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Effect of One-Time Application of Biochar and Compost on Soil and Maize During 5-Time Consecutive Periods of Crop Cultivation

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Abstract

This study evaluates the impact of a single-time biochar application during initial cultivation on the performance of five consecutive crop cycles. The research compares the effects of biochar alone versus biochar combined with soybean compost on maize yield and soil properties over a period of 2.8 years. Fundamental soil properties—including pH, cation exchange capacity, organic matter content, and macronutrient levels—were assessed before each planting cycle and at the end of the fifth cycle. Maize yield and productivity were evaluated based on the number of maize ears, kernel biomass, and both fresh and dry kernel weights. Five experimental plots, each with four replicates, were established with the following treatments: compost applied at 0.56 kg/sq m (TM), cassava stem (CS) biochar applied alone at 2.5 kg/sq m (TB2.5) and 3.0 kg/sq m (TB3.0), and combinations of compost at 0.56 kg/sq m with CS biochar at 2.5 kg/sq m (TMB2.5) and 3.0 kg/sq m (TMB3.0). Results indicated that the sole application of biochar and its combination with compost positively affected soil properties and maize yield. Biochar applications alone significantly improved soil nutrient levels and maize yields compared to the compost alone. Notably, the beneficial effects of biochar on maize and soil were observed from the first cultivation and persisted throughout all five cycles. Based on these findings, it is recommended to apply biochar at 3.0 kg/sq m, in combination with compost at 0.56 kg/sq m, every three crop cycles to sustain nutrient levels and enhance maize yields effectively.

Keywords:

Biochar;
Plant-Available Nutrients;
Long-Term Cultivation;
Nutrient Retention;
Biochar Persistent.

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1- Introduction

Soil degradation has been reported as a major problem in developing countries [1]. Intensive agricultural practices, particularly the excessive use of chemical fertilizers, not only contribute to soil degradation but also disrupt ecosystems [2]. This over-reliance on chemical inputs makes land increasingly difficult to manage for agricultural purposes [1]. Furthermore, smallholder farmers often face high production costs due to the expense of chemical fertilizers, underscoring the need for sustainable agricultural practices to mitigate these challenges.

Previous research has reported that compost, while environmentally friendly and beneficial for soil nourishment, has certain limitations. Nutrients in compost are often organically bound and insoluble, rendering them unavailable for immediate plant uptake [3]. Additionally, compost is prone to leaching, leading to significant nutrient losses and affecting soil nutrient levels [4-6]. In contrast, biochar has been recognized as an effective soil amendment material,

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gaining attention in sustainable agriculture over the past decade [7, 8]. Biochar has also been reported to enhance fertilizer efficiency by acting as a matrix for nutrient retention [9, 10]. Consequently, numerous studies have explored the application of biochar, either alone or in combination with fertilizers, to address soil issues and improve agricultural productivity [11-14].

Biochar is a stable carbon-rich material produced through the thermochemical decomposition of biomass at temperatures of 350–700°C under oxygen-limiting conditions, a process known as pyrolysis [15, 16]. This process converts the organic material into a stable form of carbon with distinctive chemical and physical properties that influence its effectiveness as a soil amendment. A comprehensive review of the literature revealed that biochar can be derived from many feedstock types, including wood biomass and wood waste [15], agricultural residues [17], agro-industrial waste [18], urban wastes [16], and animal dung [6, 19]. A meta-analysis of the literature by Tomczyk et al. [20], Joseph et al. [21], and Tan et al. [22] indicated that the key characteristics of biochar affecting agricultural applications are alkalinity, high carbon content, high porosity, large surface area, and persistence in the soil environment. However, these properties can vary significantly depending on the feedstock type and the pyrolysis conditions. Previous studies have demonstrated that pyrolysis temperature and holding time significantly affect the biochar properties [17, 23, 24], especially in carbon content [18] and its morphology [16, 25]. Among different feedstock types, manure-based biochar is noted for having the highest nutrient content [19, 26, 27], whereas wood-based biochar generally exhibits higher carbon content, greater surface area, and porosity [28, 29]. However, agricultural residues represent a significant feedstock to convert to biochar, contributing to upcycling waste and alternative agricultural waste management methods.

Previous studies have been carried out to assess the use of biochar in various soil properties, addressing issues such as saline soil [9], unfertile soil [30, 31], acidic soil [32, 33], alkaline soil [34, 35], and unsaturated moist soil [36]. Biochar has been reported to improve soil quality by adjusting soil pH [37, 38], increasing cation exchange capacity [39, 40], influencing nutrient dynamics [41-43], enhancing soil organic carbon and soil organic matter [22, 44, 45], and reducing nutrient leaching [46, 47]. Moreover, biochar has been reported to improve soil drainage and aeration [48, 49] and decrease soil density by enhancing porosity [50]. It also affects soil microbial communities, increasing the number and diversity of soil microbes as well as their activities [51-53]. Accordingly, a suitable soil environment enhanced by biochar supported plant growth. Furthermore, evidence suggests that biochar can increase crop yields [54-56], enhancing plant growth both above and below ground in field and pot experiments [57, 58]. Positive effects have been observed and reported in rice [2, 32], vegetables [11], and field crops [59, 60]. However, some studies have reported that biochar does not significantly affect soil and plants in some cases, such as temperate soils [61] and drought conditions [62]. Massaccesi et al. [63] found that compost combined with biochar has no synergistic effect in lettuce cultivation. On the other hand, Wijitkosum & Sriburi [64] reported that biochar alone could also increase crop yields and plant biomass, while Ye et al. [65] found that biochar alone could not enhance crop yields regardless of the control measures used. Similarly, Jeffery et al. [61] and Regmi et al. [66] found that biochar, whether applied alone or combined with organic or inorganic fertilizers, could adversely affect soil and plants. Moreover, potential negative impacts of biochar on soil and plants have been reported. Olszyk et al. [67] found that applying poultry litter biochar alone and pine chip biochar blended with poultry litter biochar decreased soybean shoot, root, or pod biomass.

Despite the growing attention to biochar research in agriculture and environmental management, findings remain varied. Biochar research aims to elucidate the complex mechanisms of biochar in soil environments and to establish effective guidelines for its use. Some research attempts to explore the mutual enrichment mechanisms of biochar and fertilizers [63, 68, 69]. Most research has focused on short-term effects (one year) across different plants [70-72]. Long-term studies have reported on the impacts of biochar on soil and crop yields over periods such as three years for rice [2], four years for citrus [73], and eight years for rotation of seven plant cultivation [74]. In biochar research conducted over more than 1 year of cultivation, there is still a frequency of using biochar and fertilizer as applied every year or every crop cycle [45, 75, 76]. Several studies have indicated that biochar application rates and frequency influence success results. Cong et al. [77] reported that excessive biochar application rates (63.00-126.00 tons/ha) once in seven years of maize cultivation inhibited maize growth. Similarly, Bai et al. [78] reported that high-dose biochar had a significantly negative impact on the germination rate, shoot length, and root length of seeds in rice and corn. Moreover, efficiency, effectiveness, and cost-effectiveness were discussed extensively [44, 77].

Studies on using biochar for continuous cultivation have received increasing attention. Nonetheless, there is a scarcity of research on the impact and efficacy of single-time biochar applications, either alone or in combination with compost, on continuous crop cultivation, especially in tropical soils prone to high nutrient leaching. Accordingly, this research focused on one-time biochar applications in continuous maize cultivation in low-fertility agricultural areas. The research evaluates the effects of applying biochar alone versus biochar mixed with compost on maize yield and soil properties over 2.8 years of successive cultivation. The objective is to assess the potential synergy of applying biochar with compost or biochar alone and their feasibility as a new farming strategy that could reduce fertilizer frequency and offer a viable approach to soil fertility management for smallholder farmers.

