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Rice straw biochar and irrigation effect on yield and water productivity of okra

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Abstract

Dry season vegetable production is challenging due to water scarcity, a drawback on sustaining year-round crop production. Biochar improves soil moisture and nutrient retention and may be used to improve vegetable water productivity. We examined the combined effect of rice straw biochar and irrigation on yield, water productivity, and phosphorus (P) uptake of okra (*Abelmoschus esculentus* L.) grown on a sandy clay loam soil in the dry season. Biochar was applied at 0, 5, 10 Mg ha^{-1}, and 10 Mg ha^{-1} biochar fortified with P [10 Mg ha$^{-1}{}_{(P)}$] under full irrigation (FI) and deficit irrigation (DI) and replicated in each growing season for three years. Under DI, the 10 Mg ha^{-1} and 10 Mg ha$^{-1}{}_{(P)}$ biochar treatments significantly ($p < .05$) increased okra fresh fruit yield (Y_{FF}) by 67 and 82% but had no impact on total aboveground biomass yield (Y_{TBM}) in the first growing season. Biochar at 5 Mg ha^{-1} had no impact on okra yield. Okra yield was higher under biochar fortified with P compared to the traditional method of applying P alone, e.g. 30 Mg ha$^{-1}{}_{(P)}$ produced significant Y_{TBM} over 30 Mg ha^{-1} under DI. Biochar had no impact on P uptake in the first growing season. Estimated okra water use was 224 and 193 mm under FI and DI. Yield reduction under DI compared to FI was only 8%. Amid water scarcity, a minimum of 10 Mg ha^{-1} rice straw biochar under DI is therefore recommended for farmers in the area.

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Abbreviations

CWR	crop water requirement
DI	deficit irrigation

FC	field capacity
FI	full irrigation
LAI	leaf area index
NDVI	normalized difference vegetation index
PAHs	poly aromatic hydrocarbons
TAW	total available water
TDR	time domain reflectometry
TSP	triple-super-phosphate
WP	water productivity

Core Ideas

- Rice straw biochar rate of 10 Mg ha^{-1} significantly increased okra yield.
- Okra biomass and fruit yield were not significantly affected by 5 Mg ha^{-1} biochar.
- Okra yield was higher when P was mixed with biochar instead of giving the two in separate applications.
- Deficit irrigation increased water productivity of okra.

1 INTRODUCTION

Sustainable food crop production on a year-round basis is one of the remedies for enhancing global food security. The growing world population is projected to increase to 9.5 billion by 2050, and this demands an increase in agricultural production of 70% or more between 2005 and 2050 (Lal, 2015). This necessitates the adoption of crop productivity strategies that could balance water demand and supply and at the same time enhance resilience in climate variability (Fischer et al., 2019).

Vegetable crop production in Ghana has improved from peasant to commercial farming. It provides source of food and income to the local farmer, hence promoting food security. However, it is less sustainable because of limited production in the dry season due to water scarcity. This has resulted in some urban farmers using untreated waste water to irrigate their vegetable crops to meet market demands in the dry season; a practice that poses health risks.

Okra (*Abelmoschus esculentus* L.) is a popular vegetable crop grown in Ghana and noted for its nutritional value, yet information on its water requirement is limited. For example, information on crop coefficient (K_c) of okra, defined as the ratio of crop evapotranspiration (ET_c) to reference evapotranspiration (ET_o), was not available in the study area. Crop water requirement (CWR) represent the amount of water required to compensate for water loss through ET_c (Allen, Pereira, Raes, & Smith, 1998). Okra is one of the few crops whose K_c and water requirement was not reported in the popular referenced FAO 56 publication (Allen et al., 1998). Furthermore, okra belongs to under-researched crops in Ghana and other parts of Africa with less attention given to its role in global food security (Baa-Poku, 2018).

Crop production depends tremendously on water, making agriculture the world's largest consumer of water. Consequently, water has been identified as one of the key limiting factors in agricultural crop production (Makurira, Savenije, Uhlenbrook, Rockström, & Senzanje, 2007). Ghana among other countries in the tropics, is challenged with changes in hydro-climate regimes which has caused imbalance in water demand and supply making crop production vulnerable to climate change (United Nations, 2017). Nevertheless, crop production in Ghana depends on seasonal rainfalls making it difficult to cultivate food crops throughout the year. Meanwhile, the onset and intra-seasonal distribution of such rainfalls are characterized by marked fluctuations (Mawunya, Adiku, Laryea, Yangyuoru, & Atika, 2011). Effective utilization of agricultural inputs such as water, fertilizers and soil amendment materials e.g. biochar, can improve crop yield for sustainable agriculture.

