Biochar

ORIGINAL RESEARCH

Biochar improves soil properties and corn productivity under drought conditions in South Korea

Jae-Hyuk Park[1], Jin-Ju Yun[2], Seong-Heon Kim[2], Jong-Hwan Park[3], Bharat Sharma Acharya[4], Ju-Sik Cho[1,5] and Se-Won Kang[1,5]*

Abstract

Biochar has been shown to improve soil properties and plant productivity in soils with inherently low fertility. However, little has been reported for upland corns under dry and wet precipitation regimes. This study investigates the effect of biochar addition on a range of soil physicochemical, biological, and hydrological properties, and corn growth and productivity under agrometeorological drought and wet conditions. Here, experiments were laid out in a randomized complete block design with three replications at two sites during 2017 and 2018 in South Korea. Treatments included (i) CN: control (ii) IF: inorganic fertilizer (N–P–K) at 145–30–60 kg ha^{-1}; (iii) BS: barley straw at 5 t ha^{-1}; (iv) CWBC: corn waste biochar at 5 t ha^{-1}; (v) CWBC + IF: corn waste biochar + inorganic fertilizer; (vi) CWBC + BS: corn waste biochar + barley straw. The year 2017 was relatively dry, whereas the year 2018 was wet. Despite drought conditions in the year 2017, biochar facilitated soil water conservation. However, higher precipitation in 2018 increased the quantity and distribution of soil water and nutrients in the top 15 cm. Biochar reduced soil bulk density, and increased porosity, cation exchange capacity and total organic carbon in both years but increased total bacterial counts during the dry year only. Bacterial population was generally higher under wet conditions. Similarly, more soil CO_2 was emitted in the wet year than in the dry year. Results further indicated that biochar can enhance corn biomass and grain yield regardless of precipitation conditions. The grain index was, however, affected by rainfall and was significantly different across treatments in the year 2018 only. All biomass, grain yield, and grain index were highest in CWBC + IF treatment and lowest under CN treatment. Indeed, biochar addition appeared to improve soil quality and soil conditioning effects in the drought and wet years, ameliorating soil and plant properties. Overall, biochar can improve water and nutrients storage, availability, and uptake, and therefore corn productivity during hydrological extremes.

Highlights

- Biochar application consistently increased soil water content.
- Biochar improved soil physicochemical characteristics in the drought and wet year.
- Biochar increased bacterial population during the drought year.
- Grain yield was higher in the wet year than in the drought year.
- Grain yield and grain index was highest under CWBC + IF and lowest under CN treatment.

Springer

Graphical abstract

1 Introduction

Climate change is unequivocal; global atmospheric carbon concentration has increased from 277 ppm in 1750 to 412 ppm in 2020 (Friedlingstein et al. 2022) and earth temperature by an average of 0.08 °C per decade since 1880 (Lindsey and Dahlman 2020). Climate change and weather extremes affect agriculture by modifying precipitation, temperature, and seasonality, input supplies, and soil functions, among others (Paudel et al. 2014). Agriculture is also a significant contributor of greenhouse gases accounting for nearly 14% of total global anthropogenic greenhouse gas emissions; thereby causing anthropogenic radiative forcing of climate (Duxbury 1994). This has ultimately impacted drought characteristics including drought frequency, duration, and severity (Chiang et al. 2021).

Drought generally refers to precipitation deficit conditions relative to the average value and declining soil moisture conditions. Mishra and Singh (2010) provided details on the concept of droughts. Drought impacts agriculture in many ways. Direct impacts of drought include plant damage, disease, insect-pest infestation, and reduced productivity. Drought reduces seedlings growth, crop's transpiration, stomatal conductance, leaf water potential, and root activities; all affecting vegetative and generative yield and harvest index (Dietz et al. 2021). For example, Ray et al. (2018) reported significant yield reduction in rainfed and irrigated crops after drought, particularly precipitation deficit, during 2008 to 2016 in Texas. In their study, drought appeared to have a greater impact on winter wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) across Texas. Indeed, droughts could reduce crop growth, yield, and hectarage589 due largely to reduced soil moisture storage and availability (Ray et al. 2018).

Amending agricultural soils with biochar has been purposed as a means to reduce greenhouse gases, improve soil quality, and adapt agriculture to climatic change and extremes (Blanco-canqui et al. 2020; Park et al. 2023). Biochar is a carbon-enriched material produced through the pyrolysis of organic feedstocks in a low or no oxygen environment. Biochar generally reduces soil bulk density through mixing and dilution effects and by improving aggregation and porosity. Porosity increases due largely to new pores formation, soil aggregation, and reduced soil packing (Blanco-Canqui 2017). All these effects could translate into increased water holding capacity, but the effects could vary with soil types, biochar feedstocks, and pyrolysis temperature. Yun et al. (2022) observed the improved soil chemical properties and decreased CH_4 emissions with pelleted bamboo biochar application in a rice cropping system in South Korea. Bohara et al. (2019) also reported the increased soil water holding capacity, plant available water, saturated water permeability, and drought tolerance with pinewood biochar in a very fine sandy loam soil.

Indeed, biochar could improve soil water storage, reduce fertilizer drainage and nutrient leaching, and enhance crops' resiliency to droughts (Li et al. 2021). Agricultural crops are often water demanding and require ample water supply for growth and productivity. In South Korea, corn is an important food crop, accounting for nearly 12 million tonnes of consumption in 2022–2023 (www.world-grain.com). Corn is increasingly being used in different industries including compound feed. While the demand for corn is steadily increasing, drought

and extreme weather events could negatively affect their growth, yield, and quality (Eom et al. 2013; Lobell et al. 2011). Intense water stress during growing season could limit leaf area and plant growth, thereby reducing yield (He et al. 2017; Ge et al. 2012; Song et al. 2019). As such, applying carbon-enriched materials such as biochar to agricultural soils may improve soil properties and plant productivity. However, little is known about their impacts on upland corn under wet and drought conditions. This study aimed to understand the effects of biochar addition on a range of soil physicochemical, biological, and hydrological properties, and corn growth and productivity under drought and wet conditions. We conducted multi-sites study to gain a quantitative understanding of how biochar helps to cope with water stress in upland corn.

