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Evaluating Impacts of Biochar and Inorganic Fertilizer Applications on Soil Quality and Maize Yield Using Principal Component Analysis

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Abstract: A 2-year field experiment was conducted to test the effects of individual and co-application of biochar and inorganic fertilizer on soil quality using the principal component analysis (PCA) technique. The dry season field experiments were performed with biochar applied at 0 and 20 t ha^{-1}, and fertilizer at 300 and 0 kg ha^{-1} (control). The factorial combinations of the above-mentioned treatments were subjected to irrigation at 60, 80, and 100% of irrigation amounts (IAs). Soil hydro-physical and chemical properties and grain yield were determined at harvest. Results from the PCA indicated that the soil total nitrogen (N) and moisture content (MC) were the soil properties mostly affecting the grain yield. The amendments' effects on the soil physico-chemical properties and maize yield were in the order control < biochar < fertilizer < biochar + fertilizer. The derived comprehensive soil quality index (CSQI) from the PCA showed that the soil quality increased by 76, 100, and 200% in treatments individually applied with biochar, inorganic fertilizer, and the co-applications. This study therefore showed that the PCA revealed the actual dynamics in soil properties, in terms of the SQI upon the soil amendment addition, as well as their relationship with maize yield under different weather conditions.

Keywords: soil amendments; maize productivity; principal component analysis; soil quality; soil properties

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1. Introduction

Degraded soil is a major challenge generally affecting crop yield. As crops are cultivated in farmland, agricultural activities such as tillage disturb the natural soil systems, thereby resulting in erosion and compaction, as well as degradation [1]. The exposure of soils to erosion due to agricultural activities may cause decline in nutrients and organic matter, consequently resulting in reduction in agricultural production [2]. This is possible since nutrient cycling, release, and uptake in soils are negatively affected due to disturbance of soils. Therefore, the sustainable improvement of soil quality with the use of a widely proven effective soil amendment like biochar is required [3].

Biochar is a charcoal-like material commonly produced through the process of pyrolysis (absence of oxygen) from biomass. It is often used as a soil amendment, which has provided multiple benefits to the environment in several dimensions, in that it enhances the fertility of the soil by improving the soil Cation Exchange Capacity (CEC) [4–6], altering the base saturation, increasing soil pH [7], and preventing the leaching of soil nutrients in soils. The above functions of biochar when amended with soils often result in an improved yield of crops, while the prevention of the soil nutrients' leaching consequently leads to improvement in the efficiency of fertilizer applications in soils [8,9]. Also, biochar addition to soils has been well proven to enhance its capacity to hold or retain water [10,11], therefore resulting in an increase in water use efficiencies of crops [12–14] in water-limited conditions and under irrigation, when the evaporative demand is met and when crops are subjected to deficit irrigation. These challenges are exacerbated by climate change [15]. However, the use of biochar in agricultural practices offers a promising solution. By improving soil structure and resilience against extreme weather events, such as droughts and floods, biochar aids in adapting agricultural systems to climate change impacts [16–18].

However, despite multiple studies that have positively documented the positive effects of biochar addition on crop yield, there exist a few other studies that reported negative/no effect [19]. In the temperate region, for example, Karer et al. [20] reported the negative influence of biochar on the yield of some crops (wheat and maize) at a 72 t ha^{-1} application rate. This growth and yield response of crops to biochar addition is dependent on several factors like pyrolysis conditions of livestock waste and agricultural feed stock, climate, biochar type, and initial soil conditions. Also, large marginal increases in crop yields between unamended and biochar-amended soils were commonly reported by some researchers [21–23] due to low pH and nutrients of the initial soil condition, with the most positive effects observed in the tropics [24]. Another reason for the variation in the yield of crops upon biochar addition is the individual or combined applications of organic or inorganic fertilizer with biochar [23]. Also, recently, Luan [25] reported the improvement in the growth of Chinese cabbage due to the interaction between biochar and the soil microorganisms. Therefore, the increase in the crop yield has been largely attributed to the improvement in soil properties [5,8]. In most cases, there are several soil physico-chemical properties (data) commonly considered to evaluate the impacts of biochar and inorganic fertilizer on crop yield. This common approach of considering several soil properties could be time-consuming and expensive (when these soil properties are measured in a laboratory), hence the need to adopt a precise technique of identifying the key soil properties responsible for the improved yield of maize. In this context, a principal component analysis (PCA) has been majorly noted as one of the most scientifically and widely proven techniques for reducing a large number of variables by identifying those soil properties that are most significant among the soil data. In addition, variability of the physico-chemical properties of the soil can generally be quantitatively represented by the soil quality index (SQI). The SQI is defined as the soil ability to supply nutrients to plants, which are required to maintain the crop yield throughout the growth season [26]. The SQI includes physico-chemical and biological properties, which can be related to the fertility status and health status of the soil through a quantitative assessment [27].

Therefore, the aim of this study was to (i) quantitatively determine the impact of biochar and inorganic fertilizer on the soil quality using the PCA technique; and (ii) identify the key soil properties responsible for improved maize yield in soil amended with biochar and inorganic fertilizer.

2. Materials and Method

2.1. Description of the Study Area and Characterization of Biochar Used for the Experiment

Dry season experiments were carried out under drip irrigation with the maize crop planted on the experimental field between the months of February and May, 2017. The field experiment was similarly carried out in the second year of 2018 with the experiment lasting between November and February, both at the irrigation field of the Department of Agricultural Engineering, Federal University of Technology Akure. The latitude and longitude of the site were 7°16′ N and 5°13′ N, respectively. The mean air temperature and rainfall during the growing season are shown in Figure 1 below.

