STUDIES ON THE IMPACT OF AGRICULTURAL WASTE BIOCHAR AND ORGANIC AMENDMENTS ON SOIL NUTRIENT RECOVERY AND CARBON POOL IN JHUM LAND

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Submitted

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CERTIFICATE

This is to certify that the thesis entitled **"Studies on the impact of agricultural waste biochar and organic amendments on soil nutrient recovery and carbon pool in jhum land"** submitted by **Smt. Alice Kenye** for the award of degree of **Doctor of Philosophy** in **Forestry** of Mizoram University, Aizawl, embodies the record of original investigation carried out by her under my supervision. She has duly registered and the thesis presented is worth of being considered for the award of the Ph.D. degree. The work has not been submitted for any degree to any other University.

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DECLARATION

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JULY, 2024

I **Miss Alice Kenye**, do hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form basis of the award of any previous degree to me or to the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/ Institute.

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Chapter 1

General Introduction

1.1 Growing human population and the need for sustainable practices

The world's population reached a staggering 7.8 billion in mid-2020, adding a supplementary 1 billion to 2008's figure and 2 billion more than in 1996. The global population is projected to further hit 8.5 billion in 2030, while rising steadily to approximately 9.7 billion in 2050 and 10.5 billion in 2100 (United Nations, 2019). This rapid growth in world population and gradual decrease in available cultivable lands and freshwater reserves have stimulated a discussion on the need for sustainable farming practices (Garnett et al. 2013; Godfray and Garnett 2014). Even though land use could be multiplied to meet the mounting pressure on crop demand to some extent, this could have a high detrimental effect on the environment (Garnett et al. 2013). Moreover, apart from the fact that the land capacity that provides sustenance for human and their bioenergy requirements is inadequate, it is also deteriorating the soil quality in numerous ways (Lal, 2014; Konuma, 2016; FAO, 2015). Of late, land snatching system where affluent countries with big populations and/or a scarcity of land resources purchase arable land from impoverished countries like Africa accentuates the striking opinion that "fertile soils" are a limited world-wide resource.

1.2. Shifting cultivation in NEH region of India

The Northeast Himalayan (NEH) region of India is one of the four biodiverisity hot-spots in India extending over 26 million ha, of which forested land makes up for about 65% of the total geographical area and 16% falls under cultivated lands (Saha et al., 2012). Agriculture occupies a central position in the economy of the region and the main agricultural practice is shifting cultivation also known as slash and burn, or locally known as '*Jhumming*.' This form of cultivation is practiced in approximately 1.47 million ha of the NEH region (Yadav, 2013). According to Jha (1997) shifting cultivation is distinguished as an agricultural system that is distinguished by clearing the land using slash and burn, cropping for short periods of time (1-3 years) interspersed with lengthy periods of fallow (up to 20 years though this is frequently as short as 6-8 years) and rotating fields rather than crops. While Mertz et. al (2009) defined it as a crop cultivation strategy in which the land is left fallow for an extended length of time to enhance the fertility of the natural soil with woody vegetation that will be burned away before the plantation is established.

Mizoram is the 23rd state of India and is located at the eastern extension of the Himalayas. About 70% of the state's entire land area is situated on slopes steeper than 33° making Mizoram's landscape distinctively unique than several other tropical areas where *jhumming* is carried out (Grogan et al., 2012). Since time immemorial, the Mizos, particularly those living in the rural areas has been practising this type of cultivation and this system not only act as a major source of income, but is closely associated with the socio-cultural aspect of life and ecological landscapes. Approximately 54% of the rural population in Mizoram are involved in shifting cultivation (Maithani, 2005).

1.3 Concerns about sustainability related to shifting cultivation

One of the key concerns associated with shifting cultivation is the unselective felling of trees. Large-scale deforestation developed as a result of the careless cutting down of natural forest to make way for shifting agricultural practices. Based on estimates, shifting agriculture significantly decreased India's forest acreage by 765 km^2 in a brief period between 2017 and 2019 (ISFR, 2019). About 10% of the loss of forested regions in Latin America (Houghton et al., 1991), 30% to 35% of the loss of forest in the Amazon (Serrão et al., 1996), and 50% of the loss of forest in Indonesia were attributed to shifting cultivation (Jong, 1997). Apart from the loss of forests, there was worry that the damage to soils may jeopardise the biodiversity of forests (FAO, 1985; Myers, 1993; Bandy et al., 1993; Brady, 1996). According to Singh and Singh (1981), the amount of soil lost in the first year, second year, and abandoned jhum owing to erosion from steep slopes (60-79%) was calculated to be 147, 170, and 30 t $ha^{-1}yr^{-1}$. Reduced water infiltration and percolation, broken pore continuity from surface to subsurface, disintegration of soil stable aggregates, and increased surface runoff are all caused by bare soil and shorter jhum cycles. Additionally, this technique resulted in an annual loss of 10669, 372, and 6051 tonnes of N, P, and K from the northeast

Indian soils (Sharma, 1998). The contents of Fe, Mn, Cu, and Zn in the region's soils were also greatly lowered by the conversion of forests to jhum lands (Choudhury et al. 2021). In addition, it is possible that the shifting cultivation areas contribute significantly to global warming (Fearnside, 2005), and the soil may contribute to atmospheric CO_2 emissions (Brown and Lugo, 1990), which would not be offset by secondary forest growth in the fallow season. Deforestation and shifting cultivation are responsible for around 20% of the world's yearly CO_2 emissions (Jurvélius, 2004). Notwithstanding the extent of the challenges, it is possible to overcome them by increasing agricultural intensity while lowering nutrient imbalances and inefficiencies (Mueller et al., 2012; Withers et al., 2015). One such possibility is the use of biochar technology, which can both slow down climate change and help recover nutrients from waste while increasing crop yields (Woolf et al., 2010; Woolf et al., 2016).

1.4 Biochar and its uses

The use of biochar as a soil conditioner was increasingly explored in the recent years owing to the assumed positive impacts on soil characteristics such as soil pH, cation exchange capacity, soil water holding capacity, carbon sequestration as well as on crop productivity and offsetting greenhouse gas emission (Chan et al., 2007; van Zwieten et al., 2020; Case et al., 2012; Biederman and Harpole 2013; Cayuela et al., 2014). Many studies reported the beneficial effect of biochar and compost combination on soil quality and plant growth by increasing the potential to use nutrients efficiently, improved soil structure and water holding capacity and reducing the dependency on inorganic fertilizer (Fischer and Glaser, 2012; Trupiano et al., 2017). Barus (2017) found a significant increase in the number of pods, dry weight of grain and biomass of soybean as compared to control when husk biochar was applied in combination with compost to the soil. Similarly, a 10-year study in sub humid regions of Kenya showed a positive response in crop yield in all the sites when amended with a mixture of biochar and mineral fertilizer in a maize-soybean rotation (Katterer et al., 2019). The superior performance of biochar combined with compost or organic manures rather than biochar or compost alone is probably to the high porous structure and recalcitrant properties of biochar which helps in retaining the nutrients from the organic compost or manure, which otherwise would have been easily mineralised. The high specific surface area of biochar helps in nutrient retention and aids in uptake of available nutrients by plants while increasing the fertilizer use efficiency and decreasing leaching (Steiner et al., 2008; Roberts et al., 2010). Another important area where biochar might contribute is to levels of soil carbon. Significantly, modern agricultural practices have resulted in degradation of soil carbon and as consequence levels of carbon are much lower now than they were several decades ago (Jones et al., 2011). Biochar is highly resistant to decomposition in soil; its residence time ranges from tens of years to millions (Verheijen et al., 2010) The persistent nature of biochar-C in soil shows that it will contribute to soil C-sequestration (Ennis et al., 2012; Lai et al., 2013) and reduce GHGs emissions (Stewart et al., 2013).

Vermicompost is produced by a simple biotechnological process of composting organic materials involving the joint action of earthworms, especially *Eisenia foetida* to enhance the process of waste conversion and produce a better end-product. It has the potential to make unavailable nutrients more available. Vermicompost has many beneficial effects on the soil such as improving soil properties like soil aeration, soil aggregation, Water Holding Capacity (WHC) and it also increases microbial population and diversity.

1.5 Scope of the study:

Although jhum cultivation has a great adverse effect on the environment, a vast majority of rural and semi-urban household still continues to practice this form of farming system, thereby degrading the soil further leading to reduced crop yield. Also, the cutting down and clearing of forest continues to increase the emission of carbon dioxide into the atmosphere. Many studies have shown that biochar acts as a soil conditioner besides having the potential to sequester carbon. In Mizoram, maize and sugarcane are grown in a large scale. Area under maize cultivation is 5695 ha and area under sugarcane cultivation is 1476 ha (Agricultural Statistical

Abstract, 2014-2015). Sugarcane juice locally called as *futui* is commonly produced on a small commercial scale in Mizoram. After the juice is extracted out, the sugarcane bagasse is simply thrown away. Therefore, sugarcane bagasse and maize cobs have tremendous potential to be used as biochar for improving degraded land by increasing soil productivity as well as sequestering soil organic carbon. Hence this study aims to evaluate the impact of these two agricultural waste biochar on nutrient recovery and soil carbon pool in jhumland.

1.6 Objectives

The general objective of this study is to determine the impact of agricultural waste biochar and organic amendments on soil nutrient recovery and carbon pool in jhum land.

With this main objective, the study was designed to cover the following specific objectives:

1. To determine the quality of biochar made from maize cob and sugarcane bagasse.
2. To assess the impact of biochar and vermicompost on soil properties in jhumland.
3. To assess soil carbon pool in jhumland with application of biochar and vermicompost.
4. To determine the effect of biochar and vermicompost on growth and yield of soybean in jhumland.

Chapter 2

Review of literature

2.1 Biochar production and properties

Biochar is distinguished from charcoal by its purpose as a soil amendment rather than as an industrial appliance (Lehmann and Joseph, 2009). It is produced by thermal degradation of organic materials at very high temperatures in the presence of little or no oxygen, a process called pyrolysis. The process of pyrolysis not only produces biochar but also oil and gas according to the kind of feedstock used and the varying temperatures. It can be produced from a variety of organic materials such as forest and agricultural residues, kitchen wastes, etc. Substrates such as wood chips and pellets, tree trimmings, bagasse, distiller grains, press cakes from the oil and juice industry, rice husks and crop residues are largely used (Parmar et al., 2014). However, other biomass sources like sewage sludge, poultry litter, dung, bones, dairy manure, etc., can also be utilised for biochar production in addition to lignocelluloses (Kumar et al., 2016). Because food-industrial waste sludge contains a high organic matter content, phosphorous adsorption coefficient, and a variety of macro- and micronutrients, it is also regarded as reusable biomass (Aggelides and Londra, 2000; Elliott and Dempsey, 1991; Ippolito et al., 2003; Logan and Harrison, 1995). Moreover, water treatment sludge contains less pathogens and heavy metals as compared to sewage sludge making it suitable for use as a soil amendment (Elliott and Dempsey, 1991; Dayton and Basta, 2001; Oh et al., 2010). Biochar's physicochemical characteristics might vary greatly based on the kind of substrate utilised to make it as well as the pyrolysis circumstances (Pituello et al., 2015). Biochar can be produced by three common methods such as fast pyrolysis, slow pyrolysis and gasification (Ahmad et al., 2014; Mohan et al., 2014). The byproducts of pyrolysis are charcoal, synthetic gas (a mixture of hydrocarbons gases), and oil which is a mixture of hydrocarbons (Lewandowski et al., 2010; Verheijen et al., 2010). Each of these distinct byproducts has a different ratio based on the pressure, range of temperature, duration etc. (Lewandowski et al., 2010; Brewer, 2012; Cheah et al., 2016). Slow pyrolysis is the most widely used method as the maximum yield of biochar is generated by this method (Manya, 2012). Biochar yield from slow pyrolysis is typically around 35.0% in relative to its dry biomass weight (Cheah et al., 2016). Biochar obtained via slow pyrolysis is a solid carbonaceous material, highly porous in nature, relatively stable organic compound comprising of oxygen functional groups and aromatic surfaces (Amonette and Joseph, 2009). Contrastingly, fast pyrolysis and gasification generates maximum yields of liquid (bio-oil) and gas (syngas), respectively (Mohan et al., 2014). Additionally, the physical and chemical characteristics of biochar depend on the production condition and the type of feedstocks used (Brewer et al., 2011; Meyer et al., 2011) which may impact the soil properties and crop yield. Biochar produced by wood-based feedstocks mostly possess the highest surface area whereas the highest cation exchange capacity is found in straw-based feedstocks and the highest N and P concentration is found in manure feedstocks. These findings were according to a review of 5400 studies done by Ippolito et al. (2020).

2.1.2 Mechanism of biochar on soil properties

2.1.2.1 On soil physical properties

The use of charred biomass residue in soils developed from research studies conducted in the Amazonian soils known as "Terra Preta de Índios" (TPI). These soils encompassed substantial areas and were utilized by farmers belonging to a number of tribes. These dark and fertile Amazonian soils are believed to be approximately 7000 years old holding three times more nitrogen (N) and phosphorus (P) and eighteen times more organic matter than the adjoining soils (Lal, 2009). While the knowledge of using charred biomass has been in existence for a very long time now, the actual production and utilization of biochar as a soil amendment in agricultural lands has gained much importance only recently. A higher rate of biochar addition resulted in enhanced soil texture and characteristics of a hardened soil beside a considerable decrease in tensile strength (Chan et al., 2007). Several studies have reported increased soil water holding capacity (Asai et al., 2009; Karhu et al., 2011), improved soil porosity (Asai et al., 2009), increased saturated hydraulic conductivity, decreased soil strength, changed bulk density (Laird et al., 2010), and changed aggregate stability (Busscher et al., 2010; Peng at al., 2011). According to Abrol et al. (2016), adding biochar to soil can reduce bulk density and soil penetration resistance, and enhanced water holding capacity. The ability of biochar to retain a lot of water is due to its high porous surface area. However, some studies suggested that biochar application did not significantly alter the soil water retention (Khan et al., 2018) and soil water holding capacity (Gaskin et al., 2007). This indicates that it is yet unclear how biochar affects the physical characteristics of soil, including how much water it retains (Sohi et al., 2009). Amendment of biochar with chemical fertilizer (CNPK) and amendment of straw with chemical fertilizer (SNPK) increased the total soil porosity by 24.6 % and 63.5% and air permeability coefficient by 19.2 and 49.4%, respectively over NPK only amended soils. Whereas, bulk density reduced considerably by 13.95 and 26.7 % and soil hardness by 12.6 and 22.4 %, respectively (Zheng et al., 2019). Similarly, in a study conducted by Katterer et al. (2019) using biochar produced from *Acacia* spp., bulk density remained significantly lower in the plot amended with biochar as compared to amended bare fallow even after five years after biochar addition indicating the persistent effect of biochar. Additionally, water holding capacity was also higher in the biochar amended soil than unamended bare fallow. In another study (Khan et al., 2017), application of biochar at 0.5 t ha^{-1} without chemical fertilizer substantially enhanced soil infiltration rate from 140 mm ha^{-1} to 165mm ha^{-1}. They also observed an increase in stable aggregates by 34% in soil treated with biochar. Soil porosity and aggregate stability is significantly increased by the application of biochar which results in the enhancement of soil infiltration rate (Jones at al., 2010). This increase in soil infiltration rate on application of biochar is also observed by Dumroese et al. (2014). Addition of more biochar to soil increases its aggregate stability, which reduces the soil's susceptibility to erosion (Zhang et al., 2007). When added to the soil, biochar gradually transforms into stable humus (Brodowski et al., 2007). According to previous studies, humus-containing soil can improve the stability of the soil aggregate (Piccolo and Mbagwu, 1990; Piccolo et al., 1997). The aggregate stability of soil can be considerably increased by using charcoal and biochar to form a link with soil minerals through carboxylic and phenolic groups (Topoliantz et al., 2005).

2.1.2.2 On soil chemical properties

Approximately, half of the world's cultivable land, predominantly in humid tropics is affected by the problem of soil acidity (Von Uexkull and Mutert, 1995). In India's context, soil acidity affects nearly one-third i.e., 49 M ha of the total arable land (Mandal, 1997). Acidic soils are characterized by aluminium (Al) and iron (Fe) toxicity, phosphorus (P) deficiency, and other problems associated with acidity which adversely affects the crop productivity (Manoj et al., 2012; Patiram, 1991). To offset this problem, liming can be a possible alternative; however, it is not a cost-effective option for resource poor farmers. Moreover, it does not solve the problem of subsoil acidity. Although studies conducted by Berek et al. (1995) and Xu Tang and Chen (2006) have reported an improvement in soil acidity by direct addition and combination of green manures, animal wastes, and crop residues, this effect is short lived because of the speedy mineralization of the added organic amendments. While the use of chemical fertilizers enhances crop productivity boosting crop yields by roughly 30-50% (Zhu et al., 2002), the increased use of it and the less organic input into the land has become one of the major issues in intensive agriculture owing to the low efficacy of fertilizer utilization and probable environmental pollution (Zhao et al., 2016; Choudhary et al., 2017). Jha et al. (2016) observed an increase in the soil pH, electrical conductivity, exchangeable base cations while reducing the concentration of exchangeable aluminium (Al) during an incubation study of acidic alfisol incorporated with *Leucaena* biochar. They also observed that the addition of biochar enhanced the process of nitrification and led to a significant reduction in ammoniacal-N while increasing the nitrate-N content. Several other studies also reported a reduction in Al toxicity due to increase in soil pH while making some nutrients such as magnesium, potassium, phosphorus and nitrogen more accessible on addition of biochar (Srinivasarao et al., 2013; Alling et al., 2014). Biochar's high molecular weight organic chemicals may have complexed with aluminium to reduce its toxicity (Alleoni et al., 2010). The increase in electrical conductivity as well as cation exchange capacity of the soil on addition of biochar is corroborated by several other studies (Carter et al., 2013; Lentz et al., 2014;

Partey et al., 2016; Mohan et al., 2018). The high surface area and oxygen retention capacity of biochar contributes to their high CEC (Lee et al., 2010). Carbonyl, carboxyl, and phenolic groups that are present in biochar's oxygen content help to stimulate CEC. Therefore, in addition to augmenting soil CEC, biochar can also act as a long-term carbon sequestration agent (Abdel- Fattah et al., 2015).

2.1.2.3 On soil microbial activity

Due to their sensitivity to environmental changes, soil microorganisms have been extensively employed as markers of alterations in soil quality (Marschner et al., 2003). According to a number of recent studies, biochar amendment of soil altered the microbial community structures and abundances of some taxa-specific communities, thereby influencing the physicochemical properties and nutrient availability of the soil (Khodadad et al., 2011; Lehmann et al., 2011; Gomez et al., 2014; Mitchell et al., 2015). The addition of 40 t ha^{-1} of biochar over control resulted in a considerable increase in soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN), but not at the rate of 20 t ha^{-1} (Chen et al., 2016). Conversely, Li et al. (2018) found that whereas larger doses of biochar (40 kg ha^{-1}) dramatically reduced MBC, a moderate application of biochar (20 kg ha^{-1}) increased microbial diversity and MBC. Past researches have also shown that biochar's porous structure and wide surface area provide an ideal environment for microbial colonisation (Pietikainen et al., 2000; Ezawa et al., 2002; Saito and Marumoto, 2002; Luo et al., 2013). According to Kolb et al. (2009), adding charcoal to the soil enhanced its surface area, encouraged the growth of soil microorganisms, and consequently raised the biomass and activity of those microbes. According to Zavalloni et al. (2011), biochar also absorbed hazardous and toxic compounds from the soil, which indirectly raised the MBC of the soil. According to Zhang et al. (2016) and Fierer and Jackson (2006), low microbial abundance and diversity are often linked to acidic soil. Therefore, it is possible that such turnover will be observed in acidic soil, where amendment of biochar has been hypothesised to promote microbial communities via multiple mechanisms.

2.1.2.4 On greenhouse gas emissions

One of the biggest risks to our survival and well-being today is the climate change (IPCC, 2021). Concerns about the effects and symptoms of climate change are becoming more and more obvious every day. The main factor contributing to the surplus of carbon in our atmosphere is human-caused climate change acceleration. One key to reducing or reversing the effects of climate change is reestablishing the natural equilibrium and figuring out a way to sequester carbon from the atmosphere (IPCC, 2021). Stable carbon storage is not addressed by the current mitigation efforts for climate change (Krier, 2012). Furthermore, it is imperative to persistently investigate every possible option and adjust in line with our constantly evolving surroundings. Climate forcing in the atmosphere is mainly caused by the GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Lal, 2004; Lal, 2008; Van Zwieten et al., 2009). These GHGs especially CH_4 and N_2O are emitted by several agricultural practices such as drainage of wetlands, ploughing, land use modification, rice paddy fields, application of fertilizers including rearing of livestock in addition to other anthropogenic activities such as fossil fuel burning and industrial processes (Luo et al., 2010; Minamikawa et al., 2011; Gogoi and Baruah, 2012; Yao et al., 2012). Researchers have long studied the potential of biochar as a soil amendment and as a resource to combat climate change (IPCC, 2014). When plants use photosynthesis, carbonaceous plant metabolites are produced. These metabolites are then converted back to CO_2 during the plant's decomposition process (Conte et al., 2016). Up to 60% less carbon is released when plants are harvested and turned into biochar. When plant matter is allowed to break down naturally, carbon is released far more quickly than in the form of charcoal, or biochar. By preventing the possibility of decomposition, this mechanism lowers the amount of CO_2 in the atmosphere (Conte et al., 2016). According to theoretical frameworks proposed by Matthews (2008), Preston (2009), Lee et al. (2010), and others, sustainable systems utilise biomass to generate energy and charcoal, which when applied to land, transfers carbon from the short-term cycle mediated by photosynthesis to a long-term storage. Therefore, the energy produced in this way has the potential to be certified as carbon negative and can create income through both its sale and the creation of tradable carbon credits (Mathews, 2008). However, applying biochar amendments may either have no effect at all or even raise GHG emissions (Zimmerman, 2010; Zimmerman et al., 2011; Jones at al., 2011).

2.1.2.4.1 Emission of N_2O from soils treated with biochar

Studies conducted in the field and during incubation have indicated a decrease in nitrogen dioxide emissions from soils treated with biochar (Rogovska et al., 2011; Castaldi et al., 2011; Zhang et al., 2012). In a field trial, for instance, biochar from wheat straw (Triticum sativum) produced at 350–550 °C was added to hydroagric Stagnic Anthrosol paddy soil. The results showed that, at application rates of 10 and 40 Mg ha^{-1}, respectively, N_2O emission decreased by 50 and 70% and CH_4 emission increased by 31 and 49% (Zhang et al., 2012). The addition of biochar has sometimes led to notable decreases in the amount of N_2O released after incorporation; this is often measured by laboratory incubations (Spokas and Reicosky, 2009; Yanai et al., 2007; Case et al., 2014; Smith et al., 2010). Theoretically, this is caused by the biochar's effects on the microbial population (Lehmann et al., 2011) and the microorganisms that fix nitrogen (Zhang et al., 2010). According to Castaldi et al. (2011), soil N_2O fluxes in biochar-treated plots varied from 26 to 79% lower than those in control plots. Conversely, high N-containing biochars have also been found to increase N_2O emissions (Spokas and Reicosky, 2009; van Zweiten et al., 2010). These findings showed how biochar applications could be used to control the rates of nitrogen cycling in soil systems by affecting ammonia adsorption and nitrification rates, as well as increasing ammonium ion storage by raising the CEC in the soils (Spokas et al., 2012). This would increase the efficiency of N inputs into agroecosystems (Clough and Condron, 2010). A long-term column incubation experiment in a different study showed that N_2O emission was reduced but CO_2 emission was increased on a fine loamy Clarion soil modified with biochar made from oak (*Quercus* spp.) and hickory (*Carya* spp.) at 450–500 °C. An increase in soil aeration decreased N_2O emission, according to this study's modest correlation between soil BD and N_2O flux (Rogovska et al., 2011). N_2O emission from treated sandy loam was, nonetheless, inhibited up to 98% as compared to the control in another soil incubation investigation using hardwood biochar; however, this impact was not due to the biochar amendment's augmentation of soil aeration (Case et al., 2012). While the majority of researches show that soils treated with biochar reduce N_2O emissions, there are some instances where N_2O emissions are increased by the altered soils. Singh et al. (2010) reported, for instance, an early increase in N_2O owing to the greater labile N content of biochar and microbial activity; however, this spike gradually subsided over time.

2.1.2.4.2 Emission of CO_2 and CH_4 from soils treated with biochar

Soils treated with biochar have the potential to increase CO_2 and CH_4 emissions, as opposed to typically decreasing N_2O emissions (Rondon et al., 2005, Spokas et al., 2009). Biochar-amended soils have initial surges in CO_2 emission due to both biotic and abiotic processes (Zimmerman et al., 2005; Smith et al., 2010; Zimmerman et al., 2011; Jones et al., 2011). According to Liu et al. (2011), adding bamboo (Bambuseae spp.) and rice straw biochar that has been pyrolyzed at 600 °C to paddy soil reduced CH_4 and CO_2 emissions by 51 and 91%, respectively. In a greenhouse experiment, acidic soil supplemented with biochar inhibited CH_4 by 100% and N_2O by 80% (Rondon et al., 2005). In another study, addition of biochar to rice paddy soil decreased the emission of CO_2 and increased the emission of CH_4 (Zhang et al., 2010), but biochar addition does not always decrease CO_2 emission. There have been reports of both rises and falls in CO_2 emissions in soils modified with 16 different kinds of biochar (Spokas and Reikosky, 2009). The addition of pine wood biochar to Swiss loam soil did not alter CO_2 emissions; however, the addition of biochar generated from grass increased CO_2 emissions (Hilscher et al., 2009). Mohan et al. (2018) observed that when compared to control soil and 3.0% wt/wt corn stover-amended soil, the CO_2

emission from the corn stover biochar -amended soil was 15% lower and 84% lower, respectively implying that instead of reusing the stover directly in agricultural areas, a significant amount of CO_2 emissions might be prevented by first turning it into biochar. Application of biochar may occasionally initially increase CO_2 emissions. According to Jones et al. (2011) the short-term CO_2 emission's initial carbon loss is insignificant in comparison to the carbon stored in the biochar, and as such, it should not overwhelm the long-term carbon sequestration potential of biochar. However, 17%–23% of biochar-C has the potential to be mineralized and release CO_2 (Rogovska et al, 2011).

2.1.2.4.3 No shift in the emissions of CH_4 or CO_2

In field trials or laboratory incubation studies with biochar, some researches have shown negligible effects or no discernible variations in the net GHG fluxes (Spokas and Reikosky, 2009; Scheer et al., 2011; Singh et al., 2010; Castaldi et al., 2011). Meanwhile, a field study conducted by Scheer et al. (2011) in Australia found no apparent change in greenhouse gas fluxes between treated red Ferrosol treated with biochar made from cow dung at 550 °C. and control. When comparing the CO_2 concentrations in soil amended with biochar to controls, eight of the 16 biochar utilised showed no significant change, according to Spokas and Reicosky (2009). Correspondingly, according to Singh et al. (2010), the addition of biochar did not significantly increase CO_2 emission overall, but it did lower N_2O emission from wood and poultry manure biochar-amended Alfisols and Vertisols by 73% when compared to the control.

2.1.2.5 On crop performance and productivity

The efficiency of crop production worldwide has been influenced greatly by the depletion in soil fertility owing to erosion and reduced or imbalanced organic matter (Foley et al., 2015). Although mineral fertilization is regarded as one of the options to counterbalance this problem, long term application can increase soil acidification which adversely affects edaphon and nutrient cycling therefore declining agricultural output (Pietri and Brookes, 2008). About one-third of the arable land in India is affected by soil acidity (Mandal, 1997). Acidic soils limit crop productivity due to Al and Fe toxicity, low Phosphorus content and other acidity-related soil fertility and available nutrient problems (Manoj et al., 2012). Soil pH has a strong correlation with nutrient availability. The availability of macronutrients for plants is decreased in low-pH soil, which lowers agricultural output. Although, ashes from the burning of biomass may provide a liming effect and supply nutrients to the soil, its accumulation on the soil is short lived because of the loss through erosion. Biochar is not readily susceptible to chemical and biological degradation because of its aromatic formation and hence can remain in soil for a long period of time (Singh et al., 2015). Besides increasing the soil pH, biochar has the ability to enhance soil carbon sequestration, retain soil nutrients, improves the soil properties and increases crop production (Chan et al., 2007; Basso et al., 2013; Song et al., 2018, Zheng et al., 2019). The application of biochar enabled the effective utilization of fertilizers, significantly increasing the rice yield by 15.3-44.9 % as compared to the sole application of chemical fertilizers (Zhang and Kwang, 2014; Wang et al., 2015). Zheng et al. (2019) found an increase in total porosity and air permeability and a decrease in bulk density and hardness of soil in soils amended with a combination of biochar and chemical fertilizers as compared to un-amended control. They also reported a significant increase in rice yield with the combined application of biochar and chemical fertilizer. A quantitative review of 177 different papers by Jeffrey et al. (2011) indicated a marginal, yet statistically significant increase by 10% in crop yield as a result of biochar application to soils. The marginal increase might be because of the varied biochar feedstock and substrates under different conditions (Schulz et al., 2013). Moreover, the outcome is liable to differ because of the types of soil, climate and crop, resulting in slightly negative to highly positive effect on crop productivity (Liu et al., 2013). There are numerous studies which investigated and reported the positive effect of biochar on the growth and yield of soybean (Suppadit et al., 2012; Yooyen et al., 2015) whereas others did not find any significant effect on the growth parameters (Sukartono and Sudantha, 2016; Ma et al., 2019).

2.1.3 Negative impact of biochar on soil and plants

While many researches have shown the beneficial effects of biochar, there are also several studies which proved the negative effects of using biochar as a soil amendment especially from biochar that are freshly yielded. This may lead to a decline in the growth of plants owing to nutrient immobilisation caused particularly by dissolved organic carbon (DOC) and adsorption of mineral nitrogen (Nmin) (Ding et al., 2010; Graber and Elad, 2013; Jin, 2010; Taghizadeh-Toosi et al., 2011). One proposed method to reduce or neutralize any detrimental impacts of biochar is to supplement freshly created biochar with organic or mineral nutrients (Alburquerque at al., 2012; Bruun et al., 2011; Gathorne-Hardy et al., 2009; Joseph et al., 2013). The combined application of biochar with fertiliser can stimulate plant development, as demonstrated by Chan et al. (2007), Asai et al. (2009), and Saarnio et al. (2013). However, without fertilisation, a negative effect may occasionally be seen due to lower bio-availability through nitrogen sorption (Zavalloni et al., 2011; Case et al., 2012). In another study, a decrease in vegetable growth was found with increasing application of macadamia nut (*Macadamia integrifolia*) charcoal without fertiliser. This is possibly due to phenolic and other C compounds in the charcoal by inducing microbial immobilisation and growth (Deenik et al., 2010). Zimmerman et al. (2011) also reported on the negative C mineralization priming effect of biochar, and they discovered that the amount of this effect depended on the kind of biochar and the content of soil organic C (OC). Meanwhile Lentz and Ippolito (2012) observed that in 2009, biochar had minimal effect on the nutrients contained in maize silage; however, in the following year, yields and concentrations of TN and S in silage were reduced. The 2010 yield decreased may be attributed to the decreased availability or uptake of one or more nutrients, depending on the concentration of nutrients in the silage corn. Their findings indicate that the delayed impact of biochar on maize silage N, micronutrient uptake, and yield may indicate two possible reasons: either the mechanism was not fully understood until the amendment had aged, or biochar interacted with an unidentified factor in 2010 that changed its impact on the crop or soil compared to 2009. Time-dependent characteristics or impacts of soil-applied biochar exist.

The review of literature reveals that although a lot of work has been conducted on the effect of biochar on soil physical and chemical properties, the role of biochar on carbon emission reduction, and on crop productivity, the works pertaining the objectives of the present study are very and far between in Indian context, and there are substantial gap to our understanding the role played by maize cob and sugarcane bagasse biochar on soil physical and chemical properties including their ability to SOC sequestration, carbon forms (labilility level) and effect on growth and yield of soybean when applied alone and in combination with vermicompost in the degraded jhum lands.

Table 2.1. Effect on soil properties based on the literatures

Reference	Country	Amendment	Soil property	Results
Mohan et al., 2018	India	Rice husk biochar and corn stover biochar	Water holding capacity	Increased
Jha et al., 2016	India	Leucaena leucocephala biochar	Soil EC, Exchangeable base cations, exchangeable Al content, available P,	Increased, increased, reduced, reduced
Zheng et al., 2019	Northeast China	Rice straw Biochar with chemical fertilizer	Bulk density, soil hardness	Decreased
Carter et al., 2013	Cambodia	Rice husk biochar	Soil pH CEC	Increased in both
Mensah and Frimpong, 2018	Ghana	Corncob biochar + compost	pH, exchangeable bases, exchangeable acidity, ECEC, mineral N	Increased in all, decreased exchangeable acidity
Tian et al., 2018	China	Corn straw biochar	TOC, TN, soil inorganic N, pH, available P, available K	Increased in all except in available P
Katterer et al., 2019	Kenya	Acacia spp. biochar	Bulk density, water holding capacity	Increased, decreased
Alburqueque et al., 2013	Southern Spain	Wheat straw and olive tree pruning biochar	Soil field capacity, bulk density	Increased, decreased
Coumaravel and Maragatham, 2015	India	Cottonstalk biochar + NPK + FYM + azospirilium	Available N, P, and K, organic carbon	Increased
Partey et al., 2016	Africa	Tectona grandis biochar + organic fertilizer	Available N, available P, CEC	Increased in all
Naeem et al., 2018	Pakistan	Wheat straw biochar + compost + fertlizer	pH, EC, SOC	Decreased, increased, increased
Trupiano et al., 2017	Italy	Orchard pruning biochar + olive waste compost	EC, P_{tot}, P_{av}, C_{tot}	Increased in all

Table 2.2. Effect on the yield of various crops based on the literatures

Soil type	Crop	Location	Duration of expt.	Type of expt.	Biochar type	Biochar rate	Major findings	Ref
Inceptisol	Cotton	China	3 years	Field	Corn straw	0-20 t ha^{-1}	+10 to 17.1% (2013); +9.6 to 13.5 % (2014); +8.1 to 18.6 % (2015)	Tian et al., 2018
Acrisol	Rice	Africa	3 cropping seasons	Field	Tectona grandis	0-5 t ha^{-1}	Mean grain yield 1.8 t ha^{-1} (biochar amended plot); 1.3 t $^{ha-1}$ (unamended plot)	Partey et al., 2016
Calcerous inceptisol	Maize	China	2 years	Field	Straw	0-40 t ha^{-1}	+11.9 to 35.4 %	Zhang et al., 2016
Alfisol	Radish	Australia	6 weeks	Pot	Green waste	0-100 t ha^{-1}	+95 to +266 %	Chan et al., 2007
Light clay	Maize	Australia	1 year	Field	Wood	0-25 t ha^{-1}	+8 to 29 %	Agegnehu et al., 2016
Calcerous inceptisol	Maize	China	2 years	Field	Wheat straw	0-40 t ha^{-1}	+11.9 % (2011); +35.4 % (2012)	Zhang et al., 2015
Oxisol	Beans	Colombia	75 days	Pot	*Eucalyptus deglupta*	0-90 g kg^{-1}	+39 % (biomass increase at 60 g kg^{-1}); biomass decrease to the level of control at 90 g kg^{-1})	Rondon et al., 2016
Andisol and Ultisol	Lettuce and corn	U. S	4-6 weeks	Greenhous e/ lab	Macademia nut shell	0-20 % (w/w)	-22.5 and -73.2 % decline in lettuce dry matter (DM) production at 10 and 20 % w/w, respectively; - 45 and -39 % decline in corn DM production at 10 and 20 %, respectively	Deenik et al., 2010
Ferrosol and Calcarosol	Radish, wheat, soybean	Australia	42-56 days	Pot	Waste wood chips	48.6%; 69.3 %	Increased radish biomass production for both biochars in the ferrosol and increased biomass for biochar 2 in the calcarosol; 2.5-fold increase in wheat biomass production in the biochar+fertiliser treatment in the ferrosol; significant decrease in the wheat and radish biomass production	van Zwieten et al., 2010
Xanthic ferralsol	*Oryza sativa* L. and *Sorghum*	Brazil	2 yearss	Field	Charcoal	11 mg ha^{-1}	Highest cumulative grain yield (12.4 mg ha^{-1}) and stover production (14.2 mg ha^{-1}) in charcoal + chicken manure	Steiner et al., 2007

Oxisol	Maize	Colombia	4 years	Field	Wood	0-20 t ha^{-1}	+28 t ha^{-1} (2004); +30 t ha^{-1} (2005); +140 t ha^{-1} (2006)	Major et al., 2010
Inceptisol; Oxisol; Grassland oxisol	Rice	Colombia	10 weeks	Greenhouse	*Eucalyptus deglupta*	25.5 and 45.5 g/dry kg of soil	+294 %, +800% total grain increase in biochar amended and biochar+earthworm amended soil; -21% decrease in sole earthworm amended soil	Noguera et al.,2020
Laotian paddy	Rice	Laos	1 year	Field	Teak and rosewood	0-16 t ha^{-1}	Higher grain yield in biochar amended sites with low P availability; highest rate (16 t ha^{-1}) cause N limitation resulting in low grain yield	Asai et al., 2009
Sandy clay loam	Wheat	Australia	2 years	Field	Oil mallee	0-6 t ha^{-1}	Enhanced tillering biomass at low fertliser rate; +18 % increase in plot banded with 6 t ha^{-1} and 30 kg/ha soluble fertlisers	Solaiman et al., 2010

Chapter 3

Study site description, climate and soil

3.1 Study site

Mizoram is the 23rd state of India located at 21º58' to 23º35' N latitude and 92º15' to 93º29' E longitude. It is surrounded by Tripura, Assam and Manipur in north-frontier regions; Bangladesh in west; and Myanmar in east and south. The altitudinal range of Lushai hills varies from 21 to 2157 m above the mean sea level (average 920 m) with an annual rainfall of 2000-3200 mm. During winter, the temperature varies from 11-21ºC; and in the summer, it varies between 20-29 ºC. The entire area is under the direct influence of the South-West monsoon with heavy rainfall from May to September. The soils of Mizoram are dominated by sedimentary formation. The soils in the hills are highly acidic with pH ranging from 4.5 to 5.5, whereas the soils in alluvial deposits are less acidic in nature. The present study was carried out in a jhum fallow under Sakawrtuichhun village, Aizawl district of Mizoram. The site has been left fallow since 2015.The soil of study site falls under sandy loam textural class.

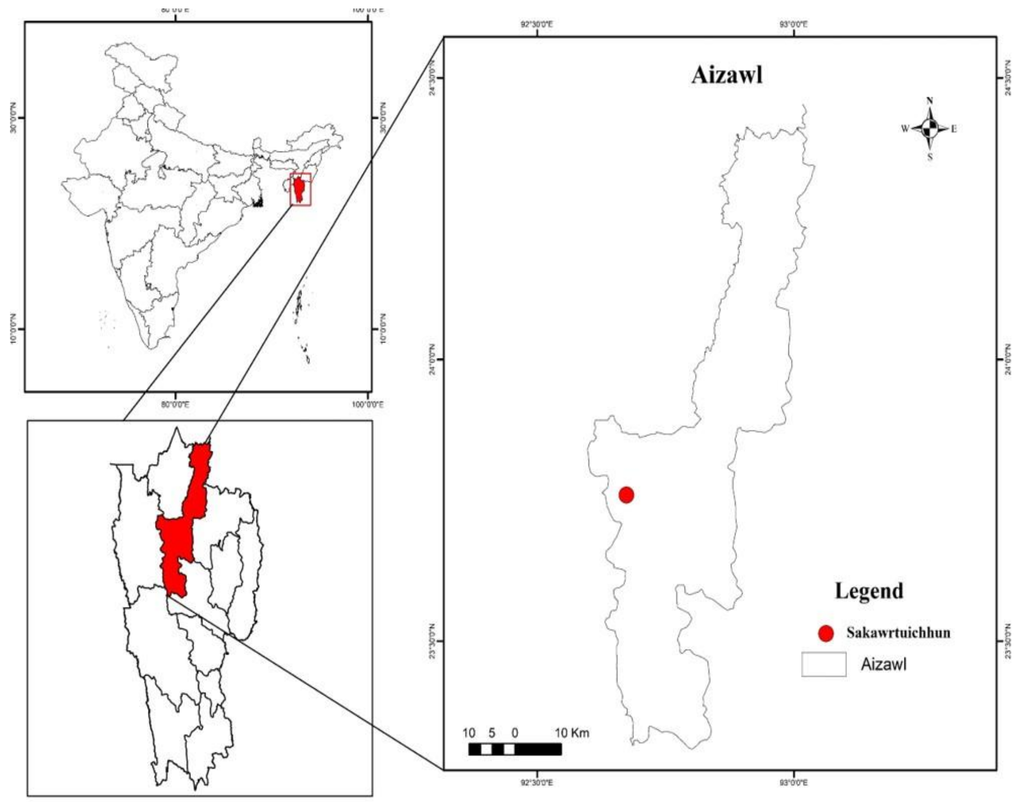


Figure 3.1. Map of India showing the location of the study area.

