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The Interactive Impact of Straw Mulch and Biochar Application Positively Enhanced the Growth Indexes of Maize (*Zea mays* L.) Crop

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Abstract: A two-year experiment was carried out at Shenyang Agricultural University's research field area in China to evaluate the impact of the combined application of straw mulch (0 and 8 t ha^{-1}) and biochar (0, 4, 12, and 36 t ha^{-1}) on the morphological traits and grain development of rainfed maize during 2018 and 2019. The results showed that straw mulch and different biochar application rates significantly impacted the maize growth index. Compared to non-biochar-treated soils, the introduction of straw mulch improved plant height, stem diameter, leaf area index (LAI), leaves, stem, root, and crop growth rate (CGR), and dry weight of rainfed maize crop. The highest plant height, stem diameter, LAI, leaves, stem, root growth rate, CGR, and dry weight of rainfed maize crop were reported when soil was treated with a higher rate of biochar (36 t ha^{-1}). Biochar increased grain filling rate while decreasing grain filling duration in rainfed maize crops. Our results indicate that straw mulch and biochar-based soil management strategies can improve the rainfed maize growth with the environmental benefits of global warming mitigation. However, due to the wide range of biochar properties, the interactions between straw mulch and biochar should be given special consideration in the maize cropping system.

Keywords: *Zea mays* L.; organic amendments; physiology; growth; leaf area index

1. Introduction

The present global population is around 7.6 billion, with a consequent growth to 9.8 billion projected in 2050 and 11.2 billion in 2100 [1]. This rapidly growing population is urging farmers to produce more food and fiber from the existing land resources to ensure the food security of the rising global population, which will lead to pressure to increase agriculture production [2]. Globally, arable land is rapidly dwindling due to land degradation, urbanization, industrialization, drought, flooding, and salinity changes [3,4]. These factors hinder and create a challenge to achieving United Nations' sustainable development goals [4]. This will increase the pressure on the use of our limited natural resources, such as land, water, and nutrients. Therefore, there is an urgent need to increase soil, water, and nutrient use efficiencies in the maize cropping systems, especially in rainfed agricultural systems [5].

The scientific community faces a significant challenge in feeding the world's population, utilizing unfertile agricultural land and bringing such unfertile soil into the agricultural production system by combating salinization, desertification, and soil contamination as a result of different environmental pollutants [6]. To the best of our knowledge, rainfed agriculture covers 80% of the world's cultivated land and contributes about 60% of the total crop production throughout the globe [7]. Low productivity in many arid and semi-arid rainfed agricultural systems is often due to degraded soil fertility and limited soil water and nutrient inputs. Water is the limiting factor in promoting crop yield worldwide, especially in dry land farming ecosystems, which hinder crop growth and productivity [8,9]. In addition, maximizing the production of major crops along with investigating the fallow fertile lands can help to meet the current challenges regarding food demands. Maize is an important cereal crop and staple food to meet the dietary conditions of the world's population [10], with calculated total annual production recorded as being higher than wheat and rice crops [11]. Maize has obtained popularity to meet the global food demands due to the maximum production per unit hectare relative to other major staple food crops grown throughout the globe [12].

Globally, the current major concern nowadays is waste reduction through biochar production to enhance crop production. Biochar application is used as a soil amendment to improve the physical characteristics of agricultural soils [13,14] and boost soil fertility [15,16]. Biochar's capability to enhance the fertility of soil is elucidated by the structure of organic compounds, which helps to re-establish soil organic carbon (SOC) levels [16,17] and dry-ash matter, which consists of essential macro- and micronutrients for enhancing the productivity of the crops [18,19]. Land supervisors and farmworkers should be persuaded that using biochar as soil remediation has a monetary benefit, including steadily increasing agricultural output, as well as enhanced biomass and yield of the crops.

Little research has been conducted on the effect of organic improvements on maize (*Zea mays* L.) production and growth when combined with biochar. In China, using manure composting, biochar, and pyroligneous solution in saline conditions for two years has significantly improved soil's physical, chemical, and biological properties to interact with plant productivity and ultimately enhance maize yield [16,20]. Therefore, compost and biochar addition in Indonesia has resulted in a more than doubled maize biomass and yield combined application with calcareous soil over two cropping seasons [21]. Similarly, in Laos, using biochar combinations on low fertility soils has yielded promising results as it improved soil fertility and enhanced the production of crops [22]. Compared to the above studies on tropical soils, maize in a temperate climate shows very little of an effect [19], which biochar applications have noticed. In the present study, we hypothesized that applying maize straw mulch and maize straw biochar as soil amendments would improve the leaf growth, crop growth rate, and grain filling of maize.