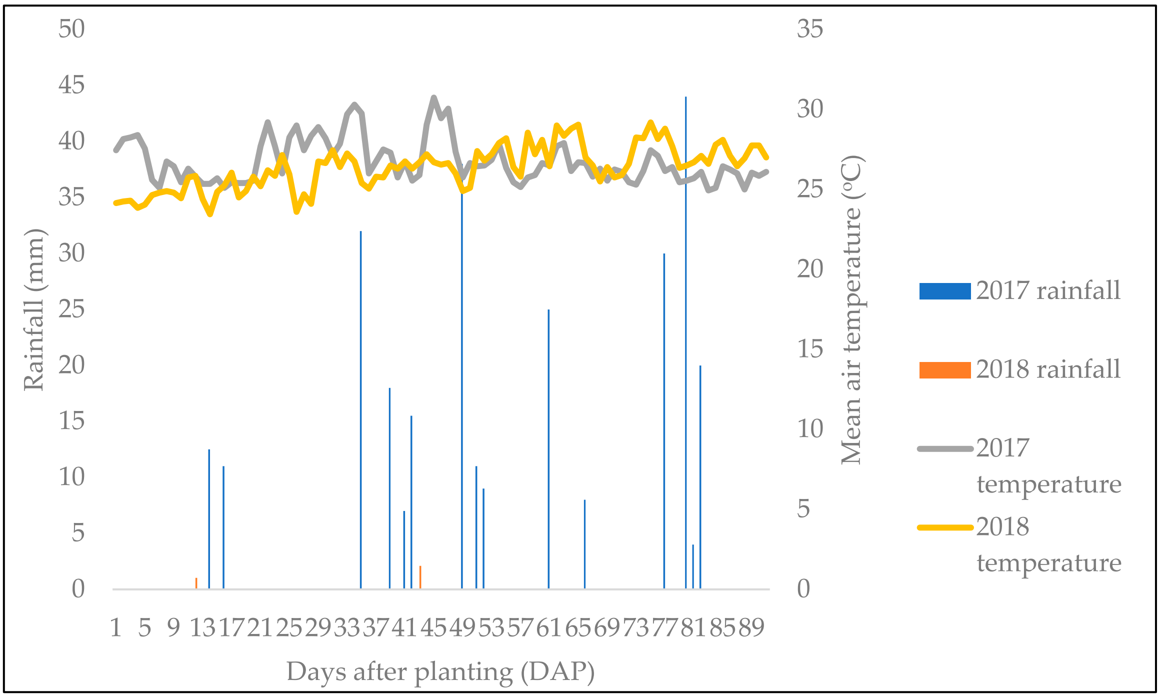

Figure 1. The rainfall and mean air distribution pattern during the growing seasons of 2017 and 2018 at the experimental site.

The total amounts of 304.3 and 3.13 mm of rainfall were recorded during the growing seasons of the year 2017 and 2018. The graphical illustration representing rainfall distribution during the growing season is shown in Figure 1. The soil at the experimental site is sandy clay loam with sand content ranging between 52 and 68.8%, and clay content ranged between 21 and 25.1% and the silt content ranged between 6.1 and 16% in a soil depth of 0–60 cm. Dry maize cobs were used for the production of biochar at a temperature of 500 °C using a fixed batch-type pyrolizer, as documented by Faloye et al. [28]. Also, the methods of biochar characterization were based on an international biochar initiative [29], and soil at the experimental site was randomly sampled for the physico-chemical properties' characterization before planting the maize crop. The soil properties of the experimental site before planting the maize crop are presented in Table S1 (Supplementary Data).

2.2. Field Experimentation

Experiments were consecutively and successfully carried out in an open field for a period of two years during the dry season. The conventional method of pulverizing the soil was adopted during tillage operation, which involves the initial opening of the soil (plowing), and thereafter, the soil was harrowed. Thirty-six seed beds were formed in 2017 and 2018 growing seasons, respectively. The size of each plot was 2.2 m wide and 2.5 m long in both growing seasons, leaving a space of 0.5 m between plots, thus making a total dimension of 31.9 m by 8.5 m. Before the establishment of the plots, a portion of 40 m by 40 m of the experimental plot was cleared. Biochar was thoroughly mixed with the soil and incorporated into the top 0.15 m of the soil before planting maize.