2 Materials and methods

2.1 Site description

This research was conducted from March to July 2017 on the experimental site 1, and from March to July 2018 at site 2 of the Gwangyang-eup, Gwangyang-si, Jeollanam-do, South Korea. The climate of the region is temperate with distinct seasonal qualities, and an annual average temperature of 10 ℃–15 ℃, annual relative humidity of 60–75%, and annual precipitation of 1000–1800 mm. Over 70% of the annual precipitation occurred from June to September.

The temperature and precipitation during corn cultivation period (March to July) in this study is illustrated in Fig. 1. Over the last 5 years, the mean daily maximum and minimum air temperatures ranged from 34.7 to 36.7 ℃ and −4.9 to −1.7 ℃, respectively. This temperature data surveyed over the last 5 years were similar to temperature degrees and pattern surveyed in 2017 and 2018 in the experimental area, whereas precipitation varied significantly. The total precipitation in the study area averaged 747 mm in 2012–2016, 286 mm in 2017, and 797 mm in 2018.

Both experimental sites had similar soil properties (Table 1). The soil texture in both sites was silt loam. Details on the location and soil characteristics of two sites are summarized in Table 1. Briefly, at Site 1 and Site 2 bulk densities were 1.38 and 1.30 g cm^{-3}, porosity 46.4 and 50%, and total organic carbon (TOC) 13.2 and 14 g kg^{-1}, respectively.

2.2 Preparation of barley straw and corn waste biochar

Here, barley straw (BS) and corn waste were collected from a local farm in Gwangyang-si, South Korea. The biochar was produced from corn waste only. The corn waste was completely dried in an oven at 75 ℃ for 2 days, before converting it into corn waste biochar (CWBC). The biochar was produced using a biochar processing equipment at the experimental farm of Sunchon National University. Briefly, N$_2$ gas was injected to purge the processing container to
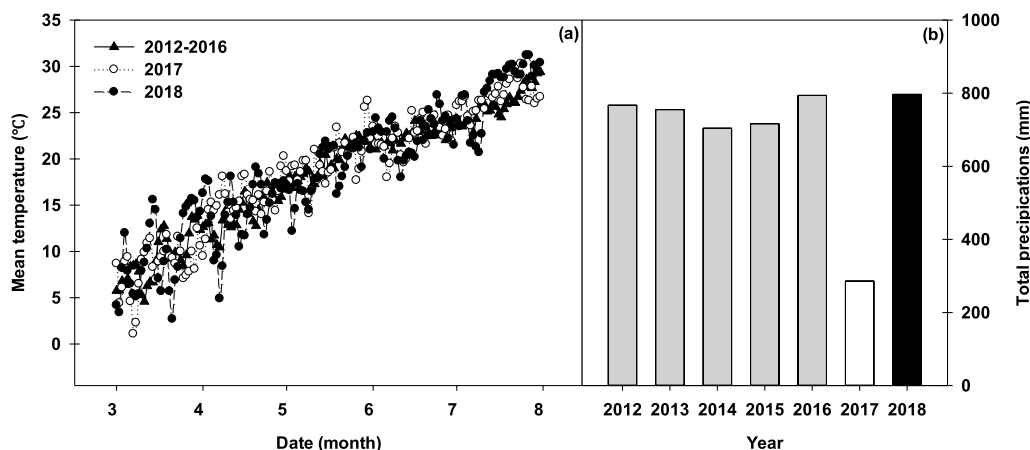
Fig. 1 Mean air temperature (**a**) and total precipitation (**b**) during corn's season

Table 1 Select soil properties at two experimental sites, South Korea

Year	Location	Bulk density (Mg m^{-3})	Porosity (%)	pH (1:5H$_2$O)	EC (dS m^{-1})	TOC (g kg^{-1})	TN (g kg^{-1})	CEC (cmol$_c$ kg^{-1})
2017	34° 94′ 24″ N, 127º 56′ 55″ E	1.38	46.4	5.86	0.21	13.2	1.66	9.48
2018	34° 56′ 21″ N, 127° 33′ 53″ E	1.30	50.0	5.80	0.24	14.0	2.09	10.3

allow limited oxygen, and the temperature in the internal chamber was ramped to 600 °C at a rate of 4 °C min^{-1}, after which the peak temperature was sustained for 1 h. BS had 0.31% total nitrogen (TN), 0.08% total phosphorus (TP), potassium (K), 0.33% calcium (Ca), and 0.12% magnesium (Mg). The CWBC had a low bulk density (0.12 Mg m^{-3}) and high pH (10.3). In addition, it constituted other inorganic components (0.27% TN, 1.84% TP, and 4.71% K).

2.3　Experimental design and field management

The field experiment was laid out in a randomized complete block design with three replications. Each plot was 4 m^2 in area and was conventionally tilled. Each plot consisted of 6 rows and 3 columns, having 0.5 m row-to-row distance. The field experiment included organic/inorganic treatments: (i) Control: no application; (ii) IF: inorganic fertilizer (N–P–K) at 145–30–60 kg ha^{-1}; (iii) BS: barley straw at 5 t ha^{-1}; (iv) CWBC: corn waste biochar at 5 t ha^{-1}; (v) CWBC+IF: corn waste biochar+inorganic fertilizer; (vi) CWBC+BS: corn waste biochar+barley straw.

The corn seeds used in this study were yellow sweet corn with high sugar content. Seeds were sowed on March 17 and 16 in 2017 and 2018, respectively. Plant spacing was 0.3 m×0.6 m, with two seedlings per hole, resulting in a plant density of 12 plants m^{-2}. Plots were tilled and barley straw and biochar were well mixed to a depth of 20 cm using a smooth steel roller about 20 days before sowing of corn. Depending on field situations, pre-emergence herbicide and manual weeding were applied to control weeds. Fully grown corn was harvested on July 7, 2017 and July 6, 2018, respectively, and plant height, productivity, and grain index were immediately examined.

