–10079. https://doi.org/10.3390/su131810079.

[37] Glaser, B., & Birk, J.J. (2012). State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). 82, 39–51. https://doi.org/10.1016/j.gca.2010.11.029.

[38] Gorovtsov, A., Minkina, T., Mandzhieva, S., Perelomov, L., Soja, G., Zamulina L., Rajput, V. D., Sushkova, S., Mohan, D., & Yao, J. (2019). The mechanisms of biochar interactions with microorganisms in soil. Environmental Geochemistry and Health, 42(8), 2495–2518. https://doi.org/10.1007/s10653-019-00412-5.

[39] Gough, C., & Cullimore, J. (2011). Lipo-chitooligosaccharide Signaling in Endosymbiotic Plant-Microbe Interactions. Molecular Plant-Microbe Interactions®, 24(8), 867–878. https://doi.org/10.1094/mpmi-01-11-0019.

[40] Grycova, B., Koutník, I., & Pryszcz, A. (2016). Pyrolysis process for the treatment of food waste. Bioresource Technology, 218, 1203–1207. https://doi.org/10.1016/j.biortech.2016.07.064.

[41] Guyana Lands and Surveys Commission. (2013). Guyana National Land Use Plan. Georgetown: Ministry of Natural Resources and Environment.

[42] Ha M, Bumguardner ML, Munster CL, Vietor DM, Capareda S, Palma MA, Provin T. (2010). Optimizing the logistics of a mobile fast pyrolysis system for sustainable bio-crude oil production. American Society of Agricultural and Biological Engineers. Annual international meeting. Pittsburgh, Pennsylvania, USA.

[43] Hailegnaw, N.S., Mercl, F., Pračke, K., Tlustos, P. (2019). Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. J Soils Sediments 19, 2405–2416 (2019). https://doi.org/10.1007/s11368-019-02264-z.

[44] Hansen, V., Hauggaard-Nielsen, H., Petersen, C. T., Mikkelsen, T. N., & Müller-Stöver, D. S. (2016). Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. Soil and Tillage Research, 161, 1 – 9. https://doi.org/10.1016/j.still.2016.03.002.

[45] Hayat, R., Ali, S., Amara, U., Khalid, R., & Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth

promotion: a review. Annals of Microbiology, 60(4), 579–598. https://doi.org/10.1007/s13213-010-0117-1

[46] He, Y., Zhou, X., Jiang, L., Li, M., Du, Z., Shao, J., Wang, X., Xu, Z., Bai, S.H., Wallace, H. M., & Xu, C.-Y. (2017). Effects of biochar application on soil greenhouse gas fluxes: a meta-analysis. Gcb Bioenergy, 9(4), 743–755. https://doi.org/10.1111/gcbb.12376.

[47] Holder, N. L. (1995). Proposal for agricultural development of the Intermediate Savannahs of Guyana. Georgetown: Organization of American States.

[48] Hosseini, E., Zarei, M., Sepehri M., & Safarzadeh, S. (2022). Do bagasse biochar and microbial inoculants positively affect barley grain yield and nutrients, and microbial activity? Journal of Plant Nutrition, 45:4, 522-539, DOI: 10.1080/01904167.2021.1952229.

[49] Jatav, H.S; Singh, S.K; Jatav, S.S; Rajput, V. D; Parihar, M; Mahawer, S.K; Singhal, R. K; & Sukivtee. (2020). Importance of biochar in agriculture and its consequence. In Abdelhafez, A.A.; & Abbas, M.H.H. (Eds.), Applications of Biochar for Environmental Safety.

[50] Jatav, H.S., Rajput, V. D., Minkina, T., Singh, S.K., Chejara, S., Gorovtsov, A., Barakhov A., Bauer, T., Sushkova, S., Mandzhieva, S., Burachevskaya, M., & Kalinitchenko, V. (2021). Sustainable Approach and Safe Use of Biochar and Its Possible Consequences. Sustainability, 13(18), 10362–10362. https://doi.org/10.3390/su131810362.

