Chapter

Increasing the Amount of Biomass in Field Crops for Carbon Sequestration and Plant Biomass Enhancement Using Biochar

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Abstract

The agricultural sector, especially in developing countries, is vulnerable to the effects of climate change partially caused by greenhouse gas (GHG) emissions from agricultural areas. Field crops are capable of bio-sequestration in its aboveground and belowground biomass. Incorporating biochar as a soil amendment increases its potential to become an important bio-sequestration which makes the agricultural sector a key contributor to climate change mitigation. This chapter discussed and presented data obtained from research on biochar using to increase plant biomass for carbon sequestration purposes. The biochar was produced from cassava stems by pyrolysis using a patented retort that was especially designed for agriculturalists to produce a low-cost biochar for their own use. The ability to increase biomass of field crops for carbon sequestration is crucial towards reducing the GHG emissions. This research also shed light on an innovative agricultural method, in comparison to traditional farming, that leads to sustainable agriculture in the long run. The biochar research is also a way to transfer research knowledge from laboratory to practical use.

Keywords: biochar, carbon sequestration, carbon storage, biomass, agriculture

1. Introduction

The agricultural sector contributes to climate change problems through greenhouse gas (GHG) emission from various agricultural activities. However, the agricultural sector is also a carbon sink, both in terms of its potential to store carbon in various forms and its cultivated area, where agricultural areas are scattered all over the globe. Thus, agricultural areas could potentially be utilized as effective carbon sequestration areas. Moreover, the Food and Agriculture Organization (FAO) of the United Nations (UN) has also suggested the use of agricultural areas for carbon sequestration to reduce GHG emissions [1, 2].

According to the UN Framework Convention on Climate Change (UNFCCC), the measurement of GHG emission reduction and the measurement of carbon capture and storage in agricultural sectors should not have any effect on food production and farmers. The framework has been specially emphasized in agricultural and developing countries, where most of the population are farmers and are from a low socioeconomic background. Therefore, GHG reduction can be performed in the form of a carbon sink in agricultural areas, where the carbon that is sequestered by biomass during photosynthesis or bio-sequestration [2, 3] can reduce the amount of GHG emission throughout the plant's life time [4–7]. Bio-sequestration appears to be a suitable and viable means of mitigation for long-term climate objectives. Many research reports have suggested that plants are capable of bio-sequestration in the form of accumulated biomass in their stems and in the soil [1, 6, 8]. The notion of carbon sequestration in biomass as a means to climate change mitigation is based upon the aim of storing carbon in different types of forest areas [9–13]. Although carbon sequestration in plant biomass in agriculture is an effective tool for climate change mitigation, carbon sequestration in agricultural sectors has not yet been intensively evaluated in agricultural countries. The level of carbon sequestration in the aboveground and belowground biomass of plants depends on the plant's biomass and thus varies with the plant species/cultivar, age, and quantity of the plants [14, 15]. Some or many field crop areas are suitable for carbon sequestration without negative impacts on farmers and food production.

Biochar is a highly stable substance that is high in fixed carbon. Incorporating it into agricultural soils has the potential to become an important means for GHG reduction. Biochar contributes to GHG reduction by retaining the carbon within the soils and within the plants or bio-sequestration [16–20]. Moreover, biochar has been widely used as a soil amendment to improve crop yields, in terms of the quantity and quality [21–24]. It also improves the physical, chemical, and biological characteristics of the soil [23, 25–28]. Therefore, using biochar as a soil amendment can help reduce requirements for agrochemical fertilizers, which is one of the causes of GHG emissions. It fits within the framework from the UNFCCC and Kyoto Protocol report [29, 30].

In this context, this chapter discussed and presented data obtained from research on biochar using to increase plant biomass for carbon sequestration purposes. The biochar was produced from feedstocks by pyrolysis using a patented retort that was especially designed for agriculturalists to produce a low-cost biochar for their own use. The biochar research is also a way to transfer research knowledge from laboratory to practical use.

2. Biochar, carbon sequestration, and plant biomass relationships

The indirect storage of carbon is the natural CO_2 storage system from the growth of plants, which is an inexpensive method and can be implemented anywhere in the world. Most of the time, it is implemented in forested areas; however, according to a number of research studies, agricultural areas as well as forested areas are considered a promising place to store carbon [2, 4–7, 23]. It could reduce greenhouse gases as well as perform as a sink of agricultural CO_2. Undoubtedly, the method is given considerable attention, especially by the Food and Agriculture Organization (FAO) who gives very much importance on measures to reduce greenhouse gases [31]. The movement of carbon and the variation scale of CO_2 from air to soil increase carbon in soil. Subsequently, there is a decreasing amount of CO_2 released from soil to air. Therefore, carbon storage is an influential mechanism that tremendously affects the reduction of greenhouse gases, which has approximately 89% of technical efficiency, whereas there was a 9% and 2% reduction of methane gas and nitrous oxide released from soil, respectively. Moreover, the movement of carbon from carbon emissions to carbon absorptions would efficiently reduce the variation of the atmosphere [32].

IPCC [1] characterized carbon storage in forested areas into five places including biomass above ground, underground biomass, dead trees, and organic carbon in the soil, all of which consist of storage in trees, and most of it is stored underground. Each type of trees possesses different carbon storage efficiency and accumulated carbon according to the wood and types of wood changing according to the present related conditions [33–35], such as the age of the forest, the type of the forest, and the tree sizes [36], the forest density [37], the forest structure [38], and more. Nevertheless, plants except big trees can be adopted in storing carbon with more studies concerning the amount of carbon absorption or the amount of carbon storage in the life cycle of each plant. Carbon would be captured since the initial growth of plants until their full maturity. After plants are fully grown, the captured carbon would remain stable. Carbon indirect storage adopts photosynthesis of the plants, which depends on CO_2 to propel the chemical reaction to water turning into glucose and oxygen, as in Eq. (1).