2.4　Soil sampling and analysis
2.4.1　Soil water content

During the cropping season, soil water content (SWC) was determined at 7, 14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, 91, 98, 105, and 112 days after corn sowing for both years. The SWC was measured at a depth of 0–20 cm using the soil auger method. Briefly, a 54 mm diameter steel core was driven to a depth of 20 cm, and soil samples were collected, brought to lab, weighed, dried in a fan-assisted drying oven at 105 °C for 48 h, and re-weighed to determine SWC. The SWC was calculated using the following equation (NIAST 2000):

$$SWC\ (\%) = \left(\text{fresh soil weight} - \text{dried soil weight}\right) \times 100\ /\ \text{dried soil weight}.$$

2.4.2　Soil respiration

The soil CO_2 flux was measured using a static chamber with 0.02 m^2 area and 0.01 m^3 volume. The chamber was placed between corn plants to a soil depth of 20 cm. Gas sampling in the corn field was performed between 10 and 11 a.m. local time, every 7 days. Gas samples were collected at 0, 10, 20, and 30 min after the chamber closure. Gas sampling was carried out using a 25 mL gas tight syringe. Samples were immediately transferred into a gas-evacuated 10 mL soda glass vial, and analyzed on a gas chromatograph (GC-2014, Shimadzu) equipped with a flame ionization detector (FID) for CO_2 measurement. CO_2 flux and the total CO_2 for the entire corn cultivation period were computed as described by Kang et al. (2016).

$$F = \rho \times (V/A) \times (\Delta c / \Delta t) \times (273/T)$$

where, F is CO_2 flux, ρ is CO2 density (1.976 mg cm^{-3}), V is chamber volume (m^3), A is chamber area (m^2), Δc × Δt is average increase in the gas concentration, and T is 273 +mean temperature in the chamber (°C).

$$\text{Total } CO_2 \text{ flux} = \sum_{i}^{n} (R_i \times D_i)$$

where, Ri is the rate of CO_2 emission in the sampling interval, Di is the number of days in the sampling interval, and n is the number of sampling intervals.

2.4.3　Soil physicochemical properties

At the end of the experiment, soil bulk density, porosity, and aggregate distribution were examined using the core sampling and fraction method (Kang et al. 2019). For analyzing soil chemical properties, soil samples were air-dried and passed through a 2 mm stainless steel sieve. Soil pH and Electrical Conductivity (EC) were measured using a pH and EC meter, respectively (using a mixture of soil–water, ratio of 1:5, after shaking for 30 min). The TOC and TN analyses were performed using a TOC analyzer (SIEVERS InnovOx) and the Kjeldahl method, respectively. The cation exchange capacity (CEC) in the soil samples was measured by applying 1N ammonium acetate extraction. This study conducted soil analysis as described by NIAST (2000).

2.4.4　Quantitative real-time PCR analyses to evaluate total number of bacteria

Soils from different treatments were subjected to total soil DNA extraction. FastDNA® SPIN Kit (MP-Biomedicals, USA) was used to extract DNA from approximately 1.0 g soil samples. The extracted DNA was resuspended in 50 μL DES (DNase/Pyrogen-Free Water), and DNA concentration and quality were measured using an Optizen NanoQ spectrophotometer (Optizen, Korea). SYBR Green-based quantitative real-time PCR (qPCR) was used to determine the total number of bacteria (TNB). The primers used were 1114-F (5′-CGGCAACGAGCG

CAACCC-3′) and 1275-R (5′-CCATTGTAGCACGTG TGTAGCC-3′) (Denman and McSweeney 2006). Quantitative PCR was performed using an Eco™ Real-Time PCR (Illumina, San Diego, CA, USA) in a 20 μL reaction mixture consisting of 10 μL 2×QuantiSpeed SYBR mix (PhileKorea, Korea), 0.8 μL of each 10 μM primer, and 50 ng template DNA. The qPCR reactions were performed in triplicate under thermal cycler conditions of one cycle comprising 50 °C for 2 min and 95 °C for 2 min, followed by 40 cycles at 95 °C for 15 s, 60 °C for 1 min and 72 °C for 30 s.

2.5 Statistical analysis
Data analyses were performed using SAS-JMP software version 15.0 (SAS Institute Inc.). The mean values were determined as an average of three replicates. Each mean value was subjected to a one-way analysis of variance (ANOVA), and a comparison of treatments was performed by applying Tukey's test. Two-way ANOVA was used to determine the differences between years, treatment conditions, and the interaction between years and treatments.

3 Results
3.1 Soil water content
SWC during the corn growing periods was significantly affected by biochar addition and weather conditions (Fig. 2). SWC in the wetyear (2018) was significantly higher than that in the drought year (2017). Soil water was largely related to precipitation regimes, and ranged from 4.0% to 21.6% in 2017 and 6.4% to 23.6% in 2018. In both years, biochar application, either alone or in combination, significantly and consistently increased SWC in the top 15 cm from March to July compared to other treatments (Fig. 2). Specifically, CWBC, CWBC+IF, and CWBC+BS had significantly higher SWC values than CN, IF, and BS; however, no significant difference was observed among the three biochar treatments.

3.2 Soil respiration
In the both years of assessment, inorganic and organic materials influenced the CO_2 emission rate, as also the pattern of CO_2 emission rate differed between inorganic fertilizer, barley straw, and biochar (Fig. 3). Generally, more CO_2 was emitted in wet year (2018) than in the dryyear (2017); the CO_2 emission across all treatments and years ranged up to 1700 mg m^{-2} h^{-1}. Emission rates ranged from 10.1 to 94.5% in 2017 and 20.9 to 41.4% in 2018 with biochar treatments, as compared to those without biochar. CO_2 emission rates were significantly affected by CWBC, CWBC+IF, and CWBC+BS in each year. A significant interaction occurred between soil CO_2 and SWC within these treatments.

3.3 Soil physicochemical characteristics
Soil aggregate size distribution chart (Fig. 4) indicates a close relationship between aggregates and applied materials after corn harvesting. More than 45% of 1–2 mm aggregates were observed in Cn, IF, and BS treatments, whereas the treatments constituting biochar had 40–43% of 1–2 mm aggregates in the dry year (2017). A similar pattern of soil aggregate distribution was observed in the wet year (2018).