3.2 Climate

Mizoram's Aizwal district is located in the northeastern region of the state. It is bordered to the north and northeast by the Mizoram district of Kolasib and a portion of Manipur, to the south by the Serchip district, to the east by the Champhai district, and to the west by the Mamit district. It is 3,576.3 square kilometres in size. There are five different numbers of blocks that make up the district. The district has a tropical humid climate with chilly summers and frigid winters. The typical range of winter temperatures is 11º to 13º C. However, there isn't any snow throughout the winter. The annual rainfall average is 2,794 mm, while the normal amount is 2,216 mm. The monsoon season, which runs from early May to late September, is what causes the rains (Central Ground Water Board North Eastern Region Ministry of Water Resources Guwahati).

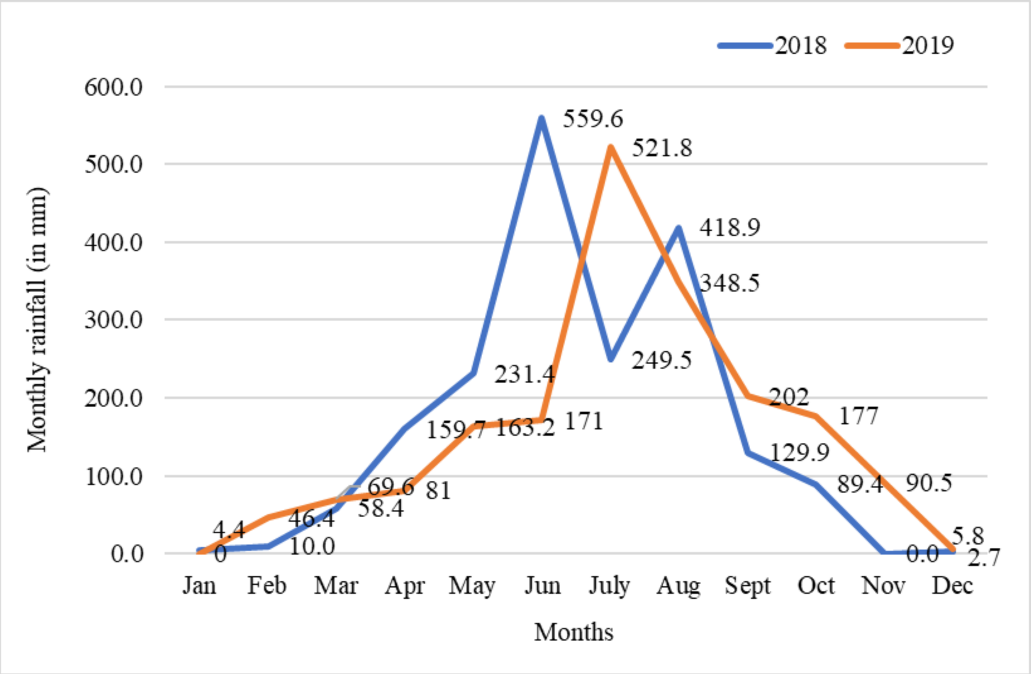
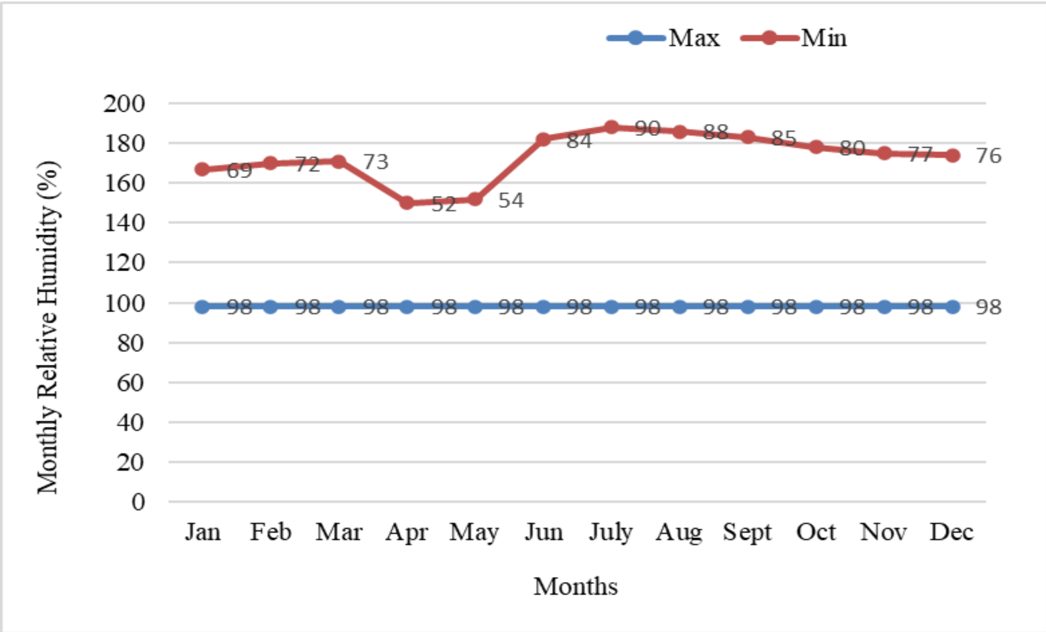
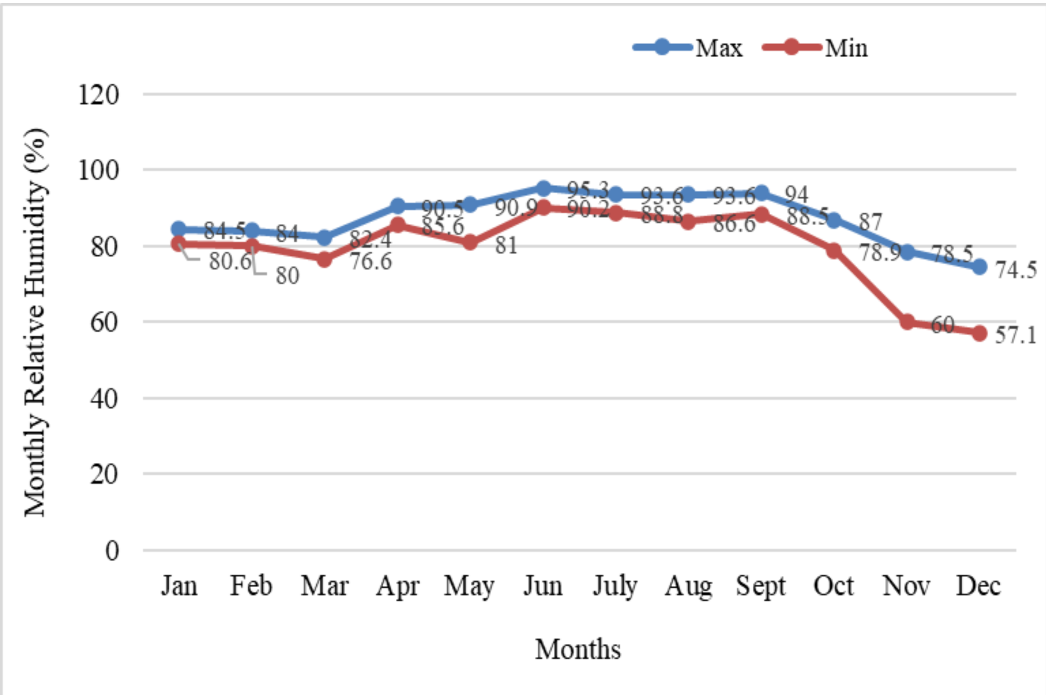


Figure 3.2. Monthly rainfall in Aizawl during 2018 and 2019.

Source: Directorate of Economics & Statistics, Planning & Programme Implementation Department,Government of Mizoram.



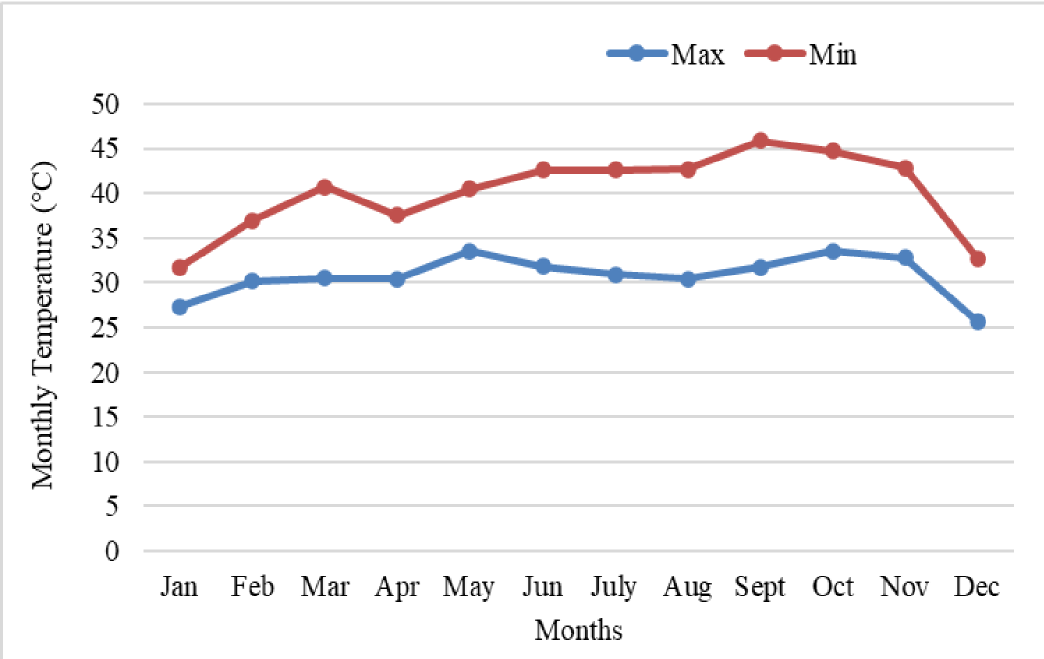
(a)



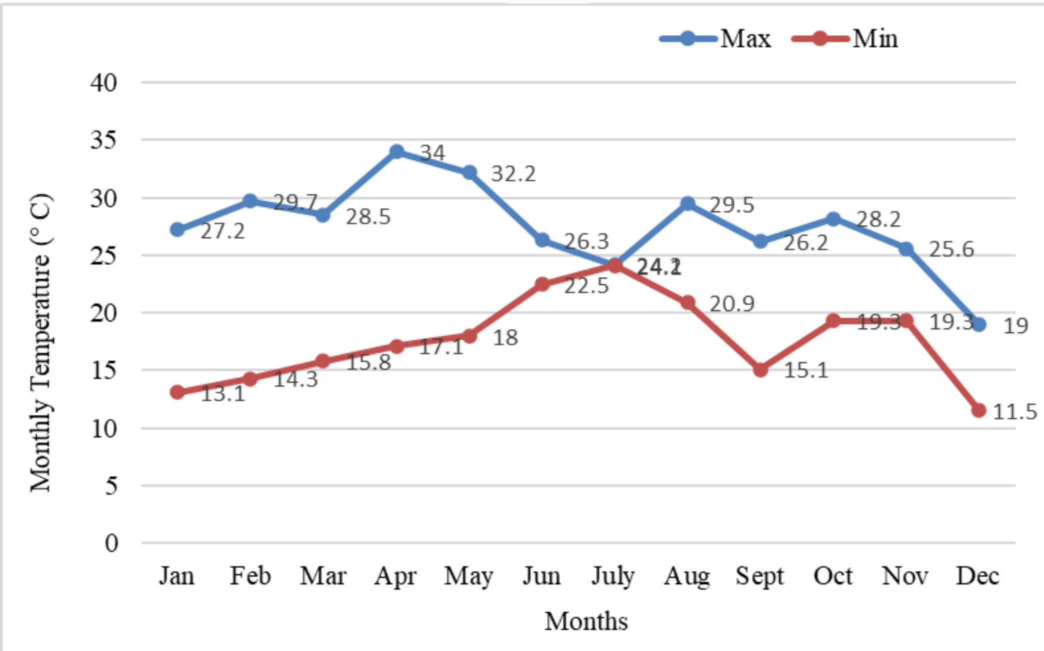
(b)

Figure 3.3. Maximum and minimum Monthly relative humidity in Aizawl during 2018 (a) and 2019 (b).

Source: Directorate of Economics & Statistics, Planning & Programme Implementation Department,Government of Mizoram.



(c)



(d)

Figure 3.4. Maximum and minimum monthly temperature in Aizawl during 2018 (c) and 2019 (d).

Source: Directorate of Economics & Statistics, Planning & Programme Implementation Department,Government of Mizoram.

3.3 Soil

The Aizawl soils are characterised by extremely deep, dark yellowish to dark brown, extremely acidic surfaces and subsurfaces, clay loam to clay, well-drained, hillside slopes with significant erosion. Due to the existence of Umbric epipedon and Cambic horizon, the soils and pedons of Aizawl were classified as Inceptisols and Ochrepts suborder. Its thickness is less than 25 cm, and its temperature regime is warmer than mesic. The pedons are classed as belonging to the Dystrochrepts soil group since their base saturation (BS) is less than 60% and they have an udic soil moisture regime. Because of their fairly deep, deep to hard rock and decreasing organic carbon content with depth, the soils of Aizawl are classified as belonging to the Typic subgroup. In general, the soils in Aizawl's various profiles range from moderate to moderately acidic (pH 4.56 to 6.08), and they also experience moderate to severe soil erosion (Colney and Nautiyal, 2013).

Chapter 4

To determine the quality of biochar made from maize cob and sugarcane bagasse

4.1 Introduction

Biochar can be prepared from a variety of feedstock such as crop residues, forest residues, algae, sewage sludge, and manure (Duku et al., 2011). The properties of biochar such as pH, Cation Exchange Capacity (CEC), ash content, volatile matter content, particle size and surface area greatly depend on the pyrolysis methods and the parent material used. Biochars from different feedstock sources or pyrolysis methods differ in pore size, pH, CEC, surface area and charge, etc. (Ahmad et al., 2012) and, therefore, behave differently in contrasting soils owing to their varying adsorption behavior and biological activity (Fungo et al., 2014). Woody feedstocks produce small amounts of ash (<1% by weight), whereas biomass with high mineral contents, such as grass, grain husks and straw residues, produce high ash biochar (Demirbas, 2004). On the other hand, biochar yield from the same feedstock depends on the conditions of pyrolysis temperature, heating rate, time and particle size (Uzun et al., 2006; Tsai et al., 2007). Three by-products such as bio-oil, syngas and biochar are produced depending on the temperature and speed of pyrolysis (Peter, 2007; Laird, 2008). Biochar produced per unit biomass is higher when the pyrolysis temperature is lower while higher temperature pyrolysis produces more syngas (Peter, 2007). Likewise, fast pyrolysis, produces 60% bio-oil, 20% biochar and 20% syngas; while slow pyrolysis produces about 50% biochar. According to Lehmann and Joseph (2009), biochar and charcoal are differentiated based on their intended uses: biochar is intended for carbon sequestration and environmental management, whereas charcoal is used for energy and fuel. Another type of char is the hydrochar which is yielded from hydrothermal carbonization of biomass (Libra et al., 2011). Hydrothermal (wet) biomass carbonisation under pressure is used to make hydro chars, whereas dry biomass (up to 10% moisture) is typically used to produce carbonisation, pyrolysis, or gasification biochar. Biochar is distinctively differentiated from other organic matter due to the greater percentage of aromatic C and compact aromatic configurations, as compared to other aromatic configurations of soil organic matter, such as lignin (Schmidt and Noack, 2000). The microbiological diversity and taxonomy of the soil may vary as a result of the physical and chemical characteristics of biochar, which can also shield microorganisms from predators and desiccation and change the soil's nutrition and C content (Lehmann et al., 2011). Biochar produced by low pyrolysis temperature is distinguished by a considerable amount of unstable matter that consists of easily degradable surface which enhances the growth of plants (Robertson et al., 2012; Mukherjee and Zimmerman, 2013). Whereas, biochars produced from high temperature pyrolysis have a large surface area and aromatic carbon content, thereby increasing the adsorption ability, which can be favorable for bioremediation and also increases the sequestration potential of carbon (Lehmann et al., 2007)? Additionally, large specific surface area, high concentration of surface functional groups, pH, and porosity are its typical characteristics (Hernandez-Mena et al,. 2014; Lehmann et al., 2011). Hernandez-Mena et al. (2014) demonstrated the high porosity of biochar, with longitudinal pores varying in size from micro- to macropores. The ultimate effect of biochar on soil is greatly influenced by the type of feedstock since its properties are determined by the nature of the original material. For example, manure-based biochars have higher cation exchange capacity as compared to wood-based biochars (Singh et al., 2010) whereas soil applied with wood chip biochar exhibited greater saturated hydraulic conductivities as compared to soil treated with manure biochar (Lei and Zhang, 2012).

The objective of this chapter is to examine the physical and chemical properties as well as the surface morphological characteristics and functional groups present in the two biochar utilized in this study.

4.2 Materials and Methods

4.2.1 Preparation of biochar

The feedstock were collected, sun dried while retaining at least 10% of the moisture and cut into uniform sizes. Biochar was prepared separately for each feedstock using drum retort method proposed by NICRA, Central Research Institute for Dryland Agriculture, Hyderabad. The feed stocks were burned separately by slow pyrolysis at about 300°C for about 2.5 h. Water was poured into the drum until self-lighting and combustion ceased. After the biochar was taken out, it was grounded and made to pass through 2mm sieve prior to applying it on the field. The yield of biochar was calculated using the following Equation (1):

$$\text{Conversion efficiency (\%)} = \frac{\text{weight of biochar converted after pyrolysis } (kg)}{\text{weight of feedstock used for pyrolysis } (kg)} \times 100 \quad (1)$$

4.2.2 Physical and chemical analysis of biochar:

4.2.2.1 Determination of pH

Biochar pH was measured by using 1:20 solid: solution ratio (deionised water; DIW) ratio after shaking the suspension on a mechanical-shaker for 90 min in deionized water (Rajkovich et al., 2012). After this, samples were allowed to stand for 30 min and then pH was measured using a calomel electrode–glass electrode system. The pH meter was calibrated using buffers of pH 7 and 10.

4.2.2.2 Determination of EC

EC was also measured by using 1:20 solid: solution ratio (deionised water; DIW) ratio after shaking the suspension on a mechanical-shaker for 90 min in deionized water (Rajkovich et al., 2012). After this, samples were allowed to stand for 30 min then EC was measured using a pre-calibrated EC meter.

4.2.2.3 Determination of moisture content

The thermal drying method proposed by Rengaraj et al. (2002) was utilised to determine the biochar samples' moisture content. 1 g of each biochar sample was measured in triplicate and put in a dried crucible and weighed after which the crucibles were placed in an oven at 105 °C and the sample was dried for 4 h till a constant weight was achieved. The moisture content was obtained by calculating the difference between the initial and final mass of the carbon as shown in Equation (2).

$$\text{Moisture content (\%)} = \frac{\text{Loss in weight on drying } (g)}{\text{initial weight } (g)} \times 100 \qquad (2)$$

4.2.2.4 Determination of ash content

To determine the ash content, crucibles were weighed after pre-heating it to about 500 °C and cooled in a desiccator. 1 g of each of the biochar sample was placed in the crucibles, re-weighed, and then placed in the furnace at 500 °C for around 1 hour 30 min. Then the crucibles were allowed to cool in a desiccator to room temperature (30 °C) and their weights taken again. The ash content was computed as shown in Equation (3).

$$\text{Ash content (\%)} = \frac{Weight\ of\ biochar\ ash(g)}{Weight\ of\ biochar\ used\ for\ heating\ (g)} \times 100 \qquad (3)$$

4.2.2.5 Determination of volatile matter

To determine the volatile matter, 1.0 g of each sample was heated for 10 minutes at 500 °C. The volatile matter was calculated as shown in Equation (4).

$$\text{Volatile matter (\%)} = \frac{Weight\ of\ volatile\ component\ (g)}{Oven\ dry\ weight\ (g)} \times 100 \qquad (4)$$

where volatile weight is the difference in weight before and after heating of the samples.

4.2.2.6 Determination of fixed carbon

The fixed carbon was calculated as shown in Equation (5)

$$\text{Fixed carbon (\%)} = 100 - (\text{ash \%} + \text{volatile matter \%}) \qquad (5)$$

4.2.2.7 Determination of CEC

A known quantity of pulverized samples was burnt for 6 hours in the muffle furnace at 760 °C to determine the nutrient contents such as Ca, Mg, Na and K. The ash obtained was mixed with HCL, diluted with deionized water and kept for further nutrient analysis. The determination of sodium and potassium was done by using flame photometer whereas atomic absorption spectrophotometer was used for determining Mg. Cation exchange capacity (CEC) of soil was calculated by summing the base cations Ca, Mg, Na and K (Antonangelo et al., 2024).

4.2.2.8 Determination of biochar surface morphology

To determine the surface morphology of biochar, Scan Electron Microscope (JEOL Model JSM -5910 SEM) at 20 kV imaging at various magnification levels was employed (Al-Wabel et al., 2013) and the images were obtained by using the proprietary JEOL software.

4.2.2.9 Fourier Transform Infra-Red Spectroscopy (FT-IR)

Biochar samples derived from different agricultural residues were analyzed on FTIR (IRAffinity-IS, Shimadzu) and the values were expressed in cm^{-1}.

4.3 Results and Discussion

Table 4.1 demonstrates the acquired result of pH, EC and CEC of the two biochar namely sugarcane bagasse biochar and maize cob biochar. The pH of the two biochar examined were found to be alkaline with the pH value of sugarcane bagasse biochar slightly higher (8.97) than maize cob biochar (8.52). These results are in accordance with previous studies which indicated that dry biochar produced by slow pyrolysis are usually alkaline in nature (Inyang et al., 2010; Enders et al., 2012). According to Lehmann and Joseph (2015) and Yuan and Xu (2011), the partial burning of various carbon-based biomass results in the production of extremely alkaline biochar with a sizable quantity of carbonaceous portion. It may be noted that the pH of biochar varies with the nature, the content and mineral constituent of the feedstock used, and the pyrolysis condition which is employed for its production (Chan and Xu, 2012; Singh et al., 2010). Similarly, the EC of sugarcane bagasse biochar was found to be slightly higher than maize cob biochar with 1.74 dSm^{-1} and 1.25 dSm^{-1}, respectively. Previous literature contains reports of biochar EC values ranging from 0.04 dSm^{-1} (Rajkovich et al. 2012) to 54.2 dSm^{-1} (Smider and Singh, 2014). Like pH, the feedstock and pyrolysis temperatures affect the EC of biochar samples. Higher pyrolysis temperature typically results in biochar with higher EC values (Cantrell et al., 2012; Claoston et al., 2014; Rehrah et al., 2014). This phenomenon has been ascribed to the rising concentration of residues or ash resulting from the pyrolysis process's loss of volatile material (Cantrell et al., 2012). According to Rehrah et al.

(2014), variations in the ash levels of biochar made from various feedstock have been linked to variations in their EC. There are variations within each of these major categories, although biochars made from wood and paper waste often have lower EC values than biochar made from manure (Singh et al., 2010; Rajkovich et al., 2012). For instance, biochar made from feedlot and dairy dung exhibited lower EC values than biochar made from poultry litter, according to Cantrell et al. (2012). Both the biochar investigated had low CEC values. The CEC estimates for biochar in the literature vary widely; they typically fall between 5 and 50 cmol (+) kg^{-1} (Agegnehu et al., 2016; Berek and Hue, 2016; Budai et al., 2014; Gamage et al., 2016; Nelissen et al., 2015; Singh et al., 2010; Song and Guo, 2012) and even up to 69 to 204 cmol (+) kg^{-1} (Lou et al., 2016; Mukherjee et al., 2011; Pandit et al., 2018; Yuan et al., 2011). These estimates of the wide range of CEC values could be attributed to many factors influencing the surface characteristics of biochar, including feedstock and charring temperature (Budai et al., 2014; Suliman et al., 2016). It could possibly be related to analytical method errors that have not been adequately addressed yet. The probable sources of error in the CEC assessment of biochar were outlined in a previous study (Graber et al., 2017). These sources could be related to the biochar's intrinsic hydrophobicity, porosity, or presence of ashes.

Table 4.1. pH, EC and CEC of SBB and MCB

Characteristics	SBB	MCB
pH	8.97 (±0.02)	8.52(±0.03)
EC (dSm^{-1})	1.74 (±0.02)	1.25 (±0.04)
CEC (Cmolc/kg)	4.05 (±0.05)	4.36 (±0.04)

SBB-sugarcane biogases biochar; MCB-maize cob biochar, EC-electrical conductivity, CEC-cation exchange capacity

4.3.1 Yield and Proximate analysis of biochar

The yield and proximate analysis of the biochars are displayed in Table 4.2. The biochar yield attained from SBB was more than that attained from MCB. According to Behera et al. (2020), biomass with high lignin content, such as sugarcane bagasse typically yields more biochar. In particular, the amount of lignin and inorganic components like ash and fixed carbon have a significant impact on the biomass's biochar output (Cheng and Li, 2018). Although, our study did not investigate the lignocellulosic composition of the two biochars used, findings from previous studies have reported higher lignin content in sugarcane bagasse as compared to maize cob (Prasad et al., 2007; Oni et al., 2019). In addition, the biomass growing conditions, age, location, harvesting method, and time of year are likely to have an impact on the biochar yield. Furthermore, the primary determinants of biochar's quantitative and qualitative yield, as well as its product composition, are the production temperature and the type of feedstock (Guida and Hannioui, 2017; Zhao et al., 2017). In fact, temperature influences the properties of biochar more so than heating rate and residence time (Zhao et al., 2018). Behera et al. (2020) reported a larger yield of biochar when the lignocellulosic material is heated at a lower temperature than at a higher temperature which can be attributed to the fact that biochar breaks down at temperatures higher than 500 °C. They observed that at 600 °C, the production of sugarcane bagasse biochar dropped precipitously from 56.27 weight per cent at 300 °C to 18.30 weight per cent at 600 °C.

The proximate analysis of biochar comprises of the volatile matter, moisture, ash, and fixed carbon content. From our result, it is observed that except for fixed carbon, sugarcane bagasse biochar possessed greater ash, moisture, and volatile matter content than maize cob biochar. The gradual concentration of inorganic components and the loss of other elements during pyrolysis are typically the causes of the increase in ash, which is the inorganic fraction that cannot be volatilized or destroyed by combustion (Hadey et al., 2022). Meanwhile, the greater fixed carbon content in maize cob biochar is probably due to the increased loss of volatile matter (Crombie et al., 2013).

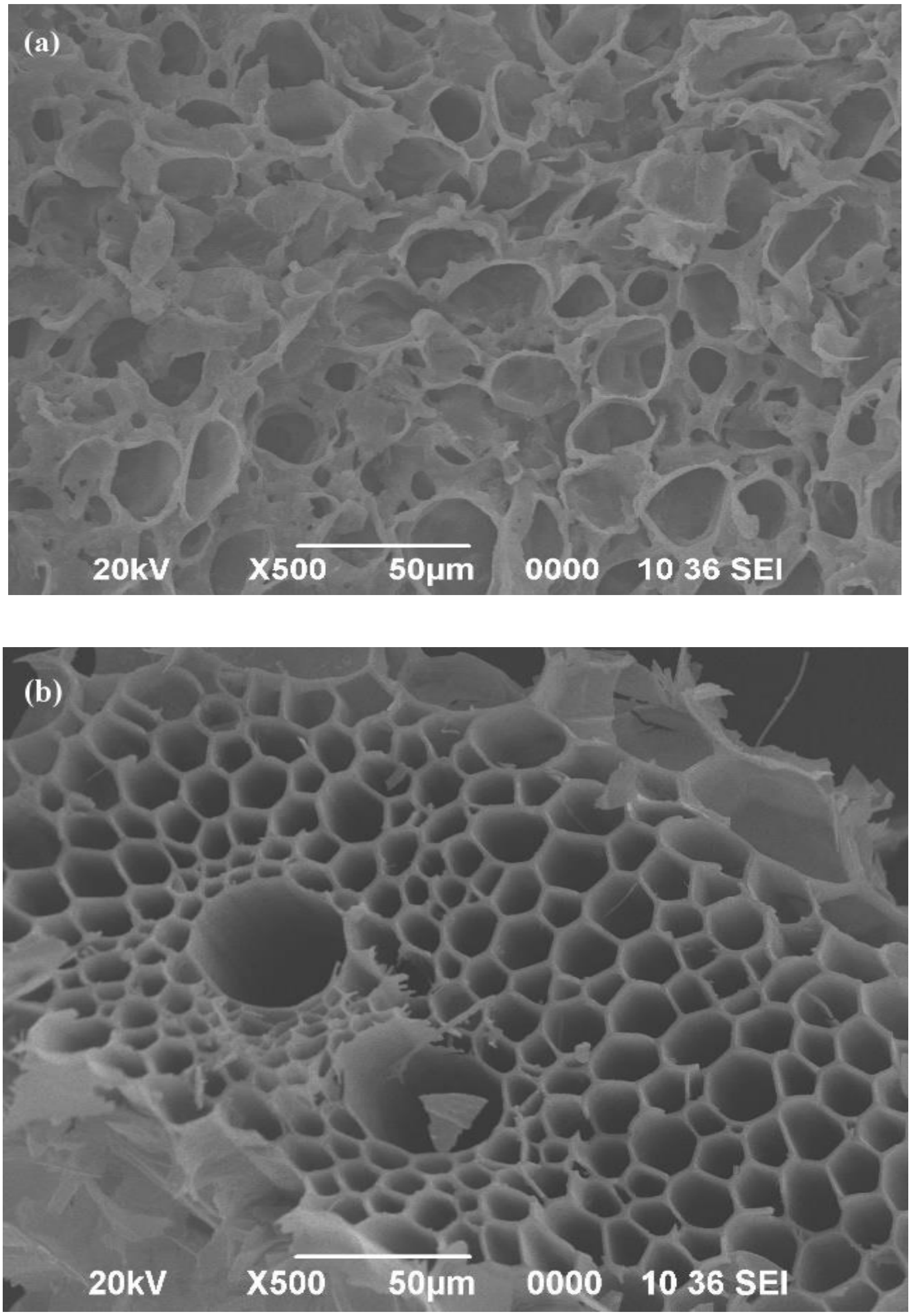
Table 4.2 Yield and Proximate composition of SBB and MCB

Characteristics	SBB	MCB
Yield (%)	27.57	23
Ash content (%)	9.01 (±0.19)	6.33 (±0.14)
Moisture (%)	4.71 (±0.35)	3.10 (±0.23)
VM (%)	38.29 (±1.44)	36.18 (±2.82)
FC (%)	44.38 (±1.98)	48.29 (±2.75)

SBB-sugarcane biogases biochar; MCB-maize cob biochar

4.3.2 Surface morphological analysis of biochar

Following the carbonisation of biomass, structural differences in terms of porosity in char particles can be investigated using SEM imaging. SEM micrographs of the two feedstocks and the biochars are given in Figure 4.1. The pore structure and pore size of the two feedstocks before and after conversion to biochar shows a significant difference. Özçimen and Ersoy–Meriçboyu (2010) suggest that comparing the photos of biochar and its raw feedstock could help us comprehend the morphological changes that occur during the carbonisation stage. With many pores of various diameters, both biochars have a very heterogeneous and complicated structural makeup. However, the MCB showed uneven particle sizes and shapes as well as a rougher, more heterogeneous surface than the SBB which may be attributed to devolatilization during pyrolysis process confirmed by low values of volatile matter detected for maize cob biochar samples (Table 4.2). The degree of devolatilization is influenced by the densities, porosities, and pore structure of the biochar generated. Many hollow channels were seen on the surfaces of the biochar made from sugarcane bagasse and maize cob. It is probable that these porous structures will offer a large internal surface area, the capacity to adsorb inorganic nutrients and soluble organic matter, as well as an ideal environment for microorganisms like arbuscular mycorrhizal fungus and bacteria. In addition to causing shrinkage, melting, and cracking, the slow pyrolysis that was the focus of this study also released hemicellulose, lignin, and volatile organic matter, all of which increased the materials' porosity.



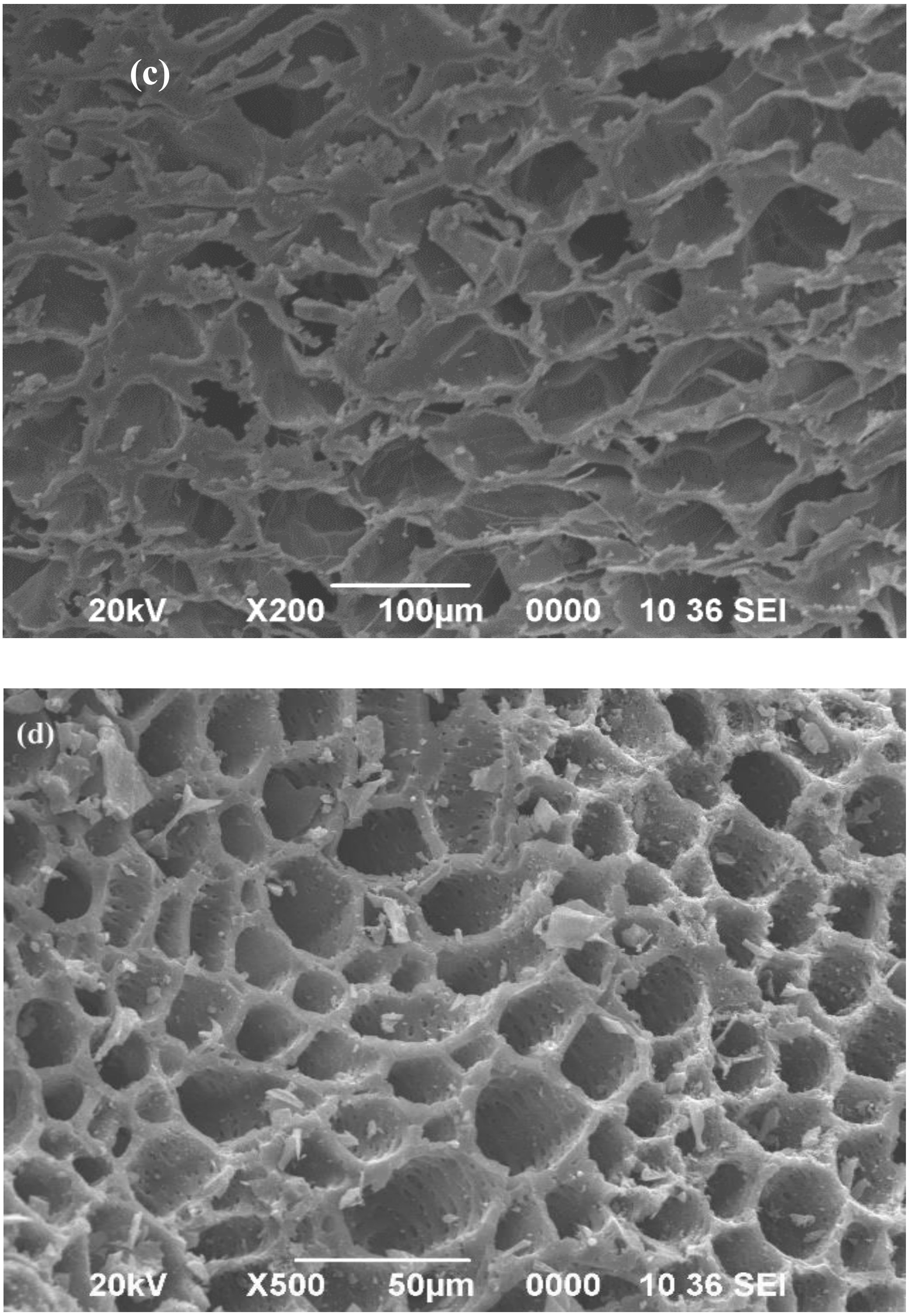


Figure 4.1. Scanning electron micrograph (SEM) images of sugarcane bagasse (a), sugarcane bagasse biochar (b), maize cob (c) and maize cob biochar (d).

4.3.3 FTIR analysis of biochar

Functional groups identified from the FT-IR spectra for the two biochar were also investigated in this study (Figure 4.3). Four primary bands at wave numbers 3250-3550 cm^{-1}, 2920 cm^{-1}, 1710 cm^{-1}, and 1620 cm^{-1} distinguished the biochar's spectra for SBB. In contrast, the biochar's spectra for MCB showed that there were just two main bands, located at 1710 and 1620 cm^{-1}, respectively. Broad bands at 3250–3550 cm^{-1} are indicative of O–H stretching (Wu et al., 2012), whereas aliphatic C–H, carbonyl (C=O), and C–C absorption bands were assigned to the bands at 2920 cm^{-1} (Li et al., 2016), 1710 cm^{-1}, 1710 cm^{-1}, and 1620 cm^{-1}, respectively. In contrast to SBB, it was discovered that the degree of O-H stretching in MCB was less noticeable. The stretching vibrations of metal–halogen in both organic and inorganic halogen compounds are responsible for the bands below 600 cm^{-1} (Hossain et al., 2011). Taek–Keun et al. (2012) stated that the biochar have the potential to improve the soil's adsorbent ability and cation exchange capacity due to the presence of functional groups like carboxyl and hydroxyl groups.

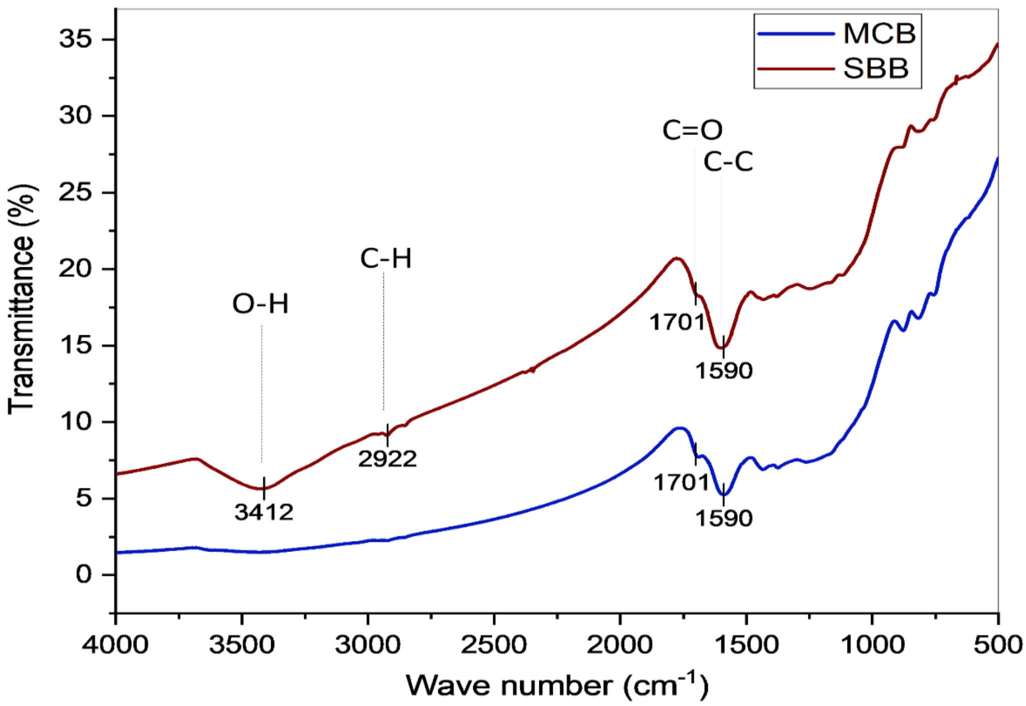


Figure 4.2. FTIR spectra of sugarcane bagasse biochar and maize cob biochar

4.4 Conclusion

Different physical and chemical properties were observed in the biochar made from sugarcane bagasse and maize cob validating the existing theory that biochar characteristics are influenced by the feedstock type. The results show that the pH of the two biochar examined were found to be alkaline and therefore have the potential to be used as a soil amendment to increase the pH of the soil in acidic soil. Similarly, the surface morphology between the two biochar also varied implying that the structural properties of biochar is also dependent on the biomass used. From the SEM macrograph of the two biochar, it is evident that numerous macropores are dispersed on the surface which indicates its potential to act as an appropriate adsorbent and creates an environment that is conducive to the growth of soil microorganisms. The utilisation of biochar may offer a potential solution to the main issue of managing and disposing of the waste biomass, as the pyrolytic process reduces the volume of waste biomass.

Chapter 5

To assess the impact of biochar and vermicompost on soil properties in jhumland

5.1 Introduction

Policy makers and researchers in India have historically placed greater emphasis on the chemical health of the soil than on the physical and biological health of the soil in an effort to increase crop productivity (Acharya et al., 1998). Research has demonstrated, however, that crop output ultimately depends on the soil's biological and physical condition in addition to its productive capacity (Acharya et al., 1998; Ghosh et al., 2012). Based on estimates, the amount of accessible nutrients (NPK) in India that come from organic sources is five million tonnes (mt) per year, and by 2025, it is predicted to rise to 7.75 mt (FAO, 2005). But because cattle dung is also used for other household needs, such as firewood and plastering kachha homes, its availability as a traditional source of organic soil amendment has significantly declined over time. FAO (2005) reports that in the early 1970s, 70% of all cattle manure that was available was used to fertilise crops; by the early 1990s, that percentage had dropped to 30%. In addition, in 2005, farmyard manure application rates were significantly lower—about 2 tonnes per hectare—than the recommended rate (10 tonnes per hectare) in the soil.