$$6\,CO_2 + 6\,H_2O \xrightarrow[\text{Sunlight energy}]{} C_6H_{12}O_6 + 6\,O_2 \tag{1}$$

Carbon storage in the soil of agricultural and forested areas is an approach several countries have adopted to reduce GHG emissions. The implementation could be immediate and inexpensive, relying on the photosynthesis of plants that store carbon in the plant tissues (cores, leaves, fruits, and roots). After the death of these parts, these organic parts decompose, while it is also hard for some parts to decompose such as humus, which remain in the soil as organic matters. The number of the fallen plant components varies according to habitats of living organisms. The factors that affect the fallen plants include plant types, environment, the care of the plants, and duration. By and large, products obtained from the plants are more than fallen plants, possibly attributable to the plant age compared to the plant density [14]. According to that, biochar is adopted in the carbon storage in the soil in order to cut the cycle of being released to the atmosphere. Furthermore, methane and nitrous oxide emissions could be cut down from agricultural areas; hence, this process is effective in greenhouse gas reduction.

Biochar can improve the degraded soil, which has been proved by research to effectively enhance agricultural products, increasing the biomass of plants [23, 39–41], which is an indirect way to reduce greenhouse gases (Carbon Negative Technology) [17, 18, 42]. What is more, biochar has a high volume of fixed carbon. After the process of pyrolysis, there would be only 50% of carbon left in biochar [18, 44, 45]. Carbon in biochar is steady and hard to decompose by microorganisms in the soil, making biochar remain underground for a long time. Thus, this could be considered a way of carbon storage in the soil [20, 46], different from other organic matters such as plants, green manure, compost manure, and manure. These could decompose quickly, especially in tropical areas, giving rise to a high volume of CO_2 emissions in a rapid manner [47]. For this reason, agricultural areas with the integration of biochar can store carbon more effectively than those with the integration of biomass with the same amount of carbon [48]. According to the research study by Maraseni [49], once there is a change in the agricultural areas from enlargement by deforestation and slash and burn systems to deforestation and slash and char systems, there is 12% reduction of losing carbon. Biochar made of grass could reduce 3 tons of CO_2 emissions per 1 ton of biochar [50].

3. Pilot project for biochar application for sustainable agriculture in Thailand

3.1 Study area

The study of increasing biomass in feeding maize (*Zea mays* L.) was performed on experimental plots in Pa Deng-Biochar Research Center (Pd-BRC), Pa Deng sub-district, Kaeng Krachan district, Petchaburi province, Thailand. This is part of the Huay Sai Royal Development Study Centre. The topology is undulating and rolling. The soil is sandy loam with a medium to high soil permeability, a medium to very low organic matter (OM = 0.04–1.16), and a pH that ranges from slightly alkaline to extremely acidic. The land has very low soil fertility and experiences soil erosion and water scarcity [51]. The majority of the area in Pa Deng is a slope complex with a gradient of more than 35%. Therefore, the Pa Deng area is enclosed by hills that limit the land utilization to only 12% of the total area [52]. The low soil fertility and limited area available for agriculture lead to the heavy use of agrochemicals among farmers to improve the quality and yield of their agricultural products. This creates long-term negative effects on the soil and environment.

3.2 Research design and experimental plots

A completely randomized design was used for this study. There were 7 treatments each with 4 replications giving a total of 16 experimental plots. Each experimental plot was 3 × 5 m in size. The maize was planted in two crop cycles. After harvesting the first cycle, the treatments were left in their original condition with no further addition of biochar or organic fertilizer. The maize was planted in May and was harvested in August. Pa Deng has been suffering from droughts for a long period of time. The crops were planted during the absence of rain period and in the strong sunlight. The crops were watered from water sprinklers.

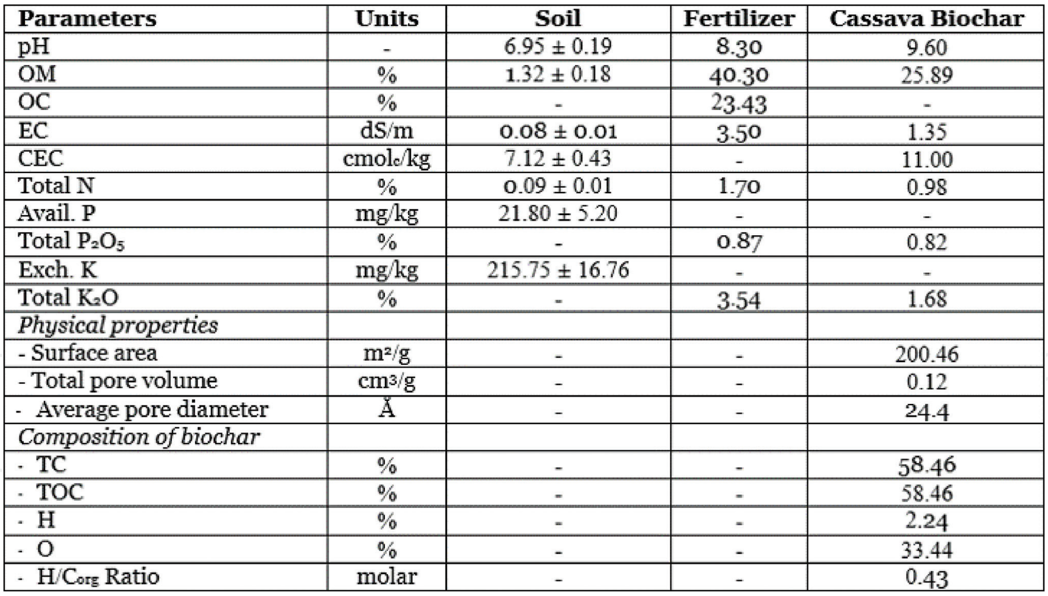
There are seven treatments in total. Four treatments consisted of soil plus 5.6 ton/ha of organic fertilizer with different amounts of added biochar at 0 (TBC0), 5 (TMBC0.5), 25 (TMBC2.5), and 30 (TMBC3.0) ton/ha, respectively. The other three treatments consisted of soil plus added biochar at 0, 5 (TBC0.5), 25 (TBC2.5), and 30 (TBC3.0) ton/ha, respectively. TBC0 was the controlled treatment.