Soil bulk density and porosity were significantly affected by biochar application (Table 2). Biochar generally reduced soil bulk density but increased porosity in both years. In the drought year, soil bulk density under biochar treatments (CWBC, CWBC+IF, and CWBC+BS) was 1.13 Mg m^{-3}. It ranged from 1.19 to 1.28 Mg m^{-3} under no biochar treatments (CN, IF , and BS). Contrastingly, bulk density under biochar treatment was 1.15 Mg m^{-3} in the wet year 2018. In no biochar treatments, bulk density ranged from 1.22 to 1.29 Mg m^{-3}. Treatment with barley straw had higher soil porosity and lower soil bulk density than CN and IF in both years.
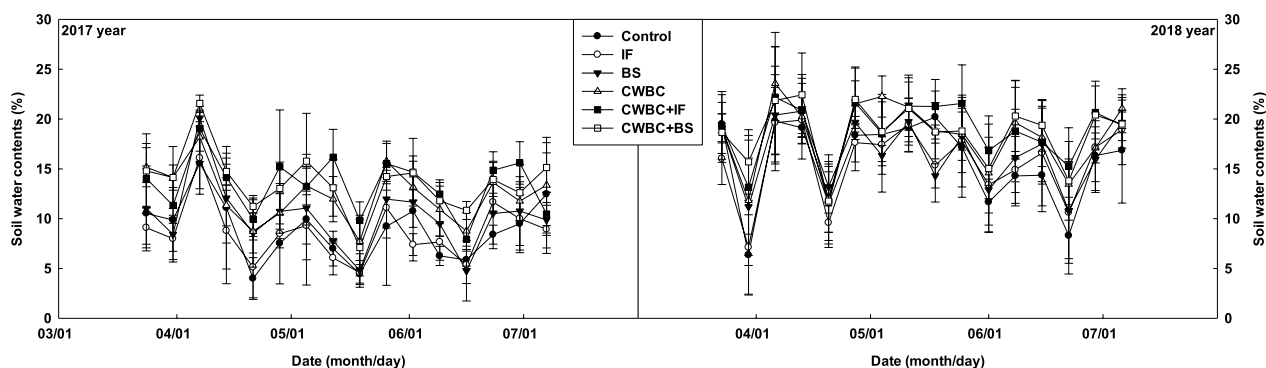

Fig. 2 Changes in soil water contents during the corn growing period in 2017 and 2018. The error bars represent standard deviations (n = 3)
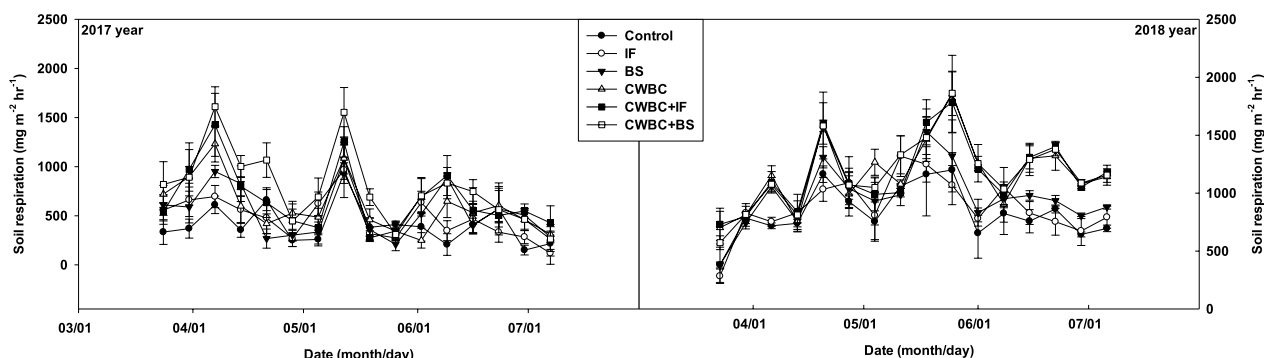
Fig. 3 Soil respiration during the corn growing period in 2017 and 2018. The error bars represent standard deviations (n = 3)
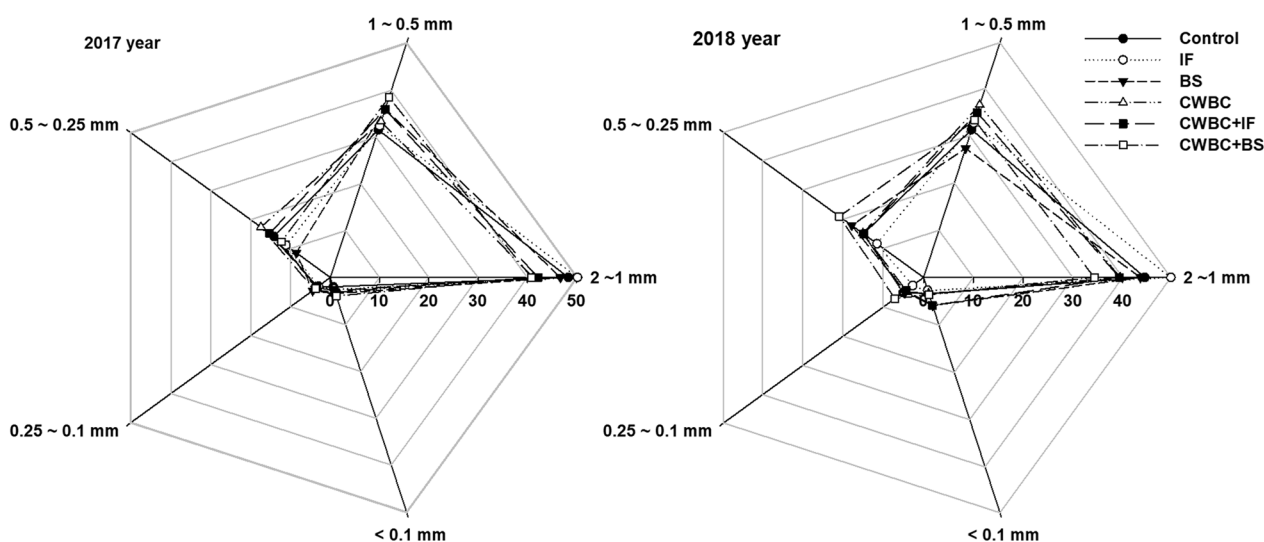