Soil possesses various physical qualities, such as the structural cohesiveness that aids in its resistance against erosion and the electrostatic forces that link its microscopic particles. Among these qualities are bulk density (BD), porosity, aggregate stability, penetrability, tensile strength, and its hydrological properties—that is, how it takes in, holds, and releases water. It directly affects the chemistry and biology of soils and regulates how easily plant roots can get into the soil to absorb water, oxygen, and nutrients. Particle size distribution (texture), or the proportions of clay, silt, and sand relative to one another, as well as the quantity and quality of SOM, are the elements that affect these qualities. The physico-chemical characteristics of low-quality soils can be remediated by applying biochar as a soil conditioner (Boivin et al., 2009; Liang et al., 2006), which can result in higher crop yield in situation where the crop growth is restricted by the properties of the soil (Lehmann et al., 2003; Peng et al., 2011; Steiner et al., 2008; Van Zweiten et al., 2010). The highly porous nature of biochar can modify numerous physical properties of soil comprising bulk density

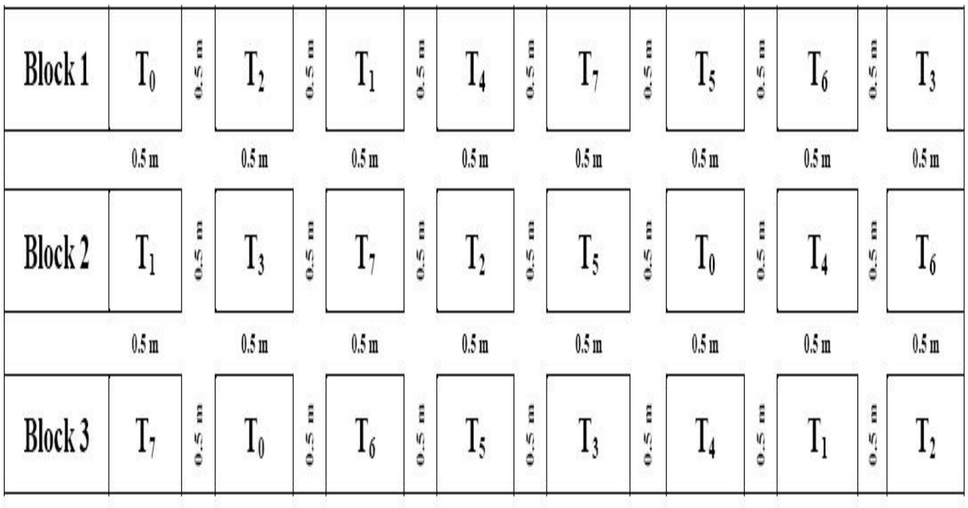
(Laird et al., 2010; Lei and Zhang, 2013; Sun and Lu, 2014), total porosity (Abel et al., 2013; Oguntunde et al., 2008; Verheijen et al., 2010), pore-size distribution (Devereux et al., 2012; Hardie et al., 2013; Major et al., 2009), water retention (Auerswald et al., 2003; Major et al., 2009; Rawls et al., 2003), water-holding capacity (Atkinson et al., 2010; Basso et al., 2013; Jones et al., 2010) and aggregate stability (Jones et al., 2010; Tejada and Gonzalez, 2007; Verheijen et al., 2010). Besides modifying the physical properties of soil, the sole application of biochar or in combination with organic matter can enhance the productivity of crops as well as soil microbes (Xu et al., 2012; Singh et al., 2017). The fertility of soil in agroecosystem as well as forest ecosystem can be indicated by the presence of soil microbial biomass implying that greater the soil microbial biomass, greater the soil fertility (Khodadad et al., 2011). Due to the porous structure and large surface area of biochar, it can harbour thousands of soil microbes and protect them from soil predators (Yadav et al., 2017). Moreover, by interacting with minerals, microorganisms, and soil organic matter (SOM), biochar can influence soil aggregation. This can impact the rate of infiltration (Asai et al., 2009; Brockoff et al., 2010) as well as saturated hydraulic conductivity (Asai et al., 2009; Uzoma et al., 2011). The depth and density distribution of plant roots can be modified due to change in physical properties brought about by the addition of biochar (Devereux et al., 2012; Brunn et al., 2014). As a result, the plants' capacity to take up water and soluble nutrients from the soil is altered (Devereux et al., 2012). Another important function of biochar is the prevention of nutrient leaching (Hussain et al., 2016).

We hypothesized that (i) application of biochar will have a significant positive effect on soil physical and chemical properties, (ii) biochar co-applied with vermicompost will have a greater benefit on soil as compared to the sole biochar application.

5.2 Materials and Methods

5.2.1 Experimental layout

A randomized block design with three replicates and 8 treatments was established for a total of 24 experimental plots. The treatments were untreated control (T0), vermicompost at 5t/ha (T1), sugarcane bagasse biochar at 5t/ha (T2), Maize cob biochar at 5t/ha (T3), vermicompost + sugarcane biochar (T4) at 2.5 t/ha each, vermicompost + maize cob biochar at 2.5 t/ha (T5), sugarcane biochar + maize cob biochar at 2.5 t/ha (T6), vermicompost + sugarcane biochar + maize cob biochar at 1.66 t/ha each (T7). The experimental plot was constructed with the size of 2m x 1.5 m and a buffer zone of 0.5 m was maintained between each treatment rows to reduce any external effect.



5.2.2 Soil sampling:

5.2.2.1 Initial soil characterisation

Prior to sowing, soil samples were collected from each plot at two soil depths i.e., 0-15 cm and 15-30 cm. The soil samples were packed in the polythene bag and brought to the laboratory, air dried, grounded and passed through 2 mm sieve for analyzing their physico-chemical properties.

5.2.2.2 Seasonal soil characterisation

Soils samples were collected twice each season *viz.* before sowing and after harvesting soybean. The soil samples were collected from each plot at two soil depths i.e., 0-15 cm and 15-30 and immediately transferred to the laboratory, mixed uniformly, and sieved at field moist state within three days. A portion of the samples were air-dried and sieved to a size of 2 mm for further laboratory analysis.

5.2.3 Laboratory analyses:

5.2.3.1 Bulk density

The soil bulk density was determined using the soil core method (Blake and Hartage, 1986). Undisturbed soil core samples were collected using a stainless-steel coring pipe from each plot at 0-15 and 15-30 cm depths. Soil cores were collected and oven dried at 105 ° C for 24 hours. Bulk density was calculated by dividing the mass of oven dried soil by the core volume.

5.2.3.2 Soil moisture content

Moisture content was determined by oven drying method (Anderson and Ingram, 1989) 100 g of soil sample from each plot by oven-drying (65° C) until constant weight is reached, and soil moisture content was calculated as

$$\text{Soil moisture content (\%)} = \frac{\text{weight of fresh sample} - \text{weight of oven dried sample}}{\text{weight of oven dried sample}} \times 100$$

5.2.3.3 Soil texture

The percentage of sand, silt and clay in the inorganic fraction of soil using hydrometer method (Bouyoucos, G.J. 1962). This method is based on Stoke's law governing the rate of sedimentation of particles suspended in water. The sample is treated with sodium hexametaphosphate to complex Ca^{++}, Al^{3+}, Fe^{3+}, and other cations that bind clay and silt particles into aggregates. Organic matter is suspended in this solution. The density of the soil suspension is determined with a hydrometer calibrated to read in grams of solids per liter after the sand settles out and again after the silt settles. Corrections are made for the density and temperature of the dispersing solution.

5.2.3.4 Soil pH

Soil pH was measured by using 1:2.5 solid: solution ratio (deionised water; DIW) ratio after shaking the suspension on a mechanical-shaker for 90 min in deionized water (Rajkovich *et al.*, 2012). After this, samples were allowed to stand for 30 min and then pH was measured using a calomel electrode–glass electrode system. The pH meter was calibrated using buffers of pH 7 and 10.

5.2.3.5 Available Nitrogen

Available Nitrogen was determined by the Alkaline permanganate method (Subbiah and Asija, 1956)

Available N (kg/ha) = $\frac{(S-B) \times 0.00028}{20} \times 10^6 \times 2.24$

Where S and B stands for the titre values of sample and blank, respectively.

The factor 0.00028 is arrived at by considering the following simple equation:

$2NH_4OH + H_2SO_4 = (NH_4)_2SO_4 + 2H_2O$

Or 98 g of H_2SO_4 (or 1L of 2*N* H_2SO_4) = 28 g N

Or 1 ml of 0.02 *N* H_2SO_4 = 0.00028 g N

5.2.3.6 Available Phosphorus

Soil available phosphorus was determined by Bray's P-1 (Bray and Kurtz, 1945).

Available P (kg ha-^{1}) = $\frac{Q \times V \times 2.24 \times 10^6}{A \times S \times 10^6}$

Where, Q = quantity of P in µg read on X- axis against a sample reading

V = volume of extracting reagent used (ml)

A = volume of aliquot

S = weight of sample (g)

5.2.3.7 Available Potassium

Soil available potassium was determined by normal neutral 1N ammonium acetate extractant, adjusting pH 7.0 with using of flame photometer (Jackson, 1973).

5.2.3.8 Microbial Biomass Carbon

Microbial biomass Microbial biomass carbon (MBC) was estimated by the commonly used technique, i.e., the fumigation-extraction method. 10 g of soil was fumigated for 24 h at 25 °C with pure ethanol-free chloroform ($CHCl_3$). The samples were then added with 50 mL 0.5 M potassium sulfate (K_2SO_4) for 1/2 h on a horizontal shaker at 200 rev per minute. The suspensions were then filtered by a filter paper (Whatman No. 42). Similarly, 10 g of soil was extracted for non-fumigation at the same time (Brookes et al. 1985). SOC in the extracts was measured by the titration technique. Then MBC was determined as microbial biomass C = (C fumigated − C non-fumigated) × 2.64.

5.2.3.9 Soil organic carbon content

Soil organic carbon content was estimated through Wet digestion or rapid titration method (Walkey and Black method) following standard procedures described by Ravindranath and Madelene (2008). It was calculated using the following equation:

$$SOC\ (\%) = [(X-Y)/2 \times 0.003 \times 100]/ S$$

Where,

Weight of the sample = Sg

Volume of FAS used in the blank= Xg

Volume of FAS used to oxidise SOC = Yg

Normality of FAS = N

Volume of 1 N K2Cr2O7 used for oxidation of carbon = (X-Y)/2

1 ml of 1 N K2Cr2O7 = 0.003 g SOC

5.2.3.10 CEC of soil

Soil CEC was determined by a modified ammonium acetate compulsory displacement method (Gaskin et al., 2008). Briefly, 2.0 g of soil were leached with five portions of 20 mL deionized water to remove excess of salts with vacuum filtration and a 0.45 µm pore size filter. In sequence, samples were washed with a 1.0 mol L^{-1} sodium acetate (pH 8.2) three times, followed by five portions of 20 mL ethanol to remove free (not-adsorbed) Na^+ ions. Samples were then washed with 20 mL of 1.0 mol L^{-1} ammonium acetate four times to displace the Na^+ on the exchangeable sites of the soil. The leachates were collected and stored in a 100 mL volumetric flask, and Na^+ contents in leachates were determined by flame photometry. The CEC

corresponds to the amount of Na^+ displaced per unit mass of soil or kg C in the biochar, expressed in cmolc kg^{-1}.

5.3 Statistical analyses

Using a one-way analysis of variance (ANOVA), the software SPSS 20.0 (SPSS Inc.) was utilised to investigate significant variations in the soil physical and chemical properties among different treatments.

5.4 Results and Discussion

The initial physico-chemical properties of the experimental site are presented in Table 5.1. The sandy loam soil has low pH and SOC, moderate bulk density and OM content and low level of available of P, while available N and available K content were fairly moderate.

Table 5.1. Some selected physico-chemical properties of soil measured before the experiment

Parameters	Soil depth (cm)	
	0-15	**15-30**
pH	4.29	4.85
SMC (%)	24.39	26.19
BD (g/cm^3)	0.94	1.03
SOM (%	4.51	4.4
SOC (%)	1.63	1.27
Available N (kg/ha)	303.25	286.12
Available P (kg/ha)	8.93	7.86
Available K(kg/ha)	65.20	48.38
Textural class	Sandy loam	

Table 5.2 and 5.3 shows the effect of biochar on bulk density and moisture content of soil. In the first year, soil bulk density was found to be significantly different between the biochar amended and un-amended control plot at 0-15 and 15-30 cm before sowing but after harvest, no significant differences were observed. Similarly, no statistically significant difference were found among the treatments in the second year. In addition, bulk density was found to be higher in the subsoil than in the top soil. Because the bulk density of biochar is significantly lower than that of mineral soils, applying biochar may result in a decrease in the bulk density of the soil by increasing the volume of soil per unit weight. Also, owing to its high porosity, biochar is anticipated to alter the bulk density and other physical characteristics of soil (Jones et al., 2010; Devereux et al., 2012; Lei and Zhang, 2013; Sun and Lu, 2014). According to Tammeorg et al. (2014), biochar application on sandy textured soils over time under field conditions has been shown to reduce soil bulk density and enhance porosity. Due to the resistant nature of biochar to decompose, the results of this and other research indicate that the effects of applying biochar under field settings may not materialise within a short period of time. Meanwhile, biochar application had no effect on soil moisture content at all times of sampling during the course of experiment. Considering all that has been mentioned thus far regarding biochar’s capacity to increase water holding capacity, one may anticipate that SMC

would be higher in the majority of soils that BC has been applied to, except for saturation. This could, however, rely on whether a significant percentage of the BC particles, to which a large amount of the available water may be bound, were present in the samples that were collected. Another plausible explanation may be due to the hydrophobic nature of biochar produced by low temperature pyrolysis. Low temperature biochar surfaces have the potential to be hydrophobic, which could decrease the amount of soil water that is retained (Sohi et al., 2009).

Table 5.2. Soil bulk density and moisture content of soil at two sampling times in 2018

Sampling time	Treatment	BD (g/cm^3)		MC (%)	
		0-15	15-30	0-15	15-30
Before sowing	T0	0.83±0.02[ab]	0.87±0.01[a]	29.06±1.35[a]	29.50±1.11[a]
	T1	0.78±0.01[ab]	0.85±0.02[abc]	26.95±2.56[a]	26.69±3.57[a]
	T2	0.76±0.02[b]	0.81±0.04[cd]	30.69±1.31[a]	29.54±0.55[a]
	T3	0.78±0.01[ab]	0.82±0.01[bcd]	28.87±0.48[a]	28.16±0.76[a]
	T4	0.76±0.01[b]	0.79±0.02[d]	29.11±1.14[a]	27.51±0.79[a]
	T5	0.77±0.01[b]	0.86±0.02[ab]	30.21±1.98[a]	29.14±1.80[a]
	T6	0.80±0.01[a]	0.81±0.03[cd]	29.15±2.00[a]	29.60±3.91[a]
	T7	0.78±0.01[ab]	0.82±0.01[bcd]	31.51±1.75[a]	29.50±1.14[a]
After harvest	T0	0.81±0.01[a]	0.85±0.01[a]	11.28±0.37[a]	11.43±0.16[a]
	T1	0.76±0.02[a]	0.83±0.01[a]	11.52±1.60[a]	11.66±1.37[a]
	T2	0.75±0.01[a]	0.80±0.02[a]	12.14±0.52[a]	12.27±.79[a]
	T3	0.76±0.01[a]	0.80±0.04[a]	11.12±1.24[a]	11.09±0.97[a]
	T4	0.75±0.01[a]	0.78±0.03[a]	11.36±1.22[a]	11.49±1.03[a]
	T5	0.76±0.02[a]	0.84±0.01[a]	12.05±1.29[a]	12.20±0.94[a]
	T6	0.78±0.02[a]	0.80±0.02[a]	11.22±0.23[a]	11.34±2.38[a]
	T7	0.77±0.02[a]	0.80±0.01[a]	12.58±0.89[a]	12.79±0.83[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 5.3. Soil bulk density and moisture content of soil at two sampling times in 2019

Sampling time	Treatment	BD (g/cm^3)		MC (%)	
		0-15	15-30	0-15	15-30
Before sowing	**T0**	0.80±0.03[a]	0.87±0.01[a]	29.87±1.17[a]	24.97±5.23[a]
	T1	0.78±0.02[a]	0.83±0.04[ab]	24.97±0.45[a]	28.65±0.94[a]
	T2	0.79±0.01[a]	0.83±0.03[ab]	28.65±2.58[a]	26.64±6.64[a]
	T3	0.79±0.03[a]	0.82±0.03[ab]	26.64±0.94[a]	30.02±3.56[a]
	T4	0.76±0.02[a]	0.78±0.01[b]	30.02±0.54[a]	25.24±0.90[a]
	T5	0.76±0.01[a]	0.81±0.05[ab]	25.24±1.53[a]	27.58±2.81[a]
	T6	0.79±0.03[a]	0.81±0.03[ab]	27.58±2.50[a]	25.03±4.22[a]
	T7	0.79±0.01[a]	0.82±0.01[ab]	25.03±1.34[a]	25.62±1.89[a]
After harvest	**T0**	0.80±0.01[a]	0.83±0.02[a]	10.99±0.72	10.40±0.95[a]
	T1	0.79±0.02[a]	0.81±0.02[a]	13.04±1.53[a]	11.77±1.00[a]
	T2	0.79±0.01[a]	0.83±0.03[a]	11.52±1.12[a]	10.73±1.43[a]
	T3	0.80±0.02[a]	0.81±0.01[a]	11.89±1.12[a]	11.55±1.20[a]
	T4	0.77±0.02[a]	0.78±0.01[a]	11.61±1.10[a]	11.07±0.99[a]
	T5	0.76±0.03[a]	0.81±0.03[a]	12.21±0.61[a]	11.76±0.49[a]
	T6	0.79±0.03[a]	0.81±0.03[a]	10.41±0.56[a]	9.73±0.64[a]
	T7	0.79±0.03[a]	0.81±0.01[a]	12.61±1.41[a]	11.20±0.73[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). BD-bulk density, MC- moisture contents, other. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Soil pH, organic matter (OM) and cation exchange capacity (CEC) were significantly increased by biochar addition before and after harvest in the first year (Table 5.4). Biochar amendment significantly increased soil pH from 4.56 in control to 5.61 in the soil treated with the combined application of maize cob biochar and vermicompost (T5) before sowing and 5.07 to 5.59 after harvest at 0-15 cm soil depth. This is in line with the studies made by previous researchers who also found an increase in soil pH with the application of biochar (Alburquerque et al., 2013; Berihun et al., 2017; Tian et al., 2018). Since BC is alkaline (Beesley et al., 2010; Houben et al., 2013; Van Zwieten et al., 2010), it usually elevates the pH of soil. This is mostly because BC dissolves metal hydroxides and carbonates that are retained within its structure (Jones et al., 2011; Lucchini et al., 2014; Singh et al., 2010). Soil organic matter increased with biochar addition, and the highest organic matter content (6.07 %) was again measured in T5 which is approximately 1.04 % higher than the control. At both soil depths, notable variations were seen between the treated and control soils. Nigussie et al. (2012) reported that application of biochar to the soil significantly increased the organic matter. The analysis of variance demonstrated that the application of biochar led to a significant ($P < 0.05$) increase in cation exchange capacity (CEC) at 0-15 cm soil depth. The highest CEC value of 11.31 cmol/kg was measured in T5 amended plot. It is also observed that although there was no distinct trend among the treatments, the addition of biochar led to a significant increase in T5 amended plot at 15-30 cm soil depth. In addition, it is unclear why CEC values were found to be lower in some of the biochar amended plot as compared to the unamended control plot. By adsorbing positively charged ions, BC, like clay and SOM, contributes a significant negative charge that enhances the CEC (Major et al., 2009). According to Sohi et al. (2009), mineral soil or SOM often has a lower inherent CEC than BC. Up to 2% BC increased pH by up to 1 pH unit and CEC by up to 20% (Laird et al., 2010). On the other hand, no statistically significant difference was observed in the soil pH between the amended and un-amended plots, whereas OM and CEC were significantly higher in the amended plots at 0-15 cm soil depth before sowing in the second year (Table 5.5). In contrast, pH was significantly higher in T5 as compared to T0 at 15-30 cm soil depth. This might be due to the downward movement or leaching of biochar brought about by the rain. Furthermore, no statistically significant differences were found among all the treatments after harvest. Our results contradicted the findings of previous studies which reported an effectiveness of biochar in the second year as compared to the first year which can be explained by aging of the raw, un-enriched biochar in soil overtime wherein biochar gradually enhances soil structure, resulting in better soil aggregation (Obia et al., 2016; Obia et al., 2017). Jones et al. (2012) examined the effects of adding 25 and 50 t ha^{-1} biochar over a 3-year period on soil characteristics, maize and grass yield, and pH-neutral (pH 6.6) sandy clay loam in Wales, UK. Based on their research, the impacts of biochar were more pronounced in year two compared to year one. A plausible explanation for the diminishing effect of biochar on soil physical and chemical properties in the second year as compared to the first could be attributed to the fact that biochar was applied only once at a low rate of 5 t/ha at the beginning of the experiment. Another possible reason is due to the biochar loss owing to soil erosion as our experimental site was located on a slightly sloping land.

Table 5.4. Few selected soil chemical properties at two sampling times in 2018

Sampling time	Treatment	pH		SOM (%)		CEC (cmol/kg)	
		0-15	15-30	0-15	15-30	0-15	15-30
Before sowing	T0	4.56±0.24[b]	4.41±0.14[a]	5.03±0.28[b]	4.18±0.37[b]	8.35±0.48[b]	6.01±0.65[b]
	T1	5.15±0.50[ab]	4.87±0.29[a]	5.74±0.05[a]	4.84±0.09[a]	8.35±0.46[b]	5.21±0.45[bc]
	T2	5.31±0.12[a]	5.16±0.07[a]	5.87±0.04[a]	5.01±0.38[a]	8.71±0.43[b]	4.82±0.20[bc]
	T3	5.17±0.09[ab]	5.07±0.07[a]	5.95±0.05[a]	5.15±0.21[a]	8.19±0.54[b]	3.70±0.31[c]
	T4	5.41±0.33[a]	5.18±0.19[a]	5.90±0.02[a]	5.63±0.15[a]	9.27±0.41[ab]	5.53±0.55[b]
	T5	5.61±0.07[a]	5.34±0.04[a]	6.07±0.05[a]	4.62±0.14[a]	11.31±0.46[a]	9.39±0.50[a]
	T6	5.24±0.02[a]	5.22±0.01[a]	5.81±0.02[a]	5.34±0.26[ab]	8.24±0.51[b]	5.35±0.32[bc]
	T7	5.18±0.02[ab]	4.99±0.01[a]	5.85±0.07[a]	3.98±0.42	7.68±0.33[b]	6.43±0.23[b]
After harvest	T0	5.07±0.11[b]	4.93±0.02[a]	4.84±0.20[b]	4.13±0.16[b]	6.07±0.06[a]	3.86±0.04[a]
	T1	5.18±0.05[ab]	5.07±0.03[a]	5.02±0.24[ab]	4.72±0.26[a]	6.67±0.49[ac]	4.23±0.62[a]
	T2	5.11±0.12[ab]	4.95±0.12[a]	5.38±0.06[ab]	4.84±0.14[ab]	5.50±0.07[b]	3.61±0.34[a]
	T3	5.35±0.11[ab]	5.24±0.12[a]	5.41±0.05[ab]	4.50±0.05[ab]	7.72±0.85[a]	4.87±1.23[a]
	T4	5.25±0.13[ab]	5.02±0.05[a]	5.37±0.01[ab]	5.20±0.18[ab]	7.77±0.98[ab]	4.92±1.24[a]
	T5	5.59±0.21[a]	5.25±0.24[a]	5.53±0.02[a]	4.82±0.23[ab]	8.06±0.11[a]	5.90±0.25[a]
	T6	5.19±0.02[ab]	5.05±0.03[a]	5.36±0.02[ab]	4.58±0.08[ab]	5.53±0.19[b]	3.96±0.44[a]
	T7	5.33±0.08[ab]	5.13±0.06[a]	5.35±0.04[ab]	4.91±0.24[a]	4.70±0.06[c]	3.56±0.26[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). SOM-soil organic matter, CEC-cation exchange capacity.T_0-control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 5.5 Few selected soil chemical properties at two sampling times in 2019

Sampling time	Treatment	pH		SOM		CEC	
		0-15	15-30	0-15	15-30	0-15	15-30
Before sowing	T0	4.58±0.06[a]	4.25±0.12[b]	4.98±0.01[c]	4.24±0.33[a]	6.27±0.04[ab]	4.00±0.39[a]
	T1	5.00±0.15[a]	4.75±0.08[ab]	5.23±0.07[ac]	4.56±0.26[a]	6.07±0.42[ab]	4.00±0.68[a]
	T2	4.83±0.17[a]	4.48±0.12[a]	5.41±0.05[ab]	4.89±0.47[a]	6.36±0.20[ab]	4.01±0.22[a]
	T3	4.94±0.34[a]	4.66±0.27[ab]	5.53±0.02[a]	4.77±0.45[a]	6.68±0.66[ab]	3.72±1.30[a]
	T4	5.20±0.20[a]	4.90±0.05[ab]	5.40±0.02[ab]	4.83±0.57[a]	6.40±0.61[ab]	3.86±0.71[a]
	T5	5.23±0.09[a]	4.93±0.03[a]	5.57±0.02[a]	5.16±0.16[a]	7.01±0.23[a]	4.83±0.38[a]
	T6	4.83±0.09[a]	4.62±0.17[ab]	5.00±0.21[bc]	5.19±0.26[a]	5.78±0.27[ab]	3.64±0.14[a]
	T7	4.83±0.09[a]	4.53±0.09[b]	5.25±0.06[ac]	4.68±0.42[a]	5.08±0.24[b]	3.46±0.20[a]
After harvest	T0	4.38±0.05[a]	4.24±0.01[a]	4.35±0.04[a]	4.05±0.43[a]	5.43±0.58[a]	4.11±0.70[a]
	T1	4.57±0.05[a]	4.36±0.07[a]	5.16±0.07[a]	4.69±0.11[a]	5.19±0.51[a]	3.77±0.74[a]
	T2	4.42±0.06[a]	4.28±0.04[a]	5.01±0.05[a]	3.89±0.35[a]	6.68±0.82[a]	5.07±0.75[a]
	T3	4.63±0.19[a]	4.40±0.19[a]	5.27±0.02[a]	4.59±0.17[a]	6.97±0.20[a]	4.74±0.11[a]
	T4	4.51±0.16[a]	4.34±0.13[a]	5.31±0.03[a]	4.58±0.21[a]	6.15±0.52[a]	4.00±0.42[a]
	T5	4.75±0.10[a]	4.46±0.05[a]	5.45±0.02[a]	4.83±0.15[a]	5.49±0.55[a]	3.85±0.35[a]
	T6	4.47±0.09[a]	4.28±0.03[a]	5.23±0.21[a]	4.67±0.20[a]	5.86±0.72[a]	3.64±0.19[a]
	T7	4.44±0.04[a]	4.24±0.03[a]	4.84±0.06[a]	4.25±0.41[a]	5.72±0.36[a]	3.83±0.35[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). SOM-soil organic matter, CEC- cation exchange capacity. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Soil microbial biomass was not significantly affected by the addition of biochar with and without vermicompost measured at all the sampling times in both the years (Fig. 5.1, 5.2, 5.3 and 5.4). While MB-C generally increases following the addition of biochar, according to a recent meta-analysis (Biederman and Harpole, 2013), other medium-term field studies have also found a negligible change in microbial biomass several years after the addition of biochar, indicating that these effects are generally short-lived (Jones et al., 2012; Rousk et al., 2013). There is a lot of variation in the reported effects of biochar on soil MBC. Numerous investigations also discovered no discernible impact of biochar addition on soil MBC (Kuzyakov et al., 2009; Zavalloni et al., 2011; Castaldi et al., 2011). Adding biochar has been shown in several studies to promote microbial biomass through altered soil physicochemical properties, sorption of different signalling molecules, and detoxification of substances (allelochemicals). Due to the toxicity impact, which is dependent on the types of feedstocks and pyrolysis temperature, Dempster et al. (2012) found that the addition of biochar reduced the amount of soil microbial biomass. According to Lehmann et al. (2011), the amount of biochar incorporated and the soil's texture play a significant role in regulating microbial activity and can affect how soil microbial biomasses respond.

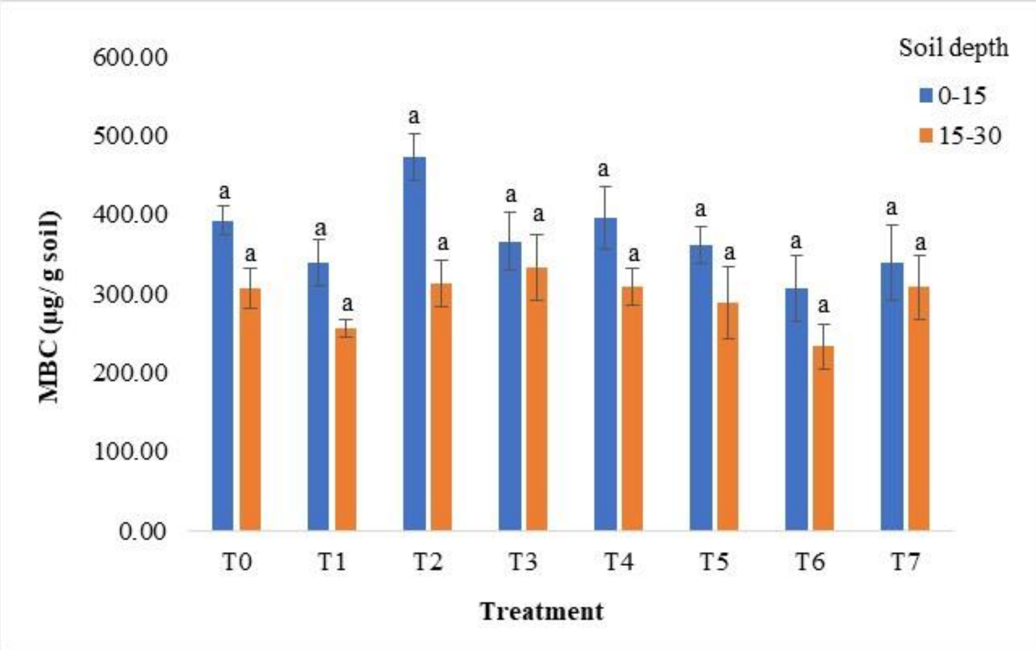


Figure 5.1. Microbial biomass carbon (MBC) under different treatments and different soil depths in 2018 before sowing. Different letters indicate significant differences among the treatments. Error bars represent the standard error for
means of each treatment (n = 3). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

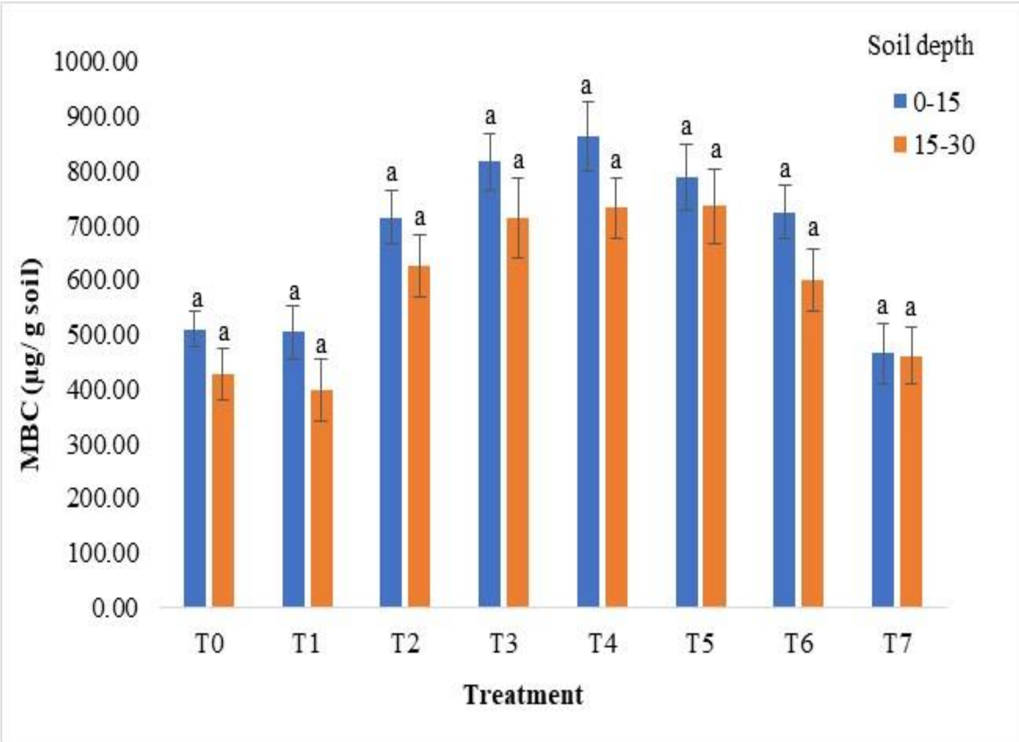


Figure 5.2 Microbial biomass carbon (MBC) under different treatments and different soil depths in 2018 after harvest. Different letters indicate significant differences among the treatments. Error bars represent the standard error for means of each treatment (n=3). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

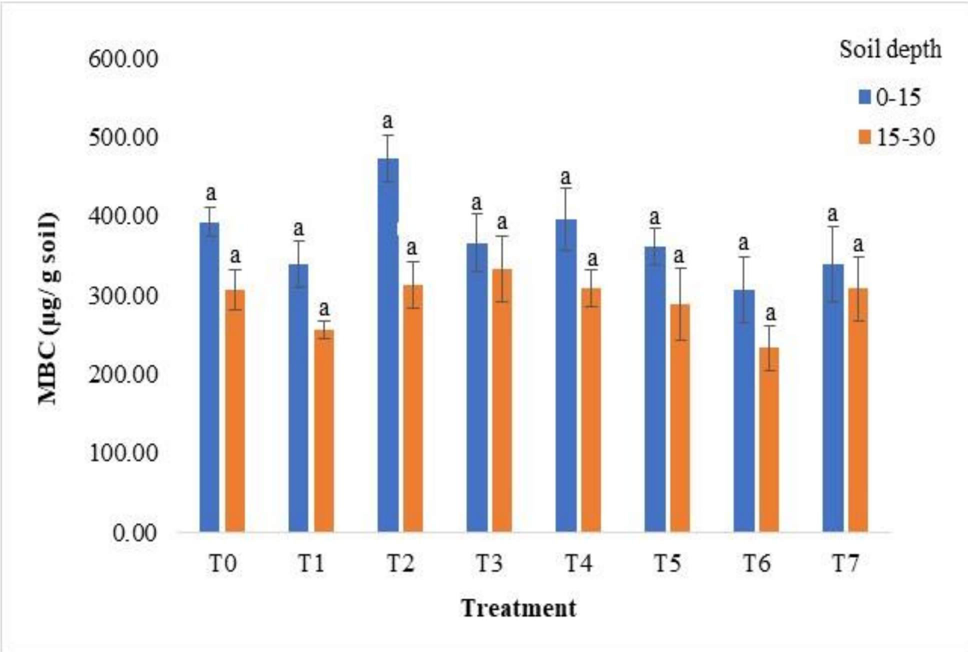


Figure 5.3 Microbial biomass carbon (MBC) under different treatments and different soil depths in 2019 before sowing. Different letters indicate significant differences among the treatments. Error bars represent the standard error for means of each treatment (n = 3). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

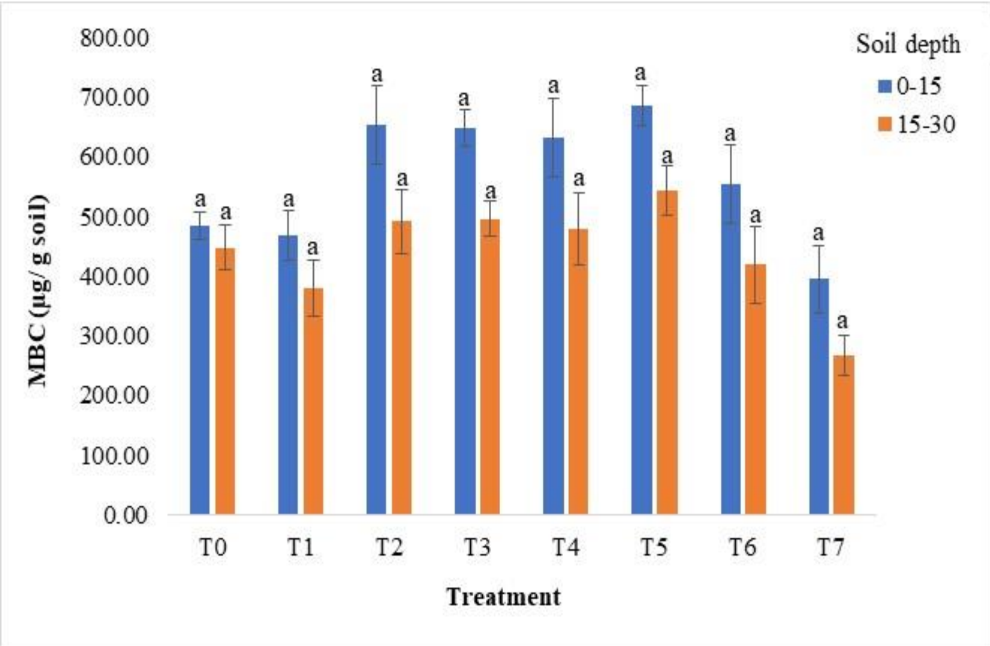
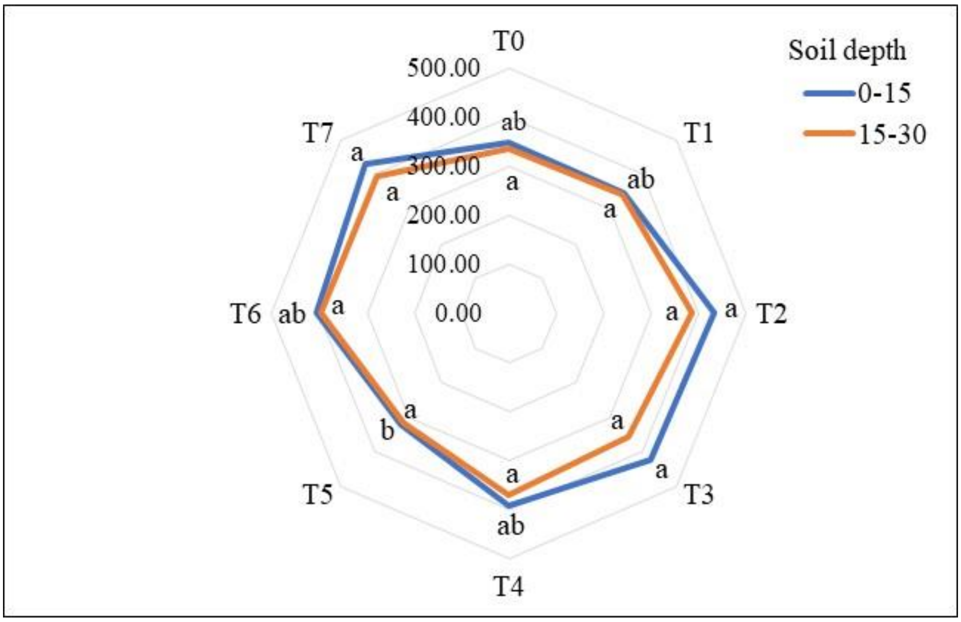
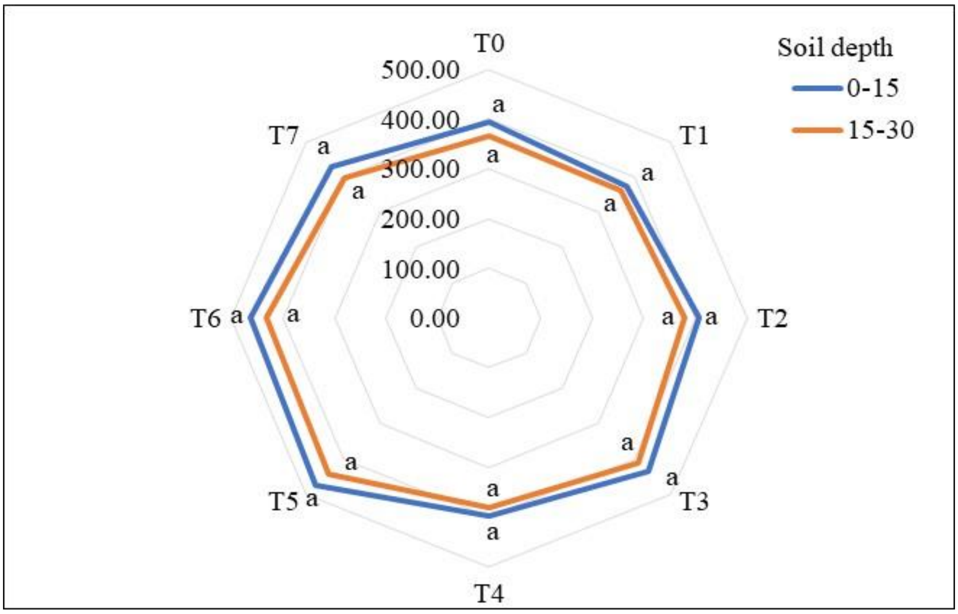


Figure 5.4 Microbial biomass carbon (MBC) under different treatments and different soil depths in 2019 after harvest. Different letters indicate significant differences among the treatments. Error bars represent the standard error for means of each treatment (n = 3). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Figure 5.5 illustrates the effect of biochar application on available N in the soil before sowing and after harvest in the first year. Different biochar types significantly affected soil N availability. AN content in T2 was 25.25 % higher than in T0 whereas T1 and T5 were 0.71 and 8.26 % lower, respectively than in T0. However, the result was not consistent after harvest with no significant differences observed among the treatments. In the following year before sowing, AN was significantly higher in T4 and T7 than in other biochar amended plots, as with control plot. On the other hand, biochar application significantly increased AN after harvest with T5 recording an increase by 21.69% over control **(**Fig. 5.6). Because of its rich pore structure and wide specific surface area, which allow it to absorb and store soil N, reduce soil N leaching loss, and enhance soil N nutrient content, biochar can greatly increase the soil N content (Abujabhah et al., 2018). According to a study, biochar can dramatically lower ammonia volatilization in field soil, which improves soil nitrogen utilisation. It can also dramatically lower soil farmland N, P, and other nutrient losses, with the exception of adsorption by retaining N element. Furthermore, biochar can control nitrification and denitrification processes to lower N loss, which lowers the amount of fertiliser used (Chongshu et al., 2014). According to studies by Lehmann et al. (2003), Taghizadeh-Toosi et al. (2010) and Ding et al. (2010), biochar can adsorb NO_3 - and NH_4^+ through cation exchange, which lowers soil ammonia volatilization and increases the amount of nitrogen that is available in the soil, enhancing soil fertility. Upon application to a field, biochar modifies the physical and chemical characteristics of the soil or interacts with it to influence the distribution, movement, and transformation of soil nitrogen (Li et al., 2020). Important variables influencing soil N movement, distribution, and leaching include soil type and amount of biochar added (Kumuduni et al., 2019). In contrast, the preservation of trace elements in soil, such as nitrogen, may be adversely affected by biochar. The effective NO_3-N and P contents of biochar were observed to be reduced by approximately 55 and 90% (w/w) upon physical activation, according to Borchard et al. (2012). It was suggested that the net transfer of unstable nitrogen to heterocyclic nitrogen and the production of volatile nitrogen molecules during activation were the causes of the decrease of accessible nitrogen (Borchard et al., 2012) which may explain the lower initial AN content in the biochar amended soils than in the control soil.