In both growing seasons, biochar was applied at 20 t ha^{-1}. Biochar (0 and 20 t ha^{-1}) and fertilizer at 0 and 300 kg ha^{-1} (N P K inorganic fertilizer with composition ratio of 15:15:15) were combined to form 3 fertilized treatments and a non-fertilized plot (unamended). The treatments formed from this combination include F0B0 (unamended), F300B20, F0B20, and F300B0, and were factorially combined with water application levels of 60, 80, and 100% of the irrigation amount (IA); this combination therefore results in a total of 12 treatments. Each of the treatments was replicated three times to give a total of 36 experimental plots. The experimental design for the three growing seasons was a full factorial design, with the treatment combinations described in Table 1. The unamended plot at the 100% IA served as the control, and irrigation scheduling from a drip irrigation system was carried out using installed tensiometers at the control plot. The drip emitter discharged water at a rate of 0.71 L/h, and the flow of water was regulated with a fixed control valve in each of the treatment plots. Irrigation was consistently applied when the tensiometer reading coincided with about 50% of field capacity (FC). Before planting maize, the moisture content at the field capacity of the soil (10 kPa) had already been determined. Therefore, during each irrigation, the remaining irrigation amount (IA) needed to bring the soil moisture to field capacity was consistently applied. Based on the irrigation scheduling, the total amount of water applied by irrigation in 2017 was 72.3, 96.5, and 120.6 mm, while it was 217.1, 289.44, and 361.8 mm at the 60, 80, and 100% AI for the 2018 growing season. The maize crop was used as a test crop in this study due to it nutritious and economic importance while the drip irrigation system was used to efficiently improve the water use efficiency [28]. During the growing seasons, soil unsaturated hydraulic conductivity (HC) was determined in each of the soil treatments for all the growing seasons using a mini-disk tension infiltrometer. The suction value used was 2 cm, which was in agreement with the value recommended by Zhang [30] in a sandy clay loam soil. In order to derive the HC, Equation (1), which describes the relationship between infiltration and time (s), was fitted according to Zhang [30].

$$I = c_1 t + c_2 t^{1/2} \tag{1}$$

I is infiltration, t is time (seconds), and C_1 is linked to the soil unsaturated hydraulic conductivity (m s^{-1}), while C_2 is the soil sorptivity (mm $s^{-1/2}$).

Table 1. Experimental treatments for both growing seasons (2017 and 2018).

S/N	Amendment Treatments	Definition
1	$F_0B_0IA_{100}$	Without fertilizer and without biochar at 100% irrigation amount
2	$F_0B_{20}IA_{100}$	Without fertilizer and with biochar at 100% irrigation amount
3	$F_{300}B_0IA_{100}$	With fertilizer and without biochar at 100% irrigation amount
4	$F_{300}B_{20}IA_{100}$	With fertilizer and biochar at 100% irrigation amount
5	$F_0B_0IA_{80}$	Without fertilizer and without biochar at 80% irrigation amount
6	$F_0B_{20}IA_{80}$	Without fertilizer and with biochar at 80% irrigation amount
7	$F_{300}B_0IA_{80}$	With fertilizer and without biochar at 80% irrigation amount
8	$F_{300}B_{20}IA_{80}$	With fertilizer and biochar at 80% irrigation amount
9	$F_0B_0IA_{60}$	Without fertilizer and without biochar at 60% irrigation amount
10	$F_0B_{20}IA_{60}$	Without fertilizer and with biochar at 60% irrigation amount
11	$F_{300}B_0IA_{60}$	With fertilizer and without biochar at 60% irrigation amount
12	$F_{300}B_{20}IA_{60}$	With fertilizer and biochar at 60% irrigation amount

Thereafter, the unsaturated hydraulic conductivity of the experimental site soil (HC) measured in mm h^{-1} was determined using Equation (2) below.

$$HC = \frac{C_1}{A} \tag{2}$$

where HC and C_1 have been previously defined and A is the Van Genuchten parameter, which depend on the soil textural type.

An improved variety of maize (*suwan-sr*) was planted, due to its high yield attribute, and the soil moisture contents were determined using the gravimetric method, with the soil samples oven-dried at 105 °C for 24 h. Thereafter, the soil moisture content in g g^{-1} was converted to the volumetric basis cm^3 cm^{-3} by multiplying with the bulk density of the respective soil depth. The soil properties were determined in each fertilized and non-fertilized plot in the 2017 and 2018 growing seasons. At harvest, all plants were harvested from each plot, and the grain yield was determined using a weighing balance.

Soil properties were determined using a standard procedure [31] in each plot of the treatment, fertilized and non-fertilized. The Kjeldahl method was applied in the laboratory to determine the content of the soil total nitrogen (N), while we used the Oslen et al. [32] method to determine the available phosphorus (P). This was achieved after the extraction of the solution of sodium bicarbonate. The saturation of exchange sites was carried out with ammonium (NH^{4+}) and the analysis of exchangeable cations; notably, potassium (k), sodium (Na), calcium (Ca), and magnesium (Mg) were used from leachates of the mixture. Thereafter, the amounts of base cations present in the soil were subsequently measured with the aid of atomic absorption spectrophotometry in a laboratory. Also, the Walkley–Black chromic acid titration method was utilized for the determination of soil organic carbon (SOC), which was later than the soil organic matter (OM) with the use of a multiplying factor of 1.72. Finally, the electrometric method was used to determine the pH of the soil in the laboratory.

2.3. Statistical Analysis

Statistical Analyses were carried out with MINITAB 17.0 and Statistical Package for the Social Sciences (SPSS) version 27 statistical packages. An analysis of variance (ANOVA) was performed on the maize yield and soil hydro-physical and chemical properties at a significance level of 0.05 by applying Tukey's test. A correlational analysis (Pearson correlation) was carried out on the soil properties. A Multivariate Analysis of Variance (MANOVA) was carried out to investigate the effects of irrigation, biochar, inorganic fertilizer, and year on the soil hydro-physical, chemical, and grain yield of maize using Wilks's lambda. Suitability of the soil properties for PCA was calculated by determining the Kaiser–Meyer–Olkin (KMO) and Barlett tests using SPSS version 27, while another analysis was carried out with MINITAB 17.0. PCA of all measured data sets of the physico-chemical and hydrological variables was also carried out using Varimax (orthogonal) rotation, which is similar to the approach of Elemile et al. [33]. In order to obtain well-interpretable PCs, the loading factors from the extracted PCAs were ranked. The PCA was based on the linear correlation between independent variables. The sum total of the loadings are squared values of each of the variables with a particular factor equivalent to the factor's eigenvalue, while the scree plot was utilized to determine the amount factors in numbers to be retained in the principal components (PCs). The relationship between the principal component (PC) and crop yield was carried out using multiple linear regression by applying the stepwise method. The multiple linear regression equation was based on the derived PC factors with eigenvalues greater than 1 [33]. A stepwise regression analysis was carried out to determine the soil properties that influence maize yield the most, due to biochar and fertilizer applications. All data were statistically processed using Minitab, version 17.0.