Irrigation plays an important role in augmenting the unpredictable seasonal rainfall as well as ameliorate drought impact on vegetable production. Successful crop production in the dry season is possible through irrigation; drip irrigation system was the most suitable due to its higher application efficiency (Simonne, Dukes, & Zotarelli, 2011). Although irrigation contributes to sustainable crop production, it is equally important to quantify the irrigation water during crop production. Supplying the right amount of water needed by the crop would reduce leaching of vital nutrients and salt accumulation in the crop root zone, as well as conserve irrigation water.

Biochar, a soil conditioner produced from pyrolysis of plant residue and biomass, has been reported to improve soil physical properties and water holding capacity among others (Eldardiry & Abd El-Hady, 2015; Razzaghi, Obour, & Arthur, 2020). Biochar can enhance the ability of plants to extract water and nutrients from the soil by improving soil microbial activities and hydraulic conductivity. Biochar also improves soil nutrient retention and enhances P fertilizer retention in soils (Cui, Wang, Fu, & Ci, 2011). Biochar amendments generally increase crop yield (Fischer et al., 2019) but is more effective when combined with mineral fertilizer than sole application (Alburquerque et al., 2013; Lehmann et al., 2011). Zao et al. (2018) reported that amendment of biochar to agricultural soils is a strategy of potential agronomic benefits. Most studies on biochar including Dumortier et al. (2020), Sheng, Zhan, and Zhu (2016), and Matovic (2011) have concentrated on its potential to sequester carbon for climate change mitigation. It is equally important to conduct more studies on biochar as an organic conditioner for soils to improve crop yield, particularly with feedstocks that are readily available in the study area under consideration. While rice production has increased over the past years in Ghana (MoFA, 2015), its straw does not serve to be valuable fodder to livestock, and in most cases the straw is mostly abandoned or burnt off on the field. These abandoned rice straw and other agro waste on the field serves as a potential pollutants to the air and surface water resources.

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Phosphorus make up about 0.2% of plant dry weight but still it is the second most limiting major nutrient for plant growth after nitrogen (N) (Schachtman, Reid, & Ayling, 1998). The nature of P reaction in highly weathered tropical soils as that used in the current study leads to formation of insoluble Al, Fe and Ca phosphates which limits P availability for plant uptake (Eduah, Nartey, Abekoe, Breuning-Madsen, & Andersen, 2019). Biochar prepared under high pyrolysis temperature (≥500°C) has the potential to increase soil pH, thereby can enhance the bioavailability of P for plant uptake. On the other hand, concentration of P (%P) in plants can be altered by changes in the soil chemical environment, plant uptake capacity, etc. (Baxter, 2009).

Emergence of remote sensing techniques in measuring vegetative indices has made it possible to predict crop yield with promising results (Christensen & Goudrian, 1993). Normalized difference vegetation index (NDVI) is a vegetative index defined as the ratio of (NIR-RED) to (NIR+RED), where NIR is reflectance in the near-infrared spectrum and RED is reflectance in the red band of the visible spectrum (Kastens et al., 2005). Many of the existing crop yield prediction models including the relationship between MODIS-NDVI data and wheat yield by Lopresti, Di Bella, and Degioanni (2015) and four different vegetation indices for corn yield prediction model using neural network techniques by Panda, Ames, and Panigrahi (2010) are empirical. Gommes (1998) attributed the challenges in developing a universal yield prediction model to variations in agroecological zones. Little research has been done to investigate the combined effect of rice straw biochar and irrigation on yield, P concentration and water use of field grown okra under drought condition in Ghana and Sub -Sahara Africa.

There is the need to adopt sustainable strategy to improve crop yield by biochar amendment that can improve soil water and nutrient conservation. Furthermore, quantifying irrigation water through CWR estimation is necessary for saving appreciable amount of irrigation water. Finally, the method of fortifying biochar with P before amendment was to investigate okra yield response to the fortification compared to the traditional method of applying mineral fertilizers solely in the soil.

Research over three consecutive growing seasons was therefore conducted to determine the impact of rice straw biochar amendment in a sandy clay loam soil on improving okra yield, P uptake and water productivity under two irrigation regimes in the dry season. The specific objectives were to (i) determine the minimum biochar rate needed to increase okra yield significantly, and (ii) determine the effect of biochar amendment on P uptake in okra shoot. Additionally, the water requirement of okra was estimated under full and deficit irrigation to optimize water productivity for dry season production. We hypothesized that rice straw biochar will increase okra yield regardless of the irrigation regime, and the yield will be greater when the biochar is fortified with P.

2 MATERIALS AND METHODS

2.1 Site description

The experiments were carried out at the University of Ghana's Forest and Horticultural Crops Research Centre, Kade (latitude 06°8.61′ N and longitude 0°54.16′ W) in the eastern region of Ghana. Kade lies at 114 m above sea level, with a temperature range from 25–38°C in a deciduous forest zone with annual rainfall of 1300–1800 mm (Nkansah, Ofosu-Budu, & Ayarna, 2011). The study area has two rainfall seasons and a dry season annually. The major rainy season covers April to July. The minor season starts in September and ends in October. The dry season spans from December to March.