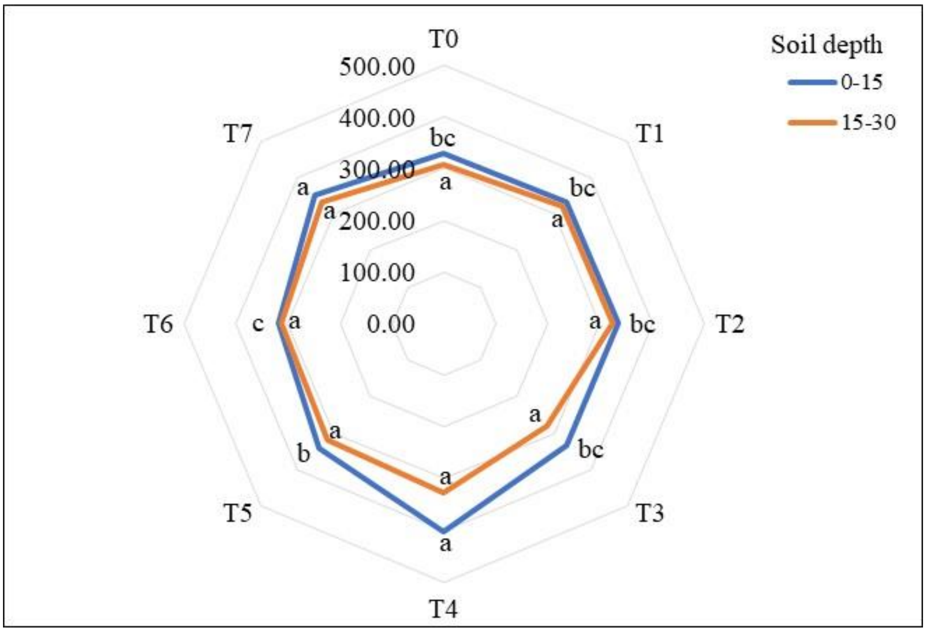


(A)

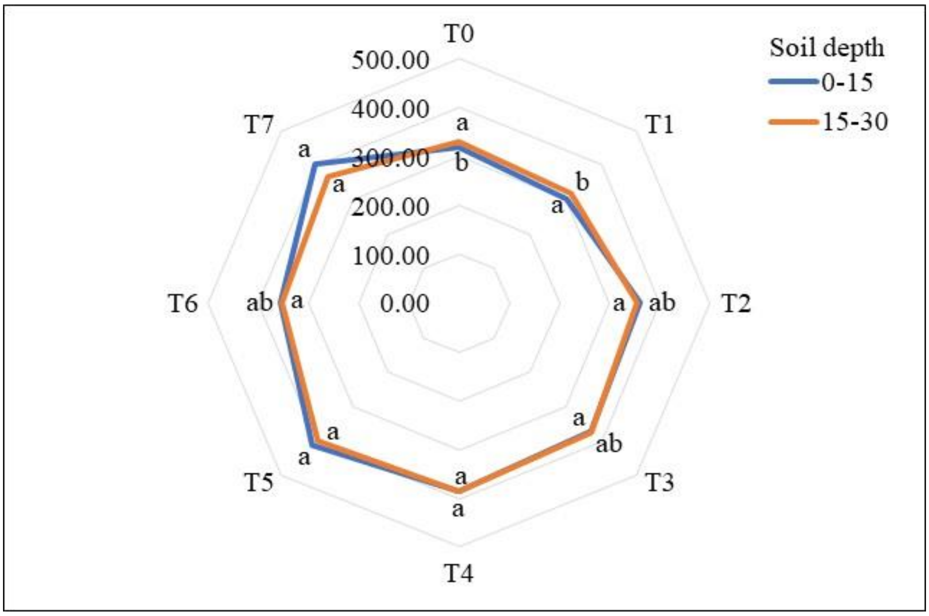


(B)

Figure 5.5. Available N under different treatments (T0-T7) and different soil depths (cm) in 2018 before sowing (A) and after harvest (B). Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.



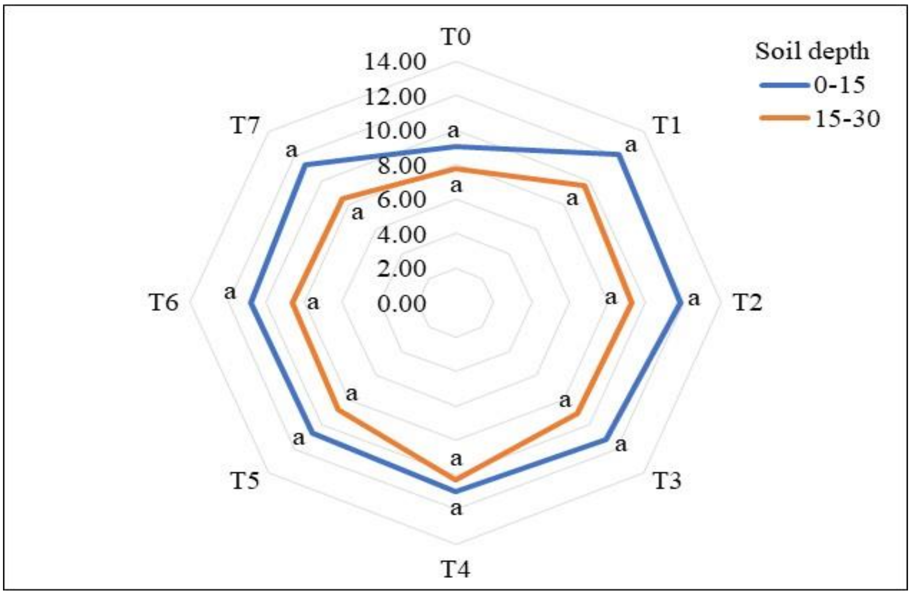
(C)



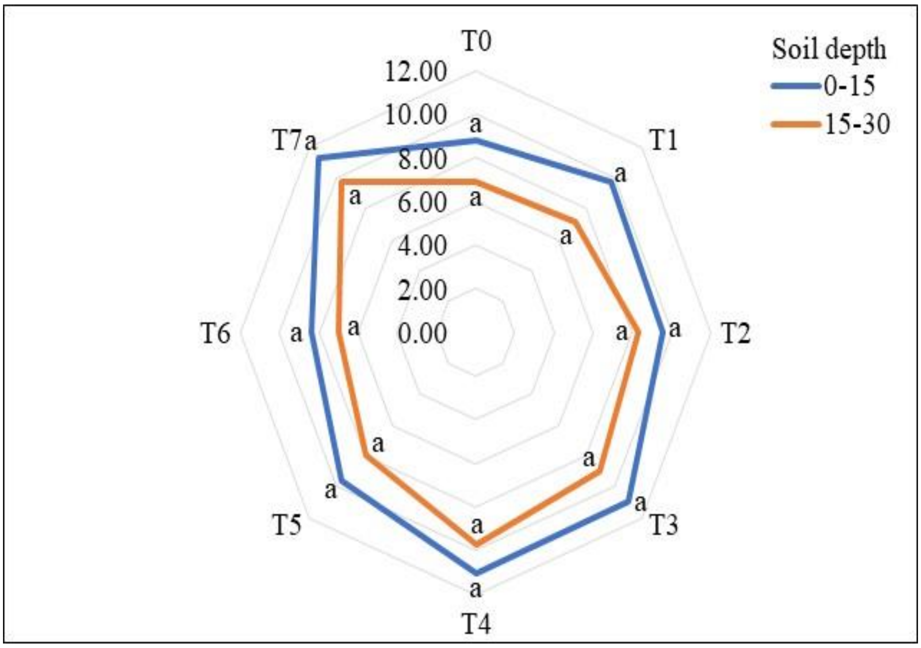
(D)

Figure 5.6. Available N under different treatments (T0-T7) and different soil depths (cm) in 2019 before sowing (C) and after harvest (D). Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Analysis of variance shows that the differences in available P content between amended and non-amended soils were not significant (Figure 5.7 and 5.8). This is in contrast to the findings by Lehmann et al. (2012), who reported an increase in the available P content after biochar application in Anthrosols and Ferralsols. Similarly, Parvage et al. (2013) also found an increase in soil available P with the addition of biochar. One probable reason for the observed non-significant effect of biochar in our study may be attributed to the considerable quantity of free Ca^{2+}, Mg^{2+}, and Fe^{3+} oxides present in the biochar which acted as P sorption sites (Xu et al., 2014). In addition, the availability of P was strongly dependent on the pH of the solution; a high pH helped precipitate phosphate into less soluble forms (Marks et al., 2014). Meanwhile, the available K content increased with the addition of biochar with and without vermicompost in both the soil depths compared with the control before sowing. In contrast, the soil available K content was lower in some biochar amended plots than in the control after harvest (Figure 5.9). This result however, was not consistent in the second year with the biochar amended soils showing higher available K content in relative to control (Figure 5.10). Increased plant-available K in the soil was a result of the biochar's high K concentration (Mengel and Kerby, 2001). According to certain research, biochar may have preserved K^+ in a Typic Plinthudult soil by means of electrostatic attraction forces (Yao et al., 2012). Biochar was found by Yuan et al. (2016) to have a higher K^+ retention effect, resulting in a reduction of 7.9–23.4% in K^+ release. In addition, the available N, available P and available K of the soil decreased in the sub soil layer as compared to the surface layer.

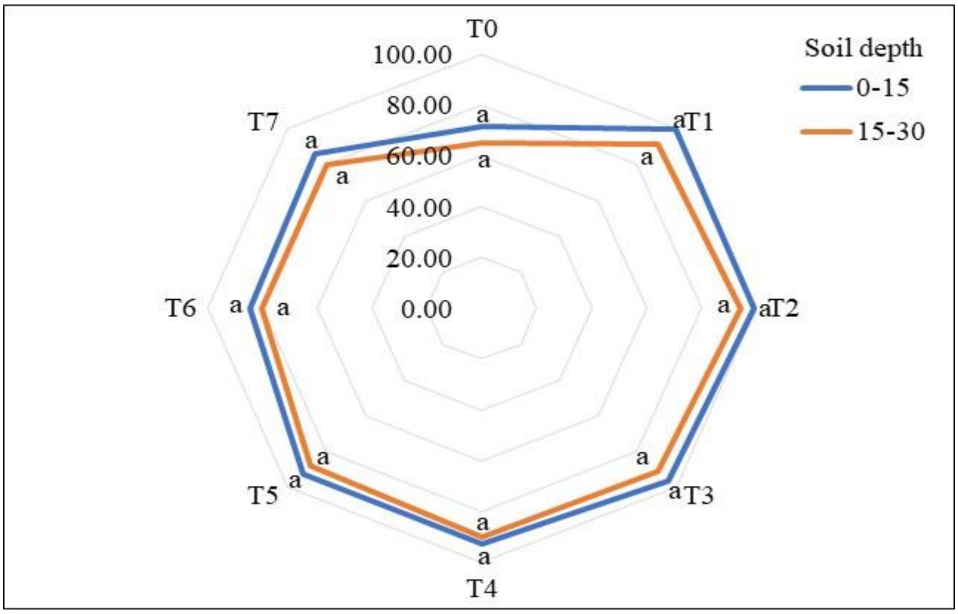


(E)

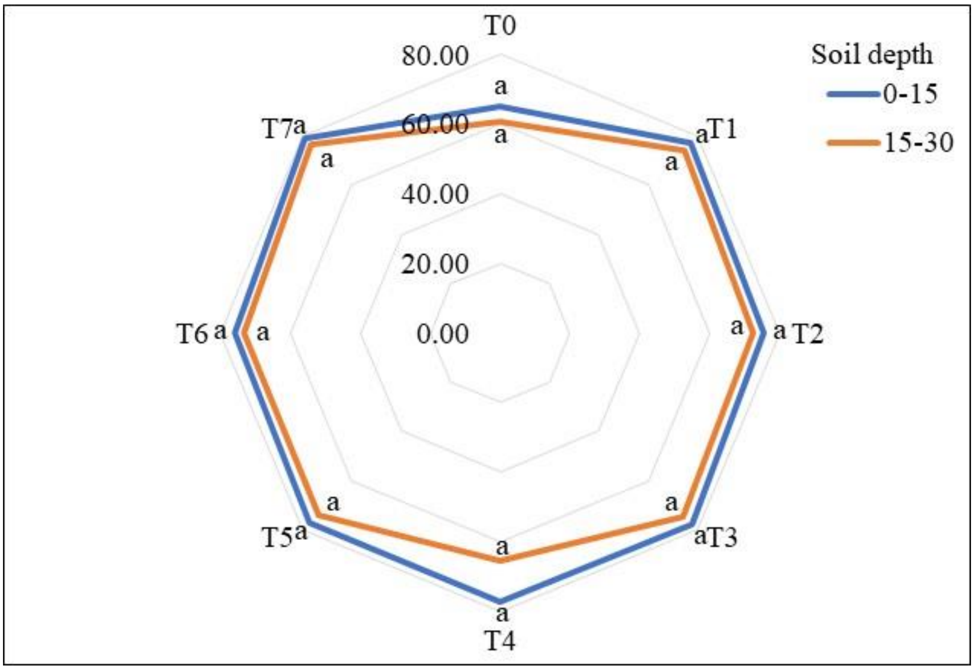


(F)

Figure 5.7. Available P under different treatments (T0-T7) and different soil depths (cm) in 2018 before sowing (E) and after harvest (F). Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

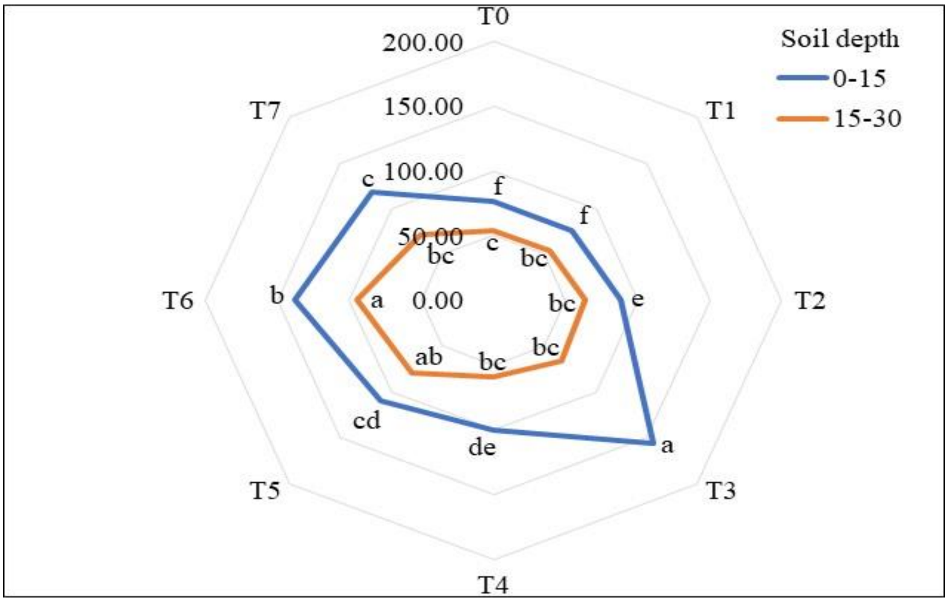


(G)

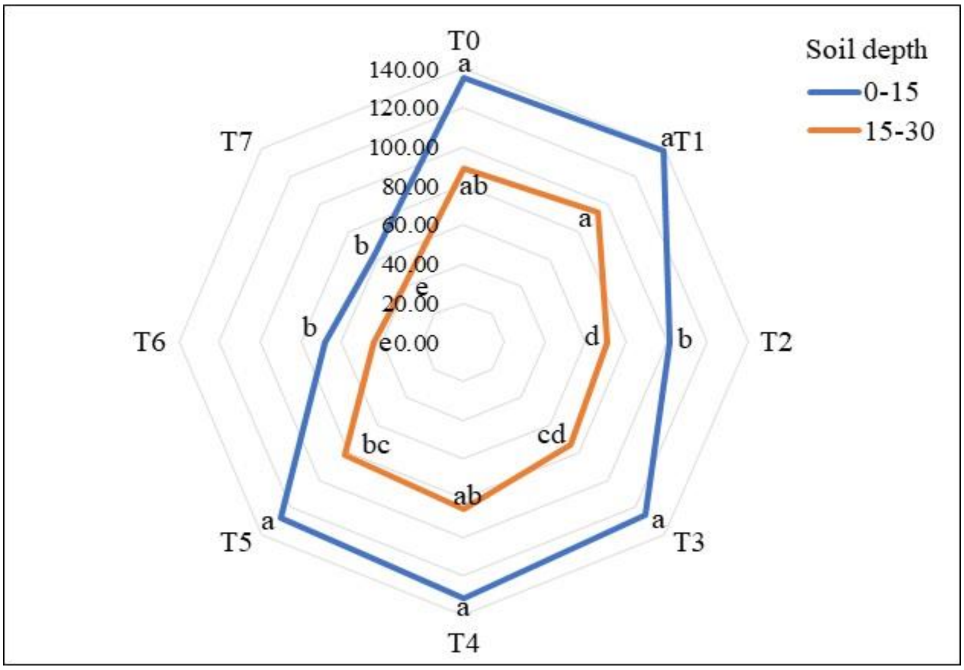


(H)

Figure 5.8. Available P under different treatments (T0-T7) and different soil depths (cm) in 2019 before sowing (G) and after harvest (H). Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

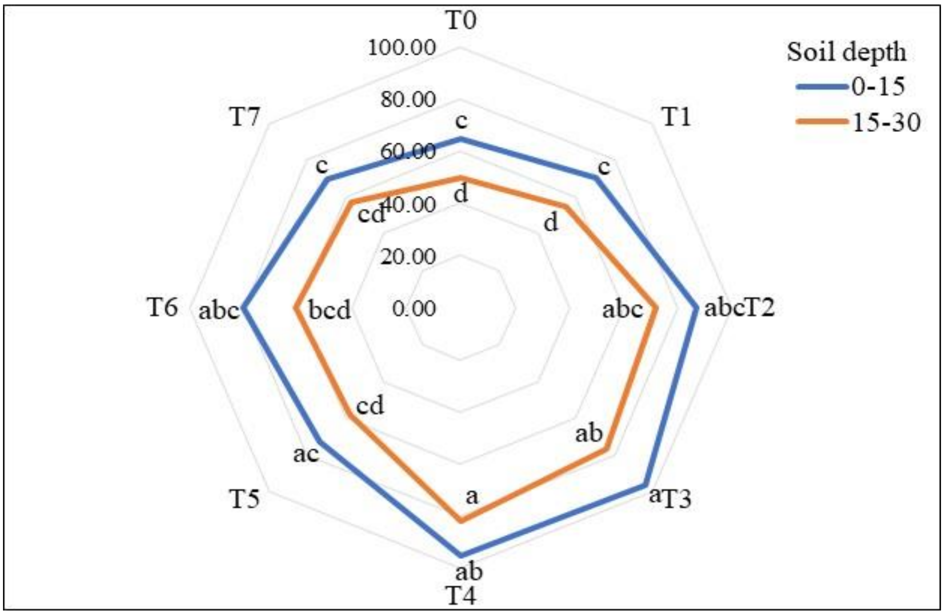


(I)

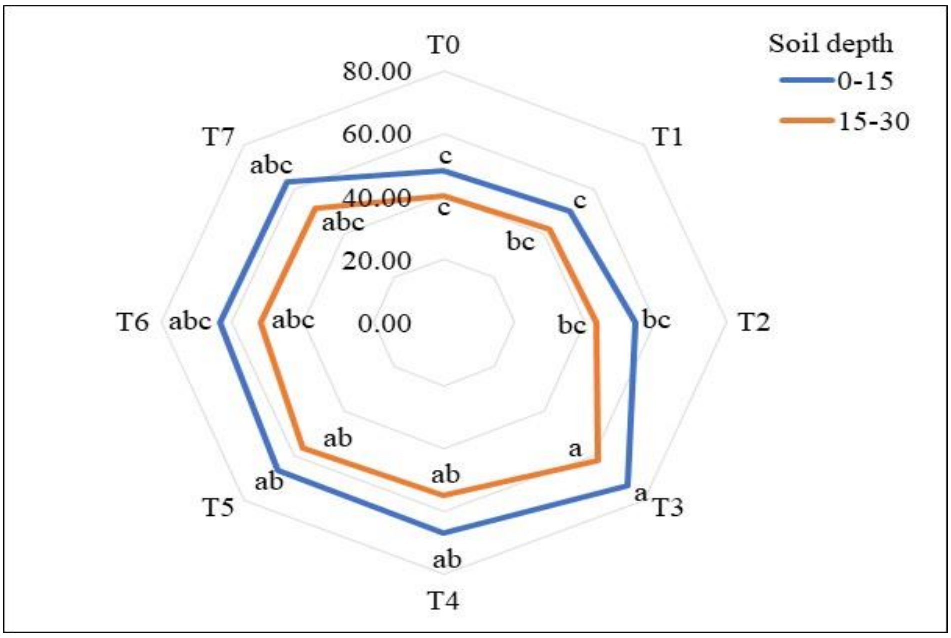


(J)

Figure 5.9. Available K under different treatments (T0-T7) and different soil depths (cm) in 2018 before sowing (I) and after harvest (J). Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.



(K)



(L)

Figure 5.10. Available K under different treatments (T0-T7) and different soil depths (cm) in 2019 before sowing (K) and after harvest (L). Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

5.5 Conclusion

It is evident from the results that the application of biochar and vermicompost decreased the bulk density of the soil during the initial sampling. Addition of amendments also increased the soil pH, organic matter, and cation exchange capacity of the soil. However, the effects diminished in the second year as biochar was applied only once @5 t ha^{-1} during the course of the experiment implying that re-application of biochar and at a higher rate might be necessary. Available N and K were also found to be higher in biochar amended soils as compared to un-amended soils, but no significant effect was observed in case of available P. From the findings of this study, it can be concluded that biochar application is safe and feasible for soil and environmental management. However, it is imperative that biochar should be applied in combination with manures or organic fertilizers rather than applying it solely on the soil.

Chapter 6

To assess soil carbon pool in jhumland with the application of biochar and vermicompost

6.1 Introduction

One of the biggest problems the modern world is experiencing is global warming. It is clearly beyond dispute that temperatures are rising and doing so at an unexpected rate (Prabha et al., 2015). With the industrial period, which began in the 1880s, the average world temperature has risen by 0.8°C. If things continue as they are, this increase could reach 3–7°C by 2100 (Prabha et al., 2015). The main effects of intensifying agriculture are the release of carbon (C) into the atmosphere as carbon dioxide (CO_2), which lowers the amount of C pools in ecosystems. 10% to 12% of all anthropogenic greenhouse gas emissions worldwide come from agriculture. Reducing greenhouse gas emissions is necessary to address the problems posed by climate change (Krishnakumar et al., 2014).

An essential component of the global carbon cycle is soil. The primary terrestrial sink of carbon dioxide (CO_2) that releases it into the atmosphere is soil. The application of biochar to soils is gaining popularity as a way to enhance soil quality and sequester carbon (Lehmann et al., 2006; Lehmann, 2007; Laird, 2008). With the additional benefits of carbon sequestration and enhanced soil properties, biochar—which frequently has a significant ash component that is alkaline in nature—can be utilised as a lime substitute (Cornelissen et al., 2013; Kelly et al., 2014; Kimetu et al., 2008; Martinsen et al., 2015; Yamato et al., 2006). Numerous studies have demonstrated the possible use of biochar to mitigate climate change by balancing carbon emissions from the burning of fossil fuels (Lehmann, 2007; Laird, 2008). The CO_2 efflux from soil metabolic processes—which are impacted by numerous soil properties—is known as soil C mineralization. Because soil organic C can decay and eventually return to the atmosphere, its quantity and availability have a significant effect on the atmospheric CO_2 concentration (Lal et al., 2007). Several physicochemical characteristics of the soil influence the rate at which soil organic C decomposes. For example, the amount of primed CO_2 emission rose with rising soil pH, according to Blagodatskaya and Kuzyakov's (2008) research. Changes in soil microbial biomass and activity may be partially caused by modifications to soil characteristics, such as surface area, pH, and C/N ratio. These changes may then have an impact on the mineralization of soil carbon, according to Warnock et al.

(2007). However, the literature's findings regarding the mineralization of carbon in soils after the addition of biochar are inconsistent. Due to the highly condensed aromatic structure's physical resistance to degradation, Novak et al. (2010) found that the addition of biochar had no discernible effect on the mineralization of soil C. Meanwhile, owing to the short-term breakdown of the biochar's labile components, Zimmerman et al. (2011) found that biochar produced at low temperatures promoted C mineralization whereas biochar produced at high temperatures reduced C mineralization. According to Luo et al. (2011), soil C mineralization was consistently aided by biochars produced at varying temperatures during pyrolysis. The varied outcomes should be explained by the concomitant changes in the physicochemical properties of the soil after biochar applications, in addition to the variations in the soils and biochars utilised in these investigations (Sohi et al. 2010). Understanding biochar's effects on soil C residence time and SOM is essential to appreciating its potential in agronomic and environmental applications.

Therefore, this chapter aims to identify the changes on the total organic carbon (TOC) and the different fractions of the total organic carbon in soil upon biochar's addition.

6.2 Materials and Methods

Using a CHNS analyzer, the total carbon (TC) in the soil samples was ascertained. Diluted HCl was used to analyse inorganic soil carbon (SIC) (Jackson, 1973). The concentration of SIC in soil was subtracted from total carbon (TC) to estimate the amount of TOC present. In a modified version of the Walkley and Black (1947) method, solutions with varying H_2SO_4 concentrations at stable $K_2Cr_2O_7$ concentrations are used to classify the various pools of C according to their degrees of lability (Chan et al., 2001). Three acid-aqueous solution ratios of 0.5:1, 1:1, and 2:1 were obtained by using 5, 10, and 20 millilitres of concentrated H_2SO_4 (corresponding to 12N, 18N, and 24N of H_2SO_4). The conventional Walkley and Black (1934) technique is equal to the 24N H_2SO_4 oxidizable C. The organic carbon (TOC) was separated into the following four fractions of decreasing oxidizability/lability based on the concentration of OC, which was calculated using the three ratios of acid to aqueous solution.

1. Very labile (VLC): Organic C oxidizable under 12N H_2SO_4
2. Labile (LC): Difference in SOC oxidizable under 18N and that under 12N H_2SO_4
3. Less labile (LLC): Difference in SOC oxidizable under 24N and that under 18N H_2SO_4
4. Recalcitrant/ Non-labile (NLC): Residual SOC after reaction with 24N H_2SO_4 when compared
with TOC.

The very labile and labile pool may be summed up and it may be designated as active pool. Similarly, less labile and non-labile pool may be summed up and designated as passive pool

6.3 Statistical analysis

Tukey HSD (honestly significant difference) post hoc test was performed to indicate significant differences ($p < 0.05$) among the treatments. Figures were prepared using MS EXCEL and using SPSS for windows (IBM SPSS ver. 20.0).

6.4 Results and Discussion

The mean total carbon (TC), inorganic carbon (TIC) and total organic carbon (TOC) concentration in soil (0-30 cm) under different treatments before sowing and after harvest in 2018 are displayed in Table 6.1. TC was highest in T7 (3.63 %) followed by T2 (3.62 %) and least in T0 (3.08 %). TIC concentration was not significantly affected by biochar addition and ranged from 0.11 to 0.18 % on average across various treatments. The highest TOC concentration was found in T5 (3.86%) followed by T2 (3.46 %) and least in T0 (2.89 %) and the differences were significant between the amended and unamended plots. The effect of biochar application persisted in the second year with T5 again recording the highest mean TC followed by T3 and T0 recording the least measured at both sampling times (Table 6.2). No significant differences were observed in the TIC concentration among the treatments. Soil contains both inorganic and organic forms of TC. $CaCO_3$ is the predominant form of inorganic carbon. Nevertheless, given that the research region is located in an area with moderate rainfall and acidic soil, it is doubtful that the soils contain $CaCO_3$. Therefore, the majority of the carbon in these soils most likely only exists in organic form. These outcomes are consistent with those of Syed (2010) and Arunkumar et al. (2019). The increase in total organic carbon with the addition of biochar as seen in our results could be due to the high carbon content in the biochar. Another reason could be due to the increased input of fresh organic carbon following the application of biochar, which enhanced crop biomass, particularly root biomass. Agricultural land can benefit from the use of biochar for soil improvement (Bai et al., 2015; Chen et al., 2020), however the impact varies depending on the type of biochar used (Liu et al., 2016), the amount of input used (Amoakwah et al., 2020; Han et al., 2021), the temperature at which it is manufactured (Deng et al., 2021), and the characteristics of the soil (Subedi et al., 2016; He et al., 2016). However, adding degradation-resistant biochar to the soil enhances the soil's SOC (Yang et al., 2020; Wang et al., 2020) and restores its biological, chemical, and physical properties (Tarin et al., 2021; Gross et al., 2022). Moreover, the combined application of biochar and vermicompost markedly increase the organic carbon content of the soil as compared to the other treatments. In addition to providing soil with a direct source of carbon, the application of mineral fertiliser (BC300 + NPK and BC500 + NPK) in conjunction with biochar promotes the addition of carbon to the soil by providing nutritional balance and crop residues as a source of carbon (Faria et al., 2018). Fischer and Glaser (2012) recommend combining the use of mineral fertiliser and biochar to ensure that the combined benefits of improving soil quality and crop productivity are realised. The study conducted by Liu et al. (2012) also demonstrated that using biochar alone might not be sufficient to provide plants with the nutrients they need; rather, combining it with other chemicals could result in a more sustainable source of soil nutrients.

Table 6.1. Total carbon (TC), soil inorganic carbon (SIC) and total organic carbon (TOC) in 0-30 cm soil depth under different treatments in 2018.

Sampling	Treatment	TC (%)	TIC (%)	TOC (%)
Before sowing	T0	3.08±0.02[b]	0.18±0.01[a]	2.89±0.02[b]
	T1	3.17±0.13[b]	0.15±0.04[a]	3.03±0.10[bc]
	T2	3.62±0.06[a]	0.17±0.01[a]	3.46±0.07[a]
	T3	3.45±0.07[a]	0.16±0.02[a]	3.29±0.08[ab]
	T4	3.49±0.15[a]	0.15±0.01[a]	3.34±0.14[a]
	T5	3.37±0.06[ab]	0.11±0.01[a]	3.86±0.06[a]
	T6	3.46±0.05[a]	0.14±0.01[a]	3.32±0.06[ab]
	T7	3.63±0.03[a]	0.16±0.04[a]	3.47±0.01[a]
After harvest	T0	2.89±0.08[b]	0.18±0.2[a]	2.71±0.07[b]
	T1	3.11±0.06[b]	0.20±0.01[a]	2.91±0.07[b]
	T2	3.71±0.03[a]	0.20±0.03[a]	3.51±0.01[a]
	T3	3.66±0.06[a]	0.16±0.01[a]	3.50±0.06[a]
	T4	3.36±0.07[a]	0.23±0.01[a]	3.13±0.06[a]
	T5	3.70±0.11[a]	0.13±0.01[a]	3.57±0.09[a]
	T6	3.56±0.07[a]	0.18±0.04[a]	3.38±0.08[a]
	T7	3.45±0.04[a]	0.17±0.02[a]	3.28±0.03[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). TC-total carbon, TIC-total inorganic carbon, TOC-total organic carbon. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 6.2. Total carbon (TC), soil inorganic carbon (SIC) and total organic carbon (TOC) in 0-30 cm soil depth under different treatments in 2019.

Sampling	Treatment	TC (%)	SIC (%)	TOC (%)
Before sowing	T0	2.66±0.10^{c}	0.19±0.02^{a}	2.47±0.11^{c}
	T1	2.88±0.08^{bc}	0.18±0.01^{a}	2.70±0.08^{bc}
	T2	3.19±0.02^{a}	0.16±0.01^{a}	3.03±0.03^{a}
	T3	3.30±0.03^{a}	0.16±0.04^{a}	3.15±0.03^{a}
	T4	3.28±0.01^{a}	0.18±0.02^{a}	3.11±0.02^{a}
	T5	3.32±0.04^{a}	0.17±0.02^{a}	3.15±0.04^{a}
	T6	3.11±0.09^{ab}	0.16±0.03^{a}	2.94±0.09^{a}
	T7	3.18±0.02^{a}	0.16±0.04^{a}	3.01±0.03^{a}
After harvest	T0	2.51±0.05^{b}	0.18±0.01^{a}	2.33±0.04^{b}
	T1	2.54±0.09^{b}	0.17±0.03^{a}	2.37±0.09^{b}
	T2	3.04±0.02^{a}	0.17±0.01^{a}	2.87±0.02^{a}
	T3	3.08±0.07^{a}	0.16±0.03^{a}	2.92±0.04^{a}
	T4	3.03±0.07^{a}	0.18±0.04^{a}	2.85±0.03^{a}
	T5	3.14±0.04^{a}	0.18±0.02^{a}	2.97±0.03^{a}
	T6	2.98±0.04^{a}	0.16±0.01^{a}	2.82±0.03^{a}
	T7	3.03±0.03^{a}	0.24±0.03^{a}	2.79±0.05^{a}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

SOC concentration of varying lability measured before sowing and after harvest in 2018 are displayed in Table 6.3 and 6.4. Biochar amendment significantly affected the VLC fraction of the TOC before sowing. Soil VLC under different treatments ranged from 1.41 % in T0 to 1.92 % in T5 in the upper soil profile, whereas in the subsequent layer, it ranged from 1.27 to 1.79 in T0 and T7 %, respectively. The LC fraction of the soil was also significantly impacted by the addition of biochar with the average values ranging from 0.63 % in T6 to 0.93 % in both T1 and T3. No significant differences were found in LLC fraction among the treatments at 0-15 cm soil depth, but were significantly different at 15-30 cm soil depth. The soil NLC fraction of the soil were not significantly affected by the addition of amendments. Meanwhile, the most easily mineralizable carbon or VLC portion of the soil analysed after harvest ranged from 1.58 to 1.88 % and 1.27 to 1.79 %, respectively in the surface and the sub surface layer of the soil. The LC fraction of the 0-15 cm soil was highest in T5 followed by T6 and least in T0 with 1.13, 1.10 and 0.62 %, respectively. Whereas, the highest value of the same at 15-30 cm soil depth was found in T5 and least in T0 with 1.06 and 0.60 %, respectively. No significant differences were found in the LLC fraction of the soil among the different treatments at both the soil depth. On the other hand, biochar addition affected only the NLC fraction in the sub surface layer. In the second year, significant differences were again observed in the VLC portion of the soil with the average values ranging from 1.20 to 1.80 % and 0.96 to 1.63 %, respectively in the two soil depths. LC carbon fraction of the soil ranged from 0.35 to 1.06 %, whereas LLC and NLC fraction did not show any significant differences at 0-15 cm soil depth. In contrast, significant differences were observed among the treatments in both LLC and NLC at 15-30 cm soil depth. The proportion of active carbon pool (VLC and LC) was higher than the passive carbon pool (LLC and NLC) in the amended as well as the control plot at all times of sampling. With an average of 47.89 and 46.64 % over the range of 43.60 to 51.03 % and 41.27 to 51.26 %, respectively across the various treatments, the VLC fraction made up a larger percentage of TOC in the soil measured before sowing and after harvest in the first year (Fig 6.1 and 6.2). Similarly, in the second year, the VLC fraction averaged 48.33 % ranging from 40.44 to 52.69 % before sowing and 46.02 % ranging from 42.16 to 49.57 % after harvest. Overall, the active carbon fraction (VLC and LC) was higher averaging 69.37 % over the passive carbon fraction (LLC and NLC) which constituted 30.63 % before sowing. After harvest, the active carbon fraction averaged 71.43 % whereas the passive carbon pool averaged 28.57 % of the total organic carbon in the first year. Correspondingly, the active carbon fraction averaged 71.99 % over the passive carbon fraction which constituted 28.01 % before sowing and 73.98% over 26.02 % after harvest in the second year. Our findings are in harmony with findings from other studies who also reported increased SOC mineralization after biochar application especially in the initial period (Ouyang et al., 2014; Figueiredo et al., 2018) since biochar produced at a lower temperature contains more labile structures that are easily mineralized when applied to soil (Novotny et al., 2015). Al-Wabel et al. (2013) and Figueiredo et al. (2018) have reported that biochars obtained at lower pyrolysis temperatures, like 300 °C, generally had smaller aromatic structures compared to those obtained at higher pyrolysis temperatures. The mineralization rates, nutrient release, and C buildup in soil of the various biochars are significantly impacted by these variations (Al-Wabel et al., 2013; Melas et al., 2017). Increased native SOM mineralization rate (Intani et al., 2016) caused by the volatile chemicals originating from the feedstock can also modify soil microbial biomass activity (Spokas et al., 2011). By preventing microbial degradation through physical protection, the sorption of biochar with SOM may eventually enhance soil C storage (Zimmerman et al. 2011).

Table 6.3. Soil organic carbon concentration (%) of varying lability at different soil depth classes before sowing in 2018.

Treatment	**Very labile carbon (VLC)**		**Labile carbon (LC)**	
	0-15 cm	15-30cm	0-15 cm	15-30cm
T0	1.41±0.08[bc]	1.27±0.03[c]	0.69±0.09[b]	0.71±0.01[a]
T1	1.55±0.13[bc]	1.38±0.10[bc]	0.93±0.03[a]	0.70±0.07[a]
T2	1.83±0.05[a]	1.56±0.05[a]	0.80±0.03[a]	0.60±0.02[a]
T3	1.83±0.04[ab]	1.67±0.06[a]	0.93±0.03[a]	0.70±0.06[a]
T4	1.85±0.05[a]	1.49±0.04[bc]	0.70±0.02[b]	0.68±0.10[a]
T5	1.86±0.05[ab]	1.74±0.03[a]	0.78±0.03[a]	0.56±0.02[a]
T6	1.79±0.10[a]	1.54±0.02[ab]	0.63±0.02[b]	0.61±0.06[a]
T7	1.92±0.01[a]	1.79±0.03[a]	0.80±0.04[a]	0.77±0.15[a]
	Less labile carbon (LLC)		**Non labile carbon (NLC)**	
T0	0.59±0.08[a]	0.26±0.01[b]	0.60±0.15[a]	0.43±0.04[a]
T1	0.37±0.10[a]	0.36±0.04[b]	0.57±0.07[a]	0.49±0.02[a]
T2	0.58±0.02[a]	0.50±0.04[a]	0.94±0.03[a]	0.20±0.13[a]
T3	0.42±0.06[a]	0.41±0.03[ab]	0.54±0.16[a]	0.40±0.07[a]
T4	0.58±0.08[a]	0.26±0.04[b]	0.79±0.04[a]	0.62±0.11[a]
T5	0.61±0.05[a]	0.57±0.01[a]	0.77±0.02[a]	0.42±0.16[a]
T6	0.62±0.03[a]	0.53±0.05[a]	0.78±0.08[a]	0.33±0.21[a]
T7	0.66±0.03[a]	0.47±0.15[a]	0.73±0.13[a]	0.30±0.04[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 6.4. Soil organic carbon concentration (%) of varying lability at different soil depth classes after harvest in 2018

Treatment	Very labile carbon (VLC)		Labile carbon (LC)	
	0-15 cm	15-30cm	0-15 cm	15-30cm
T0	1.58±0.04[c]	1.38±0.03[c]	0.62±0.14[c]	0.60±0.09[c]
T1	1.60±0.04[c]	1.52±0.03[ab]	0.76±0.09[bc]	0.65±0.01[c]
T2	1.70±0.01[b]	1.60±0.01[a]	0.91±0.03[a]	0.84±0.01[ab]
T3	1.81±0.01[ab]	1.52±0.03[ab]	1.01±0.01[ab]	0.90±0.04[a]
T4	1.63±0.02[c]	1.55±0.01[ab]	0.85±0.03[ac]	0.69±0.10[c]
T5	1.83±0.03[a]	1.48±0.05[ab]	1.13±0.04[a]	1.06±0.02[a]
T6	1.77±0.03[ab]	1.46±0.03[ab]	1.10±0.01[a]	0.83±0.04[ab]
T7	1.88±0.05[a]	1.40±0.04[b]	1.00±0.06[a]	0.89±0.04[ab]
	Less labile carbon (LLC)		**Non labile carbon (NLC)**	
T0	0.39±0.09[a]	0.37±0.10[a]	0.37±0.07[a]	0.44±0.07[b]
T1	0.42±0.01[a]	0.47±0.01[a]	0.58±0.02[a]	0.26±0.02[c]
T2	0.47±0.01[a]	0.46±0.02[a]	0.83±0.05[a]	0.36±0.05[c]
T3	0.42±0.04[a]	0.35±0.01[a]	0.84±0.08[a]	0.73±0.08[a]
T4	0.48±0.10[a]	0.52±0.05[a]	0.52±0.05[a]	0.32±0.05[c]
T5	0.54±0.02[a]	0.54±0.02[a]	0.64±0.20[a]	0.53±0.20[ab]
T6	0.41±0.04[a]	0.47±0.03[a]	0.69±0.02[a]	0.36±0.02[c]
T7	0.44±0.05[a]	0.54±0.01[a]	0.44±0.03[a]	0.30±0.02[c]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 6.5. Soil organic carbon concentration (%) of varying lability at different soil depth classes before sowing in 2019.