[51] Jeffery S, Abalos D, Spokas KA, Verheijen FG. (2015) Biochar effects on crop yield. In: Lehmann J, Joseph S (eds) Biochar for Environmental Management: Science, Technology and Implementation, 2nd edn. Routlege, London.

[52] Jeffery, S., Abalos, D., Prodana, M., Bastos, A., Willem, J., Hungate, B. A., & Frank. (2017). Biochar boosts tropical but not temperate crop yields. 12(5), 053001–053001. https://doi.org/10.1088/1748-9326/aa67bd.

[53] Jin, J., Li, Y., Zhang, J., Wu, S., Cao, Y., Peng, L., Zhang, J., Wong, M.H., Wang, M., Shan, S., & Christie, P. (2016). Influence of pyrolysis temperature on properties and environmental safety of heavy metals in biochars derived from municipal sewage sludge. Journal of Hazardous Materials, 320, 417–426. https://doi.org/10.1016/j.jhazmat.2016.08.050.

[54] Juriga, M., & Šimanský, V. (2019). Effects of Biochar and its Reapplication on Soil pH and Sorption Properties of Silt Loam Haplic Luvisol. Acta Horticulturae et Regiotecturae, 22(2), 65–70. https://doi.org/10.2478/ahr-2019-0012.

[55] Kapoor, A., Sharma, R., Kumar, A., & Swapana Sepehya. (2022). Biochar as a means to improve soil fertility and crop productivity: a review. Journal of Plant Nutrition, 45(15), 2380–2388. https://doi.org/10.1080/01904167.2022.2027980.

[56] Karimi, A., Abdolamir Moezzi, Mostafa Chorom, & Naeimeh Enayatizamir. (2020). Application of Biochar Changed the Status of Nutrients and Biological Activity in a Calcareous Soil. 20(2), 450–459. https://doi.org/10.1007/s42729-019-00129-5.

[57] Karunanayake, A. G., Todd, O., Crowley, M., & Mlsna, T. (2017). Lead and cadmium remediation using magnetized and non-magnetized biochar from Douglas fir. Chemical Engineering Journal, Volume 331, 480-491. https.//doi/org/10.1016/j.ceg.2017.08.124.

[58] Kauppinen, M., Saikkonen, K., Helander, M., Anna Maria Pirttilä, & Wäli, P. R. (2016). Epichloë grass endophytes in sustainable agriculture. 2(2). https://doi.org/10.1038/nplants.2015.224.

[59] Knoblauch, C., Priyadarshani, S., Haefele, S. M., Schröder, N., & Pfeiffer, E.-M. (2021). Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. https://doi.org/10.1111/ejss.13088.

[60] Kocsis, T., Ringer, M., & Biró, B. (2022). Characteristics and Applications of Biochar in Soil–Plant Systems: A Short Review of Benefits and Potential Drawbacks. Applied Sciences, 12(8), 4051–4051. https://doi.org/10.3390/app12084051.

[61] Kolton, M., Harel, Y.M., Pasternak, Z., Graber, E. R., Elad,, Y & Cytryn, E. (2011). Impact of Biochar Application to Soil on the Root-Associated Bacterial Community Structure of Fully Developed Greenhouse Pepper Plants. Applied and Environmental Microbiology, 77(14), 4924–4930. https://doi.org/10.1128/aem.00148-11.

[62] Kremen, C. & Merenlender, A. M. (2018). Landscapes that work for biodiversity and people. Science, 362. https://doi.org/10.1126/scien ce.aau6020.

[63] Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences of the United States of America, 108(9), 3465–3472. https://doi.org/10.1073/pnas.1100480108.

[64] Leng, L., & Huang, H. (2018). An overview of the effect of pyrolysis process parameters on biochar stability. 270, 627–642. https://doi.org/10.1016/j.biortech.2018.09.030.