2. Materials and Methods

2.1. Experimental Location and Materials Preparation

The current research was performed at Shenyang Agricultural University's Comprehensive Experimental Base for Water Resources (41–44° N, 23–27° E, 44.7 m asl). The study location has a relatively cold continental humid subtropical climate, with an average precipitation of 703.4 mm in the experimental region and much more wet spells during the maize growth periods (May–September). The monthly average temperature from May to September was 33.4 °C, as shown in Figure 1. The maize mulch used in the current experiment was prepared following the protocol outlined in our recent study [16]. Liaoning Jinhefu Agricultural Development Co., Ltd., Liaoning Province, China, provided used maize straw biochar (pyrolyzed at 350–550 °C) for biochar.

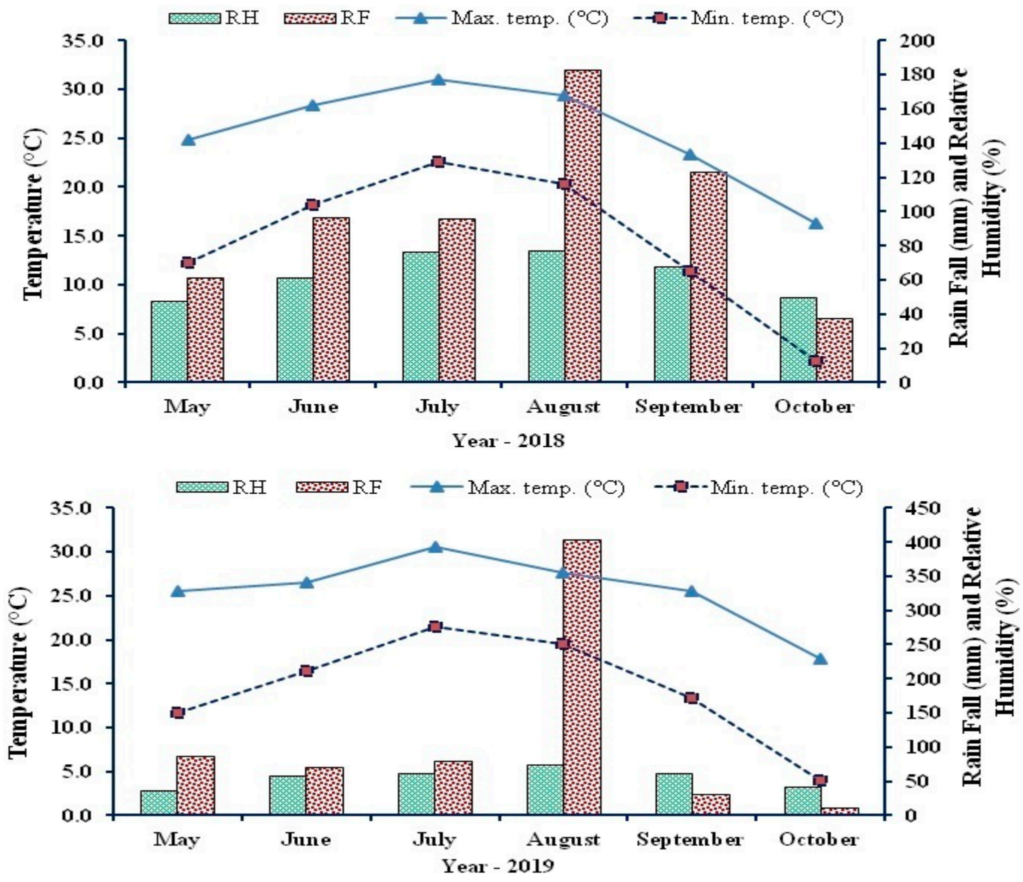

Figure 1. Metrological data of experimental site during the years of 2018 and 2019.

2.2. Experimental Details

The experimental treatments were executed using a split-plot design and replicated in triplicate. Each experimental unit (plot) had a 6 m length and 3 m width with a 0.3 m (buffer zone) surrounding area in which straw mulch treatment has been managed to keep it in the main plot, while maize straw biochar amendment (up to a depth of 20 cm) was implemented in the subplot. The treatments were comprised of different combinations with different straw mulch (0 and 8 t ha^{-1}) and maize straw biochar application rates (0, 4, 12, 36 t ha^{-1}) which were expressed as NMB0 (control, i.e., no mulch and maize straw biochar), NMB1 (no mulch and 4 t ha^{-1} biochar), NMB2 (no mulch and 12 t ha^{-1} biochar), NMB3 (no mulch and 36 t ha^{-1} biochar), SMB0 (8 t ha^{-1} straw mulch and no biochar), SMB1 (8 t ha^{-1} straw mulch and 4 t ha^{-1} biochar), SMB2 (8 t ha^{-1} straw mulch and 12 t ha^{-1} biochar), and SMB3 (8 t ha^{-1} straw mulch and 36 t ha^{-1} biochar). Straw mulch was applied in both seasons (2018–2019) at sowing, while maize straw biochar was used (at 20 cm depth) at sowing during 2018.