Treatment	Very labile carbon (VLC)		Labile carbon (LC)	
	0-15 cm	15-30cm	0-15 cm	15-30cm
T0	1.20±0.10[b]	0.96±0.06[b]	0.35±0.09[b]	0.69±0.03[a]
T1	1.32±0.08[b]	1.05±0.03[b]	0.69±0.14[ab]	0.73±0.02[a]
T2	1.69±0.02[a]	1.38±0.11[a]	0.59±0.13[ab]	0.70±0.18[a]
T3	1.73±0.03[a]	1.53±0.02[a]	0.78±0.09[ab]	0.90±0.02[a]
T4	1.74±0.02[a]	1.58±0.05[a]	0.85±0.05[ab]	0.76±0.10[a]
T5	1.80±0.01[a]	1.63±0.02[a]	1.06±0.01[a]	0.63±0.07[a]
T6	1.73±0.02[a]	1.53±0.03[a]	0.83±0.12[ab]	0.75±0.05[a]
T7	1.78±0.03[a]	1.62±0.04[a]	0.77±0.11[ab]	0.81±0.01[a]
	Less labile carbon (LLC)		**Non labile carbon (NLC)**	
T0	0.66±0.14[a]	0.59±0.01[ab]	0.50±0.04[a]	0.38±0.10[a]
T1	0.70±0.04[a]	0.63±0.08[ab]	0.36±0.08[a]	0.29±0.02[ab]
T2	0.49±0.01[a]	0.72±0.09[a]	0.51±0.13[a]	0.30±0.02[ab]
T3	0.51±0.03[a]	0.50±0.01[ab]	0.45±0.07[a]	0.21±0.02[ab]
T4	0.60±0.02[a]	0.37±0.10[b]	0.37±0.01[a]	0.28±0.02[ab]
T5	0.44±0.04[a]	0.43±0.01[ab]	0.29±0.09[a]	0.35±0.12[ab]
T6	0.45±0.06[a]	0.37±0.04[b]	0.36±0.06[a]	0.19±0.02[ab]
T7	0.63±0.05[a]	0.39±0.06[b]	0.34±0.05[a]	0.15±0.05[b]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 6.6. Soil organic carbon concentration (%) of varying lability at different soil depth classes after harvest in 2019.

Treatment	Very labile carbon (VLC)		Labile carbon (LC)	
	0-15 cm	15-30cm	0-15 cm	15-30cm
T0	1.12±0.06[b]	0.97±0.06[d]	0.93±0.05[a]	0.32±0.08[a]
T1	1.25±0.01[b]	1.05±0.07[cd]	0.99±0.04[a]	0.49±0.16[a]
T2	1.51±0.06[a]	1.23±0.05[bc]	0.94±0.10[a]	0.94±0.02[a]
T3	1.60±0.02[a]	1.48±0.02[a]	0.73±0.03[a]	0.66±0.07[a]
T4	1.53±0.03[a]	1.47±0.04[a]	0.86±0.04[a]	0.77±0.01[a]
T5	1.62±0.05[a]	1.50±0.02[a]	0.86±0.11[a]	0.85±0.03[a]
T6	1.52±0.07[a]	1.31±0.04[ab]	0.94±0.03[a]	0.76±0.16[a]
T7	1.60±0.03[a]	1.35±0.03[ab]	0.81±0.06[a]	0.79±0.02[a]
	Less labile carbon (LLC)		**Non labile carbon (NLC)**	
T0	0.18±0.07[c]	0.36±0.17[c]	0.24±0.07[a]	0.89±0.32[a]
T1	0.13±0.02[c]	0.43±0.31[bc]	0.25±0.07[a]	0.49±0.08[a]
T2	0.64±0.02[ab]	0.32±0.02[a]	0.19±0.01[a]	0.33±0.03[a]
T3	0.66±0.05[ab]	0.41±0.07[ac]	0.16±0.06[a]	0.35±0.01[a]
T4	0.60±0.03[ab]	0.21±0.01[a]	0.11±0.02[a]	0.24±0.03[a]
T5	0.64±0.07[ab]	0.22±0.01[ab]	0.16±0.02[a]	0.27±0.03[a]
T6	0.41±0.16[bc]	0.16±0.03[a]	0.33±0.14[a]	0.41±0.03[a]
T7	0.78±0.05[a]	0.20±0.08[a]	0.18±0.02[a]	0.29±0.03[a]

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

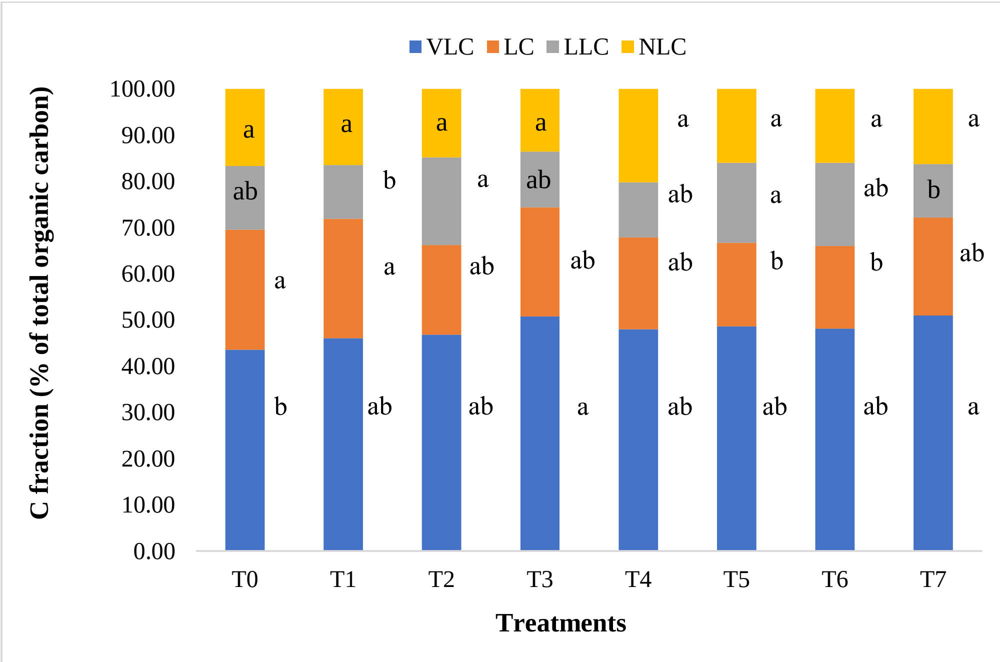


Figure 6.1. Distribution of soil organic carbon fraction of varying lability (% of total carbon) at 0-30 cm soil depth before sowing in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

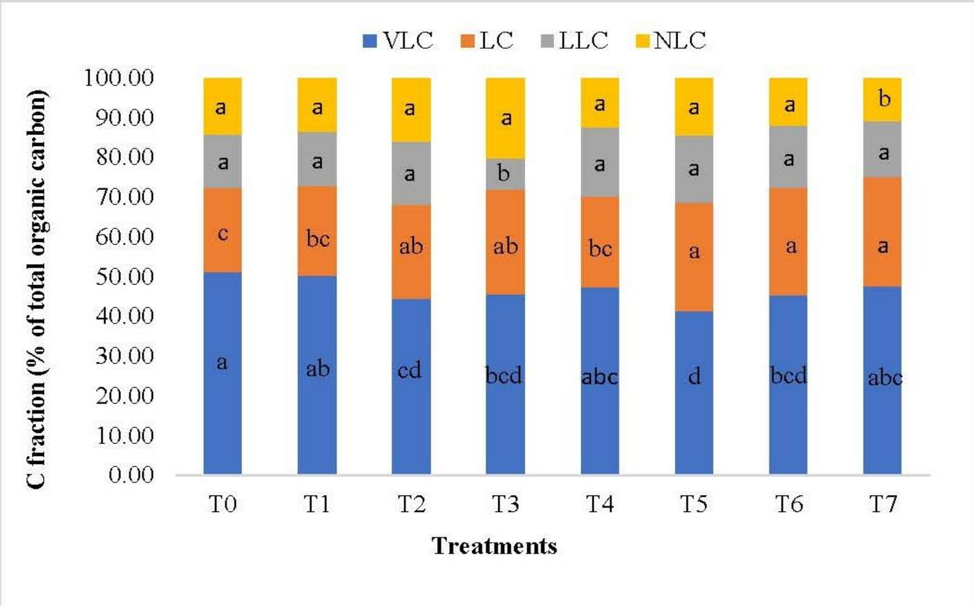


Figure 6.2. Distribution of soil organic carbon fraction of varying lability (% of total carbon) at 0-30 cm soil depth after harvest in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_5-vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

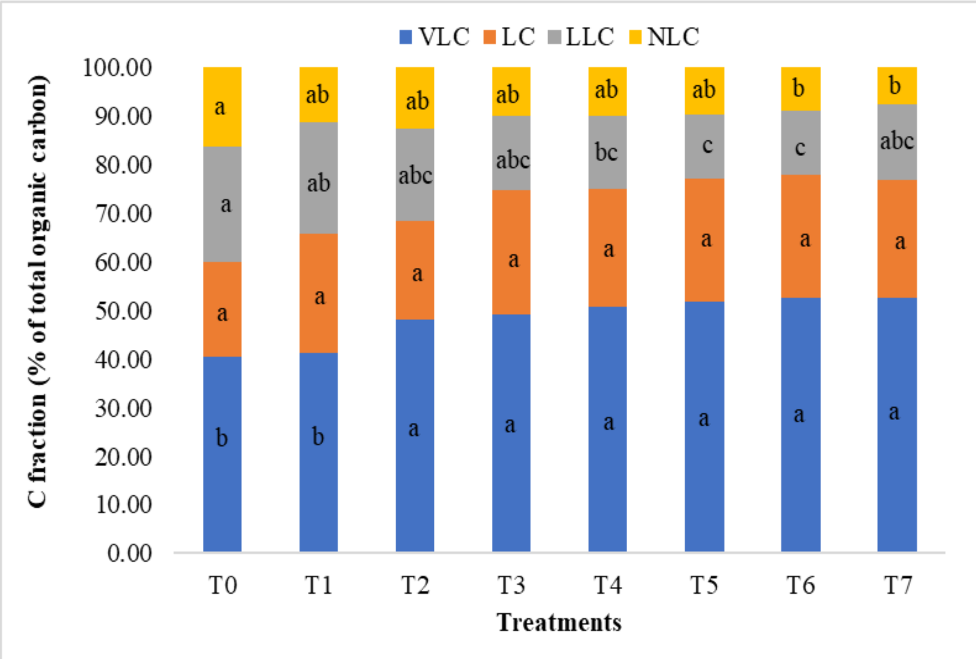


Figure 6.3. Distribution of soil organic carbon fraction of varying lability (% of total carbon) at 0-30 cm soil depth before sowing in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

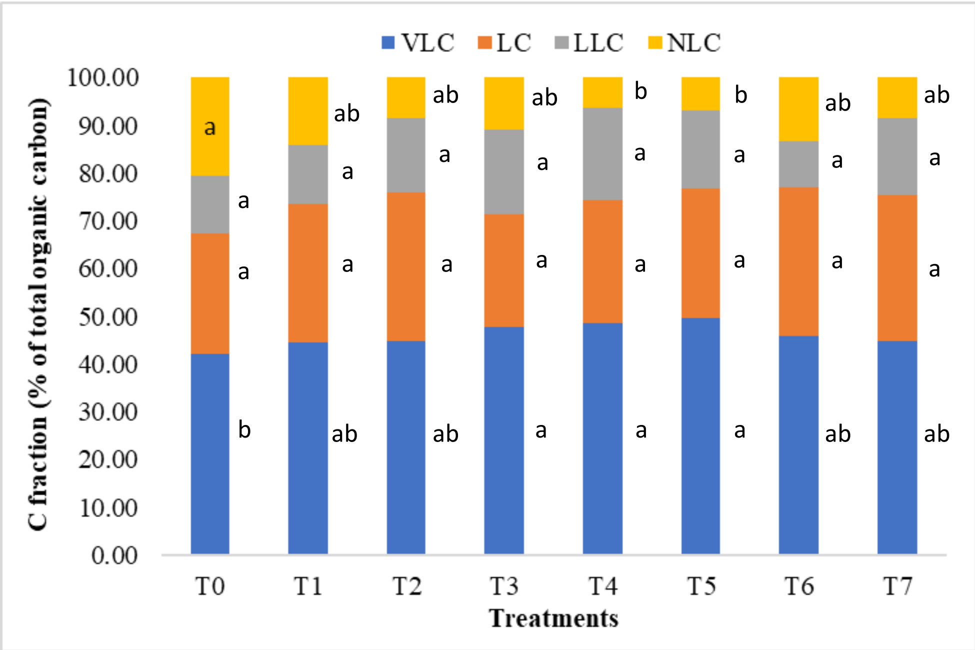


Figure 6.4. Distribution of soil organic carbon fraction of varying lability (% of total carbon) at 0-30 cm soil depth after harvest in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Furthermore, we observed a significant difference in the very labile fraction (VLC) of the carbon pool between the first and second year. The VLC fraction of the carbon pool decreased significantly in the second year as compared to the first year (Table 6.7 and 6.8) indicating that biochar in the soil became more stable overtime. When soil with artificial or fresh char is incubated, CO_2 evolution is generally higher than when the same soil is not altered with char. In the short run, however, the degree of excess decreases over time in a significantly non-linear pattern (Bruun et al., 2008; Nguyen and Lehmann, 2009). This implies a "priming" of the carbon's breakdown, either from the carbon in the added char or from the carbon already present in the soil. It is well known that charcoal can withstand the effects of weather for decades, centuries, millennia, or even tens of thousands of years when buried in the soil. However, some research indicates that some recently produced charcoal is less weather-resistant than others, and that this charcoal could easily decompose and release carbon dioxide into the atmosphere. The carbon that is easily broken down in contrast to the carbon that is resistant to breaking down, is known as "labile" carbon. Studies by Brodowski et al. (2006) and Nguyen et al. (2009) have shown that the labile fraction of biochar typically makes up 2–10% of the total carbon content of the material. However, uncertainties remain regarding the parameters that control the ratio of labile to stable components. This could probably be affected by the type of pyrolysis method (e.g., slow vs. quick pyrolysis), the feedstock type, and the temperature and residence durations that the biomass is exposed to and therefore

requires further investigation.

Table 6.7. SOC Concentration (%) of varying lability at 0-30 cm soil depth between 2018 and 2019 before sowing.

Treatments	VLC		LC		LLC		NLC	
	P	F	P	F	P	F	P	F
T0	**0.035**	9.732	**0.007**	26.427	0.073	05.841	0.512	0.516
T1	0.091	4.921	0.218	2.127	**0.014**	17.202	0.103	4.443
T2	0.068	6.141	0.136	3.471	0.159	2.991	0.155	3.056
T3	**0.021**	13.690	0.679	0.199	0.126	3.714	0.117	3.968
T4	0.789	0.082	0.266	1.671	0.491	0.574	**0.013**	18.164
T5	0.105	4.361	**0.015**	16.462	**0.015**	17.034	0.068	6.197
T6	0.471	0.632	0.080	5.419	**0.003**	44.522	**0.013**	18.431
T7	**0.007**	24.486	0.756	0.111	0.667	0.215	**0.002**	58.671

The significant values (p <0.05) are in bold. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each, T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 6.8. SOC Concentration (%) of varying lability at 0-30 cm soil depth between 2018 and 2019 after harvest.

Treatments	VLC		LC		LLC		NLC	
	P	F	P	F	P	F	P	F
T0	**0.003**	44.449	0.808	0.067	0.400	0.886	0.446	0.649
T1	**0.001**	62.517	0.718	0.151	0.405	0.865	0.330	1.225
T2	**0.009**	22.189	0.305	1.385	**0.006**	27.676	**0.002**	57.658
T3	**0.000**	169.882	0.821	0.058	**0.003**	42.123	**0.000**	137.651
T4	**0.002**	54.724	**0.000**	436.364	**0.040**	8.974	**0.000**	127.512
T5	**0.007**	26.884	0.246	1.842	**0.001**	63.074	**0.042**	8.678
T6	**0.012**	19.003	0.714	0.155	**0.055**	7.246	**0.787**	0.884
T7	**0.002**	58.266	0.561	0.400	0.904	0.016	**0.148**	3.199

The significant values (p <0.05) are in bold. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5}- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.to fully understand the mechanism between biochar and soil C turnover.

6.5 Conclusion

The effect of biochar produced from sugarcane bagasse and maize cob on soil C turnover were investigated in this study. Application of biochar significantly increased the total organic carbon of the soil especially in the soils amended with the combined application of biochar and vermicompost. The very labile fraction of the carbon pool was enhanced by the addition of biochar corroborating the existing knowledge that biochar produced at a lower temperature (<500° C) result in a C-rich product with more labile structures that are rapidly mineralized when applied to soil. Therefore, if the main aim of biochar application is to sequester C in the soil, biochars produced from higher temperature is recommended. However, we observed that the VLC fraction of the soil declined in due course of time indicating that the biochar in soil became more stable with time demonstrating the ability of biochar in sequestering carbon. Nevertheless, this is only a short-term study, hence a longer and more detailed investigation is needed in order to fully understand the mechanism between biochar and soil C turnover.

Chapter 7

To determine the effect of biochar and vermicompost on the growth and yield of soybean in jhumland

7.1 Introduction

The agricultural sector is confronted with enormous challenges in the future, including the need to (i) produce enough food to feed the world's expanding population (Foley et al., 2011; Godfray et al., 2010); (ii) lessen the environmental impact of agricultural intensification brought about by the "green revolution," which has exceeded planetary boundaries (Campbell et al., 2017; Steffen et al., 2015); and (iii) reduce the increasing reliance on non-renewable phosphate rock (Elser & Bennett, 2011). Two significant concerns endangering the sustainability of agricultural output are the depletion of soil nutrients and climate change caused by human activity (Sanchez, 2002). For the past 50 years, since the "green revolution," inorganic fertilisers have been essential to raising agricultural output and sustaining productivity (Gruhn et al., 2000). But using these chemical fertilisers by itself isn't a long-term way to maintain crop productivity and enhance soil fertility. Instead, it is generally known that excessive use of chemical fertilisers, especially nitrogen, can cause severe environmental issues and soil deterioration as SOM mineralizes more quickly, leading to a drastic decrease in soil carbon reserves (Foley et al., 2005). Agricultural productivity techniques, soil conservation, and management depend on maintaining sufficient amounts of soil organic matter (SOM) and guaranteeing efficient biological nutrient cycling (Vanlauwe et al., 2010). In order to maximise the agronomic performance of applied nutrients and, consequently, crop yield, these techniques involve the use of both organic and inorganic fertilisers along with an understanding of how to modify these practices to local conditions (Vanlauwe et al., 2010). Nonetheless, it is thought that one major barrier to the widespread use of organic fertilisers is the SOM's innately quick mineralization. Thus, in order to help boost yields, reduce adverse effects, enhance sustainability, and be available to both subsistence and commercial producers, a new strategy is required (Sohi et al., 2010).

Another major challenge is soil acidity. Approximately half of the world’s potentially cultivable land, predominantly in humid tropical regions, are affected by soil acidity (Von Uexkull and Mutert, 1995). Approximately 49 M hectares, or one-third, of India's arable land is impacted by acidic soil (Mandal, 1997). The main factors limiting crop yield in acidic soils are phosphate (P) inadequacy, aluminium (Al) and iron (Fe) toxicity, and other acidity-related soil fertility and plant nutritional issues (Manoj et al., 2012; Patiram, 1991). Aluminium (Al) saturation can be directly linked to poor crop growth in acidic soils in the majority of cases (Abruna-Rodriguez et al., 1982; Sartain and Kamprath, 1977). Liming acidic soils can lessen soil acidity, but it is not a practical solution for low-income farmers or a good way to reduce subsurface acidity. According to recent research, soil acidity can be reduced by directly applying and incorporating green manures, animal wastes, and agricultural residues (Berek et al., 1995; Hue 1992; Xu, et al., 2006). However, because additional residues quickly mineralize, the reclamation benefits of directly incorporating organic residues into soil are short-lived. One practical solution that can increase soil's natural rates of carbon absorption, decrease farm waste, and boost soil quality is the pyrolysis process, which converts organic waste into biochar (McHenry, 2009).

Biochar technology has a prospect to enhance crop yields and mitigate climate change simultaneously by aiding in the recovery of nutrients from waste (Woolf et al., 2010; Woolf et al., 2016). Research has indicated that the application of biochar can minimise the need for fertiliser and nutrient leaching while also greatly increasing soil aeration, soil base saturation, nutrient storage, and availability (Lehmann et al., 2003, Steiner et al., 2007), SOM (Glaser et al., 2002), and water holding capacity (Abel et al., 2013). Furthermore, studies have demonstrated that biochar enhances plant growth and yield (Lehmann et al., 2006), boosts microbial biomass and activity, and stimulates the soil microbial community (Thies et al., 2015). Nevertheless, the quality of the soil and crop yields are not always enhanced by adding pure biochar to the soil (Hagemann et al., 2017). Because biochar has shown encouraging results in both pot and field studies, its application in conjunction with other organic amendments, such as compost, has garnered interest recently (Kammann et al., 2016; Schimdt et al., 2015). Research reveals that combining fresh organic matter with biochar is an effective way to investigate the possible advantages of these organic amendments for higher plants (Liu et al., 2012). According to Liu et al. (2012), Fischer and Glaser (2012), Schulz and Glaser (2012), and other researchers, a variety of composted materials offer a sustainable source of accessible nutrients that may promote plant growth by enhancing the physicochemical and microbiological characteristics of soil. According to Liu et al. (2012), compost and biochar together have a beneficial synergistic effect on soil nutrient content and water-holding capacity in field settings. Additionally, it was discovered that this combination was more appropriate since it enhanced soil nutrient content and water retention capacity, stabilised soil structure, and used less chemical fertiliser (Fischer and Glaser, 2012). Additionally, because of the long-term stability of biochar, the combination of compost and biochar can improve the characteristics of compost, leading to higher added value and significantly better potential for sequestering carbon (Fischer and Glaser, 2012; Schulz and Glaser, 2012).

Therefore, this chapter aims to investigate the effect of biochar applied alone or co-applied with vermicompost on the growth and yield of soybean in a 2-year experiment.

7.2 Materials and Methods

Prior to sowing, the plots were manually tilled and the treatments were applied within the top 0-15 cm of the soil. The treatments were applied only once in the first year before sowing during the two years experiment. After the applications of the treatments, three seeds were sown per hole in every plot with a row spacing of 20cm x 25cm. One week after sowing, two plants were allowed for growing season.

7.2.1 Plant growth and yield data collection:

The following data were collected:

a) Number of leaves per plant: The number of leaves per plant was determined by counting the number of leaves manually on the plant at 2, 4, and 6, 8, 10 and 12 weeks after sowing (WAS).
b) Plant height per plant (cm): Plant height was measured from the base to top with the aid of a measuring tape at 2, 4, 6, 8, 10 and 12 WAS.

c) Stem girth per plant (cm): This was also taken with the aid of a vernier caliper at 2, 4, 6, 8, 10 and 12 WAS.

d) Number of pods per plant: All the pods of the plants were harvested and counted.

e) Average pod length: The average pod length was measured.

f) Grain yield (kg/ha): At maturity, all pods were harvested and all grains were recovered after shelling and then weighed using top load balance (with basin-like top and calibrated in Kg) per plot. The grain yield per hectare were determined as follows;

$$\text{Grain yield} = \frac{Grain\ yield\ per\ plot \times 10{,}000\ (\ m2)}{Plot\ area\ (m2)}$$

g) Harvest index (H.I): It was calculated by using the following equation:

$$\text{H.I} = \frac{\text{GY}}{\text{BY}} \times 100$$

Where H.I = Harvest index GY = Grain Yield (g) BY = Biological Yield (g) (Dagash, 2003).

7.3 Statistical analysis

Tukey HSD (honestly significant difference) post hoc test was performed to indicate significant differences ($p < 0.05$) among the treatments. Figures were prepared using MS EXCEL and using SPSS for windows (IBM SPSS ver. 20.0).

7.4 Results and Discussion

7.4.1 Effect on plant growth

Analysis of variance showed that, in the first year, the number of leaves at 2 and 4 weeks after sowing (WAS) did not show any significant differences. But at 6, 8 ,10 and 12WAS, there were significant differences among the treatments with T5 recording the highest number of leaves and T2 recording the lowest. Whereas, in the second year, there were significant differences among the treatments at all the weeks after sowing, with T5 again recording the highest number of leaves and T2 recorded the least. In both the years, maize cob biochar mixed with vermicompost (T5) and sugarcane bagasse biochar mixed with vermicompost (T4) showed greater performance on the number of leaves among other treatments. Interestingly, number of leaves was more in control (T0) and compost only (T1) amended soil over sole application of biochar. Similarly, Carter et al (2013) also reported an increase in the number of lettuce leaves and branches in biochar amended soil as compared to the untreated soil. This is in harmony with the study conducted by Garamu (2019) who reported that the leaf biomass production of rice crop increased by 17% as compared to control on a xanthic ferrasol when charcoal combined with fertilizers was added. The increase in the number of leaves due to the application of biochar combined with vermicompost may be attributed to the nutrients present in biochar and vermicompost which augments the vegetative development in soybean.

Table 7.1. Effect of biochar and vermicompost on the number of leaves of

soybean under different treatments in 2018

Treatment	2WAS	4WAS	6WAS	8WAS	10WAS	12WAS
T0	7.33 ± 0.33^{c}	18.33 ± 1.76^{b}	32.03 ± 2.96^{a}	43.72 ± 8.56^{ab}	38.97 ± 8.56^{a}	30.53 ± 8.33^{a}
T1	7.67 ± 0.33^{b}	21.33 ± 1.20^{ab}	36.81 ± 1.40^{a}	54.28 ± 4.20^{ab}	48.09 ± 4.20^{a}	39.12 ± 4.53^{a}
T2	8.33 ± 0.33^{ab}	18.33 ± 2.73^{ab}	29.72 ± 2.05^{a}	41.11 ± 2.22^{ab}	35.88 ± 2.22^{a}	27.67 ± 2.45^{a}
T3	8.00 ± 0.00^{bc}	22.60 ± 2.75^{ab}	36.81 ± 2.87^{a}	53.03 ± 5.72^{ab}	46.57 ± 5.72^{a}	38.20 ± 5.56^{a}
T4	8.00 ± 0.00^{b}	21.67 ± 1.76^{ab}	37.96 ± 2.35^{a}	55.59 ± 3.50^{ab}	49.48 ± 3.50^{a}	40.92 ± 3.67^{a}
T5	9.00 ± 0.00^{a}	29.00 ± 2.31^{a}	51.83 ± 1.69^{a}	68.33 ± 2.19^{a}	61.61 ± 2.19^{a}	52.67 ± 2.36^{a}
T6	8.00 ± 0.00^{b}	19.00 ± 3.21^{ab}	31.94 ± 3.45^{a}	44.89 ± 10.86^{ab}	39.73 ± 10.86^{a}	31.80 ± 10.59^{a}
T7	8.00 ± 0.00^{b}	20.67 ± 0.88^{ab}	29.72 ± 0.64^{a}	38.78 ± 0.73^{b}	33.35 ± 0.73^{a}	25.14 ± 0.76^{a}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 7.2. Effect of biochar and vermicompost on the number of leaves of soybean under different treatments in 2019

Treatment	2WAS	4WAS	6WAS	8WAS	10WAS	12WAS
T0	9.33 ± 0.67^{ab}	26 ± 2.65^{ab}	35.33 ± 2.96^{b}	44.33 ± 2.60^{b}	28.16 ± 2.84^{ab}	29.71 ± 3.33^{a}
T1	8.66 ± 0.67^{b}	29.33 ± 3.71^{ab}	39.00 ± 3.21^{b}	56.33 ± 5.61^{b}	38.71 ± 5.73^{ab}	41.08 ± 5.72^{a}
T2	9.33 ± 0.33^{ab}	20.66 ± 0.88^{b}	30.33 ± 0.67^{b}	42.67 ± 2.40^{b}	27.72 ± 2.27^{b}	28.01 ± 2.54^{a}
T3	9.66 ± 0.67^{ab}	24.00 ± 2.31^{b}	34.33 ± 2.03^{b}	55.67 ± 6.44^{b}	38.77 ± 5.97^{ab}	40.57 ± 5.35^{a}
T4	9.66 ± 0.33^{ab}	29.33 ± 4.81^{ab}	38.67 ± 4.91^{b}	56.00 ± 7.21^{b}	39.27 ± 6.85^{ab}	40.73 ± 6.96^{a}
T5	10.00 ± 0.00^{ab}	35.33 ± 2.19^{a}	52.00 ± 2.31^{a}	71.67 ± 3.53^{a}	54.81 ± 3.51^{a}	56.63 ± 3.68^{a}
T6	8.66 ± 0.33^{b}	25.00 ± 5.69^{b}	35.00 ± 5.69^{b}	47.00 ± 7.02^{b}	32.01 ± 6.74^{ab}	32.00 ± 6.53^{a}
T7	9.00 ± 0.00^{a}	24.66 ± 3.18^{b}	34.33 ± 3.33^{b}	45.33 ± 7.88^{b}	29.56 ± 7.91^{ab}	30.24 ± 7.54^{a}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Stem diameter did not show any significant difference at 2 and 4 WAS but showed significant differences at 6, 8, 10 and 12 WAS among the treatments in the first year (Table 7.3). T5 recorded the maximum stem diameter at all the weeks after planting. Similar to the number of leaves, the stem diameter also showed greater results on T5 and T4 amended soils compared to other treatments over the course of the 84 days experiment. Additionally, control (T0) and mere compost application (T1) plots had superior effect on stem diameter than mere biochar treated soils in the first year. But in the second year, only compost (T1) showed a more pronounced effect on the stem diameter in comparison to the plots which were treated with biochar only (T1 and

T2) (Table 7.4). This corresponds to the study carried out by Schmidt et al. (2014) who found an increase in the shoot diameter of grapevine by 10% on biochar compost treated soil, though insignificant, over control and also higher than in the other treatments.

Table 7.3. Effect of biochar and vermicompost on the stem diameter (mm) of soybean under different treatments in 2018

Treatment	2WAS	4WAS	6WAS	8WAS	10WAS	12WAS
T0	1.52±0.08^{b}	2.95±0.26^{a}	4.29±0.23^{a}	4.90±0.25^{b}	5.13±0.27^{b}	5.26±0.28^{a}
T1	1.61±0.02^{ab}	3.31±0.40^{a}	4.84±0.34^{a}	5.46±0.30^{ab}	5.69±0.30^{b}	5.72±0.24^{a}
T2	1.57±0.08^{ab}	2.67±0.22^{a}	3.71±0.20^{a}	4.22±0.20^{b}	4.43±0.20^{b}	4.55±0.20^{a}
T3	1.57±0.09^{ab}	2.88±0.19^{a}	4.06±0.14^{a}	4.59±0.15^{b}	4.81±0.15^{b}	4.93±0.16^{a}
T4	1.60±0.04^{ab}	3.39±0.37^{a}	4.87±0.23^{a}	5.50±0.25^{ab}	5.74±0.27^{b}	5.78±0.21^{a}
T5	1.71±0.03^{a}	3.45±0.08^{a}	4.95±0.06^{a}	5.60±0.05^{a}	5.85±0.03^{a}	5.99±0.02^{a}
T6	1.63±0.09^{ab}	2.89±0.56^{a}	3.99±0.53^{a}	4.47±0.54^{b}	4.69±0.54^{b}	4.81±0.53^{a}
T7	1.63±0.05^{ab}	3.10±0.10^{a}	4.30±0.06^{a}	4.82±0.09^{b}	5.06±0.08^{b}	5.33±0.07^{a}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 7.4. Effect of biochar and vermicompost on the stem diameter (mm) of soybean under different treatments in 2019

Treatment	2WAS	4WAS	6WAS	8WAS	10WAS	12WAS
T0	1.69±0.16^{a}	2.73±0.20^{a}	3.21±0.19^{b}	3.52±0.17^{b}	3.75±0.15^{b}	3.90±0.15^{bc}
T1	1.76±0.10^{a}	3.60±0.30^{a}	4.43±0.26^{ab}	4.89±0.24^{ab}	5.26±0.22^{ab}	5.47±0.22^{ab}
T2	1.74±0.03^{a}	2.73±0.24^{a}	3.21±0.25^{b}	3.48±0.25^{b}	3.70±0.25^{b}	3.82±0.25^{c}
T3	1.87±0.19^{a}	3.41±0.72^{a}	4.10±0.68^{ab}	4.47±0.66^{ab}	4.75±0.64^{ab}	4.93±0.63^{a}
T4	1.84±0.09^{a}	3.36±0.25^{a}	4.04±0.21^{ab}	4.41±0.20^{ab}	4.69±0.18^{ab}	4.87±0.16^{ac}
T5	2.07±0.10^{a}	4.51±0.40^{a}	5.15±0.45^{a}	5.62±0.38^{a}	5.95±0.31^{a}	6.25±0.22^{a}
T6	1.72±0.10^{a}	2.70±0.47^{a}	3.17±0.46^{b}	3.43±0.45^{b}	3.63±0.45^{b}	3.74±0.45^{c}
T7	1.77±0.04^{a}	3.02±0.16^{a}	3.62±0.15^{ab}	3.97±0.17^{ab}	4.24±0.18^{b}	4.38±0.20^{bc}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5}- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Plant height was significantly affected by the treatments at all the WAS in the first year whereas in the second year, no significant differences was detected at 2WAS (Table 7.5 & 7.6). The highest mean plant height was again observed in T5 and lowest in T2 at all the weeks after sowing in both the years. Plant height was comparatively smaller in the sole sugarcane bagasse biochar amended soil (T2) than the unamended control, while the sole compost amended soil (T1) showed greater plant height than biochar only (T2) and (T3) amended soils during the two years study. Biochar mixed with compost (T4 and T5) enhanced the plant height of soybean over other treatments. This is in accordance with the findings of Sukartono and Sudantha (2016) which may be due to the readily available nutrients present in compost which improves the early growth of crops.

Table 7.5. Effect of biochar and vermicompost on the height (cm) of soybean different treatments in 2018.

Treatment	2WAS	4WAS	6WAS	8WAS	10WAS	12WAS
T0	14.72±0.05^{b}	32.76±0.37^{ab}	42.81±0.96	46.35±0.57^{ab}	49.96±5.15^{ab}	53.00±0.90^{b}
T1	15.19±0.32^{ab}	34.35±1.21^{ab}	44.49±0.96	48.92±1.53^{ab}	51.62±5.00^{ab}	54.89±2.27^{b}
T2	13.76±0.48^{ab}	28.64±1.75^{b}	38.42±1.96	42.53±4.06^{b}	45.10±5.31^{c}	49.32±2.14^{b}
T3	15.84±0.46^{ab}	33.92±1.33^{ab}	43.12±0.80	48.12±1.59^{ab}	51.81±5.12^{abc}	55.76±2.24^{b}
T4	16.67±0.30^{ab}	35.97±2.64^{ab}	46.01±1.79	51.78±3.17^{ab}	55.22±5.11^{ab}	58.84±3.83^{b}
T5	18.33±0.08^{a}	38.02±0.55^{a}	48.92±0.63	53.88±0.26^{a}	57.88±5.23^{a}	61.93±0.82^{a}
T6	14.47±0.22^{ab}	29.78±3.54^{ab}	40.70±0.51	43.88±3.44^{b}	46.97±5.09^{b}	50.84±2.30^{b}
T7	15.99±0.38^{ab}	34.86±0.91^{ab}	45.06±0.70	49.10±0.85^{ab}	53.87±5.11^{ab}	57.46±0.73^{b}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

Table 7.6. Effect of biochar and vermicompost on the height (cm) of soybean different treatments in 2019.

Treatment	2WAS	4WAS	6WAS	8WAS	10WAS	12WAS
T0	16.37±0.95^{a}	33.04±3.25^{a}	43.29±3.13^{ab}	48.90±3.50^{ab}	52.90±3.08^{ab}	56.30±3.24^{ab}
T1	16.85±0.49^{a}	39.04±2.21^{a}	48.89±2.19^{ab}	54.14±1.75^{ab}	58.79±1.97^{ab}	62.48±2.26^{ab}
T2	14.87±2.58^{a}	31.94±0.34^{a}	40.78±0.54^{b}	47.43±1.17^{b}	50.92±0.67^{b}	53.63±1.19^{b}
T3	17.15±1.40^{a}	36.86±4.97^{a}	46.25±5.04^{ab}	51.95±4.22^{a}	57.04±4.87^{a}	60.23±4.96^{ab}
T4	17.94±0.66^{a}	39.32±3.06^{a}	49.10±1.64^{ab}	54.95±3.05^{ab}	58.64±2.61^{ab}	61.34±2.40^{ab}
T5	19.00±0.22^{a}	45.93±1.50^{a}	55.37±1.55^{a}	61.74±1.34^{a}	66.20±1.49^{a}	69.21±1.43^{a}
T6	16.38±0.69^{a}	32.15±3.74^{a}	41.93±3.70^{ab}	48.25±4.28^{ab}	51.65±4.69^{b}	54.75±4.81^{ab}
T7	17.67±0.22^{a}	36.49±1.31^{a}	46.30±1.29^{ab}	52.47±1.17^{ab}	56.87±1.09^{ab}	60.03±0.97^{ab}

± indicates standard error of means. Values in same column followed by different letters are significantly different ($p<0.05$). T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

In general, the least pronounced effect by the sole application of sugarcane bagasse biochar (T2) on the growth parameters of soybean might be attributed to the hydrophobic nature of biochar. Biochar prepared from sugarcane bagasse had lower density and higher ash content than maize cob biochar which might have added to its hydrophobicity. Moreover, in the present study, we employed homogenous application of the treatments in the top 0-15 cm of the soil depth. Hence, it increased the possibility of biochar removal along with other soil particles through wind and water erosion. This phenomenon is more pertinent in biochars which are less coarse or contains higher dust concentrations (Verheijen et al., 2009) as in the case of sugarcane bagasse biochar. Also, recently published literatures have proven that freshly yielded biochars may affect the plant growth adversely by immobilizing the movement of nutrient uptake by plants mainly due to adsorption of mineral nitrogen and dissolved organic carbon (Ding et al., 2010; Graber and Elad, 2013). Therefore, biochar combined with organic or inorganic nutrients can help in removing or counteracting the adverse effect of freshly yielded biochar (Gathorne- Hardy et al., 2009; Alburquerque et al., 2012). The possibility that nutrients get attached to charcoal rather than ash or mulch is very high but more evidences are required to validate the same (Lehmann et al., 2002). However, as the biochar ages, the build-up of functional carboxylic groups on the surface of biochar increases (Browdowski et al., 2005) which might possibly stimulate more interactions between biochar and other soil particles such as organic matter and soil pollutants (Cheng et al., 2006; Brodowski et al., 2005; Smernik et al., 2006). This might be a possible explanation for the better response of soybean growth in the sole maize cob biochar treated soil (T3) in the second year as compared to the first year.