2- Materials and Methods

2-1- Area and Field Establishment

The field experiment of this research was conducted at the Pa Deng Biochar Research Center (PdBRC) located in the Pa Deng Subdistrict, Phetchaburi Province, Thailand (Figure 1). The Pa Deng area is situated between 99°20'E and 99°37'E longitude and between 12°33'N and 12°45'N latitude on the western edge of Thailand, covering approximately 417.80 sq km. Of this area, only 15% is plain area suitable for agricultural use and settlements. According to the meteorological data obtained from the Thai Meteorological Department, the average annual rainfall is 914.5 mm, with 49% occurring between August and October, and an average annual rainy day is 84 days. Limited availability of flat areas compels farmers to engage in intensive farming practices, which adversely affect soil resources and long-term ecosystem sustainability. The dominant soil texture in the usable plain area is sandy loam soil, followed by silt loam and loamy sand. Most soil is generally slightly alkaline to highly acidic, with a pH range of 4.0 to 7.4, a low organic matter content (0.04% to 0.16%), and medium to high soil permeability.

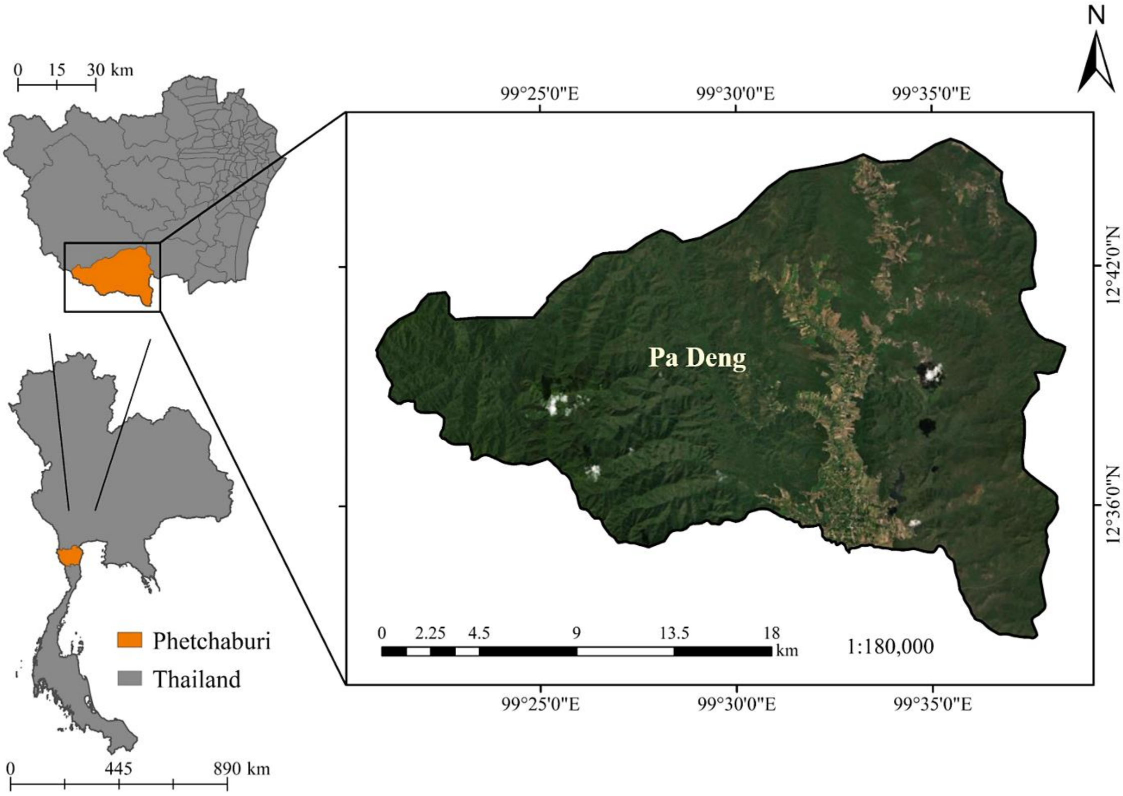


Figure 1. The field experimental area

2-2- Field Experimental Design and Crop Cultivation

This study was designed to evaluate the long-term effects of a single-time application of biochar on soil properties and maize yield on continuous cultivation. The experimental design and cultivation practices were modeled to reflect typical farming methods to enhance the practical application of biochar. Biochar application rates of 2.5 kg/sq m and 3.0 kg/sq m were chosen based on previous research indicating successful results in sandy loam soils [60]. The compost application rate was set at the minimum recommended for maize cultivation (0.56 kg/sq m). The maize (*Zea mays* L.) variety used in the experiment was the single cross-hybrid CP 888 (flint corn).

The experiment utilized a completely randomized block design with four replicates per treatment. Each experimental plot was 3 m wide and 5 m long and contained 80 plants, resulting in a total of 320 plants per treatment. The plots were spaced approximately 30 cm apart. The experimental plots were categorized into three groups: the control treatment (TM) with compost only, experimental plots with biochar applied at 2.5 kg/sq m (TB2.5) and 3.0 kg/sq m (TB3.0), and plots receiving a combination of compost and biochar at rates of 2.5 kg/sq m (TMB2.5) and 3.0 kg/m² (TMB3.0). In total, there were 20 experimental plots.

Maize was cultivated over five successive cycles, with biochar and compost applied only during the first cycle. Post-harvest, no additional fertilizers or biochar were applied. The first, third, and fifth plantings occurred in May and were harvested in August, while the second and fourth plantings were sown in November and harvested in February. The entire maize cultivation period lasted for 2.8 years. The diagram illustrating the conceptual framework and experimental design is presented in Figure 2.

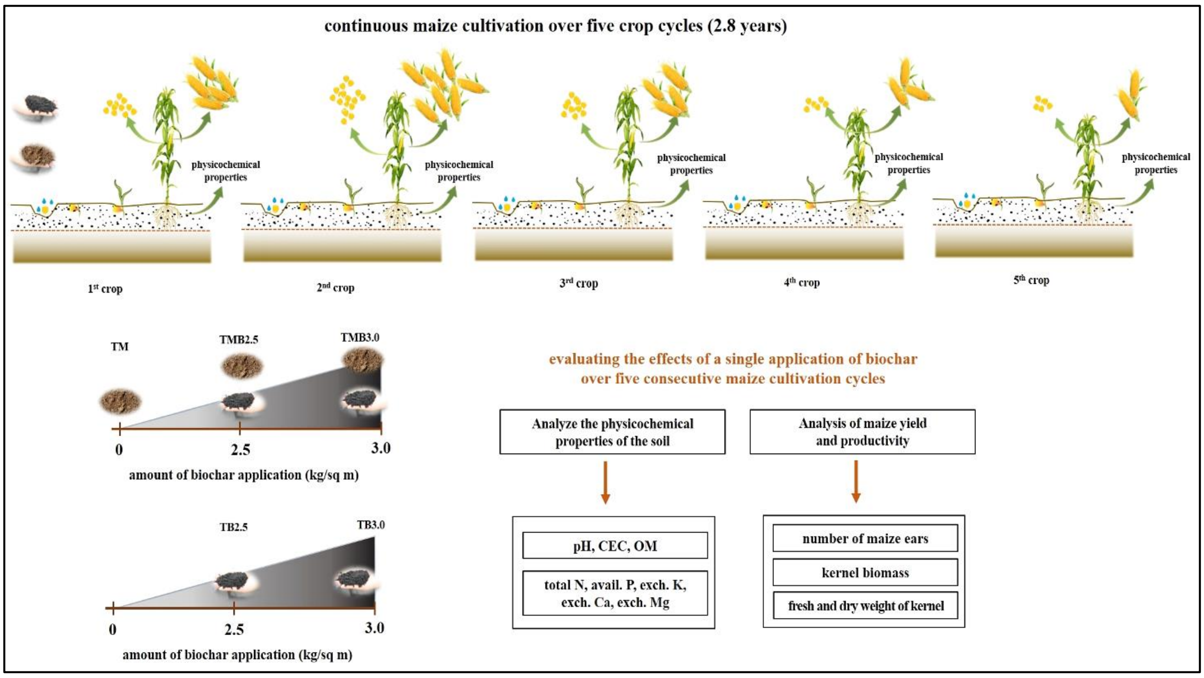


Figure 2. The conceptual framework and experimental design

2-3- Preparation for Experimental Area and Management

The experimental site was manually cleared of weeds, and the soil was pulverized and plowed to a depth of approximately 15 cm using a rake. Biochar and compost were weighed and uniformly applied to the soil surface at the specified rates on days without rain or strong winds. The biochar and compost were incorporated into the soil to a depth of 10 cm using a traditional rake.