2.2 Experimental soil and biochar characteristics

The field soil has a sandy clay loam texture and was classified as an Acrisol according to the World Reference Base classification system (IUSS, 2015). Its soil has low contents of organic matter and major nutrients such as phosphorus and nitrogen (Table 1). The soil water content at field capacity (FC) was determined as 235.2 mm and wilting point was 117.2 mm (Oppong Danso et al., 2019).

Rice straw feedstock was charred at pyrolysis temperature of 550°C using Lucia stove for 48 hours and sieved to particle size of < 2 mm after air dried. A recalcitrant biochar was produced due to the high pyrolysis temperature and had high potassium content (17700 mg kg^{-1}) compared to phosphorus and magnesium in low concentrations, i.e. 1420 mg kg^{-1} of P and 1330 mg kg^{-1} of Mg respectively. Total poly-aromatic hydrocarbons (PAHs) was given as 6.0 mg kg^{-1} (Table 2).

2.3 Site preparation and layout

The experimental field consisted of 32 plots. Each plot covered an area of 5 m by 3.6 m (18 m^2). There were 16 plots each under FI and DI with four biochar treatments in each case. Irrigation was supplied using pressure compensated drip tubes (Naandanjain, Jalgaon, India) with discharge rate of 2 L h^{-1} and emitters spaced at 0.3 m on each plot. Each plot had 8 drip lines spaced 0.5 m apart and accommodated 72 okra plants.

2.4 Treatment and experimental design

Irrigation regimes constituted the main treatment and biochar was a sub treatment applied at different rates in a randomized complete split-plot design with four replications. Rice straw biochar was broad spread and incorporated to a depth of 15 cm in the soil. It was split-applied in three consecutive growing seasons. Consequently, the first growing season had biochar applied at 0 Mg ha^{-1}, 5 Mg ha^{-1}, 10 Mg ha^{-1}, and 10 Mg $ha^{-1}{}_{(P)}$ in the soil. During the second growing season, biochar rate increased, and thus, was applied at 0 Mg ha^{-1}, 10 Mg ha^{-1}, 20 Mg ha^{-1}, and 20 Mg $ha^{-1}{}_{(P)}$. Finally, biochar rate in the third growing season was again increased (200%) and the application rates were 0 Mg ha^{-1}, 15 Mg ha^{-1}, 30 Mg ha^{-1}, and 30 Mg $ha^{-1}{}_{(P)}$ respectively. Biochar treatment with (P) subscript, e.g. 10 Mg $ha^{-1}{}_{(P)}$, designates 10 Mg ha^{-1} biochar fortified with triple-super-phosphate (TSP) containing 46% P. Biochar fortification involved soaking the given biochar amount in aqueous solution of TSP to obtain a final application rate of 60 kg P ha^{-1}. The P fortified biochar was air dried before incorporation into the soil. Alternatively, unfortified biochar amended plots received the same amount of P by broadcasting pellets of TSP at a rate of 60 kg P ha^{-1}. Thus we tested whether the concentration of P in the crop could be improved using biochar as a carrier of P-fertilizer, rather than the conventional direct soil application of TSP. Local okra variety 'Nyuigzovi' from the Volta region of Ghana was sowed at 0.6 m intercrop spacing and 0.5 m row spacing at 2 seeds per hill and thinned out to one crop per hill after germination.

All plots received equal amount of P, N and K fertilizers applied at three different growth stages. The P was applied at 60 kg ha^{-1} at pre-planting. Nitrogen fertilizer (N) obtained from Urea was applied two weeks after germination and at flowering stage at a rate of 50 kg ha^{-1}. Finally, K obtained from Muriate of potash was applied at 60 kg ha^{-1} at post-flowering to boost fruit yield.

2.5 Soil water content and irrigation scheduling

The soil moisture content was determined in each plot by using time domain reflectometry (TDR), model; TDR-100 (Campbell Scientific, Inc., Logan, UT, USA). The TDR instrument was connected to stainless steel probes of 0.06 m diameter installed to a depth of 0.80 m in each plot. Prior to irrigation scheduling, the FC of each plot was measured to constant values, two days after the soil was saturated by rainfall. All plots received equal amount of irrigation water during the first ten days after sowing, after which irrigation treatments were imposed. Full irrigation was initiated to fill back the soil to FC whenever the test crop, okra depleted 30% of the total available water (TAW). For deficit irrigation, it was allowed to deplete 70% of TAW in the soil. Total available water content in the root zone, TAW (mm) was estimated using equation 1 (Allen et al., 1998):

$$\mathrm{TAW} = 1000 \times (\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}}) \times Z_{\mathrm{r}} \quad (1)$$

where θ_{FC} is soil water content at field capacity (m^3 m^{-3}), θ_{WP} is soil water content at wilting point (m^3 m^{-3}), Z_r is rooting depth of the crop (m) given as 0.8 m, i.e. length of TDR probe.