2.3. Crop Husbandry

The maize cultivar "Liangyu 777" seeds were sown on May 1st during both cropping seasons, i.e., 2018 and 2019, using a seed rate of 25 kg ha^{-1} and following the traditional double row planting method, keeping the ridges and kerfs 60 and 40 cm apart, respectively. Plants were thinned at the 3–4 leaf stage to keep the plant separation distance at 30 cm. As the experiment was carried out in rainfed conditions and rainfall was the only irrigation, no supplementary irrigation was applied during both crop seasons. A compound fertilizer with N, P, and K contents of 27%, 13%, and 15%, respectively, was used to apply a basal dose of 280, 130, and 150 kg ha^{-1} of N, P, and K at once for maize production. The crop was harvested on November 12th and 16th during the first and second years.

2.4. Pre-Experiment Maize Straw Biochar and Soil Analysis

Prior to maize sowing, soil samples (at a depth of 20 cm) were collected from various locations and analyzed to assess the soil physiochemical properties. The properties of soil and maize straw biochar that was used in the experiment are described in our recent studies [16,23].

2.5. Plant Growth Parameters

2.5.1. Plant Height and Stem Thickness

In each experimental plot, the plant height of 10 randomly selected plants was measured using a meter rod and then averaged. Similarly, the stem diameter of the same plant was measured with a vernier caliper.

2.5.2. Leaf Area Index

The leaf area of 10 randomly selected plants was evaluated using a portable leaf area meter (Licor Model 3100, Li-COR Inc., Lincoln, NE, USA), and the leaf area index (LAI) was determined by calculating using the formula provided by [24]. The formula is as follows:

$$\text{Leaf area index} = \text{Leaf area}/\text{Land area}$$

2.5.3. Leaves, Stem, Root, and Crop Growth Rate (CGR) of Maize Crop

To determine the maize plant growth rate, five plants from each experimental plot were uprooted at various growth stages (seedling to maturity), and plant parts, such as root, stem, leaves, and cob were separated and stored in recycled paper bags for oven drying for 72 h at ±70 °C. The leaf, stem, root, and crop growth rate were determined according to [24] by using the following formula:

$$\text{CGR} = (\text{W2} - \text{W1})/(\text{T2} - \text{T1})$$

where W1 is the dry matter weight at the very first harvest, W2 is the total dry weight at the 2nd harvest, T1 is the time roughly comparable to the first harvest (days), and T2 is the time equivalent to the second harvest (days).

2.5.4. Rate and Duration of Grain Filling

Grain Filling Rate (mg day^{-1})

In each experimental plot, one cob was randomly taken after initiating anthesis at five day intervals. The grains were kept separate from the cob, and placed in an oven for 72 h at 70 °C. The dry weight was determined using an electronic balance (Octopass Scientific Co., TX323L, Shimadzu, Japan), and the grain filling rate was measured using the following formula:

$$\text{GFR} = (\text{W2} - \text{W1})/(\text{t2} - \text{t1})$$

where,
W1 = Total dry weight of grains at harvest.
W2 = Total dry weight of grains harvested at the second harvest.
t1 = Date of first observation of dry matter.
t2 = Date of second dry matter observation.

Grain Filling Duration

Grain filling duration was determined by the number of days between anthesis and grain filling completion.

2.6. Statistical Analysis

The experimental data were analyzed with the statistical software 'Statistix 8.1' using Fischer's analysis of variance (ANOVA). A two-way ANOVA was built and, at $p < 0.05$, the treatment means were kept separate by using the least significant difference (LSD) test [25].