Biocontrol measures were employed to manage pests and weeds throughout the cultivation period. During the growing seasons, the average rainfall was less than 100 mm/month. The aridity index ranged from 0.63 to 0.94 during the first, third, and fifth plantings, while it ranged from 0.03 to 0.49 during the second and fourth plantings. Maize was watered twice daily from planting until day 55, then once daily, with irrigation ceasing after 100 days of cultivation.

2-4- Biochar and Compost Characteristics

The cassava stem (CS) biochar exhibited a specific surface area of 200.459 sq m/g, a total pore volume of 0.122 ccm/g, and an average pore diameter of 24.358 Å. The composition of biochar included 58.46% carbon (C), 2.25% hydrogen (H), 1.28% nitrogen (N), and 38.01% oxygen (O). It was strongly alkaline with a pH 9.6, and had a cation exchange capacity (CEC) of 11.0 cmol/kg. The CS biochar contained a high organic matter (OM) content of 25.90%, with 0.98% total N, 0.82% total phosphorous (P_2O_5), 1.68% total potassium (K_2O), 0.97% total magnesium (Mg), and 1.18% total calcium (Ca). The H/C, O/C, and C/N ratios of the CS biochar were 0.39, 0.65, and 45.78, respectively.

The soybean compost used in the study met the standards for organic fertilizers, with an OM content of 23.43%, total N content of 1.70% (wt%), total P_2O_5 content of 0.87% (wt%), and total K_2O content of 3.54% (wt%). It was moderately alkaline with a pH of 8.30, a total organic carbon (TOC) content of 23.42% (wt%), and a C/N ratio of 13.75.

2-5- Soil Sampling and Property Analysis

Soil samples were collected before the first planting cycle and after each subsequent cultivation cycle to analyze their physicochemical properties, following the Handbook of the United States Department of Agriculture [79]. Samples were randomly taken from the top 15 cm of soil in each experimental plot, with 15 samples collected from each plot and distributed throughout the plot area, a total of 60 samples in each experimental treatment. The samples were air-dried in the shade, with visible plant roots removed, then ground and sieved through a 2-mm mesh before laboratory analysis.

Soil pH was measured in deionized water at a 1:2 (v/v) ratio after shaking for 1 hour. CEC was determined using ammonium acetate extraction (1.0 N NH_4OAc) at pH 7.0 [80]. OM was analyzed using the Walkley-Black method [81], while total N content was determined using the Kjeldahl method with a distillation apparatus [82]. Available phosphorus (avail. P) was analyzed using a spectrophotometer with 0.1 N HCl and NH_4F, according to the Bray II method. Exchangeable potassium (exch. K), exchangeable calcium (exch. Ca), and exchangeable magnesium (exch. Mg) were analyzed by extraction with 1 M NH_4OAc at pH 7 and measured with an atomic absorption spectrophotometer (AAS) [83].

2-6- Analysis of Maize Yield and Productivity

Maize was harvested to evaluate yield and productivity per plot, based on 80 plants per experimental treatment. Data collected included the number of ears, kernel biomass, fresh weight (FW) of kernels, and dry weight (DW) of kernels. Ears with complete kernels were collected and recorded. Kernels were detached from the cob, weighed fresh (FW), and then oven-dried at 105°C for 48 hours before being weighed again (DW). Kernel biomass was calculated using the formula (DW × 100)/%MC, where %MC = (FW – DW) × 100/FW [64].

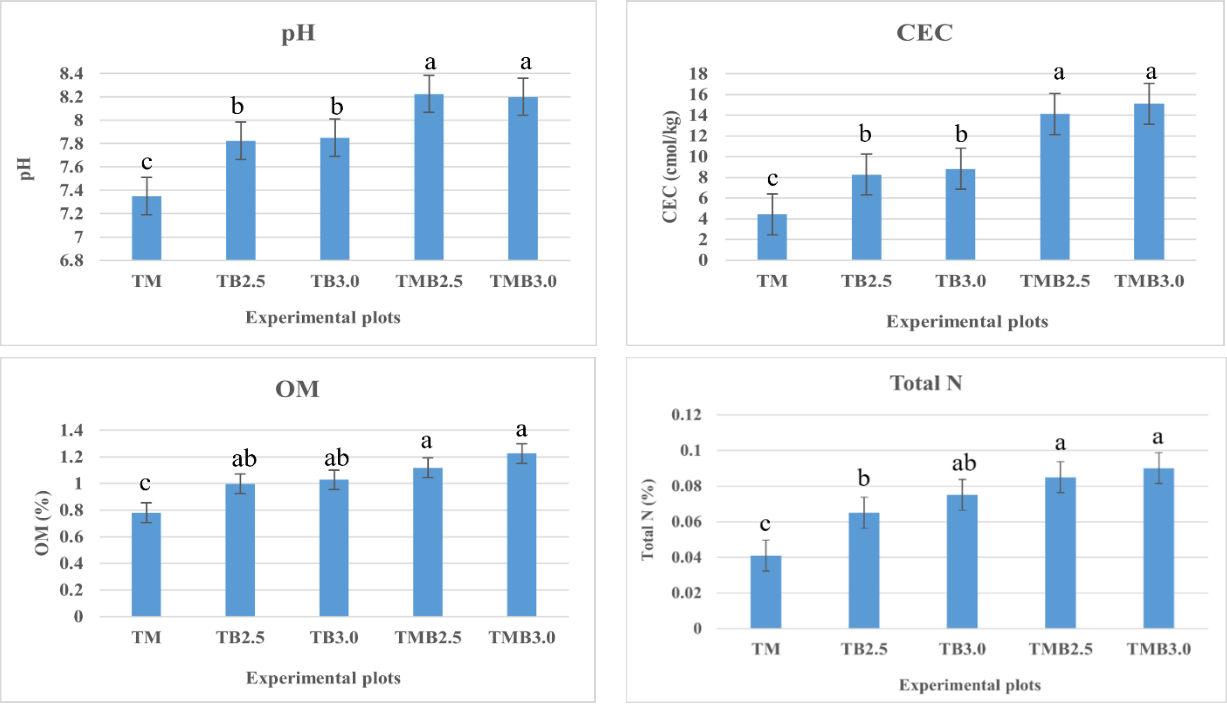
2-7- Data Analysis

Data on soil properties and maize yields were expressed as means ± standard deviation (SD) from four replicates. Statistical analysis included mean-variance (ANOVA) to compare differences between experimental plots. Tukey's multiple comparisons test was used to assess the significance of differences between means. Paired sample T-tests were employed to analyze changes in soil properties before the first cultivation and after the fifth harvest. Statistical significance was determined at a 95% confidence level. Data analysis was conducted using the Statistical Package for the Social Sciences (SPSS) software.

3- Results

3-1- Soil Properties Under Continuous Cultivation

Before consecutive cultivation, the experimental soil was neutral, with a pH of 6.95 and a CEC of 7.12 cmol/kg. The soil contained an OM content of 1.12%, total N of 0.09%, avail. P of 21.80 mg/kg, exch. K of 215.75 mg/kg, exch. Ca of 1171.75 mg/kg, and exch. Mg of 125.75 mg/kg. After consecutive cultivation cycles (Figure 3), the soil exhibited a wide range of pH and CEC values. Soil pH varied from slightly alkaline (7.35) to moderately alkaline (8.23), while CEC ranged from 4.43 cmol/kg to 15.10 cmol/kg. The highest CEC values were recorded in soils amended with compost mixed with CS biochar at 3.0 kg/sq m, whereas the highest pH was observed in soil treated with compost mixed with biochar at 2.5 kg/sq m. However, differences in soil pH and CEC among various biochar application rates were insignificant, regardless of whether the biochar was mixed with compost or applied alone. The TM plot had significantly lower pH and CEC values than the others.