Estimation of Soil Quality from the PCA

Regarding the textural soil sandy clay loam soil of this study, Equation (3) was applied to assess the soil quality index (SQI) when biochar was applied alone and when co-applied with inorganic fertilizer [34].

$$\mathrm{SQI} = \sum_{i=1}^{N} W_i \times S_i \tag{3}$$

where W_i is representing the relative weight of each of the indicators with the values within 0 and 1, and the S_i represents the value of each soil indicator (hydro-physical and chemical properties). The W_i was expressed as the component score coefficient (CSC). The CSC was directly derived from the PCA results. Thereafter, the soil indicators were standardized using Equation (4) [34], which is due to the fact that they all have different scales and units.

$$\mathrm{Z} = \frac{x - {}^{-}x}{\sigma} \tag{4}$$

where z, x, $\bar{x}$, and σ all represent the standardized values for the soil hydro-physical and chemical indicators, the value of each soil indicator, the mean (average) value of each soil indicator, and the standard deviation of each of the soil indicators, respectively. The CSQI was determined using the output of the loadings, component coefficient score, eigen value, Z-score, and percentage variability of the eigen values from the PC using the mathematical expression in Equation (5) [34].

$$\text{CSQI} = \sum_{i=1}^{N} variability\ of\ each\ PC \times SQI \times Z \quad (5)$$

where CSQI is the comprehensive soil quality index (CSQI), PC and SQI are as previously defined, and Z is the Z-score. After that, the CSQI was converted into a standard normal distribution, characterized by a mean with a value of zero and a standard deviation value of one, using Minitab version 18.0. This transformation is to ensure that the values of the CSQI ranged between 0 and 1. According to Prisal et al. [35], the soil quality was evaluated by classifying the CSQI into the following categories: very good (0.8–1), good (0.6–0.79), fair (0.35–0.59), bad (0.20–0.34), and very bad (0–0.19).

3. Results and Discussion

3.1. Influence of Biochar and Fertilizer on the Soil Hydro-Physical and Chemical Properties and Maize Yield

Positive increases in the soil nutrients were noticed after biochar and fertilizer applications (Figure S1; Supplementary Data) in all the treatments. It is clear from Figure S1 that increasing the rate of biochar amendment results in enhanced soil nutrients, when the soil properties were measured at harvest. Irrespective of the varying weather condition in the 2017 and 2018 growing seasons, the soil nutrients all increased while the maize grain yield correspondingly increased (Figure 2). The increase in the maize grain yield was more with the individual compared to the unamended plot, while the highest values were all observed with the combined application of the biochar and inorganic fertilizer across the seasons in IA100, IA80, and IA60.

Table 2 revealed the effects of irrigation treatment, biochar, inorganic fertilizer, and seasonal variation between the years 2017 and 2018 on the soil hydro-physical and chemical properties and grain yield. The main effects of the seasonal variation (year), water applied by irrigation, and biochar and inorganic fertilizer applications were significant ($p < 0.05$) on the soil hydro-physical and chemical properties and grain yield of the maize crop. The significant ($p < 0.05$) effects of the independent variables observed based on the MANOVA result revealed that the soil properties and grain yield depend on the field input (biochar, inorganic fertilizer, irrigation, and years). Moreso, despite the varying weather conditions between the two years of field experiments, biochar significantly improved the grain yield of maize, which confirms biochar as a substantial soil amendment, which could be used to combat the adverse effects of climate change.

Table 2. Outputs of the MANOVA analysis as a function of seasonal variation (year), soil amendments, and water application irrigation between the years using the Wilks's lambda calculation method.

Effects	Value	F	Hypothesis df	Error df	Sig.
Irrigation	0.494	1.869	16	70	0.041
Biochar	0.004	991.068	8	35	0.001
Fertilizer	0.028	149.156	8	35	0.001
Year	0.043	98.231	8	35	0.001