[65] Lewandowski, I. (2015). Securing a sustainable biomass supply in a growing bio-economy. Environmental Science: Global Food Security, 34-42. https://doi.org/10.1016/j.gfs.2015.10.00.

[66] Li, Y., He, N., Hou, J., Xu, L., Liu, C., Zhang, J.-H., Wang, Q., Zhang, X., & Wu, X. (2018). Factors Influencing Leaf Chlorophyll Content in Natural Forests at the Biome Scale. 6. https://doi.org/10.3389/fevo.2018.00064.

[67] Li, Y., Hu, S., Chen, J., Müller, K., Fu, W., Lin, Z., & Wang, H. (2017). Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. Journal of Soils and Sediments, 18(2), 546–563. https://doi.org/10.1007/s11368-017-1906-y.

[68] Lipper, L., Pingali, P., & Zurek, M. (2007). Less-Favoured Areas: Looking Beyond Agriculture Towards Ecosystem Services. 2007: Food and Agriculture Organisation (FAO).

[69] Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R & Paz-Ferreiro, J. (2013). Biochar's Effect on Crop Productivity and the Dependence on Experimental Conditions- A Meta-Analysis of Literature Data. Plant and Soil, 373 (1-2).DOI:10.1007/s11104-013-1806-x.

[70] Lopes A, Ayarza M, Thomas R (1999). In Guimarães E.P; Sanz J.I; Rao I.M; Amézquita MC, Amézquita E (Eds.) Agropastoral Systems in The Savannahs of Tropical Latin America: Lessons from the Agricultural Development of the Cerrados of Brazil. CIAT Publication No. 313. pp 9-30.

[71] Lopes A.S., Ayarza, M., and Thomas R.J. (2004). Managing

and Conserving Acid Savannah Soils for Agricultural Development: Lessons from the Brazilian Cerrados. In E.P. Guimarães, J.I. Sanz, I.M. Rao, M.C. Amézquita, E. Amézquita and R.J. Thomas (eds) "Agropastoral Systems for the Tropical Savannas of Latin America". CIAT-EMBRAPA, Publication 338, Cali, Colombia. Chapter 2: 12-34.

[72] López-Hernández, D., García-Guadilla, M.P., Torres, F., Chacón, P., & Paoletti, M.G. (1997). Identification, characterization and preliminary evaluation of Venezuelan Amazonian production systems in Puerto Ayacucho savanna-forest ecotone. Interciencia 22: 307-314.

[73] López-Hernández, D., Hernández, R., & Brossard, M. (2005). Recent use history of South American savannah land. Case studies in the Orinoco savannas. Interciencia. 30. 623-630.

[74] Malik, Z., Z. Shah and M. Tariq. (2019). Biochar improves viability of arbuscular mycorrhizal fungi (AMF) in soil and roots of wheat (Triticum aestivum) and maize (Zea mays L.) under various cropping systems. Sarhad Journal of Agriculture, 35(3): 834-846. http://dx.doi.org/10.17582/journal.sja/2019/35.3.834.846.

[75] Marazza, D., Pesce, S., Greggio, N., Francesco Primo Vaccari, Enrico Balugani, & Alessandro Buscaroli. (2022). The Long-Term Experiment Platform for the Study of Agronomical and Environmental Effects of the Biochar: Methodological Framework. Agriculture, 12(8), 1244–1244. https://doi.org/10.3390/agriculture12081244.

[76] Maroušek, J., Strunecký, O., & Stehel, V. (2019). Biochar farming: defining economically perspective applications. Clean Technologies and Environmental 21(7). DOI:10.1007/s10098-019-01728-7.

[77] Masud, M. M., Baquy, M., Akhter, S., Sen, R., Barman, A., & Khatun. (2020). Liming effects of poultry litter derived biochar on soil acidity amelioration and maize growth. Ecotoxicology and Environmental Safety, 202, 110865–110865. https://doi.org/10.1016/j.ecoenv.2020.110865.