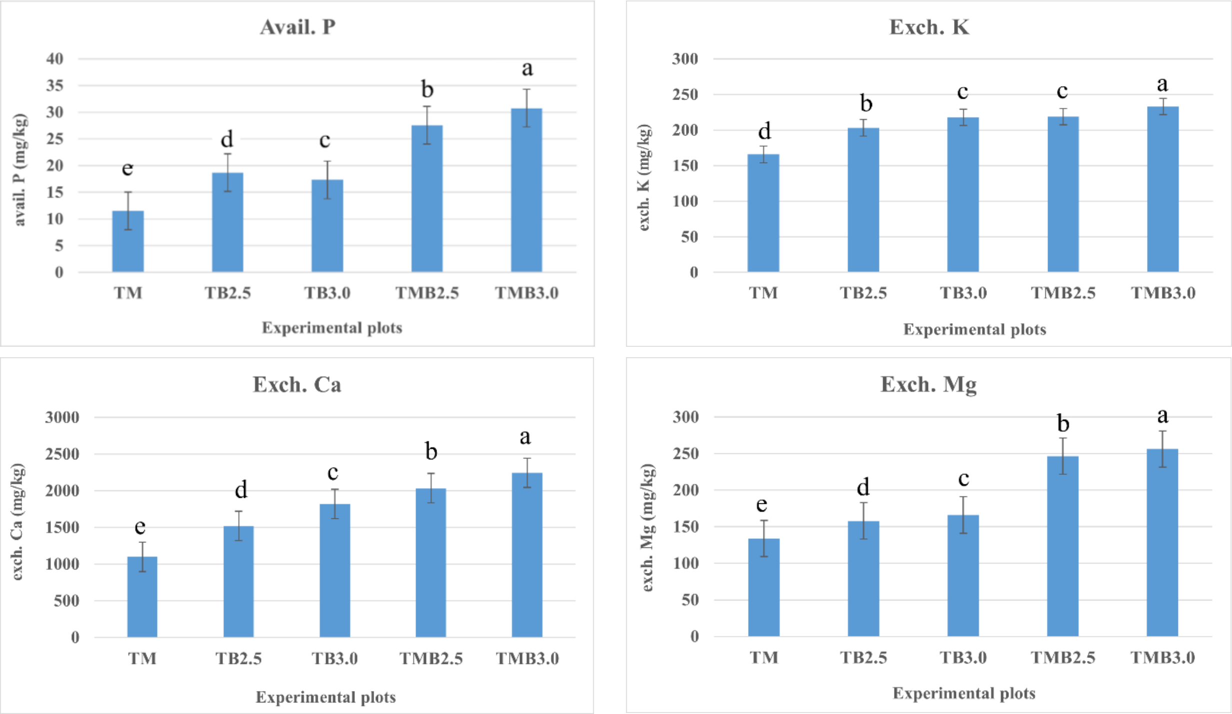


Figure 3. Physicochemical properties of post-cultivation soil from different experimental plots

Applying CS biochar alone resulted in significantly higher OM content in the soil after cultivation (0.95% in TB2.5 and 0.99% in TB3.0) than compost alone (0.78% in TM). Consequently, soils mixed with CS biochar and compost (TMB2.5 and TMB3.0) had higher OM contents than those with biochar alone (TB2.5 and TB3.0). The highest nutrient content, including total N (0.103%), avail. P (30.75 mg/kg), exch. K (233.25 mg/kg), exch. Ca (2241.99 mg/kg) and exch. Mg (256.31 mg/kg) was found in the soil treated with compost mixed with CS biochar at 3.0 kg/sq m. After cultivation, total N levels in the TB3.0 (0.087%), TMB2.5 (0.094%), and TMB3.0 (0.103%) plots were not significantly different, but they were significantly higher than in the TM plot (0.041%). Soil treated with different rates of CS biochar alone showed no significant differences in total N content, with TB2.5 at 0.085% and TB3.0 at 0.087%. Each experimental plot showed significant differences in avail. P, exch. Mg, and exch. Ca levels. The highest contents of avail. P (30.75 mg/kg), exch. K (233.25 mg/kg), exch. Mg (256.31 mg/kg), and exch. Ca (256.31 mg/kg) was found in the TMB3.0 plot, while the TM plots showed the lowest content level. The exch. K levels differed significantly among plots, except for TB3.0 and TMB2.5.

3-2- Changing in Soil Properties During the 5-time Consecutive Cultivations

Compared to pre-cultivation levels, notable changes in soil properties were observed following continuous cultivation (Table 1). Soil pH increased significantly across all plots. Specifically, in plots where biochar was applied alone at rates of 2.5 and 3.0 kg/m², the soil pH was 1.07 times higher than in plots treated with compost alone. Additionally, when biochar was applied with compost at the same rates, the soil pH was 1.12 times higher than in plots receiving compost alone. The most substantial increase in CEC was observed in soil amended with the highest amount of CS biochar mixed with compost (TMB3.0). Plots with the highest proportion of biochar alone (TB3.0) and those where biochar was mixed with compost (TMB2.5 and TMB3.0) exhibited significantly higher CEC compared to the pre-cultivation soil. In contrast, CEC decreased significantly in the TM plot. Specifically, the CEC in the TMB3.0 plot was 3.41 times higher than in the control treatment, whereas the application of biochar alone at the lowest rate (TB2.5) increased CEC by 1.86 times.

A significant increase in OM was observed only in the TMB3.0 plot, whereas the TM plot showed a significant decrease. Despite a decrease in soil organic matter in TMB2.5, TB3.0, and TB2.5 plots compared to pre-cultivation levels, these plots still had higher OM levels than the control—1.40 times higher in TMB2.5, 1.27 times higher in TB3.0, and 1.22 times higher in TB2.5. Total N increased only in the TMB3.0 plot, while significant decreases were noted in the TM and TB2.5 plots. Notably, the total N in the TB2.5 plot was 1.75 times higher than in the control, and in the TMB3.0 plot, it was 2.50 times higher. Although avail. P decreased in the TB3.0 and TB2.5 plots after successive cultivation; these plots still had greater available P—1.51 times higher in TB3.0 and 1.62 times higher in TB2.5—compared to the control. The TMB2.5 and TMB3.0 plots showed significant increases in avail. P, whereas a significant decrease was observed only in the TM plot.

Table 1. Soil chemical properties (0–15 cm) at the beginning and the end of the cultivation

Parameters	Planting times	Experimental Treatments				
		TM	TB2.5	TB3.0	TMB2.5	TMB3.0
pH	Before 1st	6.95±0.190				
	After 5th	7.35±0.229	7.83±0.205	7.85±0.166	8.23±0.083	8.20±0.071
	Sig .2-sided	0.002*	0.008*	0.006*	0.001*	0.003*
CEC)cmol/kg(	Before 1st	7.12±0.43				
	After 5th	4.43±0.148	8.25±1.195	8.83±0.427	14.10±2.119	15.10±1.179
	Sig .2-sided	0.002*	0.120	0.004*	0.014*	0.003*
OM (%)	Before 1st	1.12±0.01				
	After 5th	0.78±0.111	0.95±0.110	0.99±0.101	1.09±0.179	1.21±0.025
	Sig .2-sided	0.013*	0.062	0.093	0.779	0.009*
Total N (%)	Before 1st	0.09±0.008				
	After 5th	0.04±0.013	0.07±0.013	0.08±0.006	0.09±0.013	0.10±0.026
	Sig .2-sided	0.019*	0.030*	0.103	0.604	1.000
Avail .P (mg/kg)	Before 1st	21.80±5.20				
	After 5th	11.50±1.803	18.66±0.639	17.33±1.259	27.56±0.990	30.75±1.299
	Sig .2-sided	0.062*	0.331	0.172	0.073*	0.054*
Exch .K (mg/kg)	Before 1st	215.75±16.76				
	After 5th	165.75±1.785	203.05±0.712	217.75±1.785	219.05±1.849	233.25±1.092
	Sig .2-sided	0.007*	0.210	0.111	0.722	0.829*
Exch .Ca (mg/kg)	Before 1st	1171.75±196.35				
	After 5th	1097.94±1.907	1518.75±1.920	1820.44±1.095	2033.28±1.276	2241.99±1.856
	Sig .2-sided	0.504	0.039*	0.007*	0.003*	0.002*
Exch .Mg)mg/kg)	Before 1st	125.75±7.04				
	After 5th	133.75±1.299	158.00±1.581	165.89±1.428	246.58±1.536	256.31±1.242
	Sig .2-sided	0.152	0.002*	0.002*	0.001*	0.001*

Remark: * statistically different at $P < 0.05$.