3. Results

3.1. Effect on Plant Height (cm) and STEM Diameter (mm)

Biochar and straw mulch (SM) application alone or in combination positively influenced the plant height of rainfed maize at different growth stages ($p < 0.05$; Tables 1 and 2). At each stage of the rainfed maize crop, straw mulch and biochar amendment increased the plant height of maize. The increased biochar application rates significantly increased the plant height and stem diameter of maize crop. Combined application of straw mulch and biochar, i.e., the B3 application rate (36 t ha^{-1}), substantially enhanced the plant height and stem diameter of maize at all studied growth stages compared to no straw mulch application during both years (Tables 1 and 2). The highest plant height during both study years was recorded with the application of a higher rate of biochar, i.e., the B3 treatment. The average increase occurred during the B3 treatment by 18.2, 11.3, 13.3, 14.1, 6.8% during 2018 and 8.4, 20.9, 15.8, 12.1, 14.0% during 2019, at the seedling, jointing, tasseling, grain-filling, and maturity growth stages, respectively. However, the SM increased the plant height by 7.3, 5.7, 5.2, 7.1, 4.9%, and 4.7, 7.9, 6.1, 7.8, and 4.0% at the 2018 and 2019 crop growth stages, respectively. Moreover, the highest value for stem diameter was also calculated during both years for the combined application of straw mulch and higher biochar application rate treatment (Table 2). Therefore, the greatest increase in stem diameter at the tasseling stage occurred due to the B3 treatment by 8.2% during the 2018 growing season while, at other stages, no significant influence of biochar treatment was observed during both cropping seasons. However, the SM increased the stem diameter by 5.0% at the jointing stage and 3.8% at the grain-filling stage during 2018, respectively, while no significant effect was noted at other crop stages during both cropping seasons. The interactive effect of straw mulch and biochar application was significant for plant height at the maturity stage and stem diameter at the jointing and tasseling stage in 2018. In this regard, the maximum plant height was observed for plants treated with SM and B3 biochar at maturity. Likewise, the SM and B2 or B3 treatment gave maximum stem diameter at the jointing stage, while highest stem diameter at tasseling stage was recorded with SM and B3 application rates during first year (Tables 1 and 2).

Table 1. Interactive impact of straw mulch and biochar application rates on the plant height of the maize crop.

Treatments		Seedling	Jointing	Tasseling	Grain Filling	Maturity	Seedling	Jointing	Tasseling	Grain Filling	Maturity
Main Effects											
	Year			2018					2019		
						(cm)					
Biochar	B0	43.9 C	97.0 C	203 C	206 D	235 C	47.4 B	105 D	202 D	214 D	235 C
	B1	47.1 B	111 B	215 B	216 C	250 B	48.2 B	115 C	218 C	224 C	255 B
	B2	49.8 AB	117 A	219 B	227 B	259 A	52.5 A	123 B	225 B	231 B	262 AB
	B3	51.9 A	108 B	230 A	235 A	251 AB	53.2 A	127 A	234 A	240 A	268 A
Mulching	NM	49.9 A	111 A	223 A	229 A	255 A	51.4	122	226 A	236 A	260 A
	SM	46.5 B	105 B	212 B	214 B	243 B	49.1	113	213 B	219 B	250 B
Interaction											
B0	NM	42.1	89.0 d	192	199	225 e	47.9	102	194	207	230
B1		45.2	113 ab	212	208	251 bc	47.3	111	214	214	250
B2		48.3	116 ab	215	220	260 ab	50.2	116	218	221	257
B3		50.2	104 c	225	229	235 de	51.2	122	227	232	262
B0	SM	45.7	105 c	213	214	244 cd	46.8	108	210	222	240
B1		49.0	109 bc	219	225	249 bc	49.0	118	222	233	260
B2		51.2	119 a	225	235	258 ab	54.7	130	232	241	268
B3		53.5	112 b	236	241	267 a	55.2	133	240	247	274

Note: At $p < 0.05$, values that share the same letter do not differ substantially. Lower-case represents the interaction of straw mulch and biochar treatments, while upper-case letters symbolize the direct effects. Here, B0 = no biochar; B1 = 4 tons biochar per hectare; B2 = 12 tons biochar per hectare; B3 = 36 tons biochar per hectare; NM = no mulch; SM = straw mulch.

Table 2. Interactive impact of straw mulch and biochar application rates on the stem diameter of the maize crop.