The organic fertilizer used in this study was produced from the composting of soybean stems, and its characteristics were as follows: pH 8.3, electrical conductivity (EC) of 3.50 dS/m, 40.30 wt.% OM, 23.43 wt.% total organic carbon (TOC), 1.70 wt.% total nitrogen (total N), 0.87 wt.% total phosphorus (total P_2O_5), 3.54 wt.% total potassium (total K_2O), and a 13.75 C/N ratio. In general, all the properties of fertilizer were shown in **Table 1**. The organic fertilizer used in this study was in accordance with all the parameters of the Organic Fertilizer Standard of the Thai Department of Agriculture in 2005 [53].

The maize used in this study was a single-cross hybrid CP 888 variety (flint corn) with strong stems. This maize can be waited for a long harvest. The maize is drought tolerant and can grow well in upland areas with medium precipitation making it suitable in the Pa Deng area. It is also popular among farmers. Biochemical pesticides and herbicides were used to prevent pests and weeds, especially during the period of 13–25 days after seeding emergence. This is the most critical period to prevent flora and pests from severely affecting the crops [53, 54].

3.3 Biochar production and its characteristic

Biochar was produced from cassava stems (cassava crop waste) by pyrolysis process using the Controlled Temperature Biochar Retort for Slow Pyrolysis Process (patented) that the research team invented to suit local uses. The biochar process is simple and low-cost [20, 23]. The retort was a controlled temperature biochar retort for slow pyrolysis which was complied with the standard set by FAO [56], with a controlled temperature between 450 and 600°C. After the process was finished, the biochar was ground and sieved to less than 3 mm diameter. This particle size was selected since it improves soil aeration and other processes in the soil [55, 57].



Parameters	Units	Soil	Fertilizer	Cassava Biochar
pH	-	6.95 ± 0.19	8.30	9.60
OM	%	1.32 ± 0.18	40.30	25.89
OC	%	-	23.43	-
EC	dS/m	0.08 ± 0.01	3.50	1.35
CEC	$\mathrm{cmol_c/kg}$	7.12 ± 0.43	-	11.00
Total N	%	0.09 ± 0.01	1.70	0.98
Avail. P	mg/kg	21.80 ± 5.20	-	-
Total P_2O_5	%	-	0.87	0.82
Exch. K	mg/kg	215.75 ± 16.76	-	-
Total K_2O	%	-	3.54	1.68
Physical properties				
- Surface area	m^2/g	-	-	200.46
- Total pore volume	cm^3/g	-	-	0.12
- Average pore diameter	Å	-	-	24.4
Composition of biochar				
- TC	%	-	-	58.46
- TOC	%	-	-	58.46
- H	%	-	-	2.24
- O	%	-	-	33.44
- H/C_{org} Ratio	molar	-	-	0.43

Table 1.
The properties of pre-experimental soil, fertilizer, and cassava biochar.

The biochar sampling method was adapted from the Standardized Product Definition and Product Testing Guidelines for Biochar that is used in soil [58] by collecting samples from every pyrolysis process. The samples were randomly selected from the ground biochar and analyzed for their specific surface area, total pore volume, average pore diameter, pH, EC, cation exchange capacity (CEC), OM, total carbon (C), total organic carbon (TOC), %hydrogen (H), %Oxygen (O), and the molar hydrogen to total organic carbon ratio (H/C_{org} Ratio).

The cassava biochar composites were comprised of 58.46 wt.% total C and 58.46 wt.% TOC. The biochar from the cassava stems had a specific surface area of 200.46 m^2/g, total pore volume of 0.12 cm^3/g and average pore diameter of 24.4 Å, with an alkaline pH of 9.6, EC of 1.35 dS/m, and CEC of 11.00 cmol/kg. The cassava biochar had a very high OM content of 25.89%, total N of 0.98%, total P_2O_5 of 0.82%, and total K_2O of 1.68% (**Table 1**).

The cassava stem biochar was high in carbon, mostly in the form of amorphous carbon in which the carbon atoms were attached in aromatic rings [18, 21, 22, 42, 44]. This chemical property makes the carbon in cassava stem biochar very stable [59–61] and creates a highly porous carbon structure in the biochar [60, 62]. The pyrolysis biochar at 450–600°C also contributed to the high stability of carbon [60, 63, 64]. The high porosity of biochar allows biochar to absorb and retain water and nutrients within the soil [23, 42, 55, 61, 65]. This helps with aeration and reduces soil density [18, 60, 66–68]. Moreover, the appropriate temperature during the pyrolysis process of the cassava stems also increased porosity on the biochar's surface which led to increased ions on the its surface [17, 18, 62, 69, 89]. This resulted in a high ion exchange capacity and high CEC [26, 42, 60, 69, 70]. As a result, the cassava stem biochar had a high capacity to retain and adsorb organic carbon and non-organic matters within the soil. Moreover, it also increased activities in the soil and ion exchange between nutrients in the form of soil solution.

Cassava biochar has high alkalinity (pH 9.6). Alkalinity affects the type of biomass made into biochar [25, 71, 72]. Moreover, biochar from cassava stems also had a high OM (25.9 wt.%), which would contribute to an increased OM level in the soil and improve the soil fertility. These physical and chemical characteristics and chemical formations in biochar made it suitable as a soil amendment to increase plant growth [23, 25, 43, 44, 55, 60, 74, 75] and soil amelioration in acidic soils.