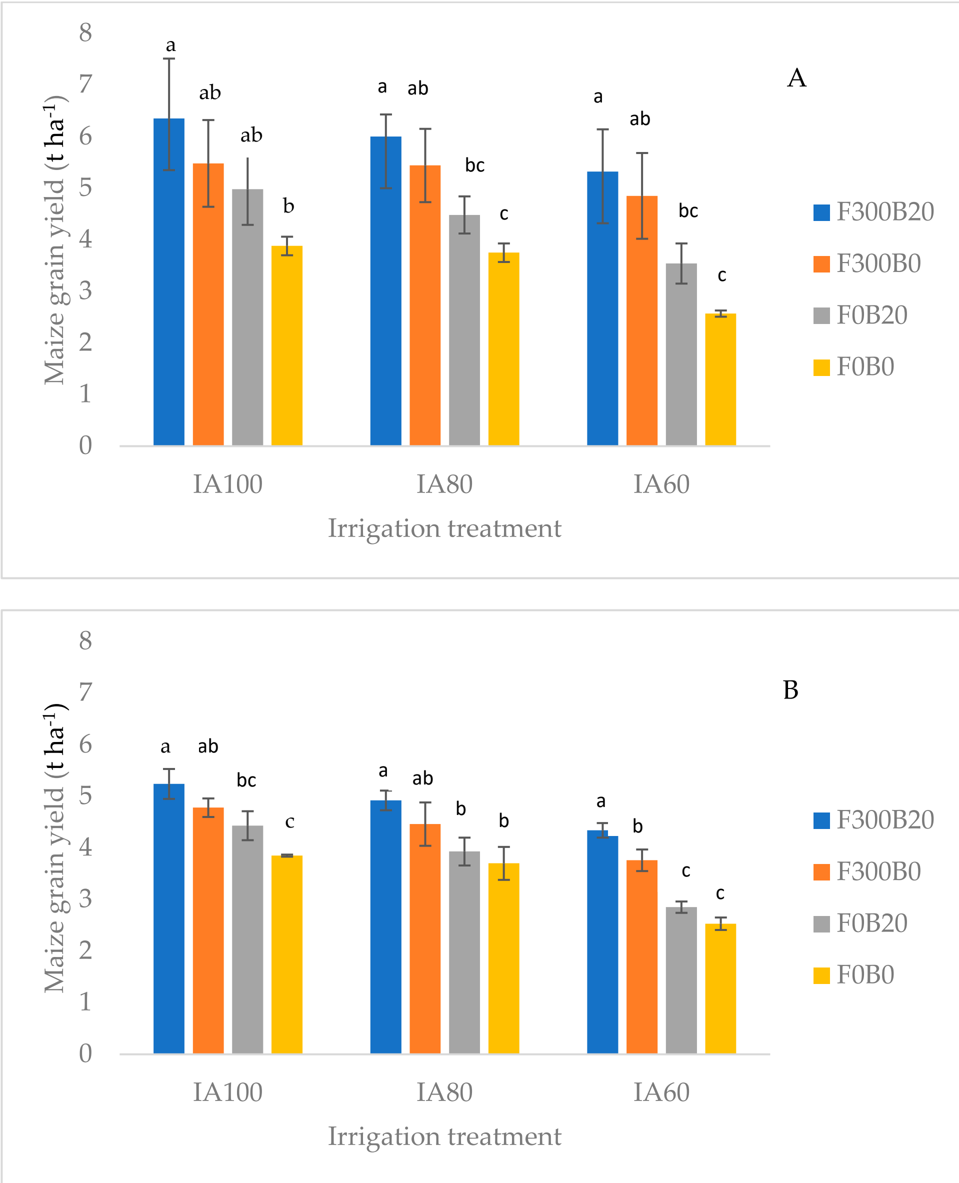

Figure 2. The influence of the individual and co-applications of the amendments on maize yield in the growing seasons of year 2017 (**A**) and year 2018 (**B**). Different letters indicate a significance level of 0.05.

3.2. Relationship between Soil Properties and Maize Yield as Influenced by Biochar Application

Table 3 describes the interrelationships between the hydrological and physico-chemical response of the soil and the soil amendments. The result of the analysis revealed that there was significant correlation between the soil OM and soil MC ($r = 0.93$; $p < 0.0001$). The soil hydraulic (hydraulic conductivity, HC) and hydro-physical (soil MC and OM) properties had significant ($p < 0.1$; $r > 0.5$) effects on the grain yield. Similarly, soil nutrients like nitrogen significantly ($p < 0.05$) correlate with maize yield. Also, the soil MC and OM both had positive effects on the grain yield, while the HC was negatively and well correlated with the grain yield.

The correlation matrix showed a significant positive ($r = 0.58$) relationship between pH and available phosphorous. Also, the relationship between the soil pH and other soil key nutrients like total nitrogen was significant at the 10% level of significance with a good correlation coefficient, r of 0.53. Also, the soil pH significantly correlates well ($r = 0.77$) with the soil organic matter ($p < 0.001$). The soil OM correlates well (r > 0.5) and significantly ($p < 0.05$) with soil key nutrients (N and P).

Table 3. Correlation between the soil properties and maize yield as affected by biochar and inorganic fertilizer applications (n = 8; data from F0B0, F300B0, F0B20, and F300B20 for the two seasons).

	pH	**OM**	**N**	**P**	**K**	**CEC**	**MC**	**HC**
OM	0.77 ****							
N	0.53 *	0.845 ****						
P	0.584 **	0.591 **	0.047 ns					
K	0.385 ns	0.569 *	−0.059 ns	−0.043 ns				
CEC	0.673 **	0.054 ns	−0.183 ns	0.078 ns	0.673 ***			
MC	0.089 ns	0.926 ****	0.503 *	−0.524 *	0.518 *	−0.817 ****		
HC	−0.094 ns	−0.802 **	−0.480 ns	−0.535 **	0.059 ns	−0.491 ns	−0.715 **	
Yield	0.664 **	0.51 **	0.558 ***	−309 ns	0.372 *	0.277 ns	0.562 *	−0.526 *

Note: *, **, ***, and **** represent significance at 0.1, 0.05, 0.001, and 0.0001, respectively; OM is the soil organic matter, N is the total nitrogen, P is the available phosphorus, K is the available potassium, CEC is the Cation Exchange Capacity, MC is the moisture content, HC is the hydraulic conductivity. ns is non-significant.