Treatments / Main Effects		Seedling	Jointing	Tasseling	Grain Filling	Maturity	Seedling	Jointing	Tasseling	Grain Filling	Maturity
	Year			2018					2019		
						(mm)					
Biochar	B0	9.76	22.13	24.77 C	24.09	24.55	10.60	24.34	24.92	26.60	26.33
	B1	10.35	23.01	25.81 B	24.91	25.36	10.79	25.00	26.20	27.05	26.88
	B2	11.17	24.33	26.48 AB	25.62	25.78	11.50	25.68	27.00	27.95	25.48
	B3	11.10	22.17	26.80 A	25.10	25.54	11.25	26.00	27.09	27.23	25.36
Mulching	NM	10.85	23.47 A	26.47	25.39 A	25.67	11.15	25.37	26.77	27.48	26.32
	SM	10.33	22.35 B	25.47	24.47 B	24.95	10.92	25.14	25.84	26.94	25.70
Interaction											
B0	NM	9.72	22.63 ab	23.97 d	23.85	24.18	10.57	23.97	24.18	26.48	26.27
B1		9.88	22.38 bc	24.90 cd	24.06	24.70	10.80	25.00	25.90	26.67	26.92
B2		10.83	24.27 a	26.87 ab	25.41	25.65	11.12	26.12	27.13	28.67	25.18
B3		10.90	20.13 d	26.13 abc	24.56	25.27	11.20	25.48	26.13	25.93	24.42
B0	SM	9.80	21.63 cd	25.58 bcd	24.33	24.92	10.63	24.72	25.65	26.72	26.38
B1		10.82	23.63 ab	26.72 abc	25.77	26.02	10.78	25.00	26.50	27.43	26.83
B2		11.50	24.40 a	26.10 bcd	25.82	25.91	11.88	25.25	26.87	27.23	25.77
B3		11.30	24.21 a	27.46 a	25.64	25.81	11.30	26.52	28.05	28.52	26.30

Note: At $p < 0.05$, values that share the same letter do not differ substantially. Lower-case represent the interaction of straw mulch and biochar treatments, while upper-case letters symbolize the direct effects. Here, B0 = no biochar; B1 = 4 tons biochar per hectare; B2 = 12 tons biochar per hectare; B3 = 36 tons biochar per hectare; NM = no mulch; SM = straw mulch.

3.2. Effect on the Number of Leaves of Maize Crop

Straw mulch and biochar application, whether solely or in combination, positively affected the number of leaves in the maize crop (Table 3). Maize grown on straw mulch incorporated soil significantly affected the number of leaves and more leaves were recorded (Table 3). The average increase in the number of leaves was strongly influenced by the application of the B3 treatment by 24.9, 19.5, 12.1, and 10.2% at the seedling, jointing, grain-filling, and maturity stage during 2018, respectively, while an influence of 25.1, 26.7, 10.3, 9.5% at all growth stages except seedling stage was seen during the 2019 growing season, respectively. The interaction of straw mulch and biochar did not affect maize leaf number. However, the plants grown on soil treated with SM and B3 produced more leaves in the 2018 and 2019 cropping seasons (Table 3).

3.3. Effect on the Leaf Area Index of Maize Crop

In the 2018 and 2019 cropping seasons, there was a trend change in the leaf area index at the seedling, jointing, tasseling, grain filling, and maturity stages of maize crops (Table 4). According to the findings, SM substantially enhanced the leaf area index of the maize crop. The addition of biochar contributed to a significantly high leaf area index throughout various stages of maize growth (Table 4). At different stages in both years, the B3 treatment had the highest leaf area index compared to the control. Similarly, the interaction between SM and biochar substantially impacted the leaf area index of maize crops during the jointing and tasseling growth stages in 2018. The interaction between SM and biochar significantly affected the soil's leaf area index during the tasseling stage in the 2019 cropping season. The highest value for leaf area index was recorded when the application of straw mulch and biochar rate (B3) was combined with other treatments.

However, the plants grown on soil treated with SM and B3 produced more leaves in the 2018 and 2019 cropping seasons (Table 4).

Table 3. Interactive impact of straw mulch and biochar application rates on the leaf number of the maize crop.

Treatments		Seedling	Jointing	Tasseling	Grain Filling	Maturity	Seedling	Jointing	Tasseling	Grain Filling	Maturity
Main Effects											
	Year			2018					2019		
Biochar	B0	4.77 C	7.11 C	8.72	9.81 C	12.7 C	5.30	6.94 B	8.61 C	10.7 C	12.6 B
	B1	5.42 B	7.89 B	9.72	10.0 BC	13.1 BC	6.00	8.40 A	9.41 B	11.2 B	13.1 AB
	B2	5.77 AB	7.83 B	9.61	10.5 AB	13.5 B	5.90	8.74 A	9.74 B	11.4 AB	13.5 A
	B3	5.96 A	8.50 A	9.56	11.0 A	14.0 A	5.95	8.68 A	10.91 A	11.8 A	13.8 A
Mulching	NM	5.38	7.97	8.36 B	10.0	13.0 B	5.44	7.98	9.18 B	10.7	12.9
	SM	5.57	7.69	10.4 A	10.6	13.7 A	6.13	8.41	10.2 A	11.9	13.5
Interaction											
B0	NM	4.88	7.11	7.77	9.33	12.0	5.11	6.33	8.44	10.3	12.4
B1		5.30	8.44	8.67	9.55	12.8	5.80	8.33	8.66	10.7	13.0
B2		5.58	8.00	8.67	10.3	13.0	5.51	8.67	8.88	10.7	13.1
B3		5.77	8.33	8.33	10.8	14.0	5.35	8.58	10.7	11.1	13.2
B0	SM	4.66	7.11	9.67	10.3	13.3	5.50	7.55	8.77	11.0	12.8
B1		5.54	7.33	10.8	10.4	13.5	6.20	8.48	10.1	11.8	13.3
B2		5.95	7.67	10.5	10.7	13.9	6.28	8.81	10.6	12.2	13.8
B3		6.14	8.66	10.8	11.2	14.1	6.55	8.78	11.1	12.6	14.3