3.4 Soil properties and soil character analysis

The soil in the experimental plots was analyzed before planting the crops. Soil was selected at random from areas scattered throughout each plot and taken from 0 to 30 cm depth. The samples were considered as composite samples in the soil analysis. Physical and chemical characteristics of the soil samplings were analyzed using the methods developed by the Soil Survey Staff [76], including the pH, OM (Walkley and Black method), soil texture (hydrometer method), CEC (leaching method), EC, total N (Kjeldahl method), available phosphorus (avail. P) (Bray II determine by spectrophotometer), and exchangeable potassium (exch. K) (ammonium acetate extraction determine by atomic absorption spectrophotometer).

The pre-experimental soil analysis results (**Table 1**) revealed that the soil in the experimental plots was a slightly alkaline sandy clay loam (%Sand = 57.0, %Silt = 22.5, %Clay = 20.5) with a pH of 6.95 and EC of 0.08 dS/m. It is suitable for growing flint corn for feeding animals [53]. The soil had a high level of primary macronutrients except total N (total N = 0.09%, avail. P = 21.80 mg/kg, and exch. K = 215.75 mg/kg) (**Table 1**).

The soil in this region had a very low fertility with an OM of 1.32%. The OM in soils is decomposed by soil microbes, and it depended on the carbon distribution at different soil densities, which helped prevent the decomposition [77].

3.5 Evaluation of the maize biomass

During the harvesting period, the maize was uprooted from the soil and washed with water. The plants were then left to dry in the shade before being measured for their whole plant fresh (wet) weight (FW). The plants were then cut so as to separate the roots, upper roots (stems + leaves + staminate), pods, and seeds. The FW of each part of the plant was measured then cut into small pieces and put in an oven at 70°C for 48 h or until the weight was stable (dry weight: DW). Using the FW/DW ratio, the crop biomass was estimated. After that, the DW of the plants was used to derive the moisture content (wt.%), from which the biomass in different parts of the crop in each experimental plot was calculated, derived from Eqs. (2) and (3):

$$\text{Biomass} = 100\,[\text{DW}\,(\text{g})]/(\text{moisture content} + 100) \tag{2}$$

$$\text{Moisture content} = 100\,[\text{FW}\,(\text{g}) - \text{DW}\,(\text{g})]/\text{FW}\,(\text{g}) \tag{3}$$

3.6 Analysis of carbon sequestration from maize grown in the different biochar-supplemented soils

The amount of carbon sequestered in each part of maize in the different experimental treatment plots consisted of the carbon concentration of the plant biomass, as shown in Eq. (4). The plant carbon stock was estimated by multiplying the total plant biomass with the carbon concentration (%). This study applied the FAO method [78] for carbon stock in biomass, derived from Eqs. (4) and (5):

$$\text{Biomass C} = [\text{Carbon concentration (\%) x biomass}]/100 \tag{4}$$

$$\text{Biomass C}_{\text{stock total}} = \text{Biomass C}_{\text{ag}} + \text{Biomass C}_{\text{bg}} \tag{5}$$

Biomass $C_{\text{stock total}}$ is the total stock of C in the biomass from every part of maize. The constituents of the biomass carbon stock aboveground were the carbon content in the upper roots, corn cobs, and seeds, while belowground they were the carbon content in the roots.

All the data collected from the different experiments and field samples during the study were compiled and processed for statistical analysis by analysis of variances (ANOVA). Comparisons between means were tested for significance with Tukey's multiple comparison test using the Statistical Package of the Social Science (SPSS) software. Significance was accepted at the $p < 0.05$ level.

3.7 Biomass of maize grown in the different biochar-supplemented soils

Biomass assessment during the first crop cycle (CC1) (**Figure 1**) indicated that the total biomass in the maize grown in TMBC3.0 was the highest (17.63 ton/ha), while the biomass was lowest (14.71 ton/ha) in the soil added fertilizer (TBC0). However, these numerical differences in the total biomass were not significant among all seven soil types. Comparing the results between biochar-incorporated treatments, it was apparent that the amount of biomass increased in relation to the amount of added biochar (highest in TBC3.0 and lowest in TBC0.5) and increased further if the fertilizer was also added. However, soil incorporated with fertilizer and the least amount of biochar (TMBC0.5) yielded less biomass than soil incorporated with solely biochar at the highest amount (TBC3.0), but again these differences were not statistically significant (**Figure 1**).

Maize biomass in the second crop (CC2) yielded (**Figure 1**) similar results to those of CC1, where numerically the highest total biomass was found in TMBC3.0, both in the whole plant (17.31 ton/ha) and in each part of the maize. Compared to the control, the total biomass and biomass of roots in TMC3.0 treatment showed significant results whereas the other ones did not. Even though there was no significant difference in biomass (total and each plant part) among soil types, which may reflect the low sample size relative to the level of intra-sample variation,

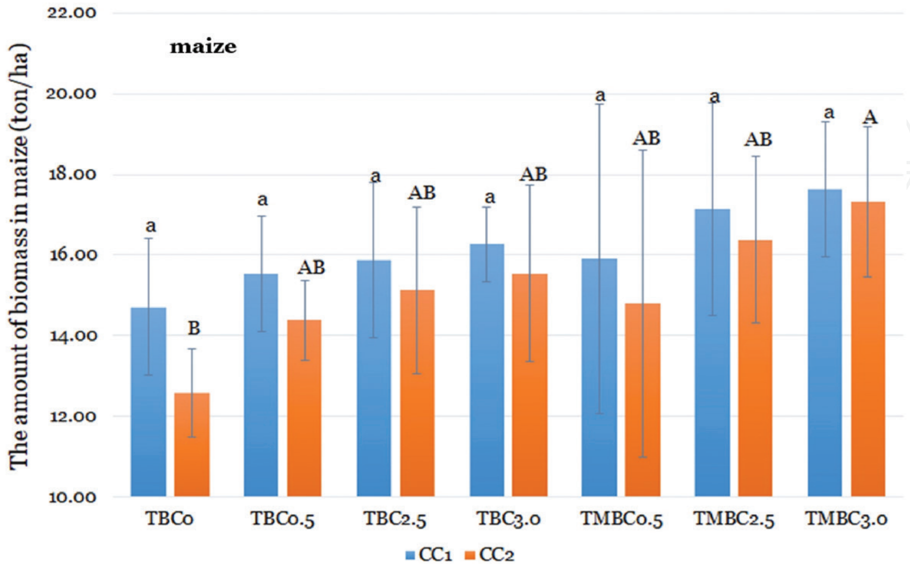


Figure 1.
*Total biomass in the maize grown in soil supplemented with different biochar levels for two successive crop cycles. CC1 and CC2 are the first and second crop cycles, respectively. Data are shown as the mean ± 1SD, derived from ** independent samples. Means within a row (small letter), or within a column (capital letter) between CC1 and CC2 of a given maize part, with a different letter are significantly different (p < 0.05).*

numerically it was apparent that incorporating the appropriate amount of biochar within the soil could increase the amount of biomass in every part of the maize.