3.3. PCA for the Biochar and Inorganic Fertilizer Addition to Soil under Irrigation

The PCA as applied in this study holistically considered the hydro-physical and chemical properties of the soil, which are commonly taken into consideration in biochar soil–plant studies. These properties include OM, MC, HC, K, P, N, CEC, and pH. The suitability of the PCA tested with the application of the Kaiser–Meyer–Olkin (KMO) and Barlett tests produced a value of 0.55 and a significant value ($p < 0.0001$), respectively. The Eigen values obtained from the PCA, which are mostly greater than one, were retained for the analysis, and they were observed within the first four PCs (Table S2) in this study. The percentage variance above 70% is acceptable for a further analysis and investigation using PCA, and as such, the first four PCs explained 98.1% of the total variance in the soil properties' data sets. The factor loadings and variance are displayed in Tables S2 and S3, in order to select the variables that correlate with each PC.

3.4. Factor Loading for the PCA

The first rotated component (PC1) accounted for 37.2% of the total data variance, and showed a strong positive loading on OM, MC, and N while a negative loading was observed on the HC. The second rotated component (PC2) accounted for 24.1% and had strong positive loading with P and strong negative loading with HC, while the third rotated component (PC3) produced a strong positive loading on pH and OM (Table S3). The fourth PC (PC4) had a positive loading on K.

3.5. PCR for the Maize Yield Prediction in Soil Treated with Biochar with Inorganic Fertilizer under Irrigation

The coefficient of determination (r^2) between the first four PCs' data and the crop yield is 60%. The retention of PC1, PC2, PC3, and PC4 for the prediction of the maize yield when the stepwise regression equation was used showed that the soil hydro-physical properties (OM and MC) and N are the major factors that affect the maize yield in soil treated with biochar and inorganic fertilizer. However, the MC had higher loading than the OM, which showed that MC had the highest loading among the hydro-physical properties. The multivariate strategy used in this study is innovative, in that the soil properties (either hydro-physical or chemical) affecting maize yield under soil treated with biochar and inorganic fertilizer were revealed using PCA.

Statistical Importance of the PCR Result for the Maize Yield Prediction

The ANOVA results based on the stepwise regression analysis that was performed to predict the grain production of the maize crop are displayed in Table S4 below. The stepwise regression model's p-value is significant (<0.001), indicating that the model was effective and efficient in predicting the response (maize grain yield) and that the results are reliable. Furthermore, since there is only a 0.1% possibility that noise could account for an F-value this great, the model's F-value of 7.25 suggests that the model is significant. PC1, PC2, PC3, and PC4 are important model terms in this instance. The model terms are not significant if the value is bigger than 0.10. Also, the insignificance of the lack-of-fit F-value of 1.06 and *p*-value of 39.4% indicates an excellent model for the prediction of maize grain output. Most notably, the statistical fitting yields an R^2 value of 0.60, which is favorable for the fit of the regression model. Furthermore, the model's ability to effectively anticipate the response (grain yield) is demonstrated by the less than 0.2 difference between the adjusted R^2 (0.52) and the forecasted R^2 (0.60). The R^2 value of 0.6 obtained in the regression showed that 60% of the variability in the response (yield) can be explained by the components of PC1, PC2, PC3, and PC4.

3.6. Soil Quality as Improved by Biochar and Inorganic Fertilizer Applications

The soil quality index results for the biochar and inorganic fertilizer applications on the soil quality for the 2017 and 2018 growing seasons are presented in Table 4 below. The results showed that the soil quality increased as the biochar application rate increased. Based on the average, the soil quality index showed that for the two (2) years, the soil quality ranged from bad in the unamended treatment plot to good in the treatment plot where biochar and inorganic fertilizer were co-applied. The values of the CSQI were 0.25, 0.44, 0.50, and 0.75 in treatments F0B0, F0B20, F300B0, and F300B20, respectively. This result confirms the actual possibility of profitably storing carbon into the soil, to improve its sequestration and, therefore, mitigate climate changes. The result of the analysis showed that the highest percentage increase was observed under F300B20 with 200% over the unamended one (F0B0), while the 76 and 100% increases over the control were observed in treatments F0B20 and F300B0, respectively.

Table 4. Influence of biochar application on the comprehensive soil quality index.

Treatment	Year 2017	Year 2018 CSQI	CSQI Average Values	Percentage Increase (%)	Ranking
F0B0	0.096	0.40	0.25		bad
F0B20	0.49	0.39	0.44	76	fair
F300B0	0.57	0.43	0.50	100	fair
F300B20	0.94	0.56	0.75	200	good

The relationships between the soil quality index and maize yield at 60, 80, and 100% IA for the pooled data of year 2017 and 2018 are illustrated in Figure 3. The relationships between the CSQI and maize grain yield have been considered in each irrigation treatment for homogeneity purposes. The graph showed that there is a good relationship with the soil quality index, as improved by biochar and inorganic addition to the experimental soil. A positive effect was observed with the positive slope, as observed in Figure 3, with r^2 ranging between 0.60 and 0.83 for the relationship between the CSQI and the maize grain yield under the different water application regimes. This implies that about 60, 65, and 83% of the variation in the crop yield could be explained by the soil indicators, when aggregated together.