2.6 Crop coefficient and water requirement

Leaf area (A_l, m^2) was determined with ImageJ software (Schneider, Rasband, & Eliceiri, 2012) using digital images of destructive samples of okra leaves. To use ImageJ software for leaf area estimation, freshly sampled okra leaves were spread on a white surface background and a digital photograph taken. An image of a reference object whose area was predetermined was loaded to the software for calibration. The photograph of okra leaves was then loaded to the ImageJ software to calculate the total leaves area in the uploaded image. Leaf area index (LAI), defined as the ratio of leaf area to the area of ground covered by the leaf, was consequently computed. The computed LAI was then used to estimate K_c using Ritchie and Burnett (1971) model (equation 2). A graph, K_c curve was produced to delineate okra growth stages and water use.

$$K_c = -0.21 + 0.70\,\mathrm{LAI}^{\frac{1}{2}}, \quad 0.1 \le \mathrm{LAI} \le 2.7 \quad (2)$$

where LAI was determined from leaf area estimated with ImageJ software.

The FAO Penmann-Monteith equation (Allen et al., 1998) was used to compute daily ET_o using climate data from an automatic weather station (Campbell Scientific, Inc., Logan, UT, USA) located 300 m away from the crop field. Okra water requirement, ET_c (mm day^{-1}) was estimated from Allen et al. (1998) as:

$$\mathrm{ET_c} = \mathrm{K_c} \times \mathrm{ET_o} \quad (3)$$

where K_c was inferred from equation 2, ET_o (mm day^{-1}).

2.7 Remote sensing of crop coefficient

Okra canopy spectral reflectance was measured weekly using a handheld remote sensing device, RapidSCAN CS-45 (Holland Scientific, Inc., Lincoln, NE, USA). The radiometer, RapidSCAN CS-45 has an inbuilt function for computing NDVI from canopy spectral reflectance measurements. A graph of NDVI against K_c were plotted to produce K_c–NDVI relationship for predicting crop coefficient using remotely sensed NDVI data.

2.8 Biomass and fruit yield

At 50 days after sowing, okra fresh fruits at the center of each plot was harvested to avoid border effects. The harvest was done every two days for six weeks. The fruits were weighed immediately after harvest to determine fresh fruit yield as Y_{FF} (kg m^{-2}). Every two weeks from 20 days after sowing, destructive crop sampling was done by uprooting six okra plants and separating into roots and shoot (stem, leaves). The shoot was oven dried at 80°C to constant weight to determine Y_{TBM} (kg m^{-2}). Data for five destructive samplings was obtained in each growing season.

2.9 Water productivity

Okra yield (kg m^{-2}) and the amount of water used (ET_c, m) were used to compute water productivity (WP, kg m^{-3}) of Y_{TBM} and Y_{FF} using equation 4 and equation 5.

$$WP_{TBM} = \frac{Y_{TBM}}{\sum ET_c} \quad (4)$$

$$WP_{FF} = \frac{Y_{FF}}{\sum ET_c} \quad (5)$$

where Σ ET_c is sum amount of water used by okra in ET_c (m).

2.10 Phosphorus uptake in okra shoot

The oven dried okra shoot, after used for Y_{TBM} estimation was milled and used in P uptake analysis. Concentration of P in the shoot was analyzed under all biochar treatments. The concentration of P in the shoot was determined using the methodology described in Bornø, Müller-Stöver, and Liu (2019). Thus, 5 ml of concentrated Sulphuric acid (H_2SO_4) was added to 0.1 g of the milled okra shoot and stored for overnight. Digestion was carried out in a fume hold digestion hot plate using drops of 15% hydrogen peroxide (H_2O_2) until a colorless solution was obtained. Digested sample was allowed to cool and topped up with distilled water to 100 ml. A drop of p-nitrophenol ($C_6H_5NO_3$) was added to 1 ml of the digest followed by drops of ammonia solution for color development. Total P content of the plant sample was then analysed using a spectrophotometer (Spectroquant Pharo 300, Thomas Scientific, New Jersey, USA). Okra P uptake (kg P ha^{-1}) was calculated as the product of %P and Y_{TBM}.

3 RESULTS

3.1 Impact of biochar and irrigation on okra yield and water productivity

Biochar effect on Y_{TBM} and Y_{FF} under FI and DI are presented in Table 3. For the three growing seasons (S_1, S_2, and S_3), okra yield under any given treatment (irrigation or biochar) increased in the order $S_3 > S_1 > S_2$. Apart from Y_{FF} under DI, biochar and irrigation had no significant positive impact on Y_{TBM} in the first growing season. Unlike DI, the FI also did not have any significant impact on Y_{FF} under biochar treatments in the first growing season.