After successive cultivation, significantly increased exch. Mg was observed in all plots except the TM plot, with TMB3.0 showing exch. Mg level is 1.92 times greater than those in the TM plot. The exch. K levels increased in all plots except the TM and TB2.5 plots, with a significant decrease noted only in the TM plot. However, the exch. K in the TB2.5 soil was 1.23 times higher than the TM plot. The exch. Ca decreased in the TM plot but increased significantly in all plots treated with biochar. Post-cultivation exchangeable Ca levels were 2.04 times higher in TMB3.0, 1.85 times higher in TMB2.5, 1.66 times higher in TB3.0, and 1.38 times higher in TB2.5, compared to the control.

Comparing soil properties across years revealed fluctuations in pH values (Figure 4). Soil pH decreased after the second cultivation, increased during the third and fourth cycles, and decreased again after the fifth cultivation. The CEC levels in the soil exhibited a decreasing trend over time in the TM plot, while fluctuations were observed in the other treatments. In plots with biochar application alone (TB2.5 and TB3.0), CEC initially increased until the second cultivation but then declined after the third cultivation. Conversely, in plots where biochar was combined with compost (TMB2.5 and TMB3.0), CEC decreased after the fifth cultivation. The OM levels decreased over time in the TM plots, whereas plots with biochar application showed a continuous increase in OM. This increase persisted until the second cultivation for TB2.5 and TB3.0 and until the third cultivation for TMB2.5 and TMB3.0, suggesting that biochar application may enhance and retain organic matter in the soil.

The total N levels increased significantly across all experimental plots but decreased after the second cultivation, except in the TB2.5 plot, where a decrease occurred after the third cultivation. This pattern indicates that the initial rise in N levels likely provided adequate nutrients for plant growth, with subsequent reductions attributable to plant uptake or leaching. The avail. P in the soil varied significantly, with the highest levels observed in TMB3.0 and the lowest in TM. This suggests that combining compost and biochar was more effective in enhancing avail. P than compost alone. Over time, avail. P decreased in TB3.0 and TMB3.0 treatments, while other treatments saw a reduction after the second cultivation.

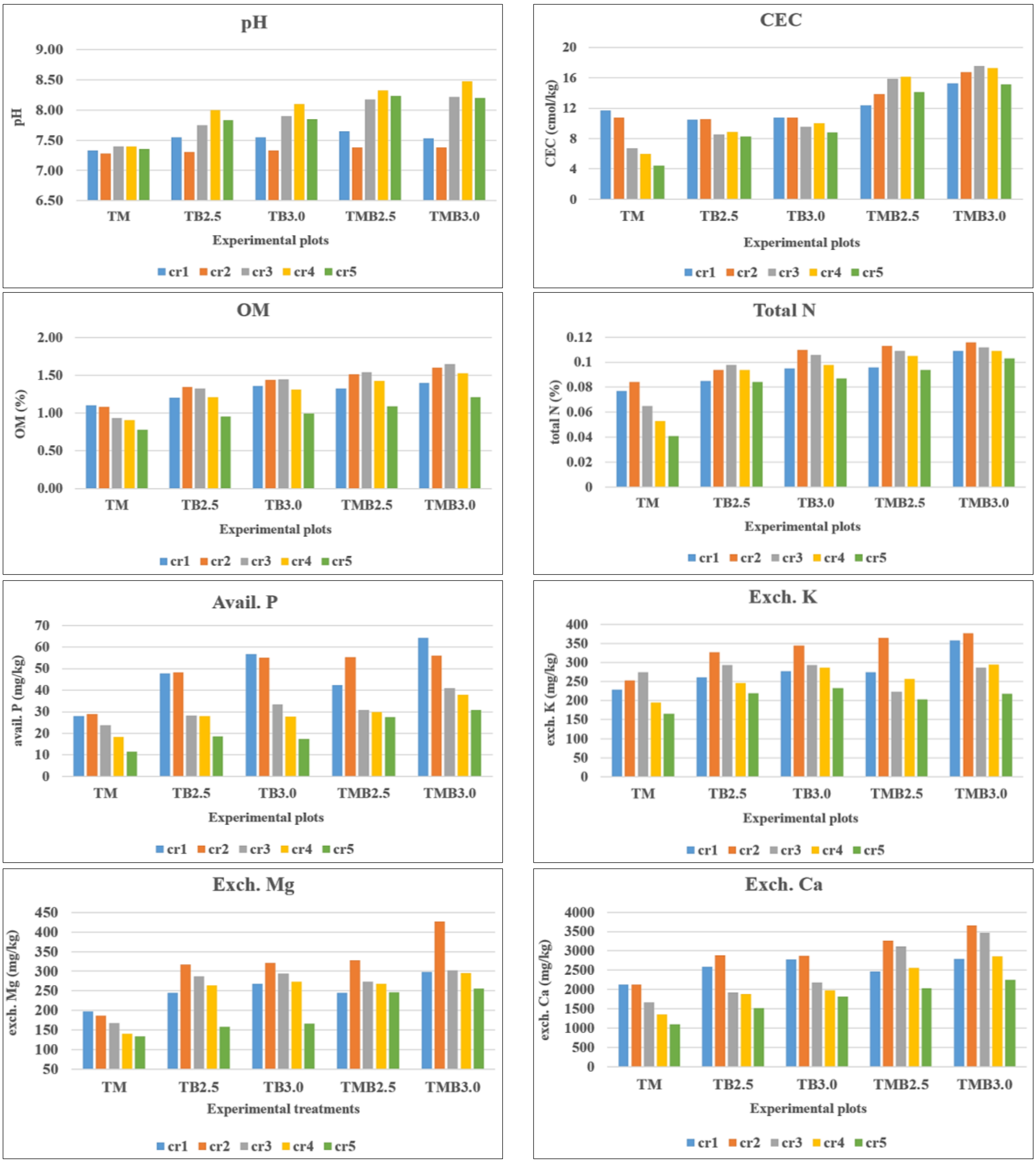
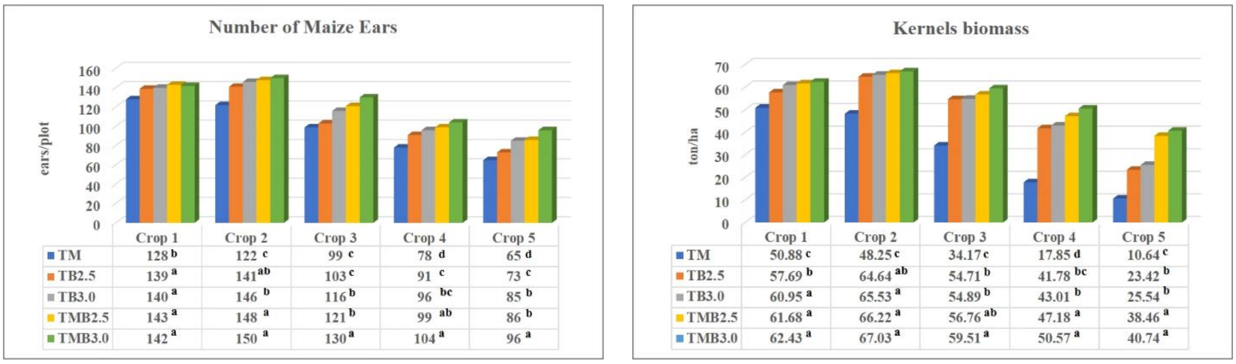


Figure 4. Physicochemical properties of soil during fifth crop cultivation across different experimental plots

Exchangeable cations, including K, Ca, and Mg, varied with each crop cycle. The highest levels of these cations were found in TMB3.0 plots, while the lowest were observed in TM plots. After the second cultivation, exchangeable cations generally decreased in all treatments except TM. In the TM plot, exch. K began to decline after the third cultivation, while exch. Ca and Mg decreased over time. These findings underscore the role of biochar, particularly when combined with compost, in increasing soil exchangeable cations, as evidenced by higher levels in biochar-amended treatments (TB2.5, TB3.0, TMB2.5, and TMB3.0).

3-3- Maize Production Across Five Crop Cultivations

The number of maize ears and kernel biomass from different experimental plots during the first to fifth crop cultivations is displayed in Figure 5. The TM plot consistently displayed the lowest number of maize ears in all cultivation cycles, significantly different from other plots amended with biochar, except during the third crop cycle, where the TB2.5 plots yielded higher than those harvested from the TM plot but were statistically insignificant. During the first harvest, the TMB2.5 plot produced the highest number of maize ears (143 ears/plot), though this was not significantly different from the TMB3.0 (142 ears/plot), TB3.0 (140 ears/plot), or TB2.5 (139 ears/plot). From the second crop cycle onward, the TMB3.0 plot exhibited the highest number of maize ears. Productivity across all biochar-treated plots increased in the second planting cycle, with the TMB3.0 plot showing the highest growth rate (5.63%), while the TB2.5 plot demonstrated the lowest increase (1.44%). However, these differences were not statistically significant.