Fig. 4 Soil aggregate distribution after corn harvesting

Two-way ANOVA revealed significant effects of biochar and/or barley straw on multifold soil properties (Table 2). For example, TOC was generally high under biochar and straw treatments. The TOCs under CWBC and CN were 15.2 and 11.4 g kg^{-1} in the drought year 2017 and 17 and 15.2 g kg^{-1} in wet year 2018, respectively. The application of biochar increased the concentration of TOC and CEC by 3.9–44.6% and 3.1–31.4%, respectively, for both years. Dry/wet years (A) significantly affected pH, EC, TOC, and TN. Treatments (B) significantly affected all measured properties except TN, but their interaction (A×B) significantly affected bulk density and porosity only. Mean soil pH ranged from 5.89– 6.04 mg kg^{-1} and 5.79–5.90 mg kg^{-1} under applied biochar treatments in 2017 and 2018, respectively. These pH values are generally higher than those observed under no biochar treatments.

3.4 Total number of bacteria in soil

Figure 5 shows the total number of bacteria (TNB) under different treatments after corn harvesting for the drought and wet year. Irrespective of treatment conditions, mean TNB in 2018 was 30.6% higher that in 2017. Indeed, drought tends to reduce bacterial counts. Interestingly, in the wet year, no significant difference was observed in TNB across the six treatments. However, during the drought year (2017), biochar treatments (CWBC, CWBC + IF, and CWBC + BS) significantly increased the TNB by 18.7 to 42.1% compared to no biochar treatments (Cn, IF, and BS).

3.5 Corn growth characteristics

Biochar significantly affected growth characteristics and grain yield, although effects were more pronounced in wet conditions (Table 3). In the drought year 2017, plant height and grain index were not significantly different between the treatment groups, but significantly

Table 2 Soil physicochemical characteristics under different treatments after corn harvest

Year	Treatment	Bulk density (Mg m^{-3})	Porosity (%)	pH (1:5H$_2$O)	EC (dS m^{-1})	TOC (g kg^{-1})	TN (g kg^{-1})	CEC (cmol$_c$ kg^{-1})
2017	Control	1.26a[1]	52.1b	5.76c	0.30e	11.4d	1.06b	9.84c
	IF	1.28a	51.9b	5.63d	0.36 cd	11.9 cd	1.07b	10.0c
	BS	1.19b	53.4ab	5.81bc	0.32de	12.7c	0.92c	10.9b
	CWBC	1.13b	55.2a	6.04a	0.38bc	15.2b	1.17a	11.3b
	CWBC+IF	1.14b	54.8a	5.89b	0.52a	15.2b	1.05b	12.3a
	CWBC+BS	1.13b	55.5a	6.03a	0.41b	16.4a	1.09b	12.4a
2018	Control	1.29a	52.0bc	5.55b	0.44c	15.2e	1.23c	9.78b
	IF	1.29a	51.8c	5.40b	0.60a	15.4de	1.67a	9.91b
	BS	1.22b	54.0b	5.52b	0.41c	16.2cd	1.45b	10.4b
	CWBC	1.16c	57.0a	5.89a	0.49b	17.0b	1.09d	12.1a
	CWBC+IF	1.17bc	56.7a	5.79a	0.58a	16.9bc	1.50b	12.8a
	CWBC+BS	1.15c	57.1a	5.90a	0.48b	18.8a	1.46b	12.3a
Statistical analysis[2]								
Year (A)		ns	ns	***	***	***	***	ns
Treatment (B)		***	***	***	***	***	ns	***
A×B		*	***	ns	ns	ns	ns	ns

[1] Different letters within the same column indicate significant differences between treatments, as determined by Tukey's test with $p < 0.05$

[2] ns, *, **, and *** denote not significant (ns) and significant differences at the 5%, 1%, and 0.1% levels, respectively
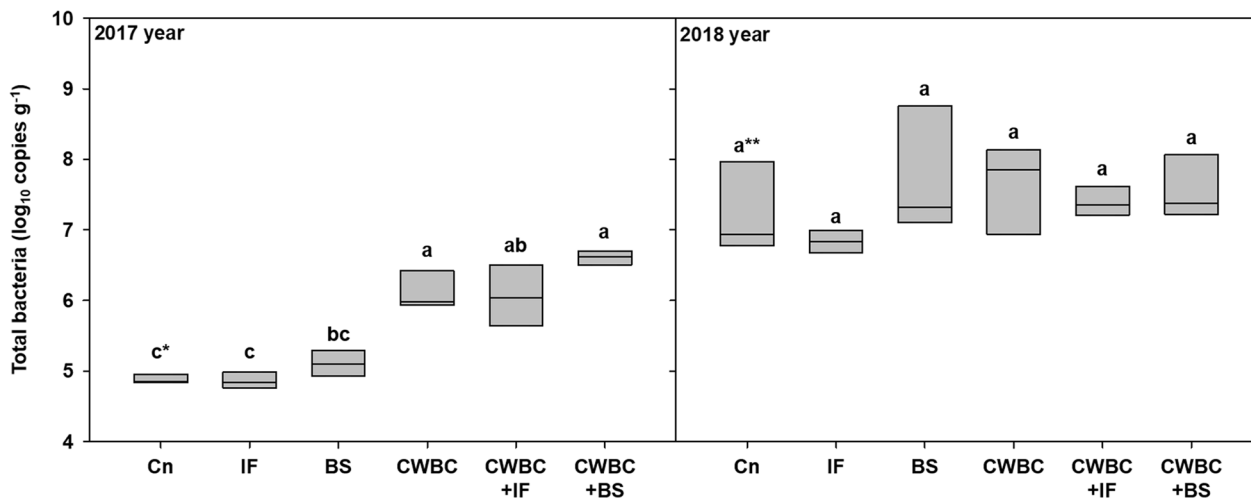

Fig. 5 Total bacterial counts after corn harvesting. Different letters within the same column indicate significant differences between treatments, as determined by Tukey's test with $p < 0.05$

higher corn productivity was observed under biochar treatments compared to CN and BS. Grain yield and biomass were the highest under CWBC+IF treatment and the lowest under CN in the drought year. When applied alone (CWBC), biochar increased corn's biomass and grain yield of by 56.9% and 18.5%, respectively, compared with CN treatment in the drought year 2017.