[78] McHenry, M.P. (2009) Agricultural bio -char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. Agriculture, Ecosystems & Environment, 129 (1 -3). pp. 1 -7.

[79] Mohanram, S & Kumar, P. (2019). Rhizosphere microbiome: revisiting the synergy of plant-microbe interactions. 69(4), 307–320. https://doi.org/10.1007/s13213-019-01448-9.

[80] Mora, E., López-Hernández, D & Toro, M. 2019. Arbuscular mycorrhiza and PGPR applications in tropical savannas. 169-178. In: Zúñiga D, Ormeño E and González Andrés F (Eds.) Microbial probiotics for agricultural systems. Advances in agronomic use. Springer. ISBN: 978-3-030-17596-2.

[81] Nair, V. D., Nair, R., Dari, B., Freitas, B., Chatterjee, N., & Pinheiro, F. M. (2017). Biochar in the Agroecosystem–Climate-Change–Sustainability Nexus. Frontiers in Plant Science, 8. https://doi.org/10.3389/fpls.2017.02051.

[82] Narro, L., Pandey, S. León, A.J. Pérez C. and Salazar. F. (2004). Maize varieties for acid soils. In E.P. Guimarães, J.I. Sanz, I.M. Rao, M.C. Amézquita, E. Amézquita and R.J. Thomas (eds) "Agropastoral Systems for the Tropical Savannas of Latin America". CIAT-EMBRAPA, Publication 338, Cali, Colombia. Chapter 1: 1-9.

[83] Neina, D. (2019). The Role of Soil pH in Plant Nutrition and Soil Remediation. 2019, 1–9. https://doi.org/10.1155/2019/5794869.

[84] Ogawa, M., & Okimori. Y. (2010). Pioneering works in biochar research, Japan. 48(7), 489–489. https://doi.org/10.1071/sr10006.

[85] Oladele, S., Adeyemo, A., Awodun, M., Ajayi, A. E., & Fasina, A.S. (2019). Effects of biochar and nitrogen fertilizer on soil physicochemical properties, nitrogen use efficiency and upland rice (Oryza sativa) yield grown on an Alfisol in Southwestern Nigeria. 8(3), 295–308. https://doi.org/10.1007/s40093-019-0251-0.

[86] Oldroyd, G. E. (2013). Speak, friend, and enter: signalling systems that promote beneficial symbiotic associations in plants. Nature Review Microbiology, 252–263. doi: 10.1038/nrmicro2990.

[87] Oliveira, F. R., Patel, K.A., Jin, Y., Adhikari, S., Lu, H., & Khanal, S.K. (2017). Environmental application of biochar: Current status and perspectives. 246, 110–122. https://doi.org/10.1016/j.biortech.2017.08.122.

[88] Palansooriya, K.N., Wong, J., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H., & Kim, K. H. (2019). Response of microbial communities to biochar-amended soils: a critical review. 1(1), 3–22. https://doi.org/10.1007/s42773-019-00009-2.

[89] Priyadharsini, P., & Muthukumar, T. (2016). Interactions between Arbuscular Mycorrhizal Fungi and Potassium-Solubilizing Microorganisms on Agricultural Productivity. pp. 111–125, https://doi.org/10.1007/978-81-322-2776-2_8.

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

[91] Rady, M. M., Semida, W. M., Hemida, K. A., & Abdelhamid, M. T. (2016). The effect of compost on growth and yield of Phaseolus vulgaris plants grown under saline soil. 5(4), 311–321. https://doi.org/10.1007/s40093-016-0141-7.

[92] Rajakumar, R., and J. Sankar. (2016). Biochar for sustainable agriculture – A review. International Journal of Applied and Pure Science and Agriculture 2:173–84.

[93] Rasouli-Sadaghiani, M., Danesh, R., Moradi, N., & Barin, M. (2021). The effect of compost, biochar and bio-inoculant on enzymatic activity and some soil microbial indices. Journal of Sol Biology, 9(2), 141–154. https://doi.org/10.22092/sbj.2021.352967.209.