	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
■ TM	128^{b}	122^{c}	99^{c}	78^{d}	65^{d}
■ TB2.5	139^{a}	141^{ab}	103^{c}	91^{c}	73^{c}
■ TB3.0	140^{a}	146^{b}	116^{b}	96^{bc}	85^{b}
■ TMB2.5	143^{a}	148^{a}	121^{b}	99^{ab}	86^{b}
■ TMB3.0	142^{a}	150^{a}	130^{a}	104^{a}	96^{a}

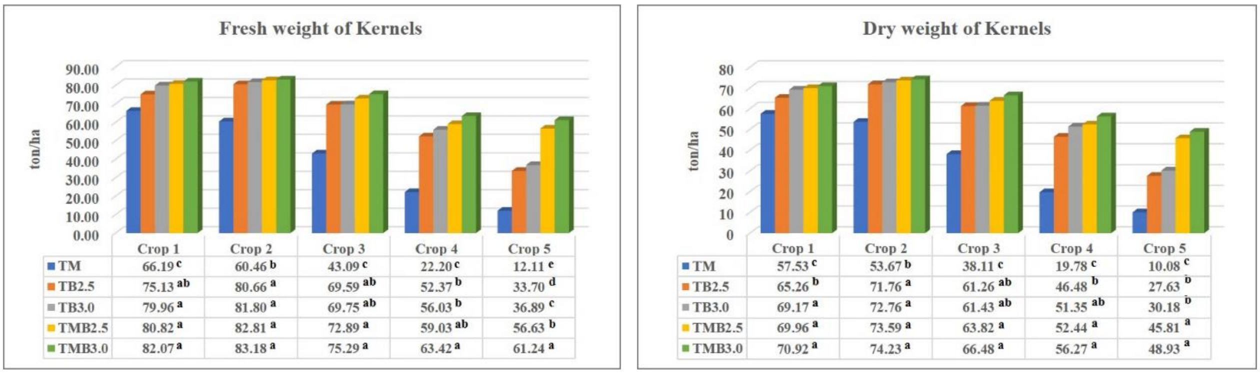
	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
■ TM	50.88^{c}	48.25^{c}	34.17^{c}	17.85^{d}	10.64^{c}
■ TB2.5	57.69^{b}	64.64^{ab}	54.71^{b}	41.78^{bc}	23.42^{b}
■ TB3.0	60.95^{a}	65.53^{a}	54.89^{b}	43.01^{b}	25.54^{b}
■ TMB2.5	61.68^{a}	66.22^{a}	56.76^{ab}	47.18^{a}	38.46^{a}
■ TMB3.0	62.43^{a}	67.03^{a}	59.51^{a}	50.57^{a}	40.74^{a}

Figure 5. Number of maize ears and kernels biomass from different experimental plots during the first to fifth crop cultivations

Additionally, the yield from each plot in the second planting cycle did not differ significantly from that of the first cycle, except for the TMB3.0 plots. The TM plot showed a noticeable decline in maize ears starting from the second crop cycle, with a decrease rate of 4.69% compared to the first harvest, and continued to decline in subsequent cycles. From the third cycle onward, significant differences in maize ear counts emerged between the TMB3.0 plot and the other biochar-treated plots, while the TMB2.5 and TB3.0 plots did not show significant differences among themselves. In contrast, other experimental plots demonstrated increased maize ear counts in the second crop cycle, which then decreased from the third to the fifth cycle. The results indicated significant differences in yields among the plots during the third and fifth crop cycles, except for the TMB3.0 plot, which only showed a difference between the third and fourth cycles. No significant differences were observed between the fourth and fifth cycles. In the fifth crop cycle, the TMB3.0 plot yielded the highest number of maize ears (96 ears), with the TMB2.5 plot (86 ears) and the TB3.0 plot (85 ears) showing no significant difference from each other. Comparing the yield of the fifth planting cycle to the first cycle, the TMB3.0 plot experienced a 32.39% reduction in maize ears, whereas the TMB2.5 and TB3.0 plots saw reductions of 39.29% and 39.86%, respectively. The TM plot had the highest reduction rate at 49.22%.

Kernel biomass (Figure 5.) was highest in the TMB3.0 plots across all cultivation cycles, while the TM plots consistently had the lowest kernel biomass. The increase in kernel biomass was positively correlated with the rate of biochar application, with combined biochar and compost resulting in greater kernel biomass than biochar alone. During the first and second planting cycles, kernel biomass did not differ significantly among the TB3.0, TMB2.5, and TMB3.0 plots. However, significant differences were noted between the TB2.5 and TM plots compared to the other treatments. The TM plot did not exhibit significant differences in kernel biomass between the first and second planting cycles. Compared to the first planting, the second planting showed a 12.04% increase in kernel biomass for TB2.5, while TB3.0, TMB2.5, and TMB3.0 showed increases of 7.35%, 7.36%, and 7.51%, respectively. From the third harvest onward, kernel biomass in the TB2.5, TB3.0, TMB2.5, and TMB3.0 plots decreased significantly. The kernel biomass in the TM plot showed a steady decline from the first harvest.

The FW of kernels was consistently highest in the TMB3.0 plots across all harvest cycles (Figure 6.). The TM plot, in contrast, consistently had the lowest FW of kernels throughout every cultivation cycle. From the first to the fourth harvest, no significant differences in FW were observed between the TMB2.5 and TMB3.0 plots, nor between the TMB2.5 and TB3.0 plots. In the second planting cycle, the FW of kernels increased with higher biochar application rates. Furthermore, plots that combined biochar with compost exhibited greater FW increases compared to those receiving biochar alone. Conversely, the plot with compost alone showed a decrease in kernel FW, with a reduction rate of 8.66%. The results indicate that starting from the third crop cycle, the FW of kernels in plots receiving biochar began to decline. Notably, the TMB3.0 plot exhibited the lowest average reduction rate per planting cycle. By the fifth harvest, the FW of kernels from all experimental plots showed statistically significant differences. Specifically, the FW of kernels from the TM plot differed significantly at each planting cycle. In contrast, significant reductions in FW were observed from the third planting cycle onward for kernels obtained from the TB2.5, TB3.0, TMB2.5, and TMB3.0 plots. Furthermore, the FW of kernels from the TMB3.0 plot during the fourth and fifth planting cycles did not differ statistically significantly, with a reduction rate of only 3.44%. In contrast, the TM plot had a high rate of decline between the fourth and fifth planting cycles of 45.45%.



	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
■ TM	66.19^{c}	60.46^{b}	43.09^{c}	22.20^{c}	12.11^{e}
■ TB2.5	75.13^{ab}	80.66^{a}	69.59^{ab}	52.37^{b}	33.70^{d}
■ TB3.0	79.96^{a}	81.80^{a}	69.75^{ab}	56.03^{b}	36.89^{c}
■ TMB2.5	80.82^{a}	82.81^{a}	72.89^{a}	59.03^{ab}	56.63^{b}
■ TMB3.0	82.07^{a}	83.18^{a}	75.29^{a}	63.42^{a}	61.24^{a}

	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
■ TM	57.53^{c}	53.67^{b}	38.11^{c}	19.78^{c}	10.08^{c}
■ TB2.5	65.26^{b}	71.76^{a}	61.26^{ab}	46.48^{b}	27.63^{b}
■ TB3.0	69.17^{a}	72.76^{a}	61.43^{ab}	51.35^{ab}	30.18^{b}
■ TMB2.5	69.96^{a}	73.59^{a}	63.82^{a}	52.44^{a}	45.81^{a}
■ TMB3.0	70.92^{a}	74.23^{a}	66.48^{a}	56.27^{a}	48.93^{a}

Figure 6. **Fresh weigh and dry weight of kernels from different experimental plots during the first to fifth crop cultivations**

Applying CS biochar caused the FW of kernels to be higher than compost in every crop cycle. In the first planting cycle, the FW of TB2.5 was 1.14 times higher, and the TB3.0 was 1.21 times higher. When biochar mixed with compost was applied, it was found that the increase in FW of kernels compared to applying compost was 1.24 times for TMB3.0 and 1.22 times for TMB2.5. Maize yield harvested from the fifth planting was found to be the FW of kernels of TMB3.0 and TMB2.5 plots was higher than that harvested from TM plot, accounting for 5.06 times and 4.68 times, respectively, while TB3.0 and TB2.5 plots yielded of kernels with higher FW than those obtained from TM plots, accounting for 3.05 times and 2.78 times, respectively.