Note: At $p < 0.05$, values that share the same letter do not differ substantially. Lower-case represent the interaction of straw mulch and biochar treatments, while upper-case letters symbolize the direct effects. Here, B0 = no biochar; B1 = 4 tons biochar per hectare; B2 = 12 tons biochar per hectare; B3 = 36 tons biochar per hectare; NM = no mulch; SM = straw mulch.

Table 4. Interactive impact of straw mulch and biochar application rates on the leaf area index of the maize crop.

Treatments		Seedling	Jointing	Tasseling	Grain Filling	Maturity	Seedling	Jointing	Tasseling	Grain Filling	Maturity
	Year			2018					2019		
Biochar	B0	0.50 C	1.14 C	2.43 C	4.59 C	3.97 C	0.51	1.20 B	2.61 D	4.51 C	4.09 D
	B1	0.54 BC	1.37 B	3.04 B	4.98 B	4.52 B	0.59	1.72 A	3.29 C	5.00 B	4.48 C
	B2	0.57 AB	1.70 A	3.46 B	5.26 B	4.71 AB	0.60	1.79 A	3.84 B	5.24 B	4.82 B
	B3	0.61 A	1.80 A	3.05 A	5.81 A	4.96 A	0.64	1.89 A	3.07 A	6.04 A	5.38 A
Mulching	NM	0.57	1.53 A	3.02	4.93 B	4.39 B	0.57	1.72	3.23	5.01	4.58
	SM	0.54	1.48 B	2.97	5.38 A	4.69 A	0.60	1.58	3.18	5.39	4.81
Interaction											
B0	NM	0.48	0.82 e	2.33 e	4.33	3.65 d	0.49	1.13	2.53 d	4.43	3.90
B1		0.54	1.62 abc	3.37 ab	4.88	4.49 bc	0.57	1.92	3.75 a	4.91	4.49
B2		0.62	1.79 ab	3.45 ab	5.04	4.81 b	0.59	1.87	3.80 a	5.00	4.77
B3		0.64	1.89 a	2.93 cd	5.48	4.60 bc	0.63	1.97	2.83 c	5.69	5.15
B0	SM	0.51	1.46 c	2.54 de	4.85	4.30 c	0.53	1.27	2.69 cd	4.59	4.28
B1		0.54	1.13 d	2.72 de	5.07	4.55 bc	0.60	1.52	2.83 c	5.09	4.47
B2		0.53	1.60 bc	3.47 a	5.49	4.61 bc	0.62	1.71	3.88 a	5.48	4.87
B3		0.58	1.71 abc	3.16 bc	6.13	5.32 a	0.65	1.81	3.32 b	6.38	5.61

Note: At $p < 0.05$, values that share the same letter do not differ substantially. Lower-case represent the interaction of straw mulch and biochar treatments, while upper-case letters symbolize the direct effects. Here, B0 = no biochar; B1 = 4 tons biochar per hectare; B2 = 12 tons biochar per hectare; B3 = 36 tons biochar per hectare; NM = no mulch; SM = straw mulch.

3.4. Leaves, Stem, Root Growth Rate and Crop Growth Rate of Maize Crop (mg day^{-1})

The rate of growth of the leaves, stems, and roots of a maize crop was highly altered by the use of SM and biochar application rates (Table 5). Compared to mulch application, SM significantly improved the growth rate of maize crop leaves, stems, and roots. Biochar application at a higher rate, i.e., B3, increased the rate of maize crop leaf, stem, and root growth, especially compared to the other biochar treatments and the control. In contrast, the growth rates of maize crop leaves, stems, and roots in the B1 and B2 biochar treatments were considerably lower than in the B3 biochar treatment. Correspondingly, except for stem growth rate, the interaction of SM and biochar had no noticeable effect on maize crop the leaves, stem, and root growth rate during the 2019 cropping period. Compared to the other treatments, the highest crop growth rate was obtained when biochar was applied at the B3 with SM combination (Table 5). Furthermore, straw mulch notably enhanced the crop growth rate compared to mulch application during the second cropping season (Table 5). During both years, the biochar application at B3 resulted in the highest crop growth rate compared to the control application. Similarly, the interaction of SM and biochar seemed to have no impact on the growth rate of leaves, stems, and roots of maize crops during the 2018 and 2019 cropping seasons. When compared to other treatments, the biochar application at the B3 with SM resulted in the highest leaf, stem, roots, and crop growth rate (Table 5).