[94] Raven, K. P., and Loeppert, R.H. (1997),"Trace Element Composition of Fertilizers and Soil Amendments." Journal of Environmental Quality, vol. 26, no. 2 pp. 551–557. https://doi.org/10.2134/jeq1997.00472425002600020028x.

[95] Ray, P., Lakshmanan, V., Labbé, J., & Craven, K. D. (2020). Microbe to Microbiome: A Paradigm Shift in the Application of Microorganisms for Sustainable Agriculture. Frontiers in Microbiology, 11. https://doi.org/10.3389/fmicb.2020.622926.

[96] Ren, H., Huang, B., Fernández-García, V., Miesel, J. R., Li, Y., & Lv. C. (2020). Biochar and Rhizobacteria Amendments Improve Several Soil Properties and Bacterial Diversity. Microorganisms, 8(4), 502–502. https://doi.org/10.3390/

microorganisms8040502.

[97] Riascos, M. S., & Heera, T. (2020). Impact of biochar use on agricultural production and climate change. A review. Agronomía Colombiana, 38(3), 367-381. DOI:10.15446/agron.colomb.v38n3.87398

[98] Rizwan, M., Ali, S., Abbas, T., Adrees, M., Ibrahim, M., Abbas, F., Qayyum, M., & Nawaz, R. (2018). Residual effects of biochar on growth, photosynthesis and cadmium uptake in rice (Oryza sativa L.) under Cd stress with different water conditions. Journal of Environmental Management, 206, 676–683. https://doi.org/10.1016/j.jenvman.2017.10.035

[99] Thirumdas, R., Kothakota, A., Annapure, U., Siliveru, K., Blundell, R., Gatt, R., & Valdramidis, V.P. (2018). Plasma activated water (PAW): Chemistry, physico-chemical properties, applications in food and agriculture. 77, 21–31. https://doi.org/10.1016/j.tifs.2018.05.007.

[100] Santana, K.V.R., Kathamania, A., & Apolônio, F., & Wisniewski, A. (2020). Valorization of cattle manure by thermoconversion process in a rotary kiln reactor to produce environmentally friendly products. BioEnergy Research. DOI:10.1007/s12155-019-10047-0.

[101] Schröder, P., Mench, M., Povilaitis, V., Rineau, F., Rutkowska, B., Schloter, M., Loit, E. (2022). Relaunch cropping on marginal soils by incorporating amendments and beneficial trace elements in an interdisciplinary approach. Science of the Total Environment, 1-12.

[102] Semida, W. M., Beheiry, H. R., Sétamou, M., Simpson, C., Taia A., El-Mageed, A., Rady, M. M., & Nelson, S. D. (2019). Biochar implications for sustainable agriculture and environment: A review. 127, 333–347. https://doi.org/10.1016/j.sajb.2019.11.015.

[103] Semida, W. M., El-Mageed, T.A., Howladar, S.M., & Rady, M. M. (2015, April 13). Response of Solanum melongena L. Seedlings grown under saline calcareous soil conditions to a new organo-mineral fertilizer. Journal of Animal and Plant Sciences. 25. 485-493.

[104] Sher, A., & Mishra, S. (2023). Effect of FYM, biochar and biofertilizers on head quality and physico-chemical attributes of soil of kharif cabbage (Brassica oleracea L. var. capitata) cv. pride of India. The Pharma Innovation Journal 2023; 12(4): 651-658.

[105] Shetty, R., & Prakash, N. B. (2020). Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity. Scientific Reports, 10(1), Article 12249. https://doi.org/10.1038/s41598-020-69262-x.

[106] Singh, B. (2018). Are Nitrogen Fertilizers Deleterious to Soil Health? *Agronomy*, *8*(4), 48–48. https://doi.org/10.3390/agronomy8040048.

[107] Srivastava. A.K. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Applied Soil Ecology, 119:156-170. DOI:10.1016/j.apsoil.2017.06.00.