During the first growing season, okra Y_{FF} significantly increased by 67 and 82% with 10 Mg ha^{-1} and 10 Mg $ha^{-1}_{(P)}$ biochar under DI compared to the control. The 5 Mg ha^{-1} biochar had no significant effect on yield compared to the no biochar treatment, 0 Mg ha^{-1} (control). This means, higher application rates of rice straw biochar from 10 Mg ha^{-1} are needed before any noticeable effect on okra yield. The positive response of the biochar at early stage of application was skewed towards Y_{FF} only under DI. Highest Y_{TBM} and Y_{FF} under both irrigation regimes were recorded in season three when biochar application rate increased by 200%. At the highest biochar rate in the third growing season, Y_{TBM} was higher under DI (12.5 Mg $ha^{-1}_{(P)}$) compared to FI (10.57 Mg $ha^{-1}_{(P)}$). The significant increase in yield was dominant in Y_{FF} and under all biochar treatments with DI throughout the three years of experiments.

Although FI consistently recorded higher Y_{FF} compared to DI at some instances in all three growing seasons, it did not record corresponding higher values of WP_{FF} in that order (Table 4). In terms of Y_{TBM}, FI only recorded higher values over DI by 14 and 9% in growing seasons one and two. In the second growing season, DI recorded higher WP_{TBM} and WP_{FF} than FI even though it had comparatively lower Y_{TBM} and Y_{FF}. Water used by the crop was higher under FI than DI in all three growing seasons but it was obvious that FI did not influence higher WP at all instances.

3.2 Crop coefficient -- normalized difference vegetation index relationship

Figure 1 shows a graph with a model equation for predicting K_c of okra using remotely sensed NDVI data. Daily K_c values were interpolated from derived weekly K_c data. The graph had a coefficient of correlation (R^2) of 0.97 indicating a strong correlation between K_c and NDVI. The linear relation deduced from Figure 1 was used in subsequent experiments to estimate K_c from remotely sensed NDVI data.

Similarly, there was a strong correlation between Y_{TBM} and NDVI. The graph of Y_{TBM} against NDVI (Figure 2) produced a prediction model for Y_{TBM} estimation using NDVI data.

3.3 Length of growth stages and water requirement

Okra growth stages considered were the Initial, Developmental, Mid-season and Late season growth stages. Variation of K_c for the four growth stages over the growing seasons are shown in the K_c curves for FI and DI treatments (Figure 3a, b). Length of each growth stage and its corresponding K_c value deduced from the K_c curves are presented in Tables 5 and 6.

Okra water use varied with the crop's growth stages throughout the growing seasons. Considering the four growth stages, the value of okra water use varied in both FI and DI characterized by different K_c values (Tables 5 and 6). Water used by okra in each growth stage was highly influenced by K_c.

3.4 Biochar and irrigation impact on okra P uptake

The concentration of phosphorus in okra tissue under biochar treatments increased from 0.35 to 0.37% in FI and P uptake ranged from 23.40 to 27.03 kg P ha^{-1}. On the other hand, the same biochar treatments under DI in the growing season one recorded 0.35 to 0.36% for P concentration with P uptake at 19.97 to 22.30 kg P ha^{-1}. The minimum P concentration (0.35%) was obtained in the 5 and 10 Mg ha^{-1} biochar treatments while the maximum P concentration (0.37%) was obtained under 10 Mg $ha^{-1}{}_{(P)}$ biochar in FI treatment. With regard to biochar influence on P concentration under DI, the minimum P concentration (0.35%) was obtained under 10 Mg ha^{-1} biochar treatment while the maximum P concentration (0.36%) was obtained under both 0, 5, and 10 Mg $ha^{-1}{}_{(P)}$ biochar treatments.

The highest P uptake in okra shoot (27.03 kg P ha^{-1}) under FI was recorded in the no biochar treatment (control). On the other hand, the highest P uptake under of DI was 22.30 kg P ha^{-1}, and it was obtained under 5 and 10 Mg ha^{-1} biochar treatments. Among all biochar treatments under FI and DI in the first growing season, there were no significant differences ($p < .05$) in P concentration and P uptake in okra biomass. Full irrigation, although insignificant, positively influenced P uptake in okra shoot compared to deficit irrigation under each of the biochar treatments (Figure 4).

4 DISCUSSION

4.1 Crop yield as influenced by biochar and irrigation

Crop yield is vital in any agricultural crop management strategy. Soil amendment materials have been shown to improve crop yield by improving on soil water holding capacity, nutrient retention and soil physicochemical properties (Asai et al., 2009; Hariz et al., 2015).

Unlike the second and third growing season, the first growing season recorded no significant difference in Y_{TBM} under all biochar treatments in either irrigation regimes. This was due to the fact that biochar had limited effect on increasing Y_{TBM} in the first growing season or early stage of its application. Major, Rondon, Molina, Riha, and Lehmann (2010) observed a similar situation whereby maize grain yield did not significantly increase in the first year of biochar application, but increased in the subsequent years.