7.4.2 Effect on yield and yield components

The effect of biochar on the yield components of soybean in the two seasons are displayed in Figure 7.1 to 7.6. Except the number of pods per plant, the addition of biochar did not significantly affect the yield of soybean. The number of pods per plant of T5 increased by 67.24, 62.93 and 62.07 % respectively over T7, T3 and T0. Unamended control (T0) and sole application of compost (T1) produced better results than sole application of biochar (T2 and T3) across all the yield components. Similarly, in the second year, no significant differences were observed in any of the measured parameters although soils amended with T5 yielded a marginally better performance as compared to the other treatments. Compost and biochar-compost combination affected the yield and yield components of soybean positively resulting in an increase in the number of pods per plant. Barus et al. (2016) also found that application of mixed husk biochar and compost significantly increased the number of pods by 55% over control. Agegnehu et al. (2015) indicated a significant relationship between yield of pods and yield of soybean grains. A study conducted by Bahaa (2016) indicated an enhancement in the morphological traits of growth and yield in wheat after biochar application, which is most likely due to the increase in the number of leaves and number of fruit bearing branches. These results are in accordance with several findings (Chan et al., 2007; Van Zwieten et al., 2010; Antonia et al., 2013) which are probably due to the high carbon but low nutrient content of biochar. Also, it is observed that soybean yield was higher in the soil treated with sole compost than the soil treated with biochar only. This is probably because biochar not provide nutrients directly to the soil. Antonia et al. (2013) also reported similar findings where wheat grain production in biochar amended soil without mineral fertilization only slightly increased the yield by -3 to 42% whereas, the use of medium mineral fertilization and full mineral fertilization without biochar increased the yield by 149 and 281 % respectively. Additionally, the results suggested the benefits of sole application of compost over sole application of biochar which is again most likely due to the high nutrient content of the compost. However, as seen from the result, the yield of soybean in the subsequent year was greater in the maize cob biochar amended soil (T3) than in the unamended control and sole compost amended soil. This might possibly be due to leaching of nutrients in compost amended soils which was also reported by Glaser et al. (2002). They found that ammonium content was notably increased just after the application of fertilization but was reduced to the same amount prior to application after 21 days. Similar effects were reported with K, Ca and Mg but they observed a decrease in leaching on application of charcoal. The high specific surface area of biochar and nutrient supplements through ash or organic amendments aids in the nutrient retention and available nutrient uptake capacity (Glaser at al., 2002) which in turn, increases the fertilizer use efficiency and decreases leaching (Steiner et al., 2008; Roberts et al., 2010).

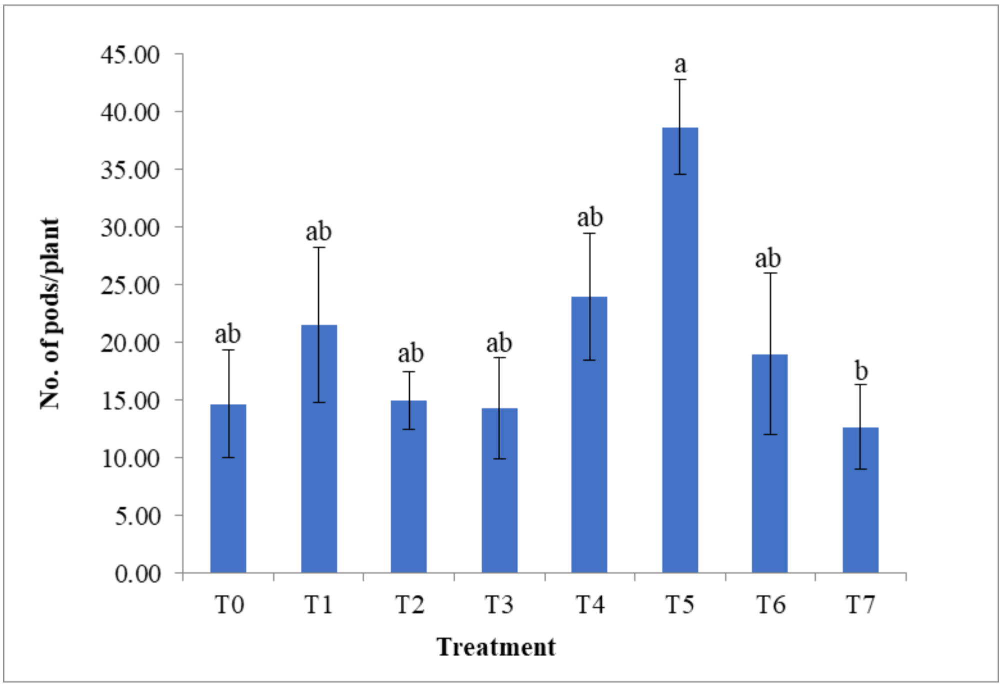


Figure 7.1. Effect of biochar and vermicompost on the number of pods per plant of soybean under different treatments in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

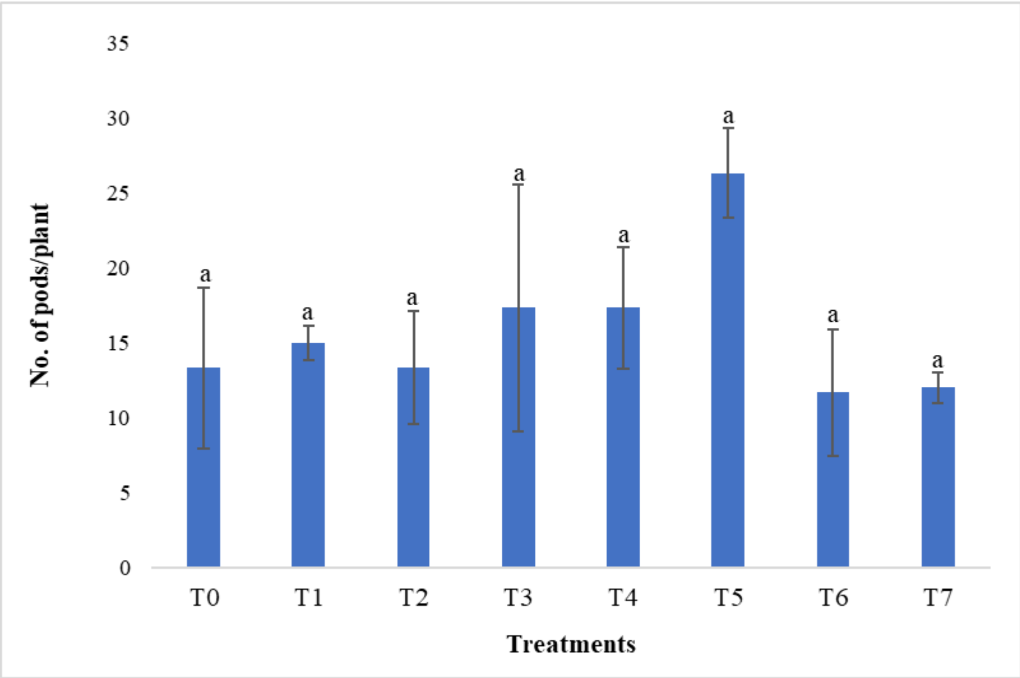


Figure 7.2. Effect of biochar and vermicompost on the number of pods per plant of soybean under different treatments in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

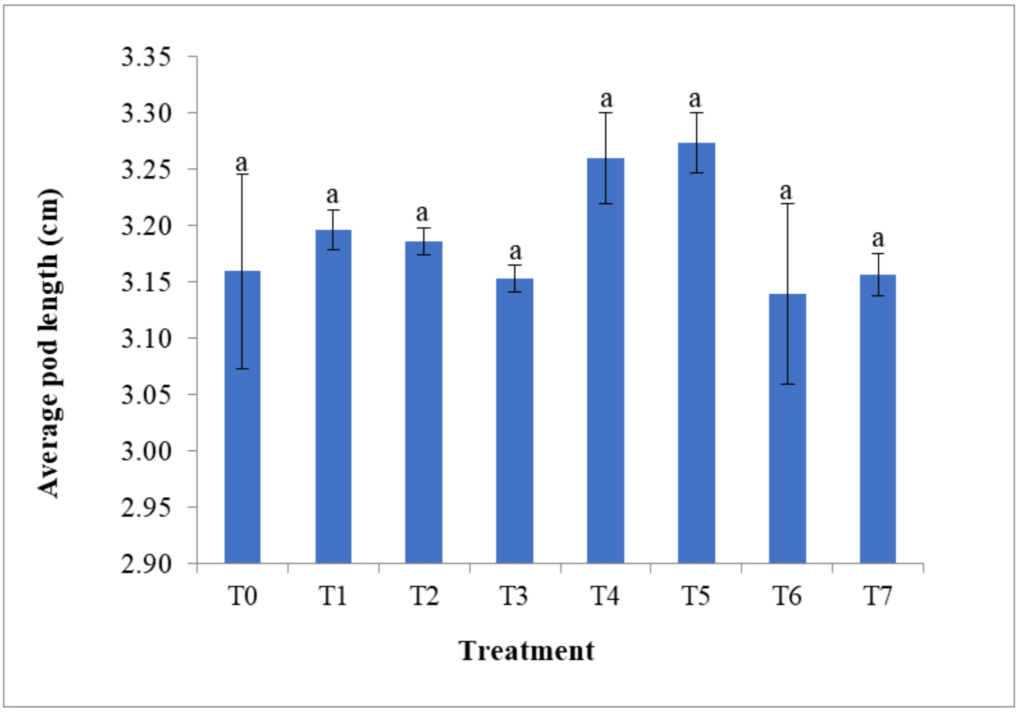


Figure 7.3. Effect of biochar and vermicompost on the average pod length of soybean in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

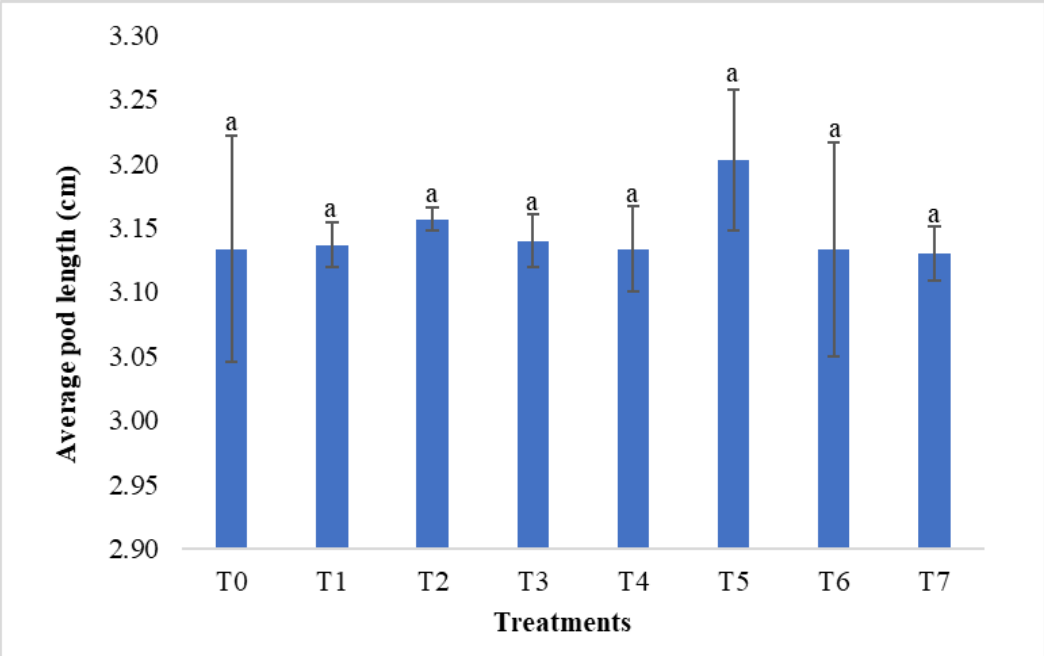


Figure 7.4. Effect of biochar and vermicompost on the average pod length of soybean in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

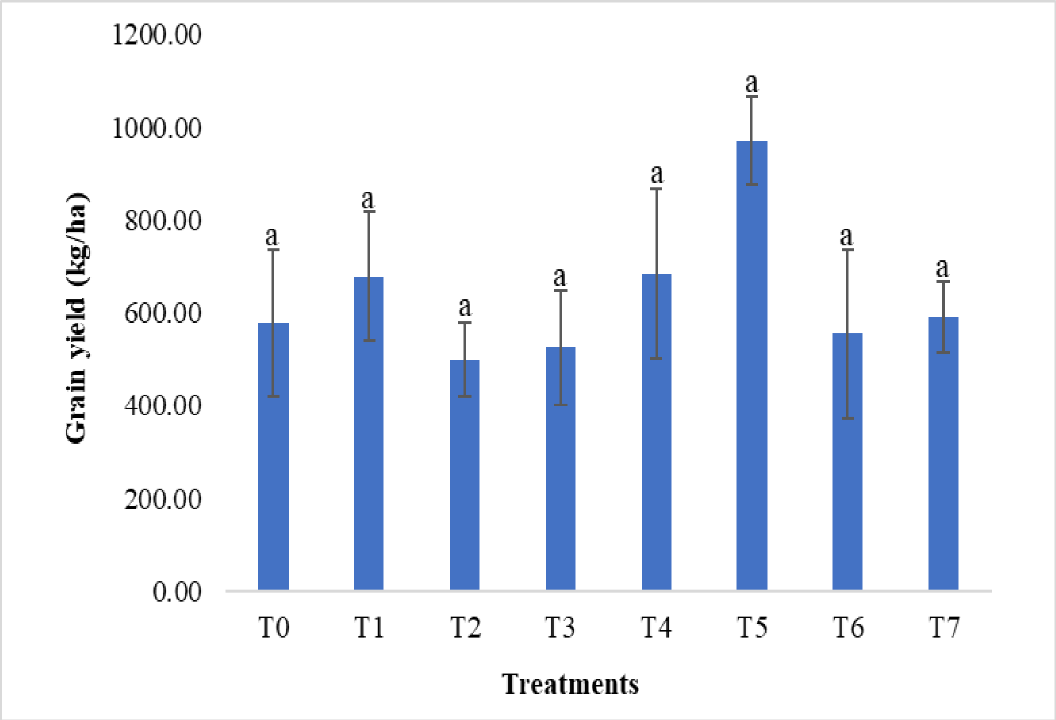


Figure 7.5. Effect of biochar and vermicompost on the grain yield of soybean under different treatments in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

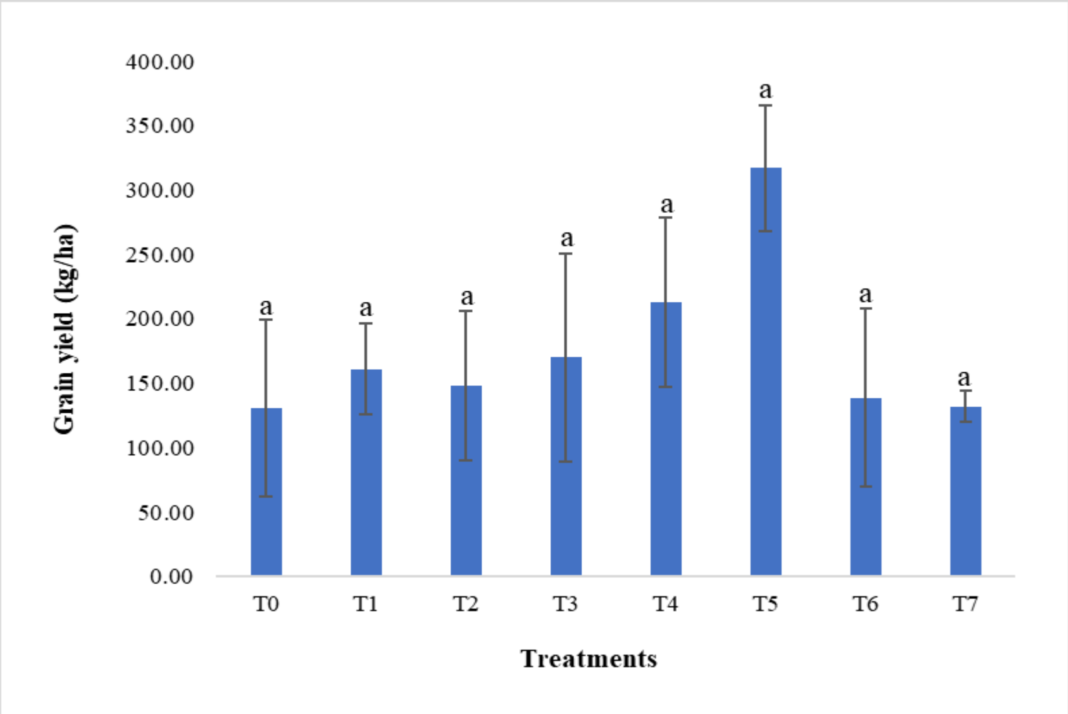


Figure 7.6. Effect of biochar and vermicompost on the grain yield of soybean under different treatments in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

7.4.3 Effect on aboveground biomass yield and harvest index

Analysis of variance did not indicate any significant differences in both the aboveground biomass yield and harvest index among the treatments (Figure 7.7 to 7.10). The aboveground biomass yield and harvest index showed a tendency to be higher in T5 among all the other treatments in the first year. In the second year, the highest aboveground biomass yield was observed in T5 whereas the T6 recorded the maximum value of harvest yield.

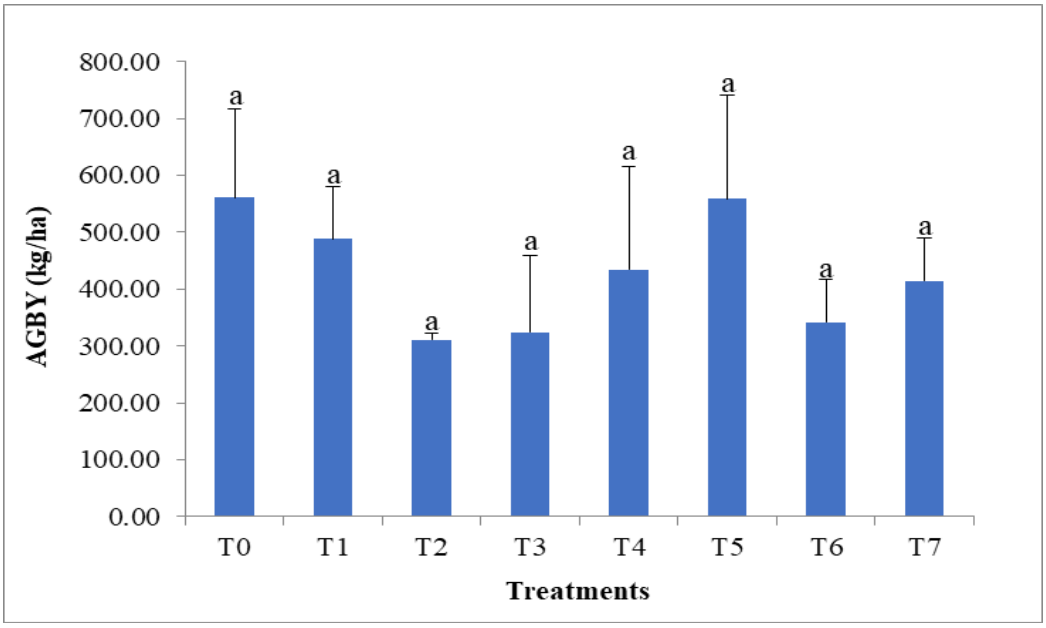


Figure 7.7. Effect of biochar and vermicompost on the aboveground biomass yield of soybean under different treatments in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_5- vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

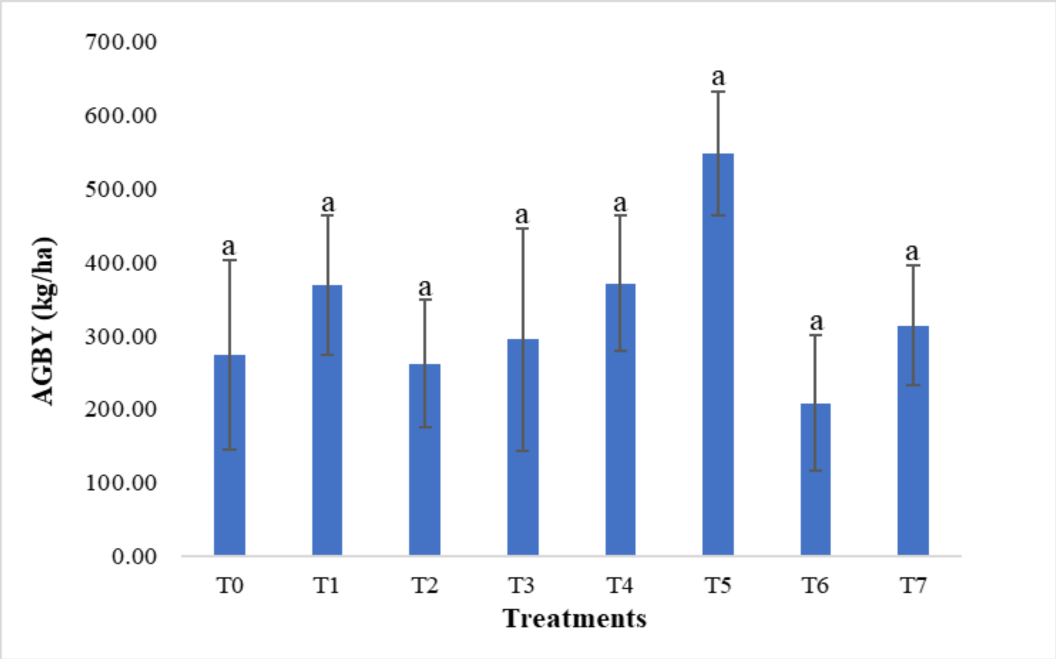


Figure 7.8. Effect of biochar and vermicompost on the aboveground biomass yield of soybean under different treatments in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

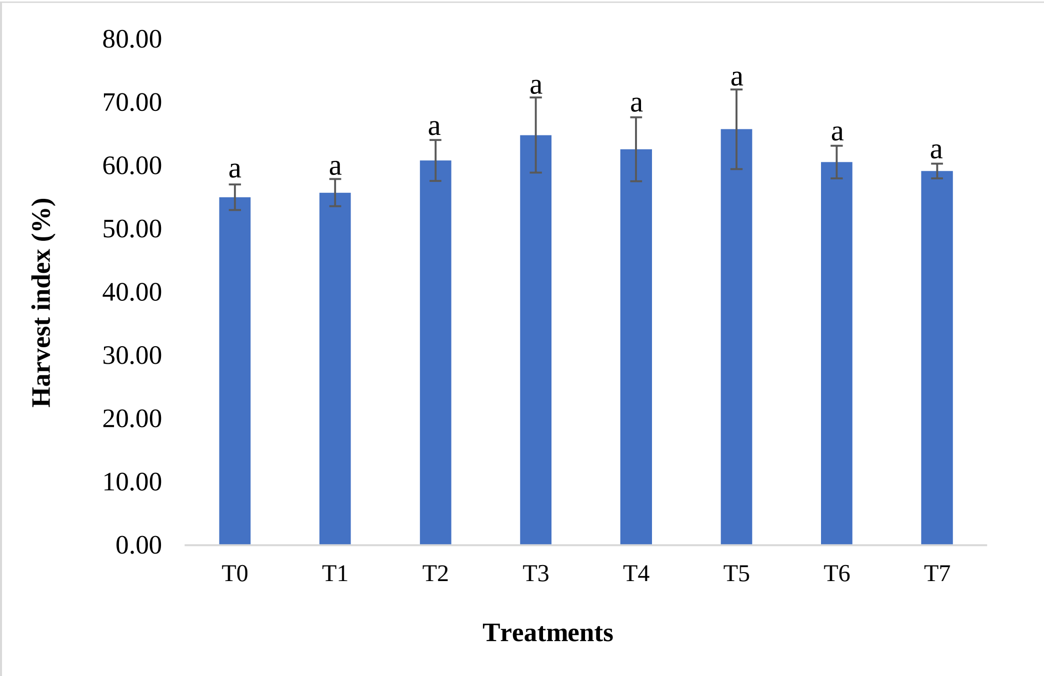


Figure 7.9. Effect of biochar and vermicompost on the harvest index under different treatments in 2018. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

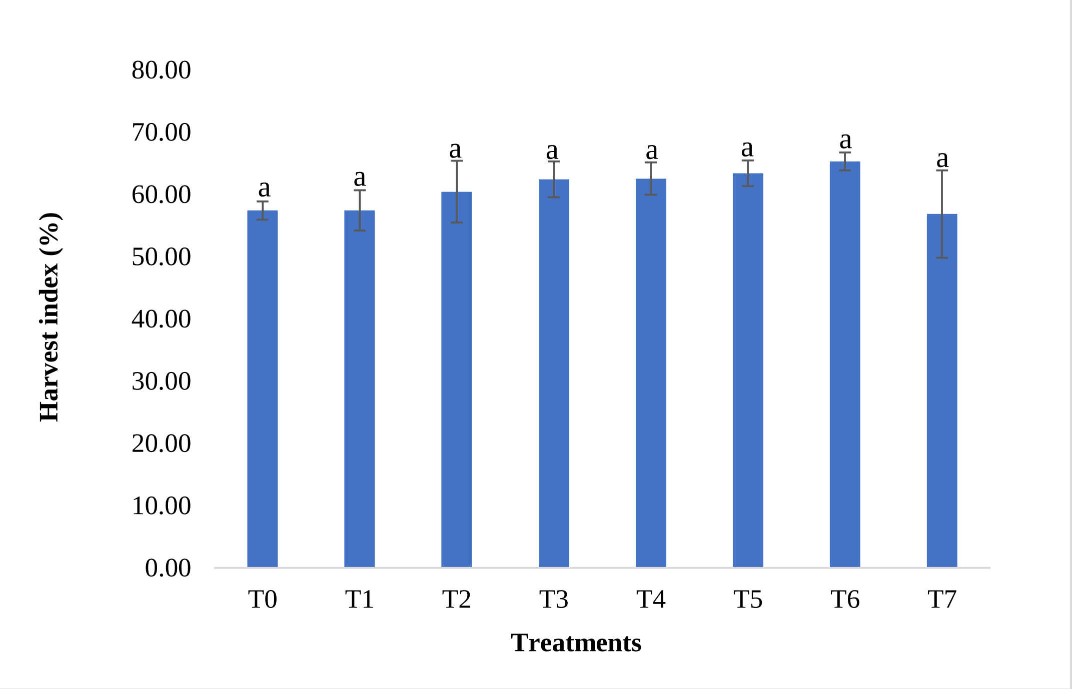


Figure 7.10. Effect of biochar and vermicompost on the harvest index under different treatments in 2019. Different letters indicate significant differences among the treatments. T_0- control, T_1-vermicompost @5t/ha, T_2-sugarcane bagasse biochar @ 5t/ha, T_3-Maize cob biochar @5t/ha, T_4-vermicompost + sugarcane biochar@ 2.5 t/ha each,T_{5-} vermicompost + maize cob biochar @2.5 t/ha, T_6-sugarcane biochar + maize cob biochar @ 2.5 t/ha, T_7-vermicompost + sugarcane biochar + maize cob biochar @ 1.66 t/ha each.

7.5 Conclusion

It is evident from the findings of this short-term trial that the combination of biochar with organic manures or compost is more beneficial than the sole application of biochar or compost for the growth and consequentially the yield of soybean. However, this is only a preliminary study which did not take into consideration other potential factors such as climatic condition, soil type, nutrient uptake by crops, and crop type. Therefore, further investigation on the long-term effect while incorporating these factors is necessary.

Chapter 8

General discussion

"Slash and burn" has been the most important agricultural system in many underdeveloped nations even today. Large tracts of virgin forest are destroyed by this agricultural method, and the burning process generates a lot of CO_2, N_2O, and CH_4. The Central Amazon people, on the other hand, used "slash and char" instead than "slash and burn" 500–7000 years ago (Downie, 2008). After burning wood in an oxygen-free environment, they were returned to the soils, which subsequently gained the name Terra Preta soils. Research on the Terra Preta soils in the Amazon Basin showed that crop productivity and soil fertility were enhanced by the addition of charcoal by humans (Glaser et al., 2002). Because of this, the idea of applying biochar to soil has generated a great deal of study interest, resulting in hundreds of peer-reviewed research publications being produced (Cheng et al., 2006). It has been demonstrated that adding biochar to certain soils can enhance their biological, chemical, and physical characteristics (Jeffery et al., 2011; Lehmann et al., 2011; Mulcahy et al., 2013). In severely depleted soils with limited organic matter, water, and chemical fertiliser inputs (nitrogen (N), phosphorus (P), and potassium (K)), biochar has been applied as an amendment to increase crop diversity and food security (Atkinson et al., 2010; Igalavithana et al., 2016).

However, to maximise its usage, biochar must be characterised before being used in a specific application. The properties of biochar are identified and measured using a variety of techniques across the globe. Numerous chemical analyses of biochar have been done, encompassing elemental composition and surface examination. According to Brewer et al. (2014), the surface area, pore size, and pore volume are frequently used to analyse the physical properties of biochar. Some research has also established the bulk density and particle size distribution of biochar (Abdullah and Wu, 2009; Jaafar et al., 2015). However, the study's objectives and the resources that are available determine the physicochemical characterisation techniques and level of analysis for biochar. The properties of the biochar investigated in this study were pH, EC, CEC, yield, ash, moisture, volatile matter and fixed carbon content, respectively. The surface morphological characteristics and identification of functional groups were also carried out. As seen from the result, both the biochar were found to be alkaline with sugarcane bagasse biochar exhibiting higher values than maize cob biochar in all the parameters analysed except in CEC and fixed carbon content. The surface morphological analysis of the two feedstock using SEM imaging demonstrated a vast difference in the pore structure before and after conversion to biochar. The construction of a carbonaceous framework that resembled the capillary structure present in sugarcane biomass culminated in the formation of a honeycomb-like structure, as seen by SEM images. The difference in the pore size and structural makeup of the two biochar indicates that the morphological characteristics of biochar are highly dependent on the type of feedstock used. These differences in the biochar will cause it to have varying capacities to adsorb soluble organic and inorganic matter, gas molecules, and nutrients in the soil matrix. Additionally, it will offer a home for microbial communities to settle, develop, and proliferate (Sainju et al., 2006). The two biochars' identical functional group composition was shown by the FT-IR spectra. The functional groups identified in the study were aliphatic C-H, carbonyl (C=O) and C-C and hydroxyl (O-H).

Our findings indicated a positive effect of biochar on the soil physical and chemical properties. We observed an increase in soil pH with the addition of biochar and vermicompost which is probably due to the alkaline nature of the biochars used in the study. Large concentrations of cations, such as Ca, Mg, and K, found in some feedstock, are transformed into oxides, hydroxides, and carbonates that are concentrated in the biochar's ash fraction, particularly in those made at high pyrolysis temperatures (Houben et al., 2013). When added to soil, biochar act as a liming agent due to the solubilization of these alkaline materials (Yuan et al., 2011; Novak et al., 2009). The application of plant-derived biochar raised the pH and exchangeable cations and decreased the readily accessible Al contents of strong acidic tea soils following a 65-day incubation research (Wang et al., 2014). A significant increase in the organic matter and the CEC of the soil was seen following the application of biochar and vermicompost although the CEC content of the biochars used in this study were lower than the CEC of the soils. Application of biochar does not increase the soil CEC instantly because CEC of biochar is usually lower than the soil CEC (Kharel et al., 2019). Therefore, one possible explanation for the increase in soil CEC might be attributed to the highly porous nature and higher surface area of biochar which enhanced its surface sorption and base saturation (Mensah and Frimpong, 2018) or due to the combined application of vermicompost, since composts are made up of stabilised OM rich in functional groups like carboxylic and phenolic acid groups which are released into the soil exchange sites (Mando and Zombre, 2001; Liu et al., 2012).

According to Khan et al. (2021), biochar is an organic nutrient reservoir that contains nitrogen, phosphate, and potassium that can increase the concentrations of important nutrients in soil. The present study demonstrated an increase in available N and available K of soil though soil available P was not significantly increased. The observed benefits of essential nutrients may stem from the significant impact of biochar on soil organic carbon and the physical characteristics of the soil, which enhance the soil's ability to retain nutrients and limit their leaching. Consequently, the availability of these essential nutrients in soil treated with biochar may increase. The qualities of biochar, such as its porosity, wide surface area, CEC, and charge density, promote an increase in the retention of nutrients and other organic molecules. The surface of biochar generated at low temperature contains labile C and acid functional groups, and this kind of biochar often adsorbs more NH_4^+ in contrast to biochar generated at high temperature (Nguyen et al., 2016). Low-temperature biochar's labile C content most likely plays a role in immobilising N in the mineral soil. This might be one of the reasons for the increase in available N following biochar application since the biochar utilized in our study were produced at a low pyrolysis temperature (~ 300 ° C). Additionally, Nelissen et al. (2012) observed that NH_4^+ is promptly immobilised by adsorption, reducing the amount of accessible N and minimising potential soil N losses in the process. Furthermore, the CEC of the soil was increased with the application of biochar thus increasing the number of exchange sites available for K adsorption. Due to its structural characteristics, which include its large surface area, negative surface charge, and porous structure, biochar generally increases soil CEC, which strengthens K retention and facilitates the delayed release of nutrients (Zhou et al., 2015).

Biochar is a highly stable material rich in carbon, and it can be applied to soil to stabilise certain carbon components over an extended period of time (Zhang et al., 2019). The quantity and composition of SOC will directly alter when a significant amount of biochar is added to the soil. In their 2018 study, Dong et al. (2018) applied biochar derived from rice and cottonseed husks at varying rates (0, 30, 60, and 90 t/ha), and they found that the SOC content rose as the application rate increased. According to this study, total carbon (TC) and total organic carbon (TOC) were significantly affected by biochar as opposed to the no-biochar treatment, particularly by the combined application of biochar and vermicompost. After applying the biochars, the content of TC and TOC rose, presumably as a result of the high carbon content of the biochar. Under the same fertilisation circumstances, Laird et al. (2010) discovered that the addition of biochar raised the SOC content. Through pot experiments in Xinjiang, China, Ma et al. (2012) discovered that biochar may significantly increase the SOC, WSOC, and SMBC content of grey desert soil. We also noticed that the SOC mineralization of the treated soils was greatly influenced by the biochar. Due to its intricate aromatic structure, biochar will retain a significant amount of organic materials on its surface throughout the pyrolysis process. During the pyrolysis process, biochar also develops a rich porous structure and contains a large number of trace elements. Because of its unique physicochemical characteristics, biochar added to soil mostly has priming effects that can alter the stability of SOC (Fang et al., 2015). The priming effect can be positive, i.e., accelerating the decomposition of SOC, or negative, i.e., inhibiting the decomposition of SOC. The results of our investigation showed that biochar had a favourable priming effect, as evidenced by the fact that the very labile fraction of TOC increased significantly in the plots altered with biochar as opposed to those that were not. SOC stability, bioavailability, and soil microbial activity are all correlated with the degree of mineralization. Firstly, soil microbes can exploit certain active chemicals in biochar to facilitate co-metabolism and enhance SOC mineralization (Hamer et al., 2004). When applying biochar to the soil, this process is more noticeable initially. Secondly, the surface of biochar frequently exhibits a high concentration of chemical functional groups. Its chemical composition is primarily composed of C, N, H, O, N, K, P, Mg, Ca, and other elements. These properties effectively enhance the physicochemical conditions of soil, including temperature, pH, and moisture content. All these can hasten the mineralization of SOC and encourage the growth and reproduction of soil microorganisms with biochar application (Zheng et al., 2021). Finally, because of its porous nature, biochar encourages SOC mineralization and offers a favourable environment for soil microbes (Singh and Cowie, 2014). Another probable reason for the increased SOC mineralization might be attributed to the fact that biochar used in our study was produced at low temperature. For the manufacture of biochar, a temperature range of 550°C to 650°C is usually ideal. A positive priming effect is more likely to occur in biochar produced at lower pyrolysis temperatures due to its higher yields and hydrophobicity; conversely, as the pyrolysis temperature rises, the positive priming impact diminishes (Cheng et al., 2018). The proportion of aged and fresh biochar-C mineralization was found to be higher in soils amended with biochars produced at 300 °C than in soils amended with biochar produced at 600 °C (Yang et al., 2022). This suggests that biochar produced at a higher temperature during pyrolysis was more stable than that produced at a lower temperature. The most important elements influencing the stability of biochar in soil are thought to be its composition and structure (e.g., DOC content, aromaticity, and aromatic condensation degree), which are mostly dependent on the pyrolysis temperature (Leng and Huang, 2018; Leng et al., 2019). High aromaticity and/or aromatic condensation degree biochar typically exhibits high stability in soil due to its great resistance to biotic and abiotic oxidation (Singh et al., 2012; McBeath et al., 2014; Yang et al., 2018). In addition, the rate of SOC mineralization depends on the soil type where previous studies reported that the amount of fresh biochar-C mineralized as higher in the sandy loam soil than in sandy clay loam soil (Yang et al., 2022). According to Bolan et al. (2012) and Han et al. (2020), the two soils differ in terms of clay content and clay mineral composition, two critical elements that can impact biochar stability in soil. However, the degree of SOC mineralization in the biochar amended soil decreased in the second year suggesting that the SOC shifted to a more recalcitrant form against microbial decomposition in the second year. This is in harmony with Liu et al. (2019) who found that the aged-biochar amended soil had a much smaller easily mineralizable C pool and a lower rate of CO_2 release than the fresh biochar-amended soil. According to earlier research (Maestrini et al., 2015; Wang et al., 2016), biochar's ageing is a critical component impacting SOC mineralization. A reduced mineralization rate was detected in the aged biochar amendment when Zhao et al. (2015) examined the mineralization rate of soil C between fresh and old biochar additions. Another study by Zimmerman et al. (2011) found that biochar produced from grasses increased C mineralization during the early incubation period (initial 90 days), while adding biochar produced from grasses at high temperatures (525 and 650 °C) resulted in a lower CO_2 emission during the later incubation stage. Thus, our research suggests that incorporating biochar into soil is a feasible solution for sequestering carbon and reducing the amount of CO_2 released into the atmosphere.

Besides improving the physico-chemical properties of the soil and sequestering C, biochar has been proven to improve the productivity of crops. Some research showed 140% increases in corn production (Major et al., 2010), 100% increases in cowpea yield (Glaser et al., 2002), and 96% increases in radishes yield (Chan et al., 2008) while growing them with chicken litter biochar. According to Liu et al. (2013), agricultural productivity increased by 11% on average after reviewing published data from 59 pot trials and 57 field studies from 21 different nations. In addition to reporting that increases in crop productivity varied with crop type, with greater increases for legume crops (30%), vegetables (29%), and grasses (14%), compared to cereal crops corn (8%), wheat (11%), and rice (7%), Liu found benefits at field application rates typically below 30 tons/ha field application. The application of biochar additions and agricultural productivity, however, seem to have a limit. According to Lehmann et al. (2006), crops react favourably to biochar additions up to 55 tons/ha; growth decreases are only seen at very high treatment levels. Biederman and Harpole's (2013) results corroborate cases in which a high rate of biochar application results in a declining yield. In a pot experiment, yields dropped to the level of the unaltered control when the equivalent of 165 tons/ha of biochar was added to a poor soil (Rondon et al., 2007). Additionally, Kammann et al. (2011) discovered that above 100–200 tons/ha, quinoa development was slowed. Significantly lower thresholds have been reported by others. It is clear from our study that addition of biochar especially with the combination of vermicompost had a more pronounced effect on the growth and yield of soybean. Contrastingly, soybean growth and yield were considerably lower in the soils amended with biochar only as compared to the non-amended and vermicompost only amended soils. Biochar has the potential to improve crop output in a number of ways by improving soil health (Agegnehu et al., 2017). Nutrients that are bioavailable to plants can be retained and supplied by biochar. Enhanced microbiological population variety is one method of doing this (Li et al., 2020). In addition to fixing nitrogen for plant uptake, the refuge that biochar pores give permits populations to grow (Ameloot et al., 2013). This is especially crucial for crops (other than legumes) that cannot fix nitrogen on their own. Joseph et al. (2010) highlights the interesting fact that the potassium included in biochar is already in a state that may be absorbed by plants. Additionally, crops that is unable to fix their own nitrogen benefit from biochar's increased availability of nitrogen for plant uptake (Zheng et al., 2013). Even legumes that fix nitrogen on their own gain nutritional advantages from the addition of biochar. Following the addition of biochar, common beans' rate of nitrogen fixation rose. The nitrogen fixation went from 50% to 72% at a biochar treatment of 90 g kg^{-1} (Rondon et al., 2007). According to Gaskin et al. (2010), biochar can help crops thrive even in the absence of conventional chemical fertilisers. Adding biochar generally results in higher nitrogen retention. In a pot experiment, the use of biochar increased the rice's uptake of nitrogen fertiliser (Huang et al., 2014). Another possible factor for the observed increase in soybean growth and yield in this study might be attributed to the increased soil pH upon biochar application. According to Wang et al. (2014), severely acidic soils—those with a pH of less than 5.0—are the ones that sustain the greatest damage. Over a comparatively short period of time—165 days—corn stover and switchgrass biochar was found to raise soil pH and other characteristics on acidic soils (Chintala et al., 2014). Crop growth is restricted by the hydrogen and aluminium atoms that are free in the soil (Akhtar et al., 2015). Munera-Echeverri et al. (2018) stated that they attach to vital plant nutrients and prevent uptake.

Chapter 9

Potentials, constraints and implications of biochar use

Based on the findings of this study, we can conclude that biochar has the potential to improve the soil quality. The functions and workings of biochar in enhancing the soil fertility could be could be explained by the following aspects- First, because biochar naturally contains soluble nutrients and because the labile fraction of the material has mineralized and contains organically bound nutrients, it can be used as a source of nutrients to improve soil fertility. Second, biochar may enhance the chemical and physical characteristics of soils mainly because biochar has the potential to enhance the physical characteristics of soil, such as increasing porosity and water-holding capacity. The enhancement of soil characteristics, such as improved pH, cation exchange capacity, and aggregation capacity, may boost soil fertility by reducing nutrient loss and increasing nutrient levels and availability. Thirdly, biochar has the potential to function as a slow-release fertiliser by storing nutrients. Biochar's unique pore structure and functional groups allow excess nutrients like phosphate, ammonium, and nitrate to be stored on the surface of the material. Because of its desorption qualities, biochar may then gradually reabsorb nutrients, hence decreasing nutrient leaching and increasing nutritional contents. Besides acting as a soil conditioner, the conversion of biomass carbon to biochar can aid in sequestering atmospheric CO_2. The current slash-and-burn method, which is also widely practised in NE india, releases greenhouse gases and seriously degrades the soil. But it also offers room for improvement, such as switching from the slash-and-burn to the slash-and-char method. As observed in our study, the very labile fraction of the carbon pool decelerated at the conclusion of the experiment indicating that biochar C became more stable with time suggesting the greater potential for long term carbon sequestration. A notable enhancement in soybean growth was also observed upon biochar's addition particularly when applied in conjunction with vermicompost. This is most likely because the physical and chemical properties of the soil were improved. Applying biochar in conjunction with other organic amendments is advised in order to maximise its benefits, as this research suggests that biochar may not contain enough nutrients for plants, even though it retains the nutrients.