[108] Stavi, I and Rattan Lal. Agroforestry and Biochar to Offset Climate Change: A Review. (2013). Vol. 33, no. 1, pp. 81–96. https://doi.org/10.1007/s13593-012-0081-1.

[109] Stewart, A., Cromey, M. (2011). Identifying Disease Threats and Management Practices for Bio-Energy Crops. Current Opinion in Environmental Sustainability, Volume 3, Issue 1, p. 75-80. https://doi.org/10.1016/j.cosust.2010.10.008.

[110] Svenningsen, N.B., Watts-Williams, S. J., Joner, E. J., Battini, F., Efthymiou, A., Cruz-Paredes, C., Nybroe, O. & Jakobsen, I. (2018). Suppression of the activity of arbuscular mycorrhizal fungi by the soil microbiota. The ISME Journal, 12(5), 1296–1307. https://doi.org/10.1038/s41396-018-0059-3.

[111] TAMS Agricultural Development Group. (1976). The Intermediate Savannahs Report. Aubre Barker Associates.

[112] Tan, S., Narayanan, M., Thu, T., Ito, N., Yuwalee, U., Arivalagan P., Nguyen T. L, & Liu, J. (2022). A perspective on the interaction between biochar and soil microbes: A way to regain soil eminence. Environmental Research, 214. DOI:hhttps://doi.org/10.1016/j.envres.2022.113832.

[113] Tan, X., Liu, S., Liu, Y., Gu, Y., Zeng, G., Hu, X., Wang, X., Liu, S., & Jiang, L. (2017). Biochar as potential sustainable precursors for activated carbon production: Multiple applications in environmental protection and energy storage. Bio-resource Technology. Volume 227, 359-372. https://doi.org/10.1016/j.biortech.2016.12.083.

[114] Tan, Z., Yuan, S., Hong, M., Zhang, L., & Huang, Q. (2020). Mechanism of negative surface charge formation on biochar and its effect on the fixation of soil Cd. Journal of Hazardous Materials, 384, 121370–121370. https://doi.org/10.1016/j.jhazmat.2019.121370.

[115] Taylor, P. (2010). The Biochar Revolution: Transforming Agriculture & Environment. Global Publishing Group Mt Evelyn, Victoria.

[116] Terres, J. M., Hagyo, A., & Wania, A. (2014). Scientific Contribution on Combining Bio-physical Criteria Underpinning the Delineation of Agricultural Areas Affected by Specific Constraints. Luxembourg: JRC Science and Policy Reports, EUR 26940 EN, Publications Office of the European Union.

[117] Tomczyk, A., Sokołowska, Z., & Patrycja Boguta. (2020). Biomass type effect on biochar surface characteristic and adsorption capacity relative to silver and copper. 278, 118168–118168.https://doi.org/10.1016/j.fuel.2020.118168.

[118] United States Department of Agriculture Natural Resources Conservation Service (NRCS) Soil Carbon Amendment 808-CPS-1 (2020).

[119] Vijay, V., Shreedhar, S., Adlak, K., Payyanad, S., Sreedharan, V., Gopi, G., Van der Voort, S., Malarvizhi, P., Yi, S., Gebert, J., & Aravind, PV. (2021). Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations. Frontiers in Energy Research, 9. https://doi.org/10.3389/fenrg.2021.710766.

[120] Vishwakarma, K., Shukla, A., Shandilya, C., Mohapatra, S., Bhayana, S. & Varma, A. (2020). Revisiting Plant–Microbe Interactions and Microbial Consortia Application for Enhancing Sustainable Agriculture: A Review. 11. https://doi.org/10.3389/fmicb.2020.560406.

[121] Vochozka M, Maroušková A, Váchal J, Straková J. (2016). Biochar pricing hampers biochar farming. Clean Technologies and Environmental Policy 18:1225-1231. https://doi.org/10.1007/s10098-019-01728-7.