Comparing between the two successive crop cycles (**Figure 2**), the amount of biomass found in each treatment in CC2 was less than in CC1, except for the roots in TBC2.5, TBC3.0, TMBC2.5, and TMBC3.0 that had a slightly higher biomass (0.061, 0.049, 0.120, and 0.125 ton/ha, respectively) in CC2 than in CC1. However, TMBC3.0, which received the highest amount of biochar plus fertilizer, had the least difference between the two crop cycles (−0.317 ton/ha) that the total biomass in the maize grown in TMBC3.0 was the highest in both crop cycles, while TBC0 (control) had the highest difference between the two crop cycles (−2.13 ton/ha). Thus, increasing the level of biochar in the soil (within this range of 5 to 3 ton/ha) numerically decreased the loss of biomass yield between the first and second successive cultivation. However, none of these numerical differences were statistically significant.

From the results, considering only the maize seed biomass that can be sold for animal feed, adding the fertilizer with highest amount of biochar into the soil gave the highest (yield) weight of maize seeds in both the first and second maize plantations, and adding only biochar into the soil gave a higher maize seed biomass in both crop cycles than that obtained when only adding fertilizer to the soil. The weight of maize seed biomass from TMB3.0 was the highest (6.280 ton/ha in CC1 and 6.149 ton/ha in CC2), while the results reported by Wijitkosum [55] revealed that TMB2.5 (13 cobs) had the highest average number of cobs per plant from 8 sample plants per treatment followed by TMB3.0 (12 cobs). In the second crop, the soil amendment with biochar and fertilizer still gave a high yield of maize seeds with only a small decrease in the biomass compared to that in the first crop cycle.

The increase of maize biomass obtained from the soil with added biochar reflects the high porosity, surface area, and ion exchange capacity of biochar [20, 21, 23, 44, 61, 62]. In addition, the highly aromatic chemical structure of

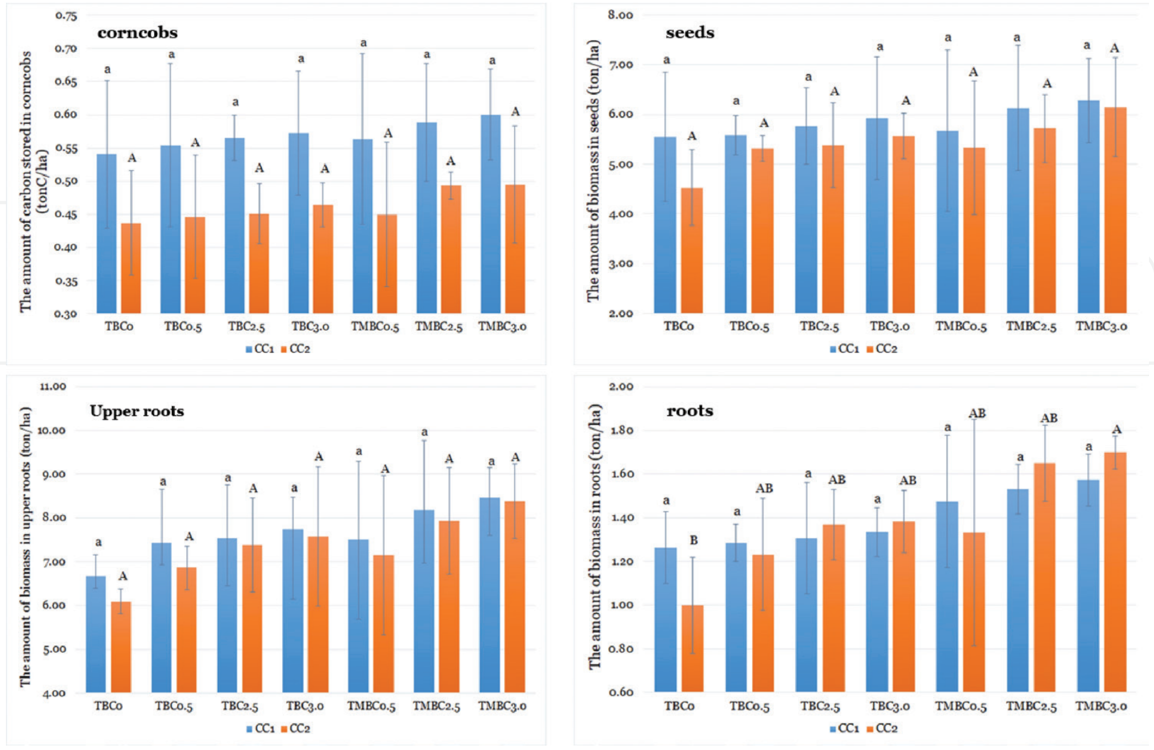


Figure 2.
*Biomass in each part of the maize grown in soil supplemented with different biochar levels for two successive crop cycles. CC1 and CC2 are the first and second crop cycles, respectively. Data are shown as the mean ± 1SD, derived from ** independent samples. Means within a row (small letter), or within a column (capital letter) between CC1 and CC2 of a given maize part, with a different letter are significantly different (p < 0.05).*

biochar leads to a high chance of oxidation reactions to form functional groups, and so biochar has many anions on its surface and hence a high ion exchange capacity [20, 42, 44, 65, 72, 73]. Moreover, biochar has many micropores that can absorb nutrients and anions from the soil solution [46, 59–62, 65, 79, 80] and to reduce nutrient leaching and provide a sustainable release to the plants.