The application rates of CS biochar significantly influenced the increases in the DW of maize kernels. The DW of kernels (Figure 6) was aligned with the observed trends in the number of maize ears, kernel biomass, and FW of kernels. In the first two crop cycles, both TB3.0 and TMB2.5 exhibited similar DW increase rates of 5.19%. Conversely, TB2.5 demonstrated the highest increase rate of 9.96%. The DW of kernels from the TMB3.0 plot was 1.23 times higher than that from the TM plot in the first planting cycle and 4.85 times higher in the fifth planting cycle. Even the plots that used CS biochar alone at the lowest rate (TB2.5) yielded kernels 1.13 times more than the TM plots in the first planting cycle and more than 2.74 times higher in the fifth planting cycle.

The results indicated that the decrease in the DW of the kernel in the biochar-based plots started from the third planting cycle. However, this decrease was not significant for the TMB2.5 and TMB3.0 plots until after the third crop cycle. The TM plot exhibited the most pronounced reduction in DW of kernels throughout all cultivation periods, with a 6.71% decrease between the first and second cycles, 28.99% between the second and third cycles, 48.10% between the third and fourth cycles, and 49.04% between the fourth and fifth cycles. Conversely, the TMB3.0 plot experienced the smallest reduction rate in FW of kernels, which decrease of 10.44% between the second and third cycles, and 15.36% between the third and fourth cycles, while the TMB2.5 plot exhibited the lowest reduction rates of 12.64% between the fourth and fifth cycles.

4- Discussions

4-1- Biochar Effects on Soil Properties and Soil Nutrient Maintenance Under Continuous Cultivating

This study elucidates the impact of biochar on soil properties and nutrient maintenance over a continuous cultivation period of 2.8 years. The results reveal that plots amended with CS biochar, both alone and in combination with compost, exhibited enhanced soil quality compared to plots receiving only conventional compost. Notably, the application of CS biochar led to a significant increase in soil pH from the outset of cultivation, with this effect sustained throughout the study. This increase in pH is primarily attributed to the alkaline nature of biochar, which originates from the formation of carbonates and inorganic alkalis during pyrolysis [16, 23, 30]. Additionally, the presence of anionic functional groups, such as carboxyl (–COOH) and hydroxyl (–OH) groups, as well as the accumulation of ash containing potassium (K), magnesium (Mg), and calcium (Ca) oxides, hydroxides, and carbonates, contributed to the elevated pH levels [15, 16, 20, 24, 28].

The study demonstrated that the highest soil pH was achieved with the highest application rate of CS biochar, corroborating findings from Zhang et al. [2], Wang et al. [9], Hailegnaw et al. [55], and Wijitkosum & Sriburi [64]. Although compost also increases pH by adding base cations and organic matter, but its effect is less enduring than biochar due to its easy decomposition [11, 23, 29, 58]. When compost is combined with biochar (TMB2.5 and TMB3.0), soil pH is increased and maintained over five cultivation cycles. This result aligns with previous research by Wijitkosum & Jiwnok [14], Massaccesi et al. [63], Wang et al. [68], and Teodoro et al. [69], indicating that biochar mixed with compost or fertilizer can elevate soil pH more effectively than biochar alone. Soil pH, in turn, influences nutrient availability through mechanisms such as ion exchange, mineral precipitation, and oxidation reactions [3, 15, 24, 33].

Carboxylate groups on biochar surfaces impart a negative charge, enhancing CEC through electrostatic interactions [5, 22, 55]. Similarly, organic matter, which is negatively charged due to carboxylic and phenolic acids, contributes to increased CEC when combined with biochar [17, 34, 39]. Consequently, higher biochar application rates result in increased CEC and OM content, with TB3.0 plots showing higher CEC and OM content than TB2.5 plots and TMB3.0 plots exhibiting greater CEC and OM content compared to TMB2.5 plots. These findings are consistent with research by Singh et al. [12], Omara et al. [72], Jarosz et al. [75], Rombolà et al. [76], and Domingues et al. [80]. Furthermore, increased OM content significantly reduced soil loss by enhancing the stability and aggregation of soil particles [44, 47, 54].

Biochar influences soil nutrients both directly and indirectly. Directly, CS biochar supplies essential nutrients such as N, P, K, Ca, and Mg. The nutrient contents in biochar generally depend on biochar feedstock [17, 19, 27]. Although CS biochar does not have a high nutrient content, it can increase nutrients in the soil mainly through indirect processes. The application of CS biochar significantly increased N content since the first cultivation, consistent with previous studies by Li et al. [45], Wijitkosum & Sriburi [64], and Zhang et al. [73]. This increase is attributed to higher pH levels, which enhance the solubility and mobility of N compounds and boost microbial activity related to N cycling [7, 21, 37, 52]. Additionally, the negative charge on biochar surfaces facilitates the adsorption of nitrate (NO_3^- -N) and ammonium (NH_4^+ -N) [38, 52, 53, 74], supporting the positive impact of biochar on total soil N content [50, 51, 67]. Although these are indirect effects, biochar also directly contributes to soil N levels through N transportation from compost and biochar. The CS biochar application rate influences total N levels, and combining biochar with compost increases total N more than compost alone. This is in agreement with findings by Gunes et al. [6], Jindo et al. [10], Wijitkosum & Jiwnok [14], and Wu et al. [33], who reported that biochar application positively affects soil total N content and that the application rate directly impacts N levels. However, Nguyen et al. [37] reported a decrease in inorganic N following biochar application, which was notably reduced after one month. Additionally, Nguyen et al. [37], Xu et al. [52], and Ye et al. [65] indicated that adding organic fertilizers mitigates N loss, aligning with this study's observation that increased total N was only found in the TMB3.0 plot by the end of the fifth cultivation, with total N in the TMB2.5 plot remaining unchanged compared to pre-cultivation levels.

Biochar contains P in various forms, including stable, labile, and semilabile P, which serves as a P source for the soil. Similarly, the main pool of K in biochar-amended soil comprises water-soluble K and exchangeable K [6, 22, 36]. The release of P from biochar is a complex process involving the dissolution and availability of P for plant growth. Initially, unstable and some semistable P forms are released upon biochar application [45, 46]. Biochar directly supplements soil K by increasing P availability, adjusting soil pH to reduce P complexation, and indirectly enhancing K through microbial activities that promote P metabolism [19, 43, 45, 46]. Biochar also adsorbs acidic and alkaline metals such as Fe^{3+} , Al^{3+} , and Ca^{2+} , associated with its surface functional groups, thereby delaying P adsorption and precipitation in the soil [46]. Increased soil pH and the negatively charged organic matter from biochar reduce P sorption on goethite [10]. These reasons support this finding that the P and K contents consequently increased in plots with CS biochar application and described why K levels could not be sustained long-term if biochar was applied at a low rate. By the end of the fifth cultivation, nutrient levels in the TB2.5 plot decreased compared to pre-cultivation levels. Similarly, while biochar initially increased available P, its levels decreased over time. However, mixing biochar with compost maintained available P throughout the cultivation period until the end of cultivation.

The significant increase in Ca and Mg in biochar-treated soils is attributed to the release of free bases from biochar [9, 32, 50, 55]. Moreover, the Ca-P bond also influences the exch. Ca in the soil [32, 34]. This finding is supported by Masud et al. [60], who reported a significant increase in exch. Mg (226%) in the soil with poultry litter biochar, and Hailegnaw et al. [55], observed enhanced soil water-soluble Ca and Mg from applying biochar. The co-application of CS biochar and compost resulted in higher contents of exch. Ca and Mg compared to biochar alone, with the application rate affecting the extent of this impact. However, Gunes et al. [6] reported differing results. The decrease in soil Mg and Ca following biochar application may result from the high adsorption capacity of biochar and its potential to alter soil pH, which is influenced by biochar type, application rate, and soil characteristics [10, 17, 21, 47, 48].