Given all of these advantages of biochar, particularly its ability to increase crop yield, farmers may be enticed to use it on their farm if the method of making it is simple and affordable. However, the practical issues of cost, application rate, availability, and associated risks with application should be fully explored before implementing it on a wide scale. Therefore, this short-term study might provide an insight into the effects of biochar, particularly in the degraded jhumland of NE India and help the policy makers or government agencies to formulate policies to help the farmers adopt biochar to improve the degraded jhumland soils.

To summarise, biochar exhibits significant promise for mitigating climate change and promoting sustainable agriculture. However, further investigation is necessary to completely comprehend its impacts and optimise its practical advantages, making this an essential matter for the future.

Photo Plates

Photo plate 1: Biochar kiln used in the study

Photo plate 2: Feedstocks before and after conversion into biochar

Photo plate 3: Crushing and sieving the biochar

Photo plate 4: Land preparation for the experiment

Photo plate 5: Vegetative stages of soybean growth

References

A. S. 2010. Short-term CO2 mineralization after additions of biochar and switch grass to a Typic Kandiudult. *Geoderma,* **154:** 281-288.

Abdel-Fattah, T. M., Mahmoud, M. E., Ahmed, S. B., Huff, M. D., Lee, J. W. and Kumar, S. 2015. Biochar from woody biomass for removing metal contaminants and carbon sequestration. *Journal of Industrial and Engineering Chemistry,* **22:**103–109.

Abdullah, H. and Wu, H. 2009. Biochar as a fuel: 1. Properties and grindability of biochars produced from the pyrolysis of mallee wood under slow-heating conditions. *Energy & Fuels,* **23:** 4174-4181.

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M. and Wessolek, G. 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma,* **203:** 183-191.

Abrol, V., Meni, B.H., Verheijen., F. G. A., Keizer, J. J., Martins, M. A. S., Tenaw, H., Tchehansky, L. and Graber, E. R. 2016. Biochar effects on soil water infiltration and erosion under seal formation conditions: rainfall simulation experiment. *Journal of Soils and Sediments,* **16 (12):** 2709- 2719.

Abruna-Rodriguez, F., Vincente-Chandler, J., Rivera, E. and Rodriguez, J. 1982. Effect of soil acidity factors on yields and foliar composition of tropical root crops. *Soil Science Society of America Journal,* **46:** 1004-07.

Abujabhah, I. S., Doyle, R. B., Bound, S. A. and Bowman, J. P. 2018. Assessment of bacterial community composition, methanotrophic and nitrogen-cycling bacteria in three soils with different biochar application rates. *Journal of Soils and Sediments.* **18(1):** 148-158.

Acharya, C. L., Kapur, O. C. and Dixit, S. P. 1998. Moisture conservation for rainfed wheat production with alternative mulches and conservation tillage in the hills of north-west India. *Soil and Tillage Research,* **46:** 153-163.

Agegnehu, G., Bass, A. M., Nelson, P. N. and Bird, M. I. 2016. Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment,* **543:** 295-306.

Agegnehu, G., Srivastava, A. and Bird, M. 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology,* **119:** 156-170.

Aggelides, S. M. and Londra, P. A. 2000. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and clay soil. *Bioresource Technology,* **71(3):** 253-259.

Akhtar, S. S., Andersen, M. N. and Liu, F. 2015. Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agricultural Water Management,* **158:** 61-68.

Alburquerque, J. A., Salazar, P., Barrón, V., Torrent, J., Campillo, M.del C.del, Gallardo, A. and Villar, R. 2012. Enhanced wheat yield by biochar addition under different mineral fertilization levels. Agron. *Sustainable Development,* **33 (3):** 475-484.

Alling, V., Hale, S. E., Martisen, V., Mulder, J., Smebye, A., Breedveld, G. D. and Cornelissen, G. 2014. The role of biochar in retaining nutrients in amended tropical soils. *Journal of Plant Nutrition and Soil Science,* **177**: 671–-680.

Al-Wabel, M. I., Al-Omran, A., El-Naggar, A. H., Nadeem, M. and Usman, A. R. A. 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bio-resource Technology,* **131:** 374-379.

Al-Wabel, M. I., Al-Omran, A., El-Naggar, A. H., Nadeem, M. and Usman, A. R. A. 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology.* **131:** 374-379.

Ameloot, N., De Neve, S., Jegajeevagan, K., Yildiz, G., Buchan, D., Funkuin, Y. N., Prins, W., Bouckaert, L. and Sleutel, S. 2013. Short-term CO2 and N2O emissions and microbial properties of biochar amended sandy loam soils. *Soil Biology and Biochemistry,* 401-410.

Amoakwah, E., Arthur, E., Frimpong, K.A., Parikh, S.J. and Islam, R. 2020. Soil Organic Carbon Storage and Quality Are Impacted by Corn Cob Biochar Application on a Tropical Sandy Loam. *Journal of Soils and Sediments,* **20:** 1960-1969.

Arunkumar, B. R., Thippeshappa, G.N., Chidanandappa, H. M., Gurumurthy, K.T., Naik, T. B. and Bhogi, B. H. 2019. *Journal of Pharmacognosy and Phytochemistry,* **8(4):**1398-1402.

Asai, H., Samson, B. K., Haefele, S. M., Songyikhangs, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T. and Horie, T. 2011. Biochar amendment techniques for upland rice production in Northern Laos. 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Research,* **111:** 81-84.

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T. and Horie, T. 2009. Biochar amendment techniques for upland rice reduction in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield. *Field Crop Res*earch, **111:** 81-84.

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma,K., Kiyono, Y., Inoue, Y., Shiraiwa, T. and Horie, T. 2009. Biochar amendment techniques for upland rice production in Northern Laos. *Field Crops Research,* **111(1-2):** 81-84.

Atkinson, C. J., Fitzgerald, J. D. and Hipps, N. A. 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and Soil,* **337:** 1-18.

Bai, S. H., Reverchon, F., Xu, C. Y., Xu, Z., Blumfield, T. J., Zhao, H., Van Zwieten, L. and Wallace, H. M. 2015. Wood Biochar Increases Nitrogen Retention in Field Settings Mainly through Abiotic Processes. *Soil Biology and Biochemistry,* **90:** 232-240.

Bandy, D. E., Garrity, D. P., and Sanchez, P. A. 1993. The worldwide problem of slash-and- burn agriculture. *Agroforestry Today,* **5(3)**: 2-6.

Behera, B., Dey, B. and Balasubramanian, P., 2020. Algal biodiesel production with engineered biochar as a heterogeneous solid acid catalyst. *Bio-resource Technology,* **310:** 123392.

Berek, A. K. and Hue, N. V. 2016. Characterization of biochars and their use as an amendment to acid soils. *Soil Science,* **181:** 412-416.

Berek, A. K., Radjagukguk, B. and Maas, A. 1995. The effect of different organic materials on the alleviation of Al toxicity in soybean on a red-yellow podzolic soil. *In Plant–Soil Interactions at Low pH: Principles and Management*, eds R. A. Date, N. J. Grundon, G. E. Rayment, and M. E. Probert, Dordrecht, The Netherlands: Kluwer Academic Publishers. 579–84.

Berihun, T., Tolosa, S., Tadele, M. and Kebede, F. 2017. Effect of Biochar Application on Growth of Garden Pea (Pisum sativum L.) in Acidic Soils of Bule Woreda Gedeo Zone Southern Ethiopia. *Hindawi International Journal of Agronomy,* **6:** 1-8.

Biederman, L. A. and Harpole, W. S. 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy,* **5:** 202-214.

Biochar's stability and effect on the content, composition and turnover of soil organic carbon.

Blagodatskaya, E. and Kuzyakov, Y. 2008. Mechanisms of real and apparent priming effects and their dependence on soil microbial biomass and community structure: critical review. *Biology and Fertility of Soils.* **45:** 115-131.

Boivin, P., Schaffer, B. and Sturny, W. 2009. Quantifying the relationship between soil organic carbon and soil physical properties using shrinkage modelling. *European Journal of Soil Science,* **60(2):** 265-75.

Bolan, N. S., Kunhikrishnan, A., Choppala, G., Thangarajan, R. and Chung, J. 2012. Stabilization of carbon in composts and biochars in relation to carbon sequestration and soil fertility. *The Science of the Total Environment,* **424:** 264-270.

Borchard, N., Wolf, A., Laabs, V., Aeckersberg, R., Scherer, H. W., Moeller, A. and Amelung, W. 2012. Physical activation of biochar and its meaning for soil fertility and nutrient leaching–a greenhouse experiment. *Soil Use Management,* **28(2):** 177-184.

Brady, N. C. 1996. Alternatives to slash-and-burn: a global imperative. *Agriculture, Ecosystems & Environment,* **58 (1)**: 3-11.

Brewer, C. E. 2012. Biochar characterization and engineering. Paper 12284, Iowa State University.

Brewer, C. E., Chuang, V. J., Masiello, C. A., Gonnermann, H., Gao, X., Dugan, B., Driver,

Brockhoff, S. R., Christians, N. E., Killorn, R. J., Horton, R. and Davies, D. D. 2010. Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar. *Agronomy Journal,* **102 (6):** 1627-31.

Brodowski, S., John, B., Flessa, H. and Amelung, W. 2006. Aggregate-occluded black carbon in soil. *European Journal of Soil Science* **57:** 539-546.

Brookes, P. C., Landman, A., Pruden, G. and Jenkinson, D. S. 1985. Chloroform fumigation and the release of soil nitrogen, a rapid direct extraction method for measuring microbial biomass nitrogen in soil. *Soil Biology and Biochemistry,* **17:** 837-842.

Browdowski, S., Amelung, W., Haumaier, L. and Zech, W. 2007. Black carbon contribution to stable humus in german arable soils. *Geoderma,* **139:** 220-228.

Brown, S., and Lugo, A. E. 1990. Tropical secondary forests. *Journal of Tropical Ecology,* **6(1)**: 1-32.

Bruun, E. W., Müller-Stöver, D., Ambus, P. and Hauggaard-Nielsen, H. 2011. Application of biochar to soil and N_2O emissions: potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry. *European Journal of Soil Science,* **62:** 581-589.

Bruun, E. W., Petersen, C. T., Hansen, E., Holm, J. K. and Hauggaard-Nielsen, H. 2014. Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. *Soil Use Management,* **30(1):** 109-18.

Bruun, S., Jensen, E. and Jensen, L. 2008. Microbial mineralization and assimilation of black carbon: dependency on degree of thermal alteration. *Organic Geochemistry,* **39:** 839-845.

Budai, A., Wang, L., Gronli, M., Strand, L.T., Antal Jr., M. J., Abiven, S., Dieguez-Alonso, A., Anca-Couce, A. and Rasse, D.P. 2014. Surface properties and chemical composition of corncob and miscanthus biochars: effects of production temperature and method. *Journal of Agriculture and Food Chemistry,* **62:** 3791-3799.

Busscher, W. J., Novak, J. M., Evans, D. E., Watts, D. W., Niandou, M. A. S. and Ahmedna,

C. 2010. *Environmental Science and Technol*ogy, **44:** 7970-7974.

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A. and Shindell, D. 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, **22:** 4.

Cantrell, K. B., Hunt, P.G., Uchimiya, M., Novak, J. M. and Ro, K. S. 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bio-resource Technology,* **107:** 419-428.

Case, S. D. C., McNamara, N. P., Reay, D. S. and Whitaker, J. 2012. The effect of biochar addition on N2O and CO2 emissions from a sandy loam soil—The role of soil aeration. *Soil Biology and Biochemistry* **51:** 125–134.

Case, S. D. C., McNamara, N. P., Reay, D. S. and Whitaker, J. 2012. "The effect of biochar addition on N2O and CO2 emissions from a sandy loam soil—The role of soil aeration." *Soil Biology and Biochemistry,* **51:** 125-134.

Case, S. J., McNamara, N. P., Reay, D. S. and Whitaker, J. 2012. The effect of biochar addition on N2O and CO2 emissions from a sandy loam soil—The role of soil aeration. *Soil Biology and Biochemistry,* **51:** 125-134.

Castaldi, S., Riondino, M., Baronti, S., Esposito, F. R., Marzaioli, R., Rutigliano, F. A., Vaccari, F. P. and Miglietta, F. 2011. Impact of biochar application to a mediterranean wheat crop on soil microbial activity and greenhouse gas fluxes. *Chemosphere,* **85:** 1464-1471.

Castaldi, S., Riondino, M., Baronti, S., Esposito, F. R., Marzaioli, R., Rutigliano, F. A., Vaccari, F. P. and Miglietta, F. 2011. Impact of biochar application to a mediterranean wheat crop on soil microbial activity and greenhouse gas fluxes. *Chemosphere,* **85:** 1464-1471.

Central Ground Water Board North Eastern Region Ministry of Water Resources Guwahati. 2013. Ground Water Information Booklet Aizwal District, Mizoram.

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A. and Joseph, S. 2007. Agronomic values of green waste biochar as a soil amendment. *Australian Journal of Soil Research,* **45(8):** 629-634.

Chan, K. Y., van Zwieten, L., Meszaros, I., Downie, A. and Joseph, S. 2008. Using poultry litter biochars as soil amendments. *Australian Journal of Soil Research,* **46:** 437-444.

Chan, K.Y. and Xu, Z. 2009. Biochar: nutrient properties and their enhancement. In: Biochar for environmental management (J. Lehmann and S. Joseph eds.), Science and Technology, Earthscan, London. pp 67-84.

Chan, K.Y., Bowman, A. and Oates, A. 2001. Oxidizable organic carbon fractions and soil quality changes in an oxicpaleustaff under different pasture lays. *Soil Science,* **166:** 61-67.

Cheah, S., Jablonski, W. S., Olstad, J. L., Carpenter, D. L., Barthelemy, K. D., Robichaud, D. J., Andrews, J. C., Black, S. K., Oddo, M. D. and Westover, T. L. 2016. Effects of thermal pretreatment and catalyst on biomass gasification efficiency and syngas composition. *Green Chemistry,* **18**: 6291-6304.

Chen, J., Sun, X., Li, L., Liu, X., Zhang, B., Zheng, J. and Cheng, K. 2016. Change in active microbial community structure, abundance, and carbon cycling in an acid rice paddy soil with the addition of biochar: Microbial community affected by biochar in a paddy soil. *European Journal of Soil Science,* **67:** 857-867.

Chen, K., Peng, J., Li, J., Yang, Q., Zhan, X., Liu, N. and Han, X. 2020. Stabilization of Soil Aggregate and Organic Matter under the Application of Three Organic Resources and Biochar-Based Compound Fertilizer. *Journal of Soils and Sediments,* **20:** 36333643.

Cheng, C. H., Lehmann, J., Thies, J. E., Burton, S. D. and Engelhard, M.H. 2006.Oxidation of black carbon by biotic and abiotic processes. *Organic Geochemistry,* **37:** 1477-88.

Cheng, F. and Li, X. 2018. Preparation and application of biochar-based catalysts for biofuel production. *Catalysts.* **8(9):** 346.

Cheng, H., Jones, D. L., Hill, P., Bastami., M. S. and Tu, C. L. 2018. Influence of biochar produced from different pyrolysis temperature on nutrient retention and leaching [J]. *Archiv für Acker- und Pflanzenbau und Bodenkunde,* **64(6):** 850-859.

Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D. and Julson, J. L. 2014. Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science,* **60:** 393-404.

Choudhury, B. U., Ansari, M.A., Chakraborty, M., and Meetei, T. T. 2021. Effect of land-use change along altitudinal gradients on soil micronutrients in the mountain ecosystem of Indian (Eastern) Himalaya. *Scientific Reports,* **11(1)**: 14279.

Claoston, N., Samsuri, A. W., Ahmad Husni, M. H. and Mohd Amran, M. S. 2014. Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars. *Waste Management and Research,* **32:** 331-339.

Colney, L. and Nautiyal, B.P. 2013. Characterization and evaluation of soils of Aizawl district, Mizoram, India using remote sensing and GIS techniques. Journal of Geomatics, 7 (1).

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G.D., Rutherford, D.W., Sparrevik, M., Hale, S. E., Obia, A. and Mulder, J. 2013. Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. *Agronomy,***3:** 256-274

Crombie, K., Mašek, O., Sohi, S. P., Brownsort, P. and Cross, A. 2013. The effect of pyrolysis conditions on biochar stability as determined by three methods. *GCB Bioenergy,* **5:** 122-131.

Dayton, E. A. and Basta, N. T. 2001. Characterization of drinking water treatment residuals for use as a soil substitute. *Water Environment Res*ource, **73(1):** 52-57.

De Almeida, S. G. C., Tarelho, L. A. C., Hauschild, T., Costa, M. A. M. and Dussán, K. J. 2022. Biochar production from sugarcane biomass using slow pyrolysis: characterization of the solid fraction. *Chemical Engineering and Processing: Process Intensification,* **179:** 109054.

Deenik, J. L., McClellan, T., Uehara, G.,Antal, M. J. and Campbell, S. 2010. Charcoal volatile matter content influences plant growth and soil nitrogen transformations. *Soil Science Society of America Journal,* **74:** 1259-1270.

Dempster, N., Gleeson, B., Solaiman, M., Jones, L. and Murphy, V. 2012. Decreased soil microbial biomass and nitrogen mineralization with eucalyptus biochar addition to a coarse textured soil. *Plant Soil,* **354:** 311-324.

Deng, B., Yuan, X.; Siemann, E., Wang, S., Fang, H., Wang, B., Gao, Y., Shad, N., Liu, X., Zhang, W., Guo, X. and Zhang, L. 2021. Feedstock Particle Size and Pyrolysis Temperature Regulate Effects of Biochar on Soil Nitrous Oxide and Carbon Dioxide Emissions. *Waste Management.* **120:** 33-40.

Devereux, R. C., Sturrock, C. J. and Mooney, S. J. 2012. The effects of biochar on soil physical properties and winter wheat growth. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh,* **103(1):** 13-18.

Devereux, R. C., Sturrock, C. J. and Mooney, S. J. 2012. The effects of biochar on soil physical properties and winter wheat growth. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh,* **103(1):**13-18.

Ding, Y., Liu, Y. X., Wu, W. X., Shi, D.Z., Yang, M. and Zhong, Z.K. 2010. Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water, Air, and Soil Pollution* **213:** 47-55.

Ding, Y., Liu, Y.X., Wu, W.X., Shi, D.Z., Yang, M. and Zhong, Z.K. 2010. Evaluation of Biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water, Air and Soil Pollution,* **213:** 47-55.

Dong, X., Singh, B. P., Li, G., Lin, Q. and Zhao, X. 2018. Biochar application constrained native soil organic carbon accumulation from wheat residue inputs in a long-term wheat- maize cropping system. *Agriculture, Ecosystems and Environment,* **252:** 200-207.

Downie, A. 2008. Adriana Downie talks about Best Energies pyrolysis gasifier and making biochar, as interview with Adriana Downie from Scott Bilby on 3 June 2008. Available from [http://beyondzeroemissions.org/]

Dumroese, D. S., Robichaud, P. R., Brown, R. E. and Tirock, J. M. 2014. Water repellency of two forest soils after biochar addition. *American Society of Agricultural and Biological Engineers,* **58:** 335-342.

Elliott, H. A. and Dempsey, B. A. 1991. Agronomic effects of land application of water treatment sludge. *Journal of the American Water Works Association*, **83:** 126-131.

Elser, J. and Bennett, E. 2011. Phosphorus cycle: A broken biogeochemical cycle. *Nature*, **478:** 29.

Enders, A., Hanley, K., Whitman, T., Joseph, S. and Lehmann, J. 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technology,* **114:** 644-653.

Fang, Y., Singh, B. and Singh, B. P. 2015. Effect of temperature on biochar priming effects and its stability in soils [J]. *Soil Biology and Biochemistry,* **80:** 136-145.

FAO. 2005. Fertilizer use by crop in India, Land and Plant Nutrition Management Service, Land and Water Development Division, Food and Agriculture Organization of the United Nations, Rome,1-45.

Faria, W. M., de Figueiredo, C. C., Coser, T. R., Vale, A. T. and Schneider, B. G. 2018. Is sewage sludge biochar capable of replacing inorganic fertilizers for corn production? evidence from a two-year field experiment. *Archives of Agronomy and Soil Science,* **64:** 505-519.

Fearnside, P. M. 2005. Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology*, **19(3)**: 680-688.

Fierer, N. and Jackson, R. B. 2006. The diversity and biogeography of soil bacterial communities. *Proceedings of National Academy of Science U S A.* **103:** 626-631.

Figueiredo, C., Lopes, H., Coser, T., Vale, A., Busato, J., Aguiar, N., Novotny, E. and Canellas, L. 2018. Influence of pyrolysis temperature on chemical and physical properties of biochar from sewage sludge. *Archives of Agronomy and Soil Science*, **64:** 881-889.

Fischer, D. and Glaser, B. 2012. Synergisms between compost and biochar for sustainable soil amelioration. In: Kumar S, Bharti A, editors. *Management of organic waste. Rijeka: InTech.* 167-198.

Fischer, D. and Glaser, B. 2012. Synergisms between Compost and Biochar for Sustainable Soil Amelioration. *In Management of Organic Waste;* Kumar, S.E., Ed.; In Tech: Shanghai, China. 167–198.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E., Kucharik, C. J., Monfreda, C., Patz, J., Prentice, I. C., Ramankutty, N. and Snyder, P. K. 2005. Global consequences of land use. *Science*, **309:** 570-574.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M. and West, P. C. 2011. Solutions for a cultivated planet. *Nature*, **478:** 337.

Food and Agriculture Organisation of the United Nations (FAO). 1985. The Tropical Forestry Action Plan. Rome: UN Food and Agricultural Organisation.

Gamage, D. N. V., Mapa, R. B., Dharmakeerthi, R.S. and Biswas, A. 2016. Effect of rice-husk biochar on selected soil properties in tropical Alfisols. *Soil Research,* **54:** 302.

Gaskin, J. W., Speir, R. A., Harris, K., Das, K. C., Lee, R. D., Morris, L. A. and Fisher, D. S. 2010. Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield. *Agronomy Journal,* **102:** 623-633.

Gathorne-Hardy, A., Knight, J. and Woods, J. 2009. Biochar as a soil amendment positively interacts with nitrogen fertiliser to improve barley yields in the UK. IOP *Conference Series Earth and Environmental Science* **6:** 372052.

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N. and Mandal, B. 2012. Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture, Ecosystems and Environment,* **156:** 134-141.

Glaser, B. and Birk, J. J. 2012. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochimica et Cosmochimica Acta,* **82:** 39-51.

Glaser, B., Haumaier, L., Guggenberger, G. and Zech, W. 2001. The 'Terra Preta' phenomenon-a model for sustainable agriculture in the humid tropics. *Naturwissenschaften,* **88:** 37-41.

Glaser, B., Lehmann, J. and Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. *Biology and Fertility of Soils*, **35:** 219-230.

Glaser, B., Lehmann, J. and Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–A review. *Biology and Fertility of Soils.* **35(4):** 219-230.

Glaser, B., Lehmann, J. and Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. *Biology and Fertility of Soil,* **35:** 219-230.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F. and Toulmin, C. 2010. Food security: The challenge of feeding 9 billion people. *Science,* **327:** 812-818.

Gomez, J. D., Denef, K., Stewart, C. E., Zheng, J., and Cotrufo, M. F. 2014. Biochar addition rate influences soil microbial abundance and activity in temperate soils. *European Journal of Soil Science*, **65:** 28-39.

Graber, E. R., and Elad, Y., 2013. Biochar Impact on Plant Resistance to Disease. CRC Press, Boca Raton.

Graber, E. R., Singh, B., H, K. and Lehmann, J. 2017. Determination of cation exchange capacity in biochar. In: Singh, B., Camps-Arbestain, M., Lehmann, *J. (Eds.), Biochar: A Guide to Analytical Methods*, 74-84.

Grogan, P., Lalnunmawia, F. and Tripathi, S. K. 2012. Shifting cultivation in steeply sloped regions: A review of management options and research priorities for Mizoram state, Northeast India. *Agroforestry System,* **84**: 163-177.

Gross, C.D., Bork, E.W., Carlyle, C.N. and Chang, S.X. 2022. Biochar and Its Manure- Based Feedstock Have Divergent Effects on Soil Organic Carbon and Greenhouse Gas Emissions in Croplands. *Science of the Total Environmental,* **806:** 151337.

Gruhn, P., Goletti, F. and Yudelman, M. 2000. Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture: Current Issues and Future Challenges. *Food, Agriculture, and the Environment,* **32:** 15-16.

Guida, M. and Hannioui, A. 2017. Properties of bio-oil and bio-char produced by sugar cane bagasse pyrolysis in a stainless-steel tubular reactor. *Progress in Agriculture Engineering Sciences,* **13(1):** 13-33.

Hagemann, N., Joseph, S., Schmidt, H. P., Kammann, C. I., Harter, J., Borch, T., Young, R. B., Varga, K., Taherymoosavi, S., Elliott, K. W., McKenna, A., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-Alonso, A., Orsetti, S., Subdiaga, E., Behrens, S. and Kappler, A. 2017. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nature Communications,* **8:** 1089.

Hamer, U., Marschne, B., Brodowski, S. and Amelung, W. 2004. Interactive priming of black carbon and glucose mineralization [J]. *Organic Geochemistry,* **35(7):** 823-830.

Han, L. F., Sun, K., Yang, Y., Xia, X. H., Li, F.B., Yang, Z. F. and Xing, B. S. 2020.

Han, L., Zhang, B., Chen, L., Feng, Y., Yang, Y. and Sun, K. 2021. Impact of Biochar Amendment on Soil Aggregation Varied with Incubation Duration and Biochar Pyrolysis Temperature. *Biochar,* **3:** 339-347.

He, L., Zhao, X., Wang, S. and Xing, G. 2016. The Effects of Rice-Straw Biochar Addition on Nitrification Activity and Nitrous Oxide Emissions in Two Oxisols. *Soil Tillage Research,* **164:** 52-62.

Hernandez-Mena, L. E., Pe´cora, A. A. B. and Beraldo, A. L. 2014. Slow pyrolysis of bamboo biomass: analysis of biochar properties. *Italian Association of Chemical Engineering,* **37:** 115-120.

Hossain, M. K., Strezov, V., Chan, K. Y., Ziolkowski, A. and Nelson, P. F. 2011. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of Environmental Management,* **92:** 223-228.

Houben, D., Evrard, L. and Sonnet, P. 2013. Mobility, bioavailability and pH-dependent leaching of cadmium, zinc and lead in a contaminated soil amended with biochar. *Chemosphere,* **92:** 1450-1457.

Houghton, R. A.; Lefkowitz, D. S. and Skole, D. L. 1991. Changes in the landscape of Latin America between 1850 and 1985. I. Progressive loss of forests. *Forest Ecology and Management*, **38 (3-4)**: 143-172.

Huang, M., Yang, L., Qin, H., Jiang, L. and Zou, Y. 2014. Fertilizer nitrogen uptake by rice increased by biochar application. *Biology and Fertility of Soils,* **50:** 997-1000.

Hue, N. V. 1992. Correcting soil acidity of a highly weathered ultisol with chicken manure and sewage sludge. *Communications in Soil Science and Plant Analysis,* **23:** 241-64.

Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., Ammara, U., Ok, Y. S. and Siddique, K. H. M. 2016. Biochar for crop production: Potential benefits and risks. *Journal of Soils and Sediments*, 1-32.

Igalavithana, A. D., Ok, Y. S., Usman, A. R. A., Al-Wabel, M. I., Oleszczuk, P. and Lee, S. S. 2016. The effects of biochar amendment on soil fertility, In: Guo, M., He, Z., and Uchimiya, S. M. (Eds.), Agricultural and environmental applications of biochar: Advances and barriers. *Soil Science Society of America*, 123–144.

Intani, K., Latif, S., Kabir, A. K. M. R. and Müller, J. 2016. Effect of self-purging pyrolysis on yield of biochar from maize cobs, husks and leaves. *Bioresource Technology,* **218:** 541-551.

Intergovernmental Panel on Climate Change. 2014. Climate Change 2014: Mitigation of Climate Change. IPCC Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change. 2021. Climate Change 2021: The Physical Science Basis. IPCC Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Inyang, M., Gao M., Pullammanappallil, B., Ding P. and Zimmerman, A. R. 2010. Biochar from anaerobically digested sugarcane bagasse. *Bio-resource Technology*, **101:** 886-887.

Ippolito, J. A., Barbarick, F. A., Heil, D. N., Chandler, J. P. and Redente, E. F. 2003. Phosphorus retention mechanisms of a water treatment residual. *Journal of Environment Quality,* **32:** 1857-1864.

ISFR. 2019. India State of Forest Report. Forest Survey of India, Dehradun, Uttarakhand, India.

J. 2018. Cation exchange capacity of biochar: An urgent method modification. *Science of The Total Environment,* **642:** 190-197.

J. O., Thies, J., Luizao, F. J., Petersen, J. and Neves, E. G. 2006. Black Carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal,* **70(5):** 1719-30.

J. W. 2019. Biochar surface oxygenation by ozonization for super high cation exchange capacity. *ACS Sustainable Chemistry & Engineering,* **7(19):** 16410-16418.

Jaafar, N. M., Clode, P. L. and Abbott, L. K. 2015. Soil microbial responses to biochars varying in particle size, surface and pore properties. *Pedosphere,* **25:** 770-780.

Jackson, M.L. 1973. Soil Chemical Analysis. Prentice Hall India Pvt. Ltd., New Delhi, 495.

Jeffery, S., Verheijen, F. G. A., van der Velde, M. and Bastos, A. C. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems and Environment,* **144:** 175-187.

Jha, L. K. 1997. Shifting Cultivation. APH Publishing Corporation, New Delhi. 1-38.

Jin, H. (Dissertation). 2010. Characterization of Microbial Life Colonizing Biochar and Biochar-Amended Soils. Cornell University Graduate School.

Jones, B. E. H., Haynes, R. J. and Phillips, I. R. 2010. Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. *Journal of Environmental Management,* **91:** 2281-2288.

Jones, B. E. H., Haynes, R. J. and Phillips, I. R. 2010. Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. *Journal of Environmental Management,* **91(11):** 81-88.

Jones, D. L., Murphy, D. V., Khalid, M, Ahmad, E., Edwards-Jones, G. and DeLuca, T. H. 2011. Short-term biochar-induced increase in soil CO2 release is both biotically and abiotically mediated. *Soil Biology and Biochemistry*, **43:** 1723-1731.

Jones, D. L., Murphy, D. V., Khalid, M., Ahmad, W., Edwards-Jones, G. and DeLuca, T. H. 2011. Short-term biochar-induced increase in soil CO2 release is both biotically and abiotically mediated. *Soil Biology and Biochemistry*, **43:** 1723-1731.

Jones, D. L., Murphy, D. V., Khalid, M., Ahmad, W., Edwards-Jones, G. and DeLuca, T. H. 2011. Short term biochar-induced increase in soil CO_2 release is both biotically and abiotically mediated. *Soil Biology & Biochemistry,* **43(8):** 1723-1731.

Jones, D. L., Murphy, D.V., Khalid, M., Ahmad, W., Edwards-Jones, G. and DeLuca, T.H. 2011. Short-term biochar-induced increase in soil CO_2 release is both biotically and abiotically mediated. *Soil Biology and Biochemistry*, **43:** 1723-1731.

Jones, D. L., Rousk, J., Edwards-Jones, G., DeLuca, T. H. and Murphy, D. V. 2012. Biochar- mediated changes in soil quality and plant growth in a three year field trial. *Soil Biology and Biochemistry,* **45:** 113-124.

Jong, W. 1997. Developing swidden agriculture and the threat of biodiversity loss. *Agriculture, Ecosystems and Environment,* **62 (2-3)**: 187-197.

Joseph, S. D., Arbestain, M. C., Lin, Y., Munroe, P., Chia, C. H., Hook, J., Van Zwieten, L., Kimber, S., Cowie, A., Singh, B. P., Lehmann, J., Foidi, N., Smernik, R. J. and Amonette, J. E. 2010. An investigation into the reactions of biochar in soil. *Australian Journal of Soil Research,* **48 (7):** 501-515.

Joseph, S., Graber, E., Chia, C., Munroe, P., Donne, S., Thomas, T., Nielsen, S., Marjo, C., Rutlidge, H., Pan, G., Li, L., Taylor, P., Rawal, A. and Hook, J. 2013. Shifting paradigms: development of high-efficiency biochar fertilisers based on nano-structures and soluble components. *Carbon Management,* **4:** 323-343.

Kammann, C., Glaser, B. and Schmidt, H. P. 2016. Combining biochar and organic amendments. *In Biochar in European Soils and Agriculture: Science and Practice;* Shackley, S., Ruysschaert, G., Zwart, K., Glaser, B., Eds.; Routledge: New York, NY, USA. 136-164.

Kammann, C.I., Linsel, S., Gößling, J.W. and Koyro, H.W. 2011. Influence of biochar on drought tolerance of Chenopodium quinoa Willd and on soil-plant relations. *Plant and Soil,* **345:** 195-210.

Karhu, K., Mattila, T., Bergström, I. and Regina, K., 2011. Biochar addition to agricultural soil increased CH4 uptake and water holding capacity – Results from a short-term pilot field study. *Agricultural, Ecosystems and Environment,* **140:** 309-313.

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B. and de Nowina, K. R. 2019. Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. *Field Crops Research,* **235:** 18-26.

Kelly, C. N., Peltz, C. D., Stanton, M., Rutherford, D. W. and Rostad, C. E. 2014. Biochar application to hardrock mine tailings: soil quality, microbial activity, and toxic element sorption. *Applied Geochemistry,* **43:** 35-48.

Khan, S., Hayat, R., Farooq, M. S., Hussain, Q. and Ali, N. A. 2018. Interactive Use of Biochar and Chemical Fertilizer on Soil Nutrients (NPK), Soil Water Retention and Biological Nitrogen Fixation by Mash Bean. *Advances in Crop Science and Technology*,**6:** 328.

Kharel, G., Sacko, O., Feng, X., Morris, J. R., Phillips, C. L., Trippe, K., Kumar, S. and Lee,

Khodadad, C. L. M., Zimmerman, A. R., Green, S. J., Uthandi, S. and Foster, J. S. 2011. Taxa-specific changes in soil microbial community composition induced by pyrogenic carbon amendments. *Soil Biology and Biochemistry*, **43:** 385-392.

Kimetu, J., Lehmann, J., Ngoze, S., Mugendi, D., Kinyangi, J., Riha, S., Verchot, L., Recha, J. W. and Pell, A. N. 2008. Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems*, **11:** 726-739.

Krier, R. 2012. Trees absorb less carbon in warming world than experts have assumed. Inside Climate News.

Kumar, G., Shobana, S., Chen, W. H., Bach, Q. V., Kim, S-H, Atabani, A. E. and Chang, J.S. 2016. A review of thermochemical conversion of microalgal biomass for biofuels: chemistry and processes. *Green Chemistry*, **19**:46-47.

Kumuduni, N. P., James, T. F. W., Yohey, H., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H. and Ok, Y. S. 2019. Response of microbial communities to biochar-amended soils: A critical review. *Biochar* **1:** 3-22.

Kuzyakov, Y., Subbotina, I. and Chen, H. Q. 2009. Black carbon decomposition and incorporation into microbial biomass estimated by 14C labeling. *Soil Biology and Biochemistry,* **41:** 210-219.

L. E., Panzacchi, P., Zygourakis, K. and Davies, C. A. 2014. New approaches to measuring biochar density and porosity. *Biomass and Bioenergy.* **66:** 176-185.

Laird, D. A. 2008. The charcoal vision: a win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal,* **100:** 178-181.

Laird, D. A., Brown, R. C., Amonette, J. E. and Lehmann, J. 2009. Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts & Biorefining,* **3(5):** 547-562.

Laird, D., Fleming, P., Wang, B., Horton, R. and Karlen, D. 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma,* **158:** 436-442.

Laird, D.A., Fleming, P., Davis, D. D., Horton, R., Wang, B. and Karlen, D. 2010. Impact of biochar amendments on the quality of typical Midwestern agricultural soil. *Geoderma*, **158:** 443-449.

Lal, R., Follett, R., Stewart, B. and Kimble, J. 2007. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science,* **172:** 943-956.

Lee, J. W., Hawkins, B., Day, D., M. and Reicosky, D. C. 2010. Sustainability: the capacity of smokeless pyrolysis for energy production, global carbon capture and sequestration. *Energy and Environmental Science,* **3:** 1695-1705.

Lee, J. W., Kidder, M., Evans, B. R., Paik, S., Buchanan, A.C., Garten, C. T. and Brown, R.

Lehmann, J. 2007. Bio-energy in the black. *Frontiers in Ecology and the Environment.* **5:** 381-387.

Lehmann, J. and Joseph, S. 2009. Biochar for environmental management: an introduction. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, 1-12.

Lehmann, J. and Joseph, S. 2015. Biochar for Environmental Management: Science and Technology; Routledge: London, UK. **13**: 976.

Lehmann, J., Da Silva, J. P., Steiner, C., Nehls, T., Zech, W. and Glaser, B. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments. *Plant and Soil,* **249(2):** 343-57.

Lehmann, J., Gaunt, J., Rondon, M. 2006. Bio-char sequestration in terrestrial ecosystems-A review. *Mitigation and Adaptation Strategies for Global Change,* **11:** 395-419.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C. and Crowley, D. 2011. Biochar effects on soil biota – A review. *Soil Biology and Biochemistry,* **43:** 1812-1836.

Lei, O. and Zhang, R. D. 2013. Effects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. *Journal of Soils and Sediments,* **13(9):** 61-72.

Leng, L. J. and Huang, H. J., 2018. An overview of the effect of pyrolysis process parameters on biochar stability. *Bioresource Technology,* **270:** 627-642.

Leng, L. J., Huang, H. J., Li, H., Li, J. and Zhou, W. G. 2019. Biochar stability assessment methods: A review. *The Science of the Total Environment,* **647:** 210-222.

Lentz R. D. and Ippolito J. A. 2012. Biochar and Manure Affect Calcareous Soil and Corn Silage Nutrient Concentrations and Uptake. *Journal of Environmental Quality.* **41(4):** 1033-43.

Lewandowski, W., Radziemska, M., Ryms, E. and Ostrowski, P. 2010. Nowoczesne metody termochemiczne konwersji biomasy w paliwa gazowe, ciekłe i stałe. Proceedings of ECOpole, 4 (2) (in Polish).

Li, F., Shen, K., Long, X., Wen, J., Xie, X., Zeng, X., Liang, Y., Wei, Y., Lin, Z. and Huang,

Li, F., Shen, K., Long, X., Wen, J., Xie, X., Zeng, X., Liang, Y., Wei, Y., Lin, Z., Huang, W. and Zhong, R. 2016. Preparation and characterization of biochars from Eichornia crassipes for cadmium removal in aqueous solutions. *PloS One,* **11(2):** 148-132.

Li, Q., Lei, Z., Song, X., Zhang, Z., Ying, Y. and Peng, C. 2018. Biochar amendment decreases soil microbial biomass and increases bacterial diversity in Moso bamboo (Phyllostachys edulis) plantations under simulated nitrogen deposition. *Environmental Research Letters.* **13(10):**1088/1748-9326.

Li, X., Wang, T., Chang, S. X., Jiang, X. and Song, Y. 2020. Biochar increases soil microbial biomass but has variable effects on microbial diversity: A meta-analysis. *Science of The Total Environment,* **749:** 141593.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., J. Skjemstad,

Libra J. A., Ro K. S., Kammann C., Funke, A., Berge, N. D., Neubauer, Y., Maria-Magdalena, T., Fühner, C., Bens, O., Kern, J. and Karl-Heinz, E. 2011. Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels,* **2(1):** 89-124.

Liu, J., Schulz, H., Brandl, S., Miehtke, H., Huwe, B. and Glaser, B. 2012. "Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions," *Journal of Plant Nutrition, Soil Science* **175(5):** 1-10.

Liu, P. M., Liu, W. J., Jiang, H., Chen, J. J., Li, W. W. and Yu, H. Q. 2012. Modification of biochar derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Bioresource Technology,* **121:** 235-240.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G. and 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):** 583-595.

Liu, Y. X., Yang, M., Wu, Y. M., Wang, H. L., Chen, Y. X. and Wu, W. X. 2011. Reducing CH4 and CO2 emissions from waterlogged paddy soil with biochar. *Journal of Soils and Sediments,* **11:** 930-939.

Liu, Y., Lu, H., Yang, S. and Wang, Y. 2016. Impacts of Biochar Addition on Rice Yield and Soil Properties in a Cold Waterlogged Paddy for Two Crop Seasons. *Field Crops Research,* **191:** 161-167.

Liu, Z., Zhu, M., Wang, J., Liu, X., Guo, W., Zheng, J., Bian, R., Wang, G., Zhang, X., Cheng, K., Liu, X., Li, L. and Pan, G. 2019. The responses of soil organic carbon mineralization and microbial communities to fresh and aged biochar soil amendments. *GCB Bioenergy,* **11:** 1408-1420.