The organic matter, important as a source of nutrients for maize growth, mostly came from the added fertilizer and some from the biochar and soil. Together, they support the growth of the roots and aid in absorbing more nutrients and transfer to the stem. The root biomass was increased in every soil amendment with biochar alone or with biochar and fertilizer, at all levels of biochar, and was higher than that obtained in the soil with only fertilizer added. This result gave the consistent with many studies (e.g. [20, 60, 72, 81, 82]) indicating that biochar could also contribute to the suitable environment for the growth of plant root. In the second maize plantation, the root biomass was significantly higher in all the biochar treatments, and especially for the addition of fertilizer with the highest level of biochar, than that obtained from the soil with only fertilizer added.

When the plant's roots grow well, they can absorb nutrients and water to build up the biomass in other parts of the plant. For example, potassium affects the growth, photosynthesis, carbohydrate synthesis, and leaf and seed formation [83–86]. Calcium affects the strength of the maize plant and activates development of the roots and leaves, as well as controlling the soil's pH [20, 87]. Biochar produced from cassava has a high nutrient content, reflected in the observation that maize grows well with a higher biomass when grown in soil with added fertilizer and biochar or added biochar compared to that in soil with only added fertilizer.

3.8 The amount of carbon sequestered from growing maize

The carbon stock in biomass in CC1 showed that the highest amount of carbon stored in biomass in TMBC3.0 at 7.22 ton/ha, while the lowest in TBC0 at 5.83 ton/ha (**Figure 3**). The study showed that the carbon storage in maize biomass was increased depending on the amount biochar added into the soil, especially when the biochar was added with the fertilizer. However, the carbon storage obtained with the

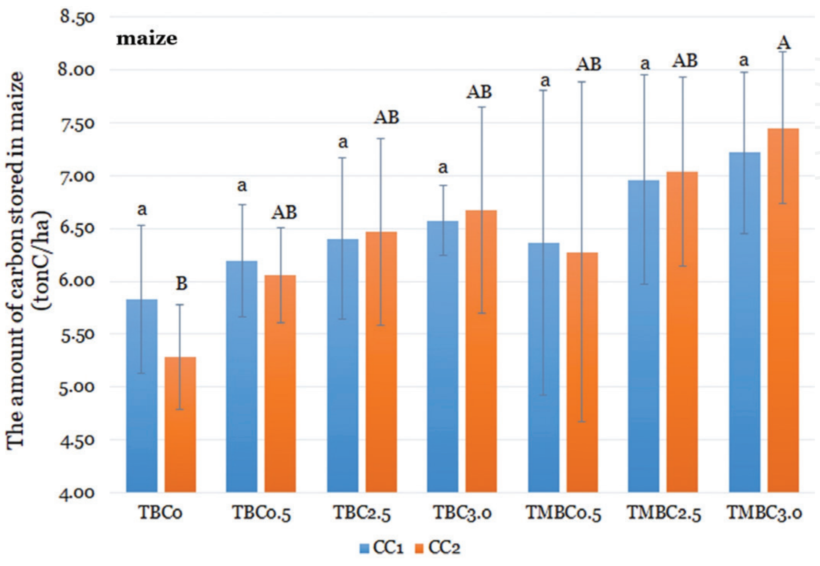


Figure 3.
*The amount of carbon stored in maize. CC1 and CC2 are the first and second crop cycles, respectively. Data are shown as the mean ± 1SD, derived from ** independent samples. Means within a row (small letter), or within a column (capital letter) between CC1 and CC2 of a given maize part, with a different letter are significantly different ($p < 0.05$).*

lowest ratio of biochar with fertilizer (TMB0.5) was lower than that in the biochar only treatment when sufficient biochar was added (TBC2.5 and TBC3.0). Carbon storage in each part of the maize and the total amount of carbon storage were not significantly different among the seven treatments. The highest percentage of carbon storage in the maize biomass was found in the upper roots (46.72–49.21%), followed by that in the seeds (33.71–35.69%), corncobs (8.32–9.27%), and roots (8.04–9.10%) (**Figures 4** and **5**).

With respect to the results from the CC2 (**Figure 3**), TMBC3.0 still gave the highest carbon storage (7.46 ton/ha), followed by TMBC2.5, TBC3.0, TBC2.5, TMBC0.5, TBC0.5, and TBC0. The amount of carbon storage was clearly different among the soil treatments, especially with the addition of fertilizer plus a high level of biochar which resulted in a significantly higher amount of carbon storage than the addition of fertilizer alone, which is the standard agricultural soil amendment used by farmers. Soil amendment with fertilizer and a sufficient amount of biochar (TMBC2.5 and TMBC3.0) resulted in significantly higher root carbon storage than the addition of only fertilizer to the soil. Similarly, the ratio of carbon storage in the other parts of the maize plants was in the same pattern as that seen in the first crop (**Figures 4** and **5**), being highest in the upper roots (46.50–48.21%), then the seeds (35.39–37.49%), corncobs (6.64–8.27%), and roots (7.57–9.55%).

With respect to the amount of carbon storage between the first and second maize plantings, the total carbon storage on maize was increased only in the soil treatments with sufficient biochar addition alone or with the fertilizer adding sufficient biochar. Treatment TMB3.0 gave the highest amount of carbon storage in maize (+0.235 ton/ha), followed by TBC3.0 (+0.094 ton/ha), TBC2.5 (+0.083 ton/ha), and TMBC2.5 (+0.076 ton/ha. In contrast, soil amendment without any biochar, but with the fertilizer only (TBC0), resulted in the highest level of decreased carbon storage (−0.551 ton/ha) between the two maize planting cycles.