In addition to improving soil physicochemical properties and plant nutrient availability, biochar significantly influences soil microorganisms [45, 49, 51]. The high surface area and porosity of biochar offer more sites for microbial colonization and activity, providing a stable habitat for beneficial soil microbes [20, 22, 51, 57]. Furthermore, biochar supplies organic carbon and nutrients to soil microorganisms, and its ability to improve pH conditions can enhance microbial diversity and activity [31, 47, 48]. Moreover, soil microorganism influenced nutrient fixation [38, 53, 74]. The interaction between biochar and soil microorganisms is complex and involves various mechanisms that contribute to improved soil conditions and promote plant growth [52, 63, 73] both above ground and root [8, 43].

Overall, even after five continuous cultivations over 2.8 years, nutrients remained present in the soil treated with CS biochar. The absorption mechanism of biochar is attributed to its large surface area, high porosity, and high CEC, which helps mitigate nutrient loss through water leaching by promoting both absorption and the uptake of soluble nutrients by plants [8, 40, 42, 47, 74]. These findings align with Hossain et al. [41], Šimanský et al. [42], Al-Wabel et al. [48], and Li et al. [71], who reported that biochar enhances nutrient availability and reduces nutrient loss in planted systems. This is consistent with findings by Zhang et al. [73], who reported increased K levels in biochar-amended soils after four years of cultivation. Similarly, Jaroz et al. [75] indicated that a slower rate of organic matter mineralization was observed in soil amended with poultry litter biochar after five growing periods, especially in a high dose (5.0 t ha^{-1}). Moreover, CS biochar with high aromaticity (O/C < 0.4) [16, 18, 25], high porosity, and its chemical properties also promote nutrient retention and gradual release for plant use over the long term [26, 41, 48, 77]. In contrast, compost decomposes rapidly, especially in tropical soils [13, 61]. Therefore, compost alone (TM plot) cannot maintain sufficient soil nutrients to increase maize yield throughout the continuous planting period, and nutrients also decrease significantly after the first planting.

4-2- Long-term Effects of Biochar on Maize Yield and Productivity Under Continuous Cultivation

The results of this study demonstrate that biochar positively impacts maize productivity, as evidenced by improvements in metrics such as the number of maize ears, kernel biomass, FW, and DW of kernels. This beneficial effect was observed from the first cultivation cycle. The enhanced maize yield and productivity can be attributed to improved soil quality, which creates a more favorable environment for plant growth. Despite the fact that CS biochar has a lower nutrient content compared to compost, its application alone has led to greater increases in maize yields than compost alone from the outset of cultivation. This result is primarily due to the indirect effects of CS biochar [12, 13, 30, 31], as supported by the soil property results over the five cultivation cycles. These findings are consistent with Lacomino et al. [4], who reported that beech wood biochar enhances crop yields for various vegetables, including aubergine, fennel, lettuce, onion, rape, and tomato. Similarly, Shin et al. [19] observed that cow manure biochar improved glasswort growth. Singh et al. [12] also noted significant increases in crop yields with herbaceous biochar (53%) and biochar derived from lignocellulosic waste (35%). Conversely, Mannan et al. [62] reported that biochar improved nutrient supply and enhanced soybean growth but did not increase yield. Keller et al. [70] found that while applying wooden biochar to sandy loam soil improved soil properties over two years, it did not affect the yields of pinto bean or sorghum–Sudan. Some studies have reported negligible effects of biochar on crop yield; for example, Singh et al. [12] found no significant impact of wood-based biochar on crop yields.

Additionally, combining CS biochar with compost significantly increased maize yield and productivity, including metrics such as the number of maize ears, kernel biomass, FW, and DW of kernels. This finding aligns with previous studies on maize [13, 49, 60, 77], rice [2, 32, 78], sweet potato [29], wheat [43], cocoyam [54], lettuce [63], Viola cornula [66], and tomato [71]. Increasing the biochar application rate also significantly improved maize yield, consistent with previous studies [14, 43, 59, 63]. However, Regmi et al. [66] observed that high rates of biochar application reduced plant growth and flowering in Viola cornula. Additionally, Lacomino et al. [4] found that mixing biochar with compost negatively impacted plant yields, reducing aubergine yields by 60% and tomato yields by 50%. Joseph et al. [21], Tang et al. [35], Bo et al. [57], and Schulz et al. [58], indicated that inappropriate biochar application rates could hinder plant growth. Jeffery et al. [61] also reported that applying 30 t ha^{-1} of biochar in temperate areas decreased crop yields by 3%.

Regarding the long-term effects of a one-time biochar application, maize yield and productivity from plots amended with CS biochar alone (TB2.5 and TB3.0) or CS biochar mixed with compost (TMB2.5 and TMB3.0) began to decline in the third cultivation cycle. This decrease is attributed to a reduction in nutrient content, which becomes insufficient for maintaining crop yields. In contrast, maize yield from plots treated with compost alone (TM) decreased after the first crop cycle. This observation aligns with Joseph et al. [44], who reported significant improvements in avocado seedling growth and fruit yield during the first three years of a four-year study. Similarly, Lacomino et al. [4] noted a decrease in crop yields for fennel, onion, rape, and tomato in the second year of cultivation. The effects of biochar on crop yield are variable and influenced by interactions with soil chemistry.

Interestingly, despite the soil pH in plots amended with CS biochar exceeding the optimal range for maize cultivation (pH 7.5), maize growth was not adversely affected. In fact, a higher soil pH seemed to have a positive effect. This may be attributed to the increased CEC of the soil associated with CS biochar, along with its adsorption capacity, which affects nutrient availability. Moreover, biochar properties and application rates are sufficient to influence soil buffering capacity [56]. However, further research is needed to fully understand the mechanisms behind nutrient availability and uptake by plants under suboptimal pH conditions.

5- Conclusion

Biochar is well-documented as an organic soil amendment that enhances soil properties, promotes plant growth, and increases crop yields. However, most field studies typically involve biochar application on a per-crop or annual basis. This study specifically focused on evaluating the effects of a single application of biochar over five consecutive maize cultivation cycles. Both standalone and combined applications of biochar and compost were investigated. The findings indicate that biochar derived from cassava stems (CS biochar) positively affects soil quality and significantly boosts maize yields, including metrics such as the number of ears, kernel biomass, fresh weight, and dry weight of kernels, throughout consecutive cultivation cycles. Notably, CS biochar-maintained macronutrient levels (N, P, K, Ca, Mg) in the soil even after five crop cycles over 2.8 years, without the addition of further compost. Application of CS biochar alone at rates of 2.5 and 3.0 kg/sq m significantly enhanced soil nutrient levels and maize yields compared to compost alone. The combination of biochar with compost yielded the highest maize productivity. The beneficial effects of CS biochar were evident from the first planting cycle and persisted throughout the five cultivation periods. The study also found that increasing the biochar application rate led to higher maize yields. The research underscores the importance of biochar and compost application frequency in maintaining soil nutrients and improving maize yields. The results suggest that a one-time application of CS biochar can be a practical agricultural strategy due to its positive impact on soil properties and productivity. Specifically, using CS biochar at 3.0 kg/sq m combined with compost at 0.56 kg/sq m every three crop cycles effectively maintain soil nutrient levels and enhances maize yields. However, the mechanisms and interactions between soil, biochar, and plants—particularly in terms of soil chemistry, nutrient uptake, and soil microorganisms under continuous cultivation—require further investigation.

6- Declarations

6-1- Author Contributions

Conceptualization, S.W.; methodology, S.W. and T.S.; validation, S.W.; formal analysis, S.W.; investigation, S.W.; resources, T.S.; data curation, S.W.; writing—original draft preparation, S.W. and P.T.; writing—review and editing, S.W.; visualization, S.W., T.S., and P.T.; supervision, S.W.; project administration, S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6-3- Funding

This research was extended from the two projects in which partial research was supported by the Office of the Higher Education Commission and the 2014 In-depth Strategic Research Fund, Ratchadapisek Sompoch Endowment Fund, Chulalongkorn University.

6-4- Institutional Review Board Statement

Not applicable.

6-5- Informed Consent Statement

Not applicable.

6-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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