With respect to irrigation effect on yield, there were higher values of Y_{TBM} recorded under all biochar treatments with FI than DI except in the last experiment where DI produced higher Y_{TBM}. Irrigation regime had effect on okra water use and yield when biochar rate was taken into consideration. Higher biochar rates produced a corresponding higher okra yield.

The trend in Y_{TBM} obtained indicated that okra yield was influenced by the quantity of biochar applied. This corresponded to the biochar's ability in conserving soil water and nutrient.

Again biochar effect on okra Y_{FF} under DI throughout the study was also in the order of increase in biochar rate directly corresponded to increase in Y_{FF}. Thus, treatment with the highest biochar rate e.g. 10 Mg $ha^{-1}{}_{(P)}$ recorded the highest yield in the first growing season and similar for the 20 Mg $ha^{-1}{}_{(P)}$ and 30 Mg $ha^{-1}{}_{(P)}$ in growing seasons two and three. This has also been observed by Ason, Ababio, Boateng, and Yangyuoru (2015) and Eldardiry and Abd El-Hady (2015) where a soil conditioner application rate was directly proportional to water retention, yield and water productivity.

The highest Y_{FF} recorded in the P-fortified biochar treatments was as a result of the biochar ability to retain and slowly release the attached phosphorus for okra assimilation. This agreed with findings of Alburquerque et al. (2013) and Lehmann et al. (2011) who also reported that biochar combined with mineral fertilizer has a significant effect on plant yield compared to the traditional method of sole application of mineral fertilizer and biochar. Throughout the growing seasons, the P fortified biochar constantly registered the highest okra yield. But in most instances, there was no significant increase in yield between the P fortified biochar and its equivalent unfortified biochar amended plots that had the same amount of P. The only exception was in the third growing season when 30 Mg $ha^{-1}{}_{(P)}$ biochar significantly produced higher Y_{TBM} under DI over the equivalent 30 Mg ha^{-1} biochar that also contained P but not fortified with the biochar.

The weathered nature of the tropical forest soil in the study area has led to the reactive nature of P to form insoluble Fe, Al and Ca phosphates, thus limiting P availability for plant assimilation (Eduah et al., 2019). The presence of biochar can decrease P adsorption on Fe-oxides and enhance P availability in soils (Cui et al., 2011). Alling et al. (2014) concluded that biochar does not only have the potential to retain available nutrients but releases the essential plant nutrients as well as alleviate Aluminium (Al) toxicity in the soil.

4.2 Crop coefficient and growth length

At basal crop canopy growth stage, soil evaporation coefficient, K_e in our study was negligible due to infrequent irrigation leaving the soil surface dry most of the time during the dry season. Hence basal crop coefficient, K_{cb} was equal to K_c following the guidelines of FAO 56 (Allen et al., 1998) in computing CWR.

Remote sensing in agricultural production is the state of the art technology in measuring crop phenology. It was suitable in predicting K_c for ET_c estimation. Similar linear relationships between K_c and NDVI have been modelled in literature including Kamble, Kilic, and Hubbard (2013). Length of the growth stages of okra was deduced from the K_c curves (Figure 3) which aided in estimating okra seasonal water use. Estimated K_c from our study was validated with related works of Kisekka, Migliaccio, Dukes, Crane, and Schaffer (2010), Panigrahi and Sahu (2013), and Oppong Danso (2014). Our mean seasonal K_c for the four growth stages were 0.23, 0.61, 0.96, and 0.9 for $K_{c\ ini.}$, $K_{c\ dev.}$, $K_{c\ mid.}$, and $K_{c\ late.}$. Panigrahi and Sahu (2013) in India recorded similar but slightly higher K_c for okra growth stages in that order, i.e. 0.38, 0.74, 0.98, and 0.49 for maturity stage. Oppong Danso (2014) on the other hand recorded 0.48, 0.86, and 0.98 for $K_{c\ ini.}$, $K_{c\ mid.}$, and $K_{c\ late}$ in Ghana. Kisekka et al. (2010) in the United States of America also reported $K_{c\ ini.}$ of 0.2 to 0.4 for high population density to low population density, 1.0 for $K_{c\ mid.}$ and 0.9 for $K_{c\ late}$. These K_c values from literature were a bit higher than values recorded in our study except that of Kisekka et al. (2010) whose $K_{c\ ini.}$ was in the same range as ours. Kisekka et al. (2010) had equal value of $K_{c\ late}$ (0.9) to that recorded in our study. Although we recorded different but closely related K_c values to that reported in literature, we attributed the slight variations to differences in okra variety and climate of the study area.

4.3 Okra water requirement

Accumulated seasonal water used by okra were 273 and 247 mm under FI and DI treatments in the first growing season. It was 182 and 157 mm in the second growing season, and finally 215 and 175 mm in the third growing season for FI and DI respectively. Under standard weather conditions with high atmospheric demand on evaporation, crop evapotranspiration could be high and therefore require substantial amount of water to compensate the losses. High ET_c may not necessarily reflect in high crop yield in that regard. Okra water use was generally higher under FI but did not produce a correspondent higher yield in favor of FI in some cases. For instance, Y_{FF} and Y_{TBM} under DI were higher than the yield obtained under FI in the second and third experiments. This was as a result of the high hydraulic conductivity in partial wetted soils depicting soils under DI in our study. This scenario was also observed by Panigrahi and Sahu (2013). The result therefore proved suitability of DI over FI under drought conditions when the soil was amended with rice straw biochar.