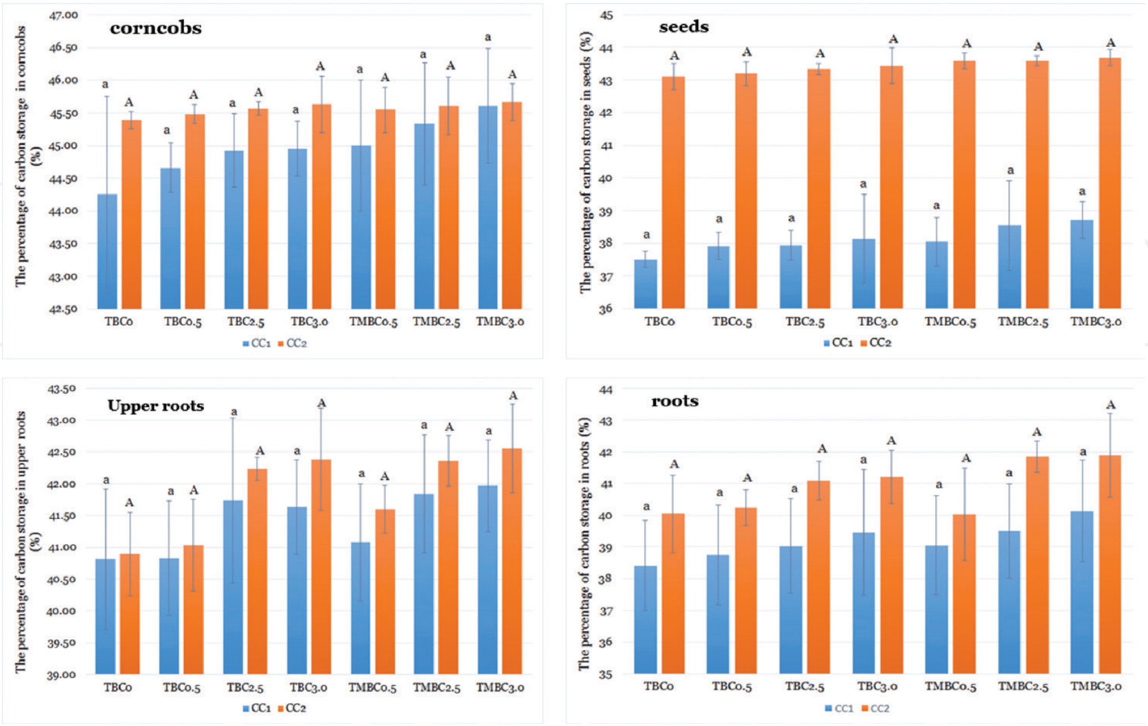


Figure 4.
*The percentage of carbon storage in different parts of maize. CC1 and CC2 are the first and second crop cycles, respectively. Data are shown as the mean ± 1SD, derived from ** independent samples. Means within a row (small letter), or within a column (capital letter) between CC1 and CC2 of a given maize part, with a different letter are significantly different ($p < 0.05$).*

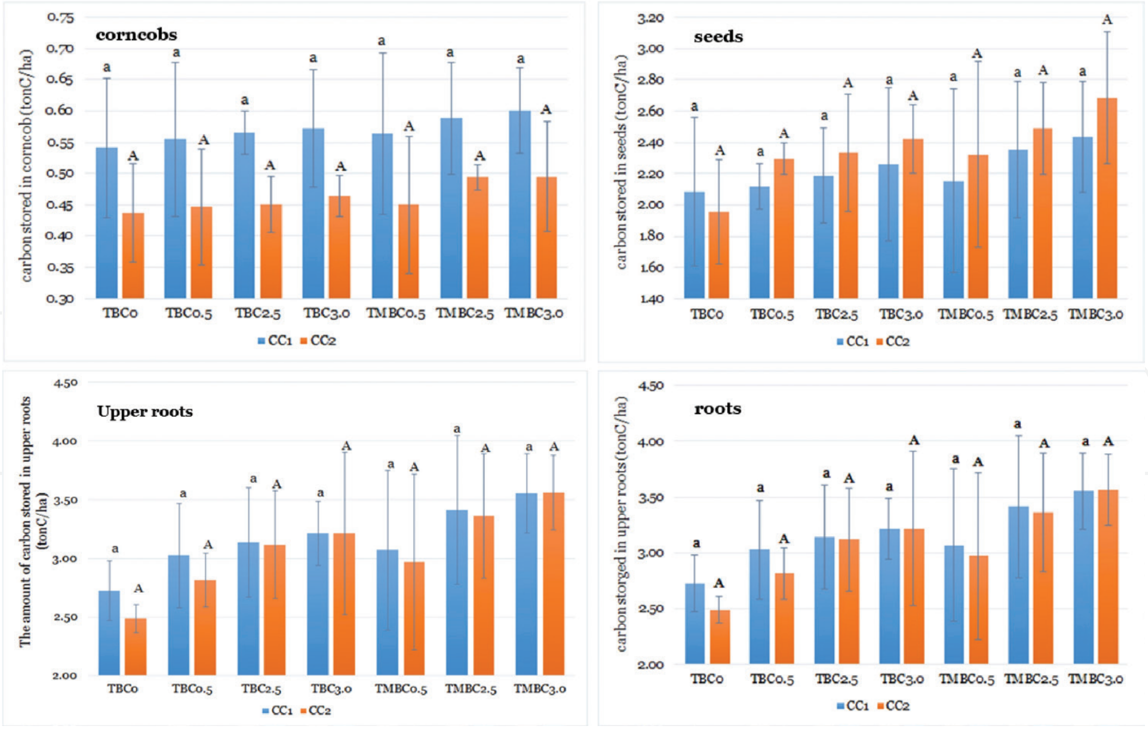


Figure 5.
*The amount of carbon stored in different parts of maize. CC1 and CC2 are the first and second crop cycles, respectively. Data are shown as the mean ± 1SD, derived from ** independent samples. Means within a row (small letter), or within a column (capital letter) between CC1 and CC2 of a given maize part, with a different letter are significantly different ($p < 0.05$).*

Considering the rate of total carbon change in maize biomass, the use of fertilizer (5.6 ton/ha) and biochar (30 ton/ha) (TMBC3.0) increased the amount of carbon storage in the maize biomass compared to that in the first crop cycle by 3.25%. The use of fertilizer alone (TBC0) or biochar alone showed a 9.45% or 2.28% decrease, respectively, in the total carbon storage in the second maize crop, whereas the soil amendment with fertilizer plus the lowest amount of biochar (TMBC0.5) gave only a 1.32% decrease in the total carbon storage in the maize biomass in the second crop.