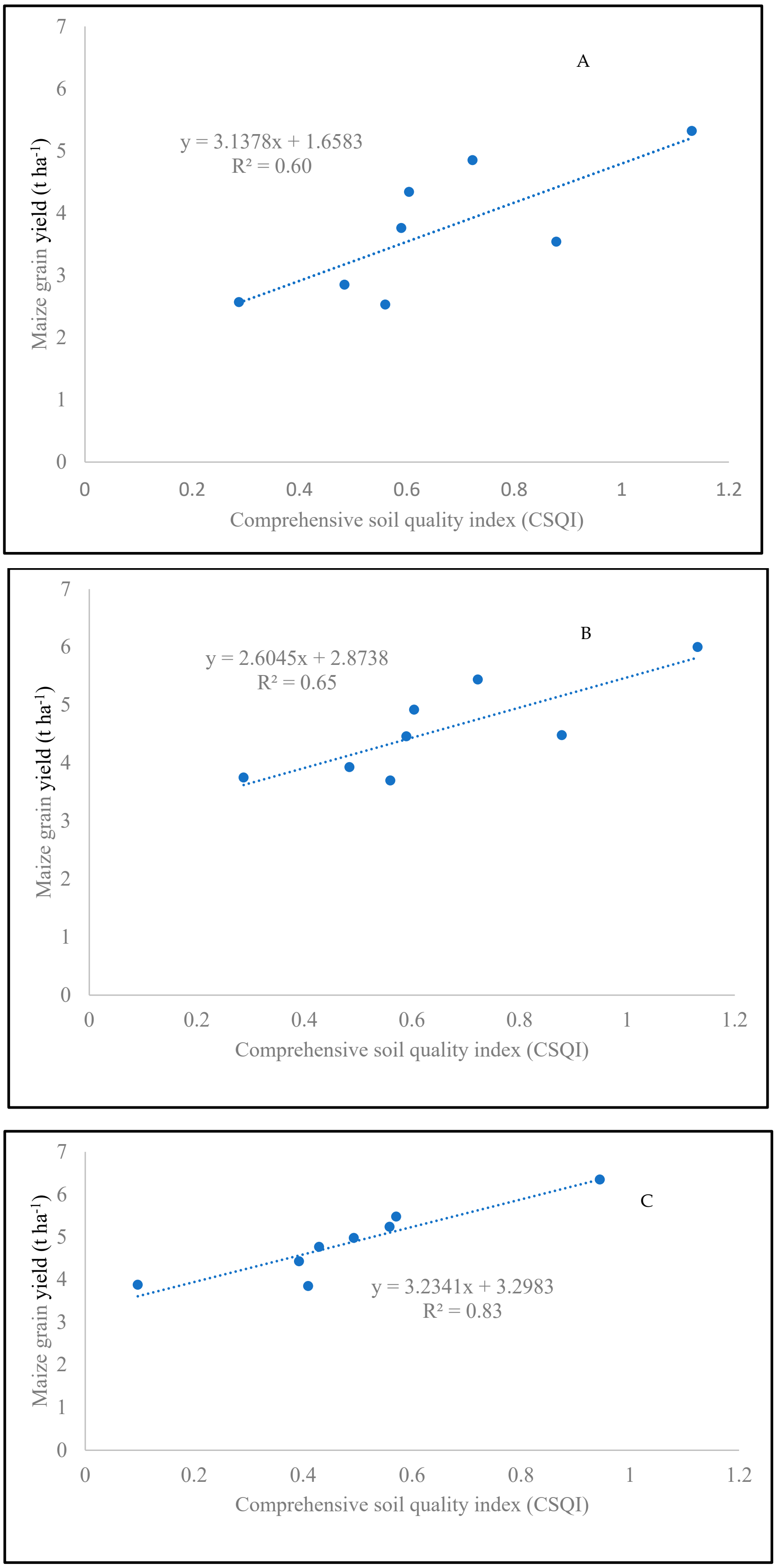

Figure 3. Relationship between comprehensive soil quality index and maize grain yield at 60% IA (**A**), 80% IA (**B**), and 100% IA (**C**).

4. Discussion

The increased maize grain yield obtained in this study is in agreement with the reports of other researchers [13,18,23], who also reported increased crop yields based on the addition of biochar to soils. The increased grain yield is attributable to an enhanced field-measured soil hydro-physical property (organic matter and moisture content) after the addition of biochar; meanwhile, the highest values were obtained with the combined application of both amendments (biochar and inorganic fertilizer). However, the soil hydraulic property (hydraulic conductivity) decreased with an increase in the application of biochar both in scenarios when only biochar was applied and when it was co-applied with inorganic fertilizer [19]. The above-mentioned trend response of the soil nutrients and hydro-physical response to the individual and co-application of biochar and inorganic fertilizer were similarly observed under the different water applications (60, 80, and 100% IA). The soil physico-chemical properties increase in the order of F0B0 < F0B20 < F300B0 < F300B20. This improvement necessitates the need to investigate the interrelationship between the soil properties as affected by biochar and inorganic fertilizer. The results showed a decrease in the soil hydraulic conductivity, while the moisture content and the physico-chemical properties of the soil increased upon biochar addition [36].