4.4 Water productivity and p uptake as influenced by biochar and irrigation

Biochar rate positively influenced WP throughout the growing seasons (Table 4). Percentage increase in WP was pronounced under DI as biochar rate increased. For instance, when biochar rate was doubled in the second experiment, there was an increase in WP_{FF} of 25 and 11% under DI and FI respectively. Again in the third growing season, there was an increase in WP_{FF} of 38 and 32% under DI and FI when biochar rate was increased by 200%.

On the other hand, WP_{TBM} was increased by 27 and 20% under DI and FI when biochar rate was increased by 100% in the second growing season. With 200% increase in biochar rate, DI recorded 54% increase in WP_{TBM} against FI (36%). It was so clear that DI had desired impact on WP under biochar amendment.

The P concentration in okra ranged from 0.35 to 0.37%. Thus, the values recorded in our study agreed with acceptable range (0.05 to 1.0%) reported by Peters and Laboski (2011). The rice straw biochar improved soil pH, aeration and microbial activities in the soil. Some of these microorganisms in the rhizosphere improved P solubility which in turn enhanced P recovery in the soil (Mikkelsen, 2013). In the first growing season, the P fortified biochar, 10 Mg $ha^{-1}{}_{(P)}$ recorded the highest P concentration under FI but did not produce a corresponding higher P uptake. This was because Y_{TBM} was higher under the no biochar treatment (0 Mg ha^{-1}) and thus, P uptake was influenced by Y_{TBM}. With respect to P concentration under DI in the same growing season, the 10 Mg $ha^{-1}{}_{(P)}$ again recorded the highest P concentration but did not produce the highest P uptake in okra shoot. The highest P uptake (22.30 kg P ha^{-1}), even though not significant was rather recorded under the 5 and 10 Mg ha^{-1} biochar respectively. This clearly indicates that, P fortified biochar, despite its positive influence on P concentration in okra shoot, does not have any significant impact on P uptake during the first growing season. Full irrigation is desired to improve P uptake under the given biochar treatments. The biochar in its first season of application did not activate any significant interaction between P and the soil for okra P uptake. We attribute the slight increase in P concentration to the biochar's property of changing the plant's physical and chemical environment (Baxter, 2009). We limited P uptake analysis to the first growing season where P was applied at 60 kg ha^{-1}, delineating the normal P application rate in the study area.

5 CONCLUSIONS

Rice straw biochar amended in the sandy clay loam soil positively improved okra yield regardless of irrigation regime. Okra yield was higher when P was mixed with biochar instead of giving the two in separate applications. The amended biochar also increased pH of the acidic soil, thereby enhanced P concentration but did not significantly increase P uptake in okra shoot. Rice straw biochar is a suitable carrier of P fertilizer and a minimum application rate of 10 Mg ha^{-1} is recommended to increase okra yield in highly weathered tropical Acrisols. Deficit irrigation under biochar amendment is suitable and recommended under drought conditions. The regression models developed from the study can be used to forecast okra yield and predict K_c in areas with similar climate conditions using remotely sensed NDVI data.

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FIGURE 1 Relationship between crop coefficient and NDVI

FIGURE 2 Relationship between total aboveground biomass yield and NDVI

FIGURE 3 Crop coefficient curve of okra under (a) full irrigation and (b) deficit irrigation. K_c1, K_c2 and K_c3 denotes crop coefficients curves for growing seasons 1, 2, and 3 respectively. Error bars represent standard error of the mean

FIGURE 4 Effect of irrigation and biochar on phosphorus uptake. Error bars represent standard error of the mean

TABLE 1 Physical and chemical properties of experimental soil (0–20 cm)

Sand	Silt	Clay	SOC	TN	P	K	pH(H_2O)	EC	ρ_b
	------ % ------				----- mg 100 g^{-1} -----			mS cm^{-1}	g cm^{-3}
68	11	21	1.33	0.12	< 0.4	14.80	5.5	0.36	1.52

SOC, soil organic carbon; TN, total nitrogen; EC, electrical conductivity; ρ_b, dry bulk density.

Commented [MJ3]: Units for SOC and TN in Table 1?

TABLE 2 Rice straw biochar characteristics

DM	OM	TC	TN	pH	P	K	Ca	Mg	Fe	Na	ΣPAHs
	---- % ----						------- mg kg^{-1} -------				
91.8	34.9	25.4	1.0	10.3	1420	17700	3020	1330	2030	1250	6.0

DM, dry matter; OM, organic matter; TC, total carbon; TN, total nitrogen; PAH, poly-aromatic hydrocarbons (calculated as the mathematical sum of 19 PAHs). Source: Arthur et al. (2019).