In the wet year 2018, plant height was the highest under CWBC+BS treatment and the lowest under CN. No significant difference in plant height was observed between IF, BS, CWBC, CWBC+IF, and CWBC+BS treatments. Grain yield and biomass was the highest under CWBC+IF treatment and the lowest under CN, which was largely similar to the drought year. The grain index was the highest under CWBC+IF and the lowest under CN treatment. Overall, grain yield was the highest under

Table 3 Growth characteristics of corn under different treatments in 2017 and 2018

Year	Treatment	Plant height (cm plant^{-2})	Corn productivity (kg m^{-2})		Grain index (%)
			Biomass	Grain yield	
2017	Control	195a[1]	2.21c	2.48d	78.6a
	IF	202a	3.21a	3.05bc	78.9a
	BS	200a	2.68b	2.71 cd	80.4a
	CWBC	197a	3.47a	2.94bc	78.4a
	CWBC + IF	206a	3.49a	3.40a	81.5a
	CWBC + BS	198a	3.39a	3.20ab	79.4a
2018	Control	186b	3.13e	3.98d	76.6d
	IF	192ab	3.88c	4.88bc	82.5dbc
	BS	195ab	3.63d	4.45 cd	80.1c
	CWBC	195ab	3.94bc	5.11b	80.5 cd
	CWBC + IF	192ab	4.37a	5.76a	87.1a
	CWBC + BS	202a	4.14ab	5.27b	86.1ab
Statistical analysis[2]					
Year (A)		**	***	***	***
Treatment (B)		**	***	**	***
A × B		ns	*	*	ns

[1] Different letters within the same column indicate significant differences between treatments, as determined by Tukey's test with $p < 0.05$

[2] ns, *, **, and *** denote not significant (ns) and significant differences at the 5%, 1%, and 0.1% levels, respectively

the wet year compared to the drought year. Overall, both year (A) and treatment (B) affected all plant height, productivity, and grain index, but the interaction effect (A × B) was observed across biomass and grain yield only (Table 3).

4 Discussion

Biochar addition to soils improve soil physical, chemical, and biological properties, and crop productivity (Blanco-Canqui et al. 2020; Razzaghi et al. 2020). These effects, however, vary with soil texture, feedstock type, and pyrolysis temperature (Blanco-Canqui et al. 2020). Our results indicated improvements in soil properties and crop productivity with biochar application in the drought and wet years. Indeed, amending soils with biochar could increase water holding and improve nutrient uptake and soil water environment during water stress (Ali et al. 2017; Mansoor et al. 2021). For example, 38 g kg^{-1} biochar application during drought significantly increased mineral nutrients Bary P, exchangeable-K, soil carbon, nitrogen mineralization and soil respiration in wheat crop (Zaheer et al. 2021).

In this study, we observed positive effect of biochar on porosity, EC, TOC, and CEC during wet and drought conditions. Similar beneficial effects of biochar on soil physical, chemical, and biological characteristics have been reported in earlier studies (Cornelissen et al. 2018; Kim et al. 2016; Wang et al. 2015). Biochar increases porosity through several mechanics, including

the addition of new pores, formation of accommodation pores between biochar particles and soil aggregates, reorganization of pore distribution, reduction of bulk density, increasing soil aggregation, or by favoring burrowing invertebrates (Blanco-Canqui 2017). Water entering the biochar pores dissolves organic and mineral compounds on the outer and inner surfaces of biochar. Consequently, EC increases largely due to the increase in dissolved organic carbon, anions, and cations in the soil solution (Joseph et al. 2021). Biochar also contains many base ions, which improve soil EC. Biochar increases soil carbon storage depending on the types of biochar and soil. A global meta-analysis indicated a significant relative increase of 64.3 and 84.3% for total carbon and organic carbon, respectively (Chagas et al. 2022). Soil carbon storage may increase through direct and indirect effects. Direct effects include the addition of stable C, whereas indirect effects include negative priming (Blanco-Canqui et al. 2020). Biochars have higher charge density and surface area for cation adsorption, which increase soil CEC. Overall, biochar improves soil physicochemical properties, which are crucial for soil structure, nutrient cycling, and soil water movement in combating water stress (Ali et al. 2017; Singh et al. 2022).

Higher soil CO_2 emission in the wet year in our study is consistent with several earlier studies (e.g., Zheng et al. 2021). In an incubation study, Bond-Lamberty et al. (2016) reported significant positive correlation between daily CO_2 fluxes and soil cores' water content.

Undoubtedly, CO_2 fluxes depend on soil texture and water content (Bouma and Bryla 2000; Li et al. 2017). We observed higher SWC and bacterial population during the wet year 2018. Undeniably, soil water regulates oxygen diffusion in soil to maintain microbial community structure (Stres et al. 2008). Water movement in soil fractions influences microbial mobility and nutrient availability (Zhou et al. 2002; Schjønning et al. 2003). Also, biochar addition was positively associated with bacterial population in this study, all of which may have translated into higher CO_2 emission. In an incubation study, Shah et al. (2017) reported significant increase in CO_2 evolution with biochar application. Also, CO_2 production increased with increasing rate of biochar amendment. Indeed, soil microbial activities are influenced by soil amendments, soil properties, nutrient cycling, and climatic conditions; all affected soil respiration and plant growth (Dai et al. 2021). Biochar generally improves soil C storage. However, young/fresh biochar increases soil respiration and CO_2 production. Such biochars are rich in labile carbon, which are readily available to microbes for energy source and mineralization (Smith et al. 2010).