The significant and good correlation between the soil OM and the soil key nutrients infers that OM stabilizes the soil pH, which plays an important role in controlling the supply of nutrients and their availability for plant intake [37]. The level of soil OM accumulation has been reported to depend basically on soil management practices [37], which was influenced by the biochar addition to the soil. The high yield increase with biochar application in the field soil (sandy soil) reported in this study could be greatly attributed to enhanced organic matter storage. This could have led to improved soil aggregation and consequently an enhanced retention of nutrients and moisture [36]. The negative correlation between the soil OM and the HC showed that as the soil organic matter increases based on the amount of biochar added to the soil, the hydraulic conductivity decreases [36]. Similarly, the positive correlation between the soil MC and OM revealed the importance of adding biochar to soil, while the negative correlation between HC and grain yield showed that the reduction in the downward movement of the soil water resulted in an increased maize yield. Among all the soil chemical properties, the soil pH also correlated well and significantly ($p < 0.05$) with the maize grain yield. This influence can be attributed to the liming effect of the added biochar. The significant ($p < 0.05$) influence of soil nutrients like N on the grain yield emphasizes the importance of adding inorganic fertilizer with biochar to soils.

The PCA loading result revealed that a strong loading was produced on the N in PC1 (which explained the highest variance), therefore indicating the importance of nitrogen to maize yield [38]. The high loading on HC in PC2 showed that the soil intensity function like the HC is very important for water flow, nutrient cycling, and retention in the soil. Several other researchers [39,40] reported the high responsiveness of maize crop yield to nitrogen supply under deficit irrigation. The dependence of maize yield on soil nutrient supply, especially the soil nitrogen, as reported from the PCA in this study, is also in agreement with the reports of Lawlor et al. [41] and Peng et al. [38]. Moreso, using the PCA technique, it was revealed that the maize yield is also highly dependent on the soil moisture content. This outcome from this study revealed the importance of adding biochar to soils, in order to enhance the soil moisture content, and consequently increase the maize yield [36]

Comparing the PCR results obtained in this study with other previous studies, a better result was obtained due to the high value of r^2. Shukla et al. [42], for instance, employed the use of PCA and discovered that four PCs generated had a significant linear correlation with the grain yield ($r^2 = 0.19$, $p < 0.02$) and biomass yield ($r^2 = 0.36$, $p < 0.003$). In a similar vein, Mallarino et al. [43] discovered that yield variability significantly varied between corn fields, deriving factors based on the covariance matrix of indicators and with r^2 ranging between 0.01 ($p < 0.254$) and 0.67 ($p < 0.001$). The ranges of r^2 mentioned above were within the range reported in our study.

Using the PCA technique for the soil quality assessment in this study, synergistic effects of biochar and inorganic fertilizer on soil and consequently on growth and yield of crops were further established [44]. Innovatively, the soil quality index can be accurately determined using PCA, aligning with what is observed in the field. For example, when the CSQI of the unamended plot was compared with the biochar-amended soil, a higher value of CSQI was observed, which also follows the convention of the soil indicators as observed on the field in this study and in other similar studies [5,44]. Previous studies, which assessed the effects of biochar application on crop yield, only evaluated the performance of the amendments on the soil individual hydro-physical and chemical parameters [45,46] without aggregating the effects of the soil amendment on the crop yield, which has been the innovation in this study. The increase in the strength of r^2 in the relationship of the CSQI with the maize grain yield with an increase in water supply explains the importance of water to plants. This revealed that availability of water is important for the nutrient cycling and uptake in the soil and by the plant [47]. The values of the r^2 in the graphical illustration show that there is a good agreement between the CSQI and the maize yield, since the r^2 value is greater than 0.5. This relationship emphasizes the fact that the CSQI is a determinant for maize grain yield prediction. This is possible because the soil indicator used for the estimation of CSQI in PCA encompasses the physico-chemical and hydraulic properties, hence enabling the adequate assessment of the CSQI and consequently resulting in the efficient prediction of the maize grain yield. The improved retention of soil moisture content and reduced unsaturated hydraulic conductivity as observed in this study might have resulted in the enhanced maize yield in the biochar-amended plots [36]. This improvement has been interestingly explained in this study using the PCA technique by relating the CSQI with the yield.

5. Conclusions

This study demonstrated that biochar and inorganic fertilizer additions markedly affected the soil sandy clay loam physico-chemical and hydraulic properties, and consequently influenced the grain yield of the maize crop. The soil hydro-physical properties (soil OM, HC, and MC) determined the grain yields, while the soil nutrients (N, P, K) also explained the yield variability. Among the soil hydro-physical properties, the soil MC was the leading factor contributing to the yield variability, while among the soil nutrients, N was the main factor that affected the maize yields. Therefore, this study revealed that the multivariate statistical approach through the use of PCA and PCR is imperative for revealing the true relationship between soil properties and maize yield of amended soil under different weather and water supply conditions. This is essential in order to develop a strategy that will improve crop yield under varying climatic conditions.

Also, the soil CSQI was quantified from the PCA. The average CSQI for both growing seasons revealed that the CSQI increased in the order F0B0 < F0B20 < F300B0 < F300B20, thus mimicking the field-obtained result for the soil physico-chemical properties, thus ultimately revealing the synergism in the co-application of biochar with inorganic fertilizer on soil properties. The grain yield is highly dependent on the improvement in the soil quality upon the amendment addition due to the high value of the coefficient of determination obtained in this study. Therefore, the aggregation of soil properties for the determination of CSQI is important for the determination of the yield of maize using the PCA technique.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14081761/s1, Figure S1: Soil hydro-physical and chemical properties of the soil as affected by biochar and inorganic fertilizer application in (C) 2017 growing season and (D) 2018 growing season; Table S1: Initial soil and maize cob-residues biochar characteristics, which was used for as soil amendment; Table S2: Percentage variance of the factor loadings for the soil characteristics; Table S3: PCA for soil properties as amended by biochar only; Table S4: ANOVA for the PCR equation.

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