Logan, T. J. and Harrison, B. J. 1995. Physical characteristics of alkaline stabilized sewage sludge (N–Viro soil) and their effects on soil physical properties. *Journal of Environment Quality,* **24:** 153-164.

Lou, Y., Joseph, S., Li, L., Graber, E.R., Liu, X. and Pan, G. 2016. Water extract from straw biochar used for plant growth promotion: an initial test. *Bioresources,* **11:** 249-266.

Lucchini, P., Quilliam, R. S., DeLuca, T. H., Vamerali, T. and Jones, D. L. 2014. Does biochar application alter heavy metal dynamics in agricultural soil? *Agriculture, Ecosystems & Environment,* **184(0):** 149-157.

Luo, Y., Durenkamp, M., Nobili, M. D., Lin, Q. and Brookes, P. C. 2011. Short term soil priming effects and the mineralization of biochar following its incorporation to soils of different pH. *Soil Biology and Biochemistry,* **43:** 2304-2314.

M. 2010. Influence of pecan biochar on physical properties of a Norfolk loamy sand. *Soil Science,* **175:** 10-14.

M. H. 2012. Variable lime requirement based on differences in organic matter content of iso- acidic soils. *Indian Journal of Hill Farming,* **25:** 26-30.

Ma, L., Lv, N., Ye, J., Ru, S., Li, G. and Hou, Z. 2012. Effects of biochar on organic carbon content and fractions of gray desert soil. Chin. *Journal of Eco-Friendly Agriculture,* **20:** 976-981.

Ma, Y., Liu, D. L., Schwenke, G. and Yang, B. 2019. The Global Warming Potential of Straw-Return Can Be Reduced by Application of Straw-Decomposing Microbial Inoculants and Biochar in Rice-Wheat Production Systems. *Environmental Pollution,* **252:** 835-845.

Maestrini, B., Nannipieri, P. and Abiven, S. 2015. A meta-analysis on pyrogenic organic matter induced priming effect. *GCB Bioenergy,* **7:** 577-590.

Major, J., Rondon, M., Molina, D., Riha, S.J. and Lehmann, J. 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil,* **333:** 117-128.

Malin´ska, K. 2012. Biowe˛giel odpowiedzia˛ na aktualne problem ochrony s´rodowiska. Inzynieria i ochrona s ´rodowiska **15:** 387-403 (in Polish).

Mandal, S. C. 1997. Introduction and historical overview. *In Acidic Soils of India (Eds.),* eds

Mando, O. A. and Zombre, N. P. 2001. “Use of compost to improve ´ soil properties and crop productivity under low input agricultural system in West Africa,” *Agriculture, Ecosystems and Environment,* **84(3):** 259-266.

Manoj, K., Khan, M. H., Singh, P., Ngachan, S. V., Rajkhowa, D. J., Kumar, A. and Devi.,

Manya, J. J. 2012. Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. *Environmental Science & Technology,* **46 (15):**7939-7954.

Marks, E. A., Alcañiz, J. M. and Domene, X. 2014. Unintended effects of biochars on short- term plant growth in a calcareous soil. *Plant Soil,* **385:** 87-105.

Marschner, P., Kandeler, E. and Marschner, B. 2003. Structure and function of the soil microbial community in a long-term fertilizer experiment. *Soil Biology and Biochemistry,* **35:** 453-461.

Martinsen, V., Alling, V., Nurida, N., Mulder, J., Hale, S., Ritz, C., Rutherford, D. W., Heikens, A., Breedveld, G. D. and Cornelissen, G. 2015. pH effects of the addition of three biochars to acidic Indonesian mineral soils. *Soil Science and Plant Nutrition,* **61:** 821-834.

Mathews, J. A. 2008. Carbon-negative biofuels. *Energy Policy,* **36:** 940-945.

McBeath, A.V., Smernik, R. J., Krull, E. S. and Lehmann, J. 2014. The influence of feedstock and production temperature on biochar carbon chemistry: a solid-state 13C NMR study. *Biomass and Bioenergy,* **60:** 121-129.

McHenry, M. P. 2009. Agricultural biochar production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agriculture Ecosystem and Environment,* **129:** 1-7.

McHenry, M. P. 2010. Carbon-based stock feed additives: a research methodology that explores ecologically delivered C biosequestration, alongside live weights, feed use efficiency, soil nutrient retention, and perennial fodder plantations. *Journal of the Science of Food and Agriculture.,* **90:** 183-187.

Melas, G. B., Ortiz, O. and Alacañiz, J. M. 2017. Can biochar protect labile organic matter against mineralization in soil? *Pedosphere.* **27:** 822-831.

Mengel, K. and Kirkby, E. A. 2001. Principles of Plant Nutrition, 5th edition. Kluwer Academic Publishers, Dordrecht, Netherlands.

Mensah, A. K. and Frimpong, K. A. 2018. Biochar and/or Compost Applications Improve Soil Properties, Growth, and Yield of Maize Grown in Acidic Rainforest and Coastal Savannah Soils in Ghana. *Hindawi International Journal of Agronomy,* **8:** 6837404.

Mertz, O., Padoch, C., Fox, J., Cramb, R., Leisz, S., Lam, N. and Vien, T. 2009. Swidden Change in Southeast Asia: Understanding Causes and Consequences. *Human Ecology*, **37(3)**: 259-264.

Mitchell, P. J., Simpson, A. J., Soong, R. and Simpson, M. J. 2015. Shifts in microbial community and water-extractable organic matter composition with biochar amendment in a temperate forest soil. *Soil Biology & Biochemistry,* **81:** 244-254.

Mohan, D., Abhishek, A., Sarswat, A., Patel, M., Singha, M. and Pittman, C. U. 2018. Biochar production and applications in soil fertility and carbon sequestration – a sustainable solution to crop-residue burning in India. *RSC Advances*, **8:** 508.

Mothe, C. G. and de Miranda, I. C. 2009. Characterization of sugarcane and coconut fibers by thermal analysis and FTIR. *Journal of Thermal Analysis and Calorimetry,* **97:** 661-665.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A. 2012. Closing yield gaps through nutrient and water management. *Nature,* **490**: 254.

Mukherjee, A., Zimmerman, A.R. and Harris, W., 2011. Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma*, **163:** 247-255.

Mulcahy, D. N., Mulcahy, D. L. and Dietz, D. 2013. Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *Journal of Arid Environments,* **88:** 222-225.

Munera-Echeverri, J., Martinsen, V., Strand, L., Zivanovic, V., Cornelissen, G., and Mulder, Myers, N. 1993. Tropical forests: the main deforestation fronts. *Environmental Conservation*, **20(1)**: 9-16.

Nelissen, V., Rütting, T., Huygens, D., Ruysschaert, G. and Boeckx, P. 2015. Temporal evolution of biochar's impact on soil nitrogen processes - a15N tracing study. *GCB Bioenergy,* **7:** 635-645.

Nelissen, V., Rütting, T., Huygens, D., Staelens, J., Ruysschaert, G. and Boeckx, P. 2012. Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. *Soil Biology and Biochemistry,* **55:** 20-7.

Nguyen, B. T. and Lehmann, J. 2009. Black carbon decomposition under varying water regimes. *Organic Geochemistry,* **40:** 846-853.

Nguyen, B., Lehmann, J., Hockaday, W. C., Joseph, S. and Masiello, C. A. 2010. Temperature sensitivity of black carbon decomposition and oxidation. *Environmental Science and Technology,* **44:** 3324-3331.

Nguyen, T. T.N., Xu, C.Y., Tahmasbian. I., Che. R., Xu. Z. and Zhou, X. 2017. Effects of biochar on soil available inorganic nitrogen: a review and meta analysis. *Geoderma,* **288:** 79-96.

Nigussie, A., Kissi, E., Misganaw, M. and Ambaw, G. 2012. Effect of biochar application on soil properties and nutrient uptake of lettuces (Lactuca sativa) grown in chromium polluted soils. *American-Eurasian Journal of Agricultural & Environmental Sciences,* **12(3):** 369-376.

Novak, J. M., Busscher, W. J., Watts, D. W., Laird, D. A., Ahmedna, M. A. and Niandou, M.

Novak, J. M., Lima, I., Gaskin, J. W., Steiner, C., Das, K. C., Ahmedna, M., Watts, D. W., Warren, J. and Schomberg, H. 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science.* **3:** 195-206.

Novotny, E. H., de Maia, C. M. B. F., de Carvalho, M. T. M. and Madari, B. E. 2015. Biochar: pyrogenic carbon for agricultural use - a critical review. *Revista Brasileira De Ciencia Do Solo,* **39:** 321-344.

Oh, T. –K., CHOI, B., Shinogi, Y. and Chikushi, J. 2012. Characterization of Biochar Derived from Three Types of Biomass. *Journal of the. Faculty Agriculture, Kyushu University,* **57 (1):** 61-66.

Oh, T. K., Nakaji, K., Chikushi, J. and Park, S. K. 2010. Effect of the application of water treatment sludge on growth of lettuce (Lactuca satuva L.) and changes in soil properties. *Journal of The Factual Agriculture Kyushu Univ*ersity, **55(1):** 15-20.

Oni, O. I., Olajuyigbe, F. M. and Fatokun, C. O. 2019. Effective Substrate Loading for Saccharification of Corn Cob and Concurrent Production of Lignocellulolytic Enzymes by Fusarium oxysporum and Sporothrix carnis. *Current Biotechnology,* **8(2):** 109-115.

Ouyang, L., Yu, L. and Zhang, R. 2014. Effects of amendment of different biochars on soil carbon mineralisation and sequestration. *Soil Research,* **52:** 46-54.

Ozcismen, D. and Mericboyu, A. E. 2010. Characterization of biochar and bio-oil samples obtained from carbonization of various biomass material. *Renewable Energy.* **35:** 1319-1324.

Pandey, A., Soccol, C. R., Nigam, P. and Soccol, V. T. 2000. Biotechnological potential of agro-industrial residues. I: sugarcane bagasse. *Bioresource Technology,* **74:** 69-80.

Pandit, N. R., Mulder, J., Hale, S. E., Martinsen, V., Schmidt, H. P. and Cornelissen, G. 2018. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low- input Nepalese soil. *Science of the Total Environment,* **625:** 1380-1389.

Parmar, A., Nema, P. K., and Agarwal, T. 2014. Biochar production from agrofood industry residues: a sustainable approach for soil and environmental management. *Current Science,* **107(10)**:1673-1682.

Parvage, M. M., Ulen, B., Eriksson, J., Strock, J. and Kirchmann, H. 2013. Phosphorus availability in soils amended with wheat residue char. *Biology and Fertility of Soils,* **49(2):** 245-250.

Patiram. 1991. Liming of acid soils and crop production in Sikkim. *Journal of Hill Research,* **4:** 6-12.

Peng, X., Ye, L. L., Wang, C. H., Zhou, H. and Sun, B. 2011. Temperature and duration dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. *Soil and Tillage Research,* **112:** 159-166.

Peng, X., Ye, L. L., Wang, C. H., Zhou, H. and Sun, B. 2011. Temperature- and duration- dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. *Soil and Tillage Research,* **112(2):**159-66.

Piccolo, A. and Mbagwu, J. S. C. 1990. Effects of different organic waste amendments on soil micro aggregates stability and molecular sizes of humic substances. *Plant Soil,* **123:** 237.

Piccolo, A., Pietramellara, G. and Mbagwu, J. S. C. 1997. Use of humic substances as soil conditioners to increase aggregate stability. *Geoderma,* **75:** 267-277.

Pituello, C., Francioso, O., Simonetti, G., Pisi, A., Torreggiani, A., Berti, A. and Morari F. 2015. Characterization of chemical–physical, structural and morphological properties of biochars from biowastes produced at different temperatures. *Journal of Soils and Sediments,* **15(4)**: 792804.

Prasad, S., Singh, A. and Joshi, H. C. 2007. Ethanol as an alternative fuel from agricultural, industrial and urban residues. *Resources, Conservation and Recycling,* **50(1):** 1-39.

Preston, T. R. (2009). Environmentally sustainable production of food, feed and fuel from natural resources 11 in the tropics. *Tropical Animal Health and Production,* **41:** 873-882.

Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A. R. and Lehmann, J. 2012. Corn growth and nitrogen nutrition aft er additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils,* **48:** 271-284.

Rehrah, D., Reddy, M. R., Novak, J. M., Bansode, R. R., Schimmel, K. A., Yu, J., Watts, D. W. and Ahmedna, M. 2014. Production and characterization of biochars from agricultural byproducts for use in soil quality enhancement. *Journal of Analytical and Applied Pyrolysis* **108:** 301.

Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T. and Meek, D. 2011. Impact of biochar on manure carbon stabilization and greenhouse gas emissions. *Soil Science Society of America Journal,* **75:** 871-879.

Rondon, M. A., Lehmann, J., Ramirez, J. and Hurtado, M. 2007. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with biochar additions. *Biology and Fertility of Soi,* **43:** 699-708.

Rondon, M., Ramirez, J. and Lehmann, J. 2005. Charcoal Additions Reduce Net Emissions of Greenhouse Gases to the Atmosphere. In Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, MD, USA, 208.

Rondon, M.A., Lehmann, J.; Ramírez, J., and Hurtado, M. 2007. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. *Biology and Fertility of Soils,* **43:** 699:708.

Saarnio, S., Heimonen, K., and Kettunen, R. 2013. Biochar addition indirectly affects N2O emissions via soil moisture and plant N uptake. *Soil Biology and Biochemistry,* **58:** 99-106.

Saha, R., Chaudhary, R. S., and Somasundaram, J. 2012. Soil health management under hill agroecosystem of North East India. *Applied and Environmental Soil Science*, 1-9.

Sainju, U. M., Singh, B. P., Whitehead, W. F. and Wang, S. 2006. Carbon Supply and Storage in Tilled and Nontilled Soils as Influenced by Cover Crops and Nitrogen Fertilization. *Journal of Environment Quality*, **35:** 1507-1517.

Sanchez, P. 2020. Soil fertility and hunger in Africa. *Science,* **295:** 2019-2020.

Sartain, J. B. and E. J. Kamprath. 1977. Effect of soil Al saturation on nutrient concentration of soybean tops, roots, and nodules. *Agronomy Journal,* **69:** 843-45.

Scheer, C., Grace, P. R., Rowlings, D. W., Kimber, S. and van Zwieten, L. 2011. Effect of biochar amendment on the soil-atmosphere exchange of greenhouse gases from an intensive subtropical pasture in northern New South Wales, Australia. *Plant and Soil,* **345:** 47-58.

Schmidt, H. P., Pandit, B. H., Martinsen, V., Cornelissen, G., Conte, P. and Kammann, C. I. 2015. Fourfold increase in pumpkin yield in response to low-dosage root zone application of urine-enhanced biochar to a fertile tropical soil. *Agriculture,* **5:** 723-741.

Schmidt, M. W. I. and Noack, A. G. 2000. Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles,* **14:** 777-793.

Schulz, H. and Glaser, B. 2012. Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. *Journal of Plant Nutrition and Soil Science,* **175:** 410-422.

Serrão, E. A., Nepstad, D., and Walker, R. T. 1996. Upland agricultural and forestry development in the Amazon: sustainability, criticality and resilience. *Ecological Economics*, **18 (1)**: 3-13,

Shenbagavalli, S. and Mahimairaja, S. 2012. Production and characterization of biochar from diferent biological wastes. *International Journal of Plant Animal and Environmental Sciences,* **2:** 197-201.

Singh, A., and Singh, M.D. 1981. Effect of various stages of shifting cultivation on soil erosion from steep hill slopes. *Indian Forester*, **106(2)**: 115-12.

Singh, B. P. and Cowie, A. L. 2014. Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil. [J]. *Scientific reports***. 4(1):** 3687.

Singh, B. P., Cowie, A. L. and Smernik, R. J. 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. E*nvironmental Science and Technology,* **46:** 11770-11778.

Singh, B. P., Hatton, B. J., Singh, B., Cowie, A. L. and Kathuria, A. 2010. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *Journal of Environmental Quality*, **39:** 1224-1235.

Singh, B., Singh, B. P. and Cowie, A. L. 2010. Characterisation and evaluation of biochars for their application as a soil amendment. *Soil Research,* **48(7):** 516-25.

Smider, B. and Singh, B. 2014. Agronomic performance of a high ash biochar in two contrasting soils. *Agriculture, Ecosystems and Environment,* **191**: 99-107.

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):** 2345-2347.

Sohi, S. P., Krull, E., Lopez-Capel, E. and Bol, R. 2010. A review of biochar and its use and function in soil. *Advances in Agronomy,* **105:** 47-82.

Sohi, S., Krull, E., Lopez-Capel, E. and Bol, R. 2010. A review of biochar and its use and function in soil. *Advances in Agronomy,* **105:** 47-82.

Sohi, S., Lopez-Capel, E., Krull, E. and Bol, R. 2009. Biochar, climate change and soil: A review to guide future research. *CSIRO Land and Water Science Report,* 05/09: 64.

Song, W. and Guo, M. 2012. Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis,* **94:** 138-145.

Spokas, K. A. and Reicosky, D. C. 2009. Impacts of sixteen different biochars on soil greenhouse gas production. *Annals of Environmental Science,* **3:** 179-193.

Spokas, K. A., Novak, J. M., Stewart, C. E., Cantrell, K. B., Uchimiya, M., DuSaire, M. G. and Ro, K. S. 2011. Qualitative analysis of volatile organic compounds on biochar. *Chemosphere,* **85:** 869–882.

Srinivasarao, Ch., Gopinath, K. A., Govindarajan, V., Dubey, A. K., Wakudkar, H., Purakayastha, T., Pathak, S., Jha, P., Lakaria, B. L., Rajkhowa, D. J., Mandal, S., Jeyaraman, S., Venkateswarlu, B. and Sikka, A. 2013. Use of biochar for soil health management and greenhouse gas mitigation in India: Potential and constraints, Review articles 2062 *Current science*. Central Research Institute for Dryland Agriculture, Hyderabad. **115(10,11):** 1-51.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M. and De Wit, C. A. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science,* **347:** 1259855.

Steiner, C., Glaser, B., Teixeira, W. G., Lehmann, J., Blum, W. E. H. and Zech, W. 2008. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science,* **171(6):** 893-99.

Steiner, C., Teixeira, W. G., Lehmann, J. and Zech, W. 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered central amazonian upland soil. *Plant and Soil,* **291:** 275-290.

Subbiah, B. V. and Asija, G. L. 1957. A rapid procedure for estimation of available nitrogen in soils. *Current Science,* **25:** 259-260.

Subedi, R., Taupe, N., Pelissetti, S., Petruzzelli, L., Bertora, C., Leahy, J. J. and Grignani, C. 2016. Greenhouse Gas Emissions and Soil Properties following Amendment with Manure- Derived Biochars: Influence of Pyrolysis Temperature and Feedstock Type. *Journal of Environmental Management,* **166:** 73-83.

Sun, F. and Lu, S. 2014. Biochars improve aggregate stability, water retention, and pore- space properties of clayey soil. *Journal of Plant Nutrition and Soil Science,* **177 (1)**: 26–33.

Sun, H., Zhang, H., Xiao, H., Shi, W., Muller, K., Van Zwieten, L. and Wang, H. 2019. Wheat straw biochar application increases ammonia volatilization from an urban compacted soil giving a short-term reduction in fertilizer nitrogen use efciency. *Journal of Soils and Sediments,* **19:** 1624-1631.

Syed, W. J. 2010. Forms and status of nutrients in different land use systems of Alfisols. M. Sc (Agri). Thesis, submitted to Univ. Agric. Sci., Bangalore.

Taghizadeh-Toosi, A., Clough, T. J., Sherlock, R. R. and Condron, L. M. 2011. Biochar adsorbed ammonia is bioavailable. *Plant and Soil,* **350:** 57-69.

Taketani, R. G. and Tsai, S. M. 2010. The Influence of Different Land Uses on the Structure of Archaeai Communities in Amazonian Anthrosols Based on 16S rRNA and amoA Genes. *Microbial Ecology,* **59**: 734-743.

Tammeorg, P., Simojokib, A., Mäkeläa, P., Stoddarda, F. L., Alakukkuc, L. and Heleniusaa, J. 2014. Short-term effects of biochar on soil properties and wheat yield formation with meat bone meal and inorganic fertiliser on a boreal loamy sand. *Agriculture, Ecosystems and Environment,* **191:** 108-116.

Tarin, M. W. K., Khaliq, M.A., Fan, L., Xie, D., Tayyab, M., Chen, L., He, T., Rong, J. and Zheng, Y. 2021. Divergent Consequences of Different Biochar Amendments on Carbon Dioxide (CO_2) and Nitrous Oxide (N_2O) Emissions from the Red Soil. *Science of the Total Environment,* **754:** 141935.

Thies, J. E., Rillig, M. C. and Graber, E. R. 2015. Biochar Effects on the Abundance, Activity and Diversity of the Soil Biota. *In Biochar for Environmental Management: Science Technology and Implementation;* Lehmann, J., Joseph, S., Eds.; Routledge: New York, NY, USA. 928.

Tian, X., Li, C., Zhang, M., Wan, Y., Xie, Z., Chen, B. and Li, W. 2018. Biochar derived from corn straw affected availability and distribution of soil nutrients and cotton yield. *PLoS ONE* **13(1)**: e0189924.

Topoliantz, S., Pong, J. F. and Ballof, S. 2005. Manioc peel and charcoal: A potential organic amendment for sustainable soil fertility in the tropics. *Biology and Fertility of Soil,* **41:** 15-21.

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A. and Nishihara, E. 2011. Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use Management,* **27(2):** 205-12.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S. and Cowie, A. 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil,* **327(1-2):** 235-46.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, J. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smalling, E. M. A., Woomer, P. L. and Sanginga, N. 2010. Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture,* **39:** 17-24.

Verheijen, F., Jeffery, S., Bastos, A.C., van der Velde, M. and Diafas, I. 2010. Biochar application to soils: a critical scientific review of effects on soil properties, processes and functions. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg.

Von Uexkull, H. R. and Mutert, E. 1995. Global extent, development and economic impact of acid soils. *Plant and Soil,* **171:** 1-15.

Wang, J., Xiong, Z. and Kuzyakov, Y. 2016. Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy,* **8:** 512-523.

Wang, L., Butterly, C. R., Wang, Y., Herath, H. M. S. K., Xi, Y. G. and Xiao, X. J. 2014. Effect of crop residue biochar on soil acidity amelioration in strongly acidic tea garden soils. *Soil Use Management,* **30:** 119-128.

Wang, M., Wang, C., Lan, X., Abid, A. A., Xu, X., Singla, A., Sardans, J., Llusià, J., Peñuelas, J. and Wang, W. 2020. Coupled Steel Slag and Biochar Amendment Correlated with Higher Methanotrophic Abundance and Lower CH4 Emission in Subtropical Paddies. *Environmental Geochemistry Health,* **42:** 483-497.

Warnock, D.D., Lehmann, J., Kuyper, T. W. and Rillig, M. C. 2007. Mycorrhizal responses to biochar in soil—concepts and mechanisms. *Plant and Soil,* **300:** 9-20.

Withers, P. J. A., van Dijk, K. C., Neset, T.-S. S., Nesme, T., Oenema, O., Rubæk, G. H. and Pellerin, S. 2015. Stewardship to tackle global phosphorus inefficiency: The case of Europe. *Ambio,* **44**: 193-206.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J. and Joseph, S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications,* **1:** 56.

Woolf, D., Lehmann, J. and Lee, D. R. 2016. Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration. *Nature Communications,* **7**:1-11.

Wu, W., Yang, M., Feng, Q., McGrouther, K., Wang, H., Lu, H. and Chen, Y. 2012. Chemical characterization of rice straw-derived biochar for soil amendment. *Biomass and Bioenergy,* **47:** 268-76.

Xu, G., Sun, J., Shao, H. and Chang, S. X. 2014. Biochar had effects on phosphorus sorption and desorption in three soils with differing acidity. *Ecological Engineering,* **62:** 54-60.

Xu, J. M., Tang, C. and Chen, Z. L. 2006. Chemical composition controls residue decomposition in soils differing in initial pH. *Soil Biology and Biochemistry,* **38:** 544-52.

Yadav, P. K. 2013. Slash-and-burn agriculture in North-East India. Expert Opinion. *Environmental Biology,* **2**: 1-4.

Yamato, M., Okimori, Y., Wibowo, I. F., Anshori, S. and Ogawa, M. 2006. Effects of the application of charred bark of Acacia mangium on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. *Soil Science and Plant Nutrition,* **52:** 489-495.

Yanai, Y., Toyota, K. and Okazaki, M. 2007. "Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments." *Soil Science and Plant Nutrition*, **53(2):** 181-188.

Yang, W., Feng, G., Miles, D., Gao, L., Jia, Y., Li, C. and Qu, Z. 2020. Science of the Total Environment Impact of Biochar on Greenhouse Gas Emissions and Soil Carbon Sequestration in Corn Grown under Drip Irrigation with Mulching. *Science of the Total Environment*, **729:** 138752.

Yang, Y., Sun, K., Han, L., Chen, Y., Liu, J., and Xing, B. 2022. Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content. *Soil Biology and Biochemistry,* **169:** 108657.

Yang, Y., Sun, K., Han, L., Jin, J., Sun, H., Yang, Y. and Xing, B. 2018. Effect of minerals on the stability of biochar. *Chemosphere,* **204:** 310-317.

Yao, Y., Gao, B., Zhang, M., Inyang, M. and Zimmerman, A. R. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere,* **89:** 1467-1471.

Yuan, H. R., Lu, T., Wang, Y. Z., Chen, Y. and Lei, T. Z. 2016 Sewage sludge biochar: Nutrient composition and its effect on the leaching of soil nutrients. *Geoderma,* **267:**17-23.

Yuan, J. H., Xu, R. K. and Zhang, H. 2011. The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology,* **102:** 3488-3497.

Zavalloni, C., Alberti, G., Biasiol, S., Vedove, G. D., Fornasier, F., Liu, J. and Peressotti, A. 2011. Microbial mineralization of biochar and wheat straw mixture in soil: A short-term study. *Applied Soil Ecology,* **50:** 45-51.

Zhang Q, Wu J, Yang F, Lei Y, Zhang Q. and Cheng X. 2016. Alterations in soil microbial community composition and biomass following agricultural land use change. *Scientific Reports,* **6:** 36587.

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

Zhang, G. S., Chan, K. Y., Oates, A., Heenan, D. P. and Huang, G. B. 2007. Relationship between soil structure and runoff/soil loss after 24 years of conservation tillage. *Soil Tillage Research,* **92:** 122-128.

Zhang, S., Yang, X., Ju, M., Liu, L. and Zheng, K. 2019. Mercury adsorption to aged biochar and its management in China [J]. *Environmental Science and Pollution Research.* **26 (5):** 4867-4877.

Zhao, B., O'Connor, D., Zhang, J., Peng, T., Shen, Z., Tsang, D. C. and Hou, D. 2018. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. *Journal of Cleaner Production,* **174:** 977-987.

Zhao, R., Coles, N. and Wu, J. 2015. Carbon mineralization following additions of fresh and aged biochar to an infertile soil. *Catena,* **125:** 183-189.

Zhao, S. X., Ta, N. and Wang, X. D. 2017. Effect of temperature on the structural and physicochemical properties of biochar with apple tree branches as feedstock material. *Energies,* **10(9):** 1293.

Zheng, H., Wang, Z., Deng, X., Herbert, S. and Xing, B. 2013. Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. *Geoderma,* **206:** 32-39.

Zheng, T., Zhang, J., Tang, C., Liao, K. and Guo, L. 2021. Positive and negative priming effects in an Ultisol in relation to aggregate size class and biochar level [J]. *Soil and Tillage Research.* **208:** 104874.

Zheng, Y., Han, X., Li Y., Yang, J., Li, N. and An, N. 2019. Effects of biochar and straw application on the physicochemical and biological properties of paddy soils in Northeast China. *Scientific Reports,* **9:**16531.

Zhou, L., Cai, D., He, L., Zhong, N., Yu, M. and Zhang, X. 2015. Fabrication of a high-performance fertilizer to control the loss of water and nutrient using micro/nano networks. *ACS Sustainable Chemistry and Engineering,* **3(4):** 645-53.

Zimmerman, A. R. 2010. Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environmental Science and Technology,* **44:** 1295-1301.

Zimmerman, A. R., Gao, B. and Ahn M. Y. 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry,* **43:** 1169-1179.

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List of Publication(s)

Sl. No.	**Title**	**Journal & Page No.**	**ISSN/ ISBN No.**	**First/ Co-author**
1	Soil organic carbon stock of different land uses of Mizoram, Northeast India	AIMS Geosciences 5(1): 25-40. 2019	ISSN: 2471-2132	First author
2	Effect of Four Land uses on Soil Edaphic Properties and Soil Organic Carbon Stock in Mizoram, North-East India	Indian Forester 145(12): 1139-1146. 2019	ISSN: 0019-4816	First author
3	Effect of Land Use Changes on Carbon Stock Dynamics in Major Land Use Sectors of Mizoram, Northeast India	Journal of Environmental Protection. 9: 1262-1285 2018	ISSN: 2152-2197	Co-author
4	Assessment of Growth, Carbon Stock and Sequestration Potential of Oil Palm Plantations in Mizoram, Northeast India	Journal of Environmental Protection. 9: 912-931 2018	ISSN: 2152-2197	Co-author
5	Active and passive soil organic carbon pools as affected by different land use types in Mizoram, Northeast India	PlosONE 14(7): e0219969.	ISSN: 1932-6203	Co-author

Paper(s) presented in Workshop/Seminar

Sl. No.	Title of the Paper	Title of Workshop/ Seminar	Organized by	National or International
1	Tree diversity and carbon stock of different plantation forests of Mizoram, Northeast India	International Conference on Biodiversity, Environment and Human Health: Innovations and Emerging Trends (BEHIET 2018)	School of Life Sciences, Mizoram University, Aizawl, Mizoram, India	International
2	Soybean growth and yield responses to the application of biochar and vermicompost grown on a degraded jhum land in Mizoram, Northeast India	International Conference (Online) on Agriculture, Biological and Life Sciences (ICABLS-2021)	Vidya Kutir Foundation, New Delhi	International
3	The ameliorating effect of biochar made from two agricultural waste on soil physico-chemical properties and soybean	Environmental Humanities in the Anthropocene Era: Ecojustice and Sustainability	Department of English and Department of Geography, Fazl Ali College, Mokokchung, Nagaland	International

Seminars/Symposia/Course/ Workshop Attended

Sl. No.	Title of symposium/ orientation/ tutorial/ workshop/ short term course attained	Place	Year
1	North East Regional Research Scholar's Meet	UGC-SAP (DRS-II) Activity Department of Life Sciences & Bioinformatics Assam University, Silchar	2017
2	Training and Awareness Programme on Protection of Plant Varieties and Farmers' Rights	Department of Horticulture, Aromatic and Medicinal Plants, Mizoram University, Aizawl	2017
3	Workshop on "Statistical and Computing Methods for Life-Science Data Analysis"	Department of Botany, Mizoram University	2018
4	NRDMS-DST Orientation Program on Geospatial Technologies, Theme "General Orientation to Geospatial Technology and Applications"	Department of Forestry, Mizoram University, Aizawl	2019
6	DST, Government of India Sponsored Training Program on "Climate Change Adaptation for Natural Resource Management for the State of Mizoram"	Department of Environmental Science, Mizoram University, Aizawl	2021
7	One Day Workshop on Research and Publications for Higher Education Faculty	Mount Tiyi College, Wokha, Nagaland	2023
8	One-Day National Seminar on NEP 2020-Transforming India	Mount Tiyi College, Wokha, Nagaland	2023

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DEPARTMENT	:	FORESTRY
TITLE OF THESIS	:	STUDIES ON THE IMPACT OF AGRICULTURAL WASTE BIOCHAR AND ORGANIC AMENDMENTS ON SOIL NUTRIENT RECOVERY AND CARBON POOL IN JHUM LAND.
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ABSTRACT

STUDIES ON THE IMPACT OF AGRICULTURAL WASTE BIOCHAR AND ORGANIC AMENDMENTS ON SOIL NUTRIENT RECOVERY AND CARBON POOL IN JHUM LAND

AN ABSTRACT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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JULY, 2024

Although jhum cultivation has a great adverse effect on the environment, a vast majority of rural and semi-urban household still continues to practice this form of farming system, thereby degrading the soil further leading to reduced crop yield. Also, the cutting down and clearing of forest continues to increase the emission of carbon dioxide into the atmosphere. Many studies have shown that biochar acts as a soil conditioner besides having the potential to sequester carbon. In Mizoram, maize and sugarcane are grown in a large scale. Area under maize cultivation is 5695 ha and area under sugarcane cultivation is 1476 ha (Agricultural Statistical Abstract, 2014-2015). Sugarcane juice locally called as *futui* is commonly produced on a small commercial scale in Mizoram. After the juice is extracted out, the sugarcane bagasse is simply thrown away. Therefore, sugarcane bagasse and maize cobs have tremendous potential to be used as biochar for improving degraded land by increasing soil productivity as well as sequestering soil organic carbon. Hence this study aims to evaluate the impact of these two agricultural waste biochar on nutrient recovery and soil carbon pool in jhumland.

Objectives

The general objective of this study is to determine the impact of agricultural waste biochar and organic amendments on soil nutrient recovery and carbon pool in jhum land.

With this main objective, the study was designed to cover the following specific objectives:

1. To determine the quality of biochar made from maize cob and sugarcane bagasse.
2. To assess the impact of biochar and vermicompost on soil properties in jhumland.
3. To assess soil carbon pool in jhumland with application of biochar and vermicompost.
4. To determine the effect of biochar and vermicompost on growth and yield of soybean in jhumland.

Major findings

To determine the quality of biochar made from maize cob and sugarcane bagasse.

For carrying out this experiment, biochar was prepared separately for each feedstock using drum retort method proposed by NICRA, Central Research Institute for Dryland Agriculture, Hyderabad. In the laboratory the physical and chemical analyses such as pH, electrical conductivity, cation exchange capacity, and proximate analyses such as moisture content, ash content, volatile matter content and fixed carbon content of sugarcane bagasse biochar and maize cob biochar were carried out. In addition, the surface morphological characteristics and the functional groups present in the biochar were also investigated.

i. As seen from the result, both the biochar were found to be alkaline with sugarcane bagasse biochar exhibiting higher values than maize cob biochar in all the parameters analysed except in CEC and fixed carbon content.
ii. The surface morphological analysis of the two feedstock using SEM imaging demonstrated a vast difference in the pore structure before and after conversion to biochar. The construction of a carbonaceous framework that resembled the capillary structure present in sugarcane biomass culminated in the formation of a honeycomb-like structure, as seen by SEM images.
iii. The functional groups identified in the study were aliphatic C-H, carbonyl (C=O) and C-C and hydroxyl (O-H).

To assess the impact of biochar and vermicompost on soil properties in jhumland.

For this experiment, a randomized block design with three replicates and 8 treatments was established for a total of 24 experimental plots. The treatments were untreated control (T0), vermicompost at 5t/ha (T1), sugarcane bagasse biochar at 5t/ha (T2), Maize cob biochar at 5t/ha (T3), vermicompost + sugarcane biochar

(T4) at 2.5 t/ha each, vermicompost + maize cob biochar at 2.5 t/ha (T5), sugarcane biochar + maize cob biochar at 2.5 t/ha (T6), vermicompost + sugarcane biochar + maize cob biochar at 1.66 t/ha each (T7). The experimental plot was constructed with the size of 2m x 1.5 m and a buffer zone of 0.5 m was maintained between each treatment rows to reduce any external effect.

The soil samples were collected twice each season *viz.* before sowing and after harvesting soybean. The soil samples were collected from each plot at two soil depths i.e., 0-15 cm and 15-30 and immediately transferred to the laboratory, mixed uniformly, and sieved at field moist state within three days. The physical, chemical and biological properties of the soil samples analysed were bulk density, moisture content, pH, available nitrogen, available phosphorus, available potassium, microbial biomass content, soil organic carbon content and cation exchange capacity.

i. Our findings indicated a positive effect of biochar on the soil physical and chemical properties. We observed an increase in soil pH with the addition of biochar and vermicompost which is probably due to the alkaline nature of the biochars used in the study.
ii. A significant increase in the organic matter and the CEC of the soil was seen following the application of biochar and vermicompost although the CEC content of the biochars used in this study were lower than the CEC of the soils.
iii. The present study demonstrated an increase in available N and available K of soil though soil available P was not significantly increased.

To assess soil carbon pool in jhumland with application of biochar and vermicompost

For this experiment the following parameters were analysed: total carbon, soil inorganic carbon and total organic carbon content of the soil samples were measured. The organic carbon (TOC) was separated into the following four fractions of decreasing oxidizability/lability based on the concentration of OC, which was calculated using the three ratios of acid to aqueous solution.

1. Very labile (VLC): Organic C oxidizable under 12N H_2SO_4
2. Labile (LC): Difference in SOC oxidizable under 18N and that under 12N H_2SO_4
3. Less labile (LLC): Difference in SOC oxidizable under 24N and that under 18N H_2SO_4
4. Recalcitrant/ Non-labile (NLC): Residual SOC after reaction with 24N H_2SO_4 when compared with TOC. The very labile and labile pool may be summed up and it may be designated as active pool. Similarly, less labile and non-labile pool may be summed up and designated as passive pool.

i. The total carbon and total organic carbon within 0-30 cm soil depth increased with the application of biochar.
ii. The very labile fraction of the carbon pool was enhanced by the addition of biochar corroborating the existing knowledge that biochar produced at a lower temperature (<500° C) result in a C-rich product with more labile structures that are rapidly mineralized when applied to soil.
iii. The fraction of active carbon pool was higher than the passive carbon pool suggesting that the carbon stored in soil could be easily lost if not properly managed.
iv. Further, the labile portion of the carbon pool decreased in the second year as compared to the first year suggesting that ability of biochar in sequestering C.

To determine the effect of biochar and vermicompost on growth and yield of soybean in jhumland

Prior to sowing, the plots were manually tilled and the treatments were applied within the top 0-15 cm of the soil. The treatments were applied only once in the first year before sowing during the two years experiment. After the applications of the treatments, three seeds were sown per hole in every plot with a row spacing of 20cm x 25cm. One week after sowing, two plants were allowed for growing season. Plant growth data such as number of leaves per plant, plant height per plant and stem girth per plant were collected at 2, 4, and 6, 8, 10 and 12 weeks after sowing (WAS) whereas yield data such as average pod length, grain yield (kg/ha) and harvest index were measured at the time of harvest.

i. In both the years, we observed that the combined application of biochar and vermicompost had a positive effect on the growth of soybean.
ii. On the other hand, sole application of biochar decreased the growth of soybean in relative to control plot which validates the fact that freshly produced biochar may affect the plant growth adversely by immobilizing the movement of nutrient uptake by plants.
iii. Of all the yield parameters measured, addition of biochar significantly increased only the number of pods per plant.
iv. Additionally, the grain yield of soybean was higher in the first year than the second which implies the fading positive effect of amendments in the second year since biochar was applied only once before the start of the experiment.
v. From these findings, we can conclude that the combination of biochar with organic manures or compost is more beneficial than the sole application of biochar or compost for the growth and consequentially the yield of crops.

Potentials, constraints and implications of biochar use

Based on the findings of this study, we can conclude that biochar has the potential to improve the soil quality. The functions and workings of biochar in enhancing the soil fertility could be could be explained by the following aspects- First, because biochar naturally contains soluble nutrients and because the labile fraction of the material has mineralized and contains organically bound nutrients, it can be used as a source of nutrients to improve soil fertility. Second, biochar may enhance the chemical and physical characteristics of soils mainly because biochar has the potential to enhance the physical characteristics of soil, such as increasing porosity and water-holding capacity. The enhancement of soil characteristics, such as improved pH, cation exchange capacity, and aggregation capacity, may boost soil fertility by reducing nutrient loss and increasing nutrient levels and availability. Thirdly, biochar has the potential to function as a slow-release fertiliser by storing nutrients. Biochar's unique pore structure and functional groups allow excess nutrients like phosphate, ammonium, and nitrate to be stored on the surface of the material. Because of its desorption qualities, biochar may then gradually reabsorb nutrients, hence decreasing nutrient leaching and increasing nutritional contents. Besides acting as a soil conditioner, the conversion of biomass carbon to biochar can aid in sequestering atmospheric CO_2. The current slash-and-burn method, which is also widely practised in NE india, releases greenhouse gases and seriously degrades the soil. But it also offers room for improvement, such as switching from the slash-and-burn to the slash-and-char method. As observed in our study, the very labile fraction of the carbon pool decelerated at the conclusion of the experiment indicating that biochar C became more stable with time suggesting the greater potential for long term carbon sequestration. A notable enhancement in soybean growth was also observed upon biochar’s addition particularly when applied in conjunction with vermicompost. This is most likely because the physical and chemical properties of the soil were improved. Applying biochar in conjunction with other organic amendments is advised in order to maximise its benefits, as this research suggests that biochar may not contain enough nutrients for plants, even though it retains the nutrients.

Given all of these advantages of biochar, particularly its ability to increase crop yield, farmers may be enticed to use it on their farm if the method of making it is simple and affordable. However, the practical issues of cost, application rate, availability, and associated risks with application should be fully explored before implementing it on a wide scale. Therefore, this short-term study might provide an insight into the effects of biochar, particularly in the degraded jhumland of NE India and help the policy makers or government agencies to formulate policies to help the farmers adopt biochar to improve the degraded jhumland soils.

To summarise, biochar exhibits significant promise for mitigating climate change and promoting sustainable agriculture. However, further investigation is necessary to completely comprehend its impacts and optimise its practical advantages, making this an essential matter for the future.