Biochar could increase crop yield during water stress conditions. In this study, we observed significantly higher or comparable grain yield and biomass with biochar in both drought and wet conditions compared to no biochar treatments. However, corn yield was generally higher under wet conditions. Drought affects plant growth and yield by inhibiting leaf expansion and stomatal conductance (Ali et al. 2017). The mean corn productivity in this study was 6.04 and 8.76 kg m^{-2} for the drought year (2017) and wet year (2018), respectively, suggesting beneficial effects of precipitation and soil water on corn productivity. Indeed, SWC was higher during the wet year compared to the drought year, and water storage increased consistently with biochar. Biochar could increase water availability by increasing the amounts of water held at field capacity (Koide et al. 2015). In addition, adding biochar improved soil pH, EC, and CEC in both years, which may significantly improve corn yield. Ali et al. (2018), Kiboi et al. (2019), Zhang et al. (2016) and Kang et al. (2018) also emphasized on the importance of soil amendments on water storage and crop growth and productivity. Interestingly, corn productivity was the highest under CWBC + IF in the dry and wet years. Possibly, corn plants may have benefited from readily available nutrients found in inorganic fertilizers and improved soil properties with biochar addition. The yield under CWBC + BS was somewhat lower than that under CWBC + IF possibly due to slow mineralization of straw nutrients. Biochar application rate is also an important factor affecting grain yield

(Yeboah et al. 2016), which was outside the scope of this study. Overall, the results from this study are valuable to improve soil water storage, crop's adaptation, and yield under drought conditions.

5 Conclusion

This study investigating the effect of biochar amendment on upland corn in Gwangyang, South Korea indicates that biochar has potential to enhance soil properties and corn yield under wet and drought conditions. Biochar could be applied either alone or in combination with inorganic fertilizer and/or barley straw. However, larger yield benefits are observed when biochar is combined with IF than straw. Biochar addition to soils could produce significantly higher or comparable grain yield and biomass during the dry and wet years compared to no biochar management. Grain yield is generally higher under the wet year than in the drought possibly due to the improved soil water storage. Biochar addition improved bacterial population and soil physiochemistry. Biochar reduced soil bulk density and increased porosity, cation exchange capacity, and total organic carbon in dry and wet years. Improvements in soil carbon could be a panacea to lower greenhouse gases and mitigate climate change and studies along these lines could be advantageous. Overall, biochar could increase soil physical, chemical, and biological properties and grain yield under drought and climatic stress, but long-term studies are needed for more definite conclusions.

Author contributions
JaHP and Kang, SW designed and conducted the experiment as well as wrote the first draft. JaHP, JY, SK, and SK conducted sample's analysis, CO_2 measurement and interpretation. Park, JoHP and JC inspired the overall work. BSA revised the final manuscript. All authors read and approved the final manuscript.

Availability of data and materials
All data gathered or analyzed in this study are included in the article.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Agricultural Chemistry, Sunchon National University, Suncheon 57922, Republic of Korea. [2]Division of Soil and Fertilizer, National Institute of Agricultural Sciences, RDA, Wanju 55365, Republic of Korea. [3]Department of Life Resources Industry, Dong-A University, Busan 49315, Republic of Korea. [4]Rodale Institute, Southeast Organic Center, Chattahoochee Hills, GA 30268, USA. [5]Department of Agricultural Life Sciences, Sunchon National University, Suncheon 57922, Republic of Korea.

References
Ali S, Rizwan M, Qayyum MF, Ok YS, Ibrahim M, Riaz M, Arif MS, Hafeez F, Al-Wabel MI, Shahzad AN (2017) Biochar soil amendment on alleviation of drought and salt stress in plants: a critical review. Environ Sci Pollut Res 24:12700–12712

Ali S, Jan A, Manzoor SA, Khan A, Khan MI, Inamullah ZJ, Daur I (2018) Soil amendments strategies to improve water-use efficiency and productivity of maize under different irrigation conditions. Agric Water Manag 201:88–95

Blanco-Canqui H (2017) Biochar and soil physical properties. SSSAJ 81(4):687–711

Blanco-Canqui H, Laird DA, Heaton EA, Rathke S, Acharya BS (2020) Soil carbon increased by twice the amount of biochar carbon applied after 6 years: field evidence of negative priming. GCB Bioenergy 12(4):240–251

Bohara H, Dodla S, Wang JJ, Darapuneni M, Acharya BS, Magdi S, Pavuluri K (2019) Influence of poultry litter and biochar on soil water dynamics and nutrient leaching from a very fine sandy loam soil. Soil Tillage Res 189:44–51

Bond-Lamberty B, Smith AP, Bailey V (2016) Temperature and moisture effects on greenhouse gas emissions from deep active-layer boreal soils. Biogeosciences 13:6669–6681

Bouma TJ, Bryla DR (2000) On the assessment of root and soil respiration for soils of different textures: interactions with soil moisture contents and soil CO_2 concentrations. Plant Soil 227:215–221

Chagas JK, de Figueiredo CC, Ramos ML (2022) Biochar increases soil carbon pools: evidence from a global meta-analysis. J Environ Manage 305:114403

Chiang F, Mazdiyasni O, AghaKouchak A (2021) Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nat Commun 12(1):2754

Cornelissen G, Jubaedah NNL, Hale SE, Martinsen V, Silvani L, Mulder J (2018) Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. Sci Total Environ 634:561–568

Dai Z, Xiong X, Zhu H, Xu H, Leng P, Li J, Tang C, Xu J (2021) Association of biochar properties with changes in soil bacterial, fungal and fauna communities and nutrient cycling process. Biochar 3:239–254

Denman SE, McSweeney CS (2006) Development of real-time PCR assay for monitoring anaerobic fungal and cellulolytic bacterial populations within the rumen. FEMS Microbiol Ecol 58:572–582

Dietz KJ, Zörb C, Geilfus CM (2021) Drought and crop yield. Plant Biol 23(6):881–893

Duxbury JM (1994) The significance of agricultural sources of greenhouse gases. Fert Res 38:51–163

Eom KC, Park SH, Yoo SY (2013) Water requirement of maize according to growth stage. Korean J Soil Sci Fert 46(1):16–22

Friedlingstein P, Jones MW, O'Sullivan M, Andrew RM, Bakker DC, Hauck J, Le Quéré C, Peters GP, Peters W, Pongratz J, Sitch S (2022) Global carbon budget 2021. Earth Syst Sci Data 14(4):1917–2005

Ge T, Sui F, Bai L, Tong C, Sun N (2012) Effects of water stress on growth, biomass partitioning, and water-use efficiency in summer maize (*Zea mays* L.) throughout the growth cycle. Acta Physiol Plant 34:1043–1053