TABLE 3 Effect of biochar and irrigation on total aboveground biomass yield (Y_{TBM}) and fresh fruit yield (Y_{FF}) of okra under full irrigation (FI) and deficit irrigation (DI)

Growing season	Biochar	Y_{TBM-FI}	Y_{TBM-DI}	Y_{FF-FI}	Y_{FF-DI}
		------------- Mg ha^{-1} -----------------			
1st	0	7.46	5.59	6.47	3.61 b
	5	6.61	6.38	5.36	4.45 ab
	10	6.96	6.42	6.50	6.03 a
	$10_{(P)}$	7.23	5.95	6.99	6.57 a
	LSD $_{.05}$	2.59	2.29	2.53	2.31
2nd	0	4.86 b	4.18 c	3.58 b	2.45 c
	10	4.85 b	4.97 bc	4.22 b	4.15 b
	20	7.00 a	5.96 ab	4.59 ab	4.94 ab
	$20_{(P)}$	7.21 a	6.34 a	6.58 a	6.16 a
	LSD $_{.05}$	1.16	1.25	2.34	1.64

3rd	0	7.10 b	6.88 c	4.71 c	3.48 c
	15	7.22 b	7.73 c	6.34 bc	5.19 b
	30	10.17 a	10.92 b	8.33 ab	6.89 a
	$30_{(P)}$	10.57 a	12.50 a	10.05 a	8.01 a
	$LSD_{.05}$	**1.70**	**1.55**	**2.56**	**1.60**

Mean values within columns not sharing a common letter are significantly different at $p \leq .05$ according to the least significant difference (LSD) test ($n = 4$). Y_{TBM-FI}, total aboveground biomass yield under full irrigation; Y_{TBM-DI}, total aboveground biomass yield under deficit irrigation; Y_{FF-FI}, fresh fruit yield under full irrigation; Y_{FF-DI}, fresh fruit yield under deficit irrigation.

TABLE 4 Yield and water productivity of okra under full and deficit irrigation treatments

Commented [MJ4]: Please revise Table 4 title to describe/define column headers. Thanks. It is not clear how the FI and DI data are shown in the table.

Growing season	Irrigation	Y_{TBM}	Y_{FF}	ΣET_c	WP_{TBM}	WP_{FF}
		--- kg m^{-2} ---		m	----- kg m^{-3} -----	
1st	FI	0.83	0.63	0.27	3.07	2.33
	DI	0.73	0.52	0.25	2.92	2.08
2nd	FI	0.70	0.47	0.18	3.88	2.61
	DI	0.64	0.44	0.16	4.00	2.75
3rd	FI	1.03	0.74	0.22	4.68	3.36
	DI	1.12	0.59	0.18	6.22	3.28

Values are mean values from okra destructive samples under biochar and irrigation treatments. Y_{TBM}, total aboveground biomass yield; Y_{FF}, fresh fruit yield

TABLE 5 Growth length, crop coefficient (K_c) and okra water use (ET_c) under full irrigation (FI)

Commented [MJ5]: Table 5 caption does not quite describe table content as written. Should this say "..., reference water use (ETo), and okra water use (ETc) under full irrigation"?

Growth Stage	Duration			K_c			ET_o			ET_c		
	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
	---- d -----						----- mm day^{-1} -----					
Initial	20	20	20	0.28	0.21	0.21	5.25	4.24	5.04	29.4	17.81	21.17
Dev.	25	10	15	0.67	0.55	0.62	6.10	3.51	4.42	102.2	19.31	41.11
Mid.	20	25	25	0.91	0.94	1.02	5.71	3.46	3.94	103.9	81.31	100.5
Late	10	20	15	0.86	0.93	0.92	4.38	3.46	3.82	37.67	64.36	52.72

S_1, S_2, S_3 are first, second, and third growing seasons; Mid. is mid-season and Dev. is developmental.

TABLE 6 Growth length, crop coefficient (K_c) and water use (ET_c) under deficit irrigation (DI)

Commented [MJ6]: Same comment as Table 5

Growth Stage	Duration			K_c			ET_o			ET_c		
	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
	---- d -----						----- mm day^{-1} -----					
Initial	20	20	20	0.16	0.21	0.16	5.25	4.24	5.04	16.80	17.81	16.13
Dev.	20	15	20	0.54	0.41	0.43	6.10	3.47	4.30	65.88	21.34	36.98
Mid.	20	20	20	0.98	0.88	0.91	5.71	3.48	3.93	111.9	61.25	71.53
Late	15	20	15	0.80	0.83	0.88	4.38	3.46	3.82	52.56	57.44	50.42

S_1, S_2, S_3 are first, second, and third growing seasons; Mid., mid-season; Dev., developmental.