Table 5. Interactive impact of straw mulch and biochar application rates on the leaves, stem, root growth rate, and crop growth rate ($g/m^2/day$) of the maize crop.

Treatments		Leaves	Stem	Root	CGR	Leaves	Stem	Root	CGR
Main Effects									
	Year	**2018**				**2019**			
		$g/m^2/day$							
Biochar	B0	5.55 C	3.86 C	2.69 C	9.41 C	4.43 D	5.05 D	4.83 B	9.48 D
	B1	5.86 BC	4.40 C	4.25 B	10.3 C	5.70 C	7.36 C	5.07 B	13.1 C
	B2	6.36 AB	5.34 B	5.82 A	11.7 B	6.51 B	8.3 B	6.19 A	14.8 B
	B3	6.76 A	6.70 A	6.08 A	13.5 A	7.17 A	10.4 A	6.40 A	17.6 A
Mulching	NM	5.66 B	4.50 B	4.55 B	10.2 B	5.20 B	7.02 B	5.23 B	12.2 B
	SM	6.60 A	5.65 A	4.87 A	12.3 A	6.71 A	8.56 A	6.02 A	15.3 A
Interaction									
B0	NM	5.20	3.11	2.66	8.31	3.75	4.83 e	4.59	8.59 g
B1		5.41	3.91	4.27	9.32	5.24	6.66 d	4.41	11.9 e
B2		5.79	5.11	5.42	10.9	5.50	6.83 d	5.90	12.3 e
B3		6.25	5.89	5.85	12.1	6.29	9.75 b	6.01	16.0 c
B0	SM	5.91	4.61	2.72	10.5	5.10	5.27 e	5.07	10.4 f
B1		6.30	4.90	4.22	11.2	6.17	8.07 c	5.74	14.2 d
B2		6.93	5.57	6.23	12.5	7.53	9.82 b	6.48	17.3 b
B3		7.27	7.51	6.30	14.8	8.04	11.1 a	6.79	19.1 a

Note: At $p < 0.05$, values that share the same letter do not differ substantially. Lower-case represent the interaction of straw mulch and biochar treatments, while upper-case letters symbolize the direct effects. Here, B0 = no biochar; B1 = 4 tons biochar per hectare; B2 = 12 tons biochar per hectare; B3 = 36 tons biochar per hectare; NM = no mulch; SM = straw mulch.

3.5. Grain Filling Rate (mg day^{-1}) and Grain Filling Duration

Straw mulch and biochar significantly impacted grain filling rate and duration compared to no straw mulch treatment in both years, and the straw mulch treatment resulted in a substantial grain filling rate and markedly shorter grain filling duration (Table 6). Biochar application significantly impacted the grain filling rate and grain filling duration of maize crops in both cropping seasons. In the 2018 and 2019 cropping seasons, the B3 biochar treatment had the highest rate of grain filling and the shortest duration of grain filling. The interaction of SM and biochar had no substantial impact on the parameters tested. When the biochar treatment B3 was combined with SM, the highest value was obtained compared to the control treatment (Table 6).

Table 6. Interactive impact of straw mulch and biochar application rates on the grain filling rate and duration of the maize crop.

Year		2018		2019	
Treatments		Graining Filling Rate	Grain Filling Duration	Graining Filling Rate	Grain Filling Duration
Biochar	B0	2.23 B	47.4 A	2.33 C	47.4 A
	B1	2.60 A	45.6 B	2.62 B	45.9 B
	B2	2.79 A	44.8 B	2.87 AB	44.4 C
	B3	2.76 A	42.7 C	3.01 A	43.0 D
Mulching	SM	2.55	46.0 A	2.63	45.6 A
	NM	2.64	44.3 B	2.78	44.7 B
Interaction					
B0	NM	2.17	48.5	2.23	48.0
B1		2.73	46.7	2.57	46.1
B2		2.71	45.7	2.76	45.0
B3		2.60	43.0	2.96	43.3
B0	SM	2.29	46.3	2.42	46.7
B1		2.48	44.6	2.66	45.6
B2		2.88	43.8	2.97	43.7
B3		2.92	42.5	3.06	42.7

Note: At $p < 0.05$, values that share the same letter do not differ substantially. Lower-case represent the interaction of straw mulch and biochar treatments, while upper-case letters symbolize the direct effects. Here, B0 = no biochar; B1 = 4 tons biochar per hectare; B2 = 12 tons biochar per hectare; B3 = 36 tons biochar per hectare; NM = no mulch; SM = straw mulch.