He J, Wen R, Tian S, Su Y, He X, Su Y, Cheng W, Huang K, Zhang S (2017) Effects of drought stress and re-watering on growth and yield of various maize varieties at tasseling stage. Agri Sci Technol 18:1145–1151

Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, Cayuela ML, Graber ER, Ippolito JA, Kuzyakov Y, Luo Y (2021) How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy 13(11):1731–1764

Kang SW, Seo DC, Cheong YH, Park JW, Park JH, Kang HW, Park KD, Ok YS, Cho JS (2016) Effect of barley straw biochar application on greenhouse gas emissions from upland soil for Chinese cabbage cultivation in short-term laboratory experiments. J Mt Sci 13:693–702

Kang SW, Kim SH, Park JH, Seo DC, Ok YS, Cho JS (2018) Effect of biochar derived from barley straw on soil physicochemical properties, crop growth, and nitrous oxide emission in an upland field in South Korea. Environ Sci Pollut Res 25:25813–25821

Kang SW, Park JH, Kim SH, Seo DC, Ok YS, Cho JS (2019) Establishment of optimal barley straw biochar application conditions for rice cultivation in a paddy field. Environ Geochem Health 41:1793–1803

Kiboi MN, Ngetich KF, Fliessbach A, Muriuki A, Mugendi DN (2019) Soil fertility inputs and tillage influence on maize crop performance and soil water content in the Central Highland of Kenya. Agric Water Manag 217:316–331

Kim HS, Kim KR, Yang JE, Ok YS, Owens G, Nehls T, Wessolek G, Kim KH (2016) Effect of biochar on reclaimed tidal land soil properties and maize (*Zea mays* L.) response. Chemosphere 142:153–159

Koide RT, Nguyen BT, Skinner RH, Dell CJ, Peoples MS, Adler PR, Drohan PJ (2015) Biochar amendment of soil improves resilience to climate change. Gcb Bioenergy 7(5):1084–1091

Li G, Kim S, Han SH, Chang H, Son Y (2017) Effect of soil moisture on the response of soil respiration to open-field experimental warming and precipitation manipulation. Forests 8:56

Li L, Zhang YJ, Novak A, Yang Y, Wang J (2021) Role of biochar in improving sandy soil water retention and resilience to drought. Water 13(4):407

Lindsey R, Dahlman L (2020) Climate change: Global temperature. Climate.gov, 16.

Lobell DB, Banziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat Clim Change 1:42–45

Mansoor S, Kour N, Manhas S, Zahid S, Wani OA, Sharma V, Wijaya L, Alyemeni MN, Alsahli AA, El-Serehy HA, Paray BA (2021) Biochar as a tool for effective management of drought and heavy metal toxicity. Chemosphere 271:129458

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391:202–216

NIAST (2000) Methods of soil and plant analysis. National Institute of Agricultural Science and Technology RDA, Suwon

Park JH, Yun JJ, Park JH, Acharya BS, Han KJ, Cho JS, Kang SW (2023). Three years of biochar and straw application could reduce greenhouse gas and improve rice productivity. Soil Sci Plant Nutr 1–9

Paudel B, Acharya BS, Ghimire R, Dahal KR, Bista P (2014) Adapting agriculture to climate change and variability in Chitwan: long-term trends and farmers' perceptions. Agric Res 3:165–174

Ray RL, Fares A, Risch E (2018) Effects of drought on crop production and cropping areas in Texas. Agric Environ Lett 3(1):170037

Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma 361:114055

Schjønning P, Thomsen IK, Moldrup P, Christensen BT (2003) Linking soil microbial activity to water-and air-phase contents and diffusivities. Soil Sci Soc Am J 67:156–165

Shah T, Khan S, Shah Z (2017) Soil respiration, pH and EC as influenced by biochar. Soil Environ 36(1):77–83

Singh H, Northup BR, Rice CW, Prasad PVVV (2022) Biochar application influence soil physical and chemical properties, microbial diversity, and crop productivity: a metal-analysis. Biochar 4:8

Smith JL, Collins HP, Bailey VL (2010) The effect of young biochar on soil respiration. Soil Biol Biochem 42(12):2345–2347

Song L, Jin J, He J (2019) Effect of severe water stress on maize growth processes in the field. Sustainability 11:5086

Stres B, Danevčič T, Pal L, Fuka MM, Resman L, Leskovec S, Hacin J, Stopar D, Mahne I, Mandic-Mulec I (2008) Influence of temperature and soil water content on bacterial, archaeal and denitrifying microbial communities in drained fen grassland soil microcosms. FEMS Microbiol Ecol 66:110–122

Wang X, Song D, Liang G, Zhang Q, Ai C, Zhou W (2015) Maize biochar addition rate influences soil enzyme activity and microbial community composition in a fluvo-aquic soil. Appl Soil Ecol 96:265–272

Yeboah E, Asamoah G, Kofi B, Abunyewa AA (2016) Effect of biochar types and rate of application on maize yield indices and water use efficiency on an Ultisol in Ghana. Energy Procedia 93:14–18

Yun JJ, Park JH, Acharya BS, Park JH, Cho JS, Kang SW (2022) Production of pelleted biochar and its application as an amendment in paddy condition for reducing methane fluxes. Agriculture 12(4):470

Zaheer MS, Ali HH, Soufan W, Iqbal R, Habib-ur-Rahman M, Iqbal J, Israr M, El Sabagh A (2021) Potential effects of biochar application for improving wheat (*Triticum aestivum* L.) growth and soil biochemical properties under drought stress conditions. Land 10(11):1125

Zhang D, Pan G, Wu G, Kibue GW, Li L, Zhang X, Zheng J, Zheng J, Cheng K, Joseph S, Liu X (2016) Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. Chemosphere 142:106–113

Zheng P, Wang D, Yu X, Jia G, Liu Z, Wang Y, Zhang Y (2021) Effects of drought and rainfall events on soil autotrophic respiration and heterotrophic respiration. Agric Ecosyst Environ 308:107267

Zhou J, Xia B, Treves DS, Wu LY, Marsh TL, O'Neill RV, Ralumbo AV, Tiedje JM (2002) Spatial and resource factors influencing high microbial diversity in soil. Appl Environ Microbiol 68:326–334