Adding the appropriate amount of biochar into the soil promotes plant growth [23, 25, 55], especially the roots stems, leaves, stamen, and corn stalk, leading to an increased plant biomass. Moreover, the presence of biochar in the soil promotes the plant growth and productivity even without soil amendment with fertilizer because biochar is organic carbon that cannot be easily digested by soil microorganisms [17, 42, 59–61, 88]. Although the soil mixed with fertilizer initially provides sufficient nutrients for maize growth, this may be insufficient in the longer term for successive crops due to the rapid microbial degradation and leaching of the nutrients, leading to the requirement for continual reapplication of fertilizer every crop cycle. To help restore the soluble nutrients and reduce their leaching from soil, [21, 41, 45, 46, 89–91], especially in tropical regions where the soil has a low organic matter and high washout rate, the biochar with the fertilizer was applied. Under these conditions, adding organic matter alone to tropical soil is not stable in the long term because the soil has a low anion exchange capacity, and so much of soluble fertilizer is washed out before being absorbed by plant roots. Instead, the requirement to continuously add a high amount of organic matter to the soil increases the production cost and decreases the soil quality and environment in the long term [47, 57, 92, 94–95]. In contrast, when adding biochar with the fertilizer into the soil, the biochar helps improve both the physical and chemical properties of the soil allowing the plant's roots to absorb the nutrients over a longer time period [20, 42, 43, 60], and so the maize received enough nutrients continuously leading to higher productivities. Thus, the total biomass of the maize in second plantation in TMBC3.0 and TMBC2.5 had decreased by less than 10%.

4. Impact of biochar on biomass, bio-sequestration, and carbon sequestration

The massive and deep rooting systems in annual crops allow for direct movement of C into the soil and make it less available for removal by harvest [96]. Therefore, the results suggested that the incorporation of the appropriate amount of biochar into soil may help increase the amount of biomass in the maize. These results are in accordance with other biochar research, where the appropriate amount of biochar induced chemical reactions within the soil which enhanced the quantity and quality of the crops [23, 25, 28, 57, 98–100]. Incorporating biochar with the fertilizer could enhance and sustain the biomass gain from the fertilizer addition. Moreover, biochar remains in the soil for a long period of time with less leaching, and so it is not necessary to add more biochar every new crop cycle. The result from the main component (70–90% by weight) of biochar is amorphous carbon [23, 25, 43, 59] arranged in aromatic rings that are highly stable in the soil for long times [21, 22, 43, 59, 61]. Moreover, other important qualities of biochar are its high density of micropores, high surface area, and high ion exchange capacity. Therefore, biochar has good soil amendment qualities and can increase the agricultural productivity in terms of both the quality and quantity of crop obtained [10, 17, 20, 23, 25, 27, 28, 62, 91, 93, 97, 99].

The amount of biomass has a direct effect on the amount of carbon stored in the biomass. The quantity of biomass is an important source of replenishing organic carbon in the soil. The potential for soils to sequester C depends on the rate of biomass production relative to that exported, such as by microbial activity [96, 100]. The treatments that resulted in a high maize biomass also had a high amount of carbon in their biomass. Using biochar in agricultural areas had a positive impact on the maize and increased the amount of biomass stored in every part of the maize (roots, stems, leaves, tassels, seeds, and corncobs), as reported previously [23]. This is because the characteristics of biochar are beneficial for plants and its ability to be used for soil amelioration [70, 71, 101, 102].

The structure of biochar is amorphous, in the form of aromatic hydrocarbons bound with oxygenated functional groups, which influences its high stability characteristic [18–22, 42–44, 49, 70]. Moreover, its highly porous structure contains a large amount of micropores with a high surface area giving a high adsorption capacity for cations [65, 70, 72, 73, 75, 89–91, 99]. Therefore, incorporating biochar within the soil in agricultural areas benefits the soil ecosystem and the physical, biological, and chemical characteristics of the soil [17, 18, 22, 23, 25–28, 62, 73, 79, 80, 101, 102]. The soil becomes more fertile, which in turn leads to higher maize productivity. Maize grown in biochar-incorporated soils had a higher amount of carbon stored in every part of the plant.

5. Conclusion

A single application of biochar to the soil used for maize plantations significantly increased the carbon storage in the plants (biomass quantity and amount of carbon in the biomass) even in the second crop. The amount of carbon storage was further increased when the fertilizer was also added with the biochar to the soil.

The amount of plant biomass depends on the completion of plant growth, which is affected by the soil richness and nutrient availability. Adding organic material helps to improve the soil qualities and accelerate plant growth, but, especially in tropical soils, it can be washed out easily. The addition of biochar into the soil directly improves the physical and chemical properties of the soil, promotes microorganism activities and reduces nutrient leaching, and so leads to better plant growth and a higher biomass in the long term.

Carbon is stored in the soil directly by adding biochar, with its high stable carbon content, and will indirectly be the increased plant biomass. This is hence a method to reduce the carbon dioxide, a GHG emission, in agricultural areas and so help to mitigate climate change. This study revealed that adding a high amount of biochar together with fertilizer to agricultural soil only once is sufficient for at least two crops of maize and so would not only increase carbon storage in plants, but also the reduced fertilizer application will further reduce GHG release in agricultural areas and also reduce the production cost for farmers.

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