4. Discussion

Straw mulch combined with biochar treatment can improve plant height, stem diameter, leaf area index, crop growth rate (CGR), grain filling rate, and duration in rainfed maize. The increase in growth-related parameters may be ascribed to biochar application, as it can effectively enhance soil composition, soil fertility, and carbon contents, and increase soil water holding capacity, improving soil efficiency [26]. Furthermore, biochar application enhanced soil physical conditions and physicochemical properties, resulting in faster decomposition of organic manures present in the soil, leading to higher nutrient availability from the soil to the crops [27,28]. The combination of biochar and straw mulch application in the soil substantially enhanced the growth of the crops, i.e., plant height and stem diameter, with varied biochar treatment concentrations as compared to no biochar application, as demonstrated in the present investigation (Tables 1 and 2). Applying biochar improved the decomposition of the organic carbon in biochar amendment soil, increased organic matter, and strengthened soil water retention, ultimately improving plant height and stem diameter. Similarly, the application of biochar significantly enhanced the plant height and stem diameter, as reported in the previous experiments [29–33]. Furthermore, the biochar application rates could strongly impact the maize stem diameter during the crop growth [34]. Biochar application increased soil microbial activity, nutrient uptake, photosynthetic rate [16,35], plant height, and stem diameter.

The straw mulch and biochar combination considerably increased the leaf area index; however, biochar showed greater effectiveness in improving the growth of the maize crop (Table 4). These results are similar to [36], who investigated if biochar enhanced the growth-related parameters of both lettuce (*Lactuca sativa* L.) and *Arabidopsis* plant. Similarly, he also investigated whether biochar had significantly increased the leaf area in *Arabidopsis* (130%), as was observed in the current study. Biochar application has been reported to enhance the leaf area and leaf area index of cotton [37] and maize compared to no biochar amendment [38]. This increase in leaf area index may be attributed to an increase in leaf cell expansion with biochar application [36]. Similarly, [20] noticed that the leaf area index of maize substantially increased when it was grown in biochar amended soil. The biochar application substantially increased leaf area per plant (172 cm^2) and leaf area index (6.48) due to soil nutrient improvement [39]. Furthermore, adding biochar increased the dry biomass of maize up to 115–600% compared to the control [39], as observed in the present study. Moreover, the results in [40] demonstrated that application of biochar as a soil amendment improves maize dry weight up to 62–113%, and there is a positive correlation between aboveground dry biomass with belowground dry biomass similarly due to altered conditions for the supply of nutrients and root growth enhanced by the biochar amendments. In the present study, the improvement in leaf growth with biochar-treated soil may be due to better below-ground biomass production, as soil amended with biochar resulted in the increased maize roots' length, surface area, volume, and tips compared with the control soil [41]. The latest findings demonstrated that straw mulch and biochar application rate considerably influenced maize crop growth in terms of leaves, stem, root growth, and crop growth (Table 6). Nevertheless, this enhancement in crop growth widely differs depending on the crop, soil, and biochar source. Therefore, the higher crop growth and dry matter production are mainly in the fluctuation in the soil nutrient contents and their availability to the crops at various growth stages [42,43]. Similarly, biochar application increases the aboveground biomass production in many crops [16,34]. Increasing the biochar application rates enhanced the soil physicochemical properties and, thus, ultimately increased the biomass production and root and shoot growth of the crop [44,45], and also helps in mitigating climate change [46] and reducing toxicity of the soil [47]. Similarly, in the current study, higher biochar application rates (36 tons ha^{-1}) increased plant height, stem diameter, crop growth and grain filling rate in maize crops grown in rainfed conditions.

5. Conclusions

Based on the findings in the current study, it is concluded that the use of straw mulch and biochar significantly impacted the growth characteristics of the maize crop. The incorporated straw mulch, i.e., 8 t ha^{-1} improved the growth-related parameters. The application of biochar doses improved the maize plant growth. Consecutively, the application of biochar (36 t ha^{-1}) could increase the leaf area index with the highest grain filling rate and duration. Straw mulching outperformed biochar in terms of leaf area index and crop growth rate, which will be pivotal to promoting its use and, thus, to protect the environment from burning residual crop residues in rainfed areas of the northern region of China. Straw mulch and biochar amendment are sustainable agricultural practices that should be utilized for the improvement of the growth and yield of rainfed maize and agricultural sustainability in rainfed areas.

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