[122] Volpiano C.G; Lisboa B.B; Granada C.E; São José G.F.B; de Oliveira A.M.R; Beneduzi A; Perevalova Y; Passaglia

L.M.P; Vargas L.K. (2019). Rhizobia for Biological Control of Plant Diseases. In Microbiome in Plant Health and Disease. In (Eds) Kumar V; Prasad R; Kumar M, Choudhary D.K. Microbiome in Plant Health and Disease. Chapter 14 Pp315-336. DOI:10.1007/978-981-13-8495-0_14.

[123] Wang, L., Kim, K. H., Alessi, D. S., Rinklebe, J., vWang, H., Xu, G., Hou, R., O'Connor, D. H., & Hou, D. (2020). New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment. 36(3), 358–386. https://doi.org/10.1111/sum.12592.

[124] Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil – concepts and mechanisms. 300(1-2), 9–20. https://doi.org/10.1007/s11104-007-9391-5.

[125] Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil–concepts and mechanisms. Plant and soil, 300, 9-20. https://doi.org/10.1007/s11104-007-9391-5.

[126] Wells, G. J., Stuart, N., Furley, P. A., & Ryan, C. M. (2018). Ecosystem service analysis in marginal agricultural lands: A case study in. Elsevier Ecosystem Services, 32 (70-77) https://doi.org/10.1016/j.ecoser.2018.06.002.

[127] Yadav, R., Ror, P., Rathore, P., & Ramakrishna, W. (2020). Bacteria from native soil in combination with arbuscular mycorrhizal fungi augment wheat yield and biofortification. Plant Physiology and Biochemistry, 150, 222–233. https://doi.org/10.1016/j.plaphy.2020.02.039.

[128] Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B. & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. Soil Use and Management, 36, 2–18. https://doi.org/10.1111/ sum.12546.

[129] Yeoh, Y.K., Dennis, P. G., Paungfoo-Lonhienne, C., Weber, L., Brackin, R., Ragan, M. A., Schmidt, S., & Hugenholtz, P. (2017). Evolutionary conservation of a core root microbiome across plant phyla along a tropical soil chronosequence. Nature Communications, 8(1). https://doi.org/10.1038/s41467-017-00262-8.

[130] Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., Tang, H., Wei, X., & Gao, B. (2019). Biochar amendment improves crop production in problem soils: A review. Journal of Environmental Management, 232, 8–21. https://doi.org/10.1016/j.jenvman.2018.10.117.

[131] Yu, O.Y., Raichle, B. W., & Sink, S. (2013). Impact of biochar on the water holding capacity of loamy sand soil. Int J Energy Environ Eng 4, 44, 4(1), 44–44. https://doi.org/10.1186/2251-6832-4-44.

[132] Zhang, C., Liu, L., Zhao, M., Rong, H., & Xu, Y. (2018). The environmental characteristics and applications of biochar. 25(22), 21525–21534. https://doi.org/10.1007/s11356-018-2521-.

[133] Zhang, L., Jing, Y., Xiang, Y., Zhang, R., & Lu, H. (2018). Responses of soil microbial community structure changes and activities to biochar addition: A meta-analysis. Science of the Total Environment, 643, 926–935. https://doi.org/10.1016/j.scitotenv.2018.06.231.

[134] Zifcakova, L. (2020). Factors Affecting Soil Microbial Processes. In: Datta, R., Meena, R., Pathan, S., Ceccherini, M. (eds) Carbon and Nitrogen Cycling in Soil. Springer, Singapore. https://doi.org/10.1007/978-981-13-7264-3_13.

[135] Zong, Y., Wang, Y., Sheng, Y., Wu, C.F., & Lu, S. (2018). Ameliorating soil acidity and physical properties of two contrasting texture Ultisols with wastewater sludge biochar. 25(26), 25726–25733. https://doi.org/10.1007/s11356-017-9509-0.

[136] Zwieten, L.V., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2009). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant and Soil, 327(1-2), 235–246. https://doi.org/10.1007/s11104-009-0050-x.