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Transforming a Valuable Bioresource to Biochar, Its Environmental Importance, and Potential Applications in Boosting Circular Bioeconomy While Promoting Sustainable Agriculture

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Abstract: Biochar produced from transforming bioresource waste can benefit sustainable agriculture and support circular bioeconomy. The objective of this study was to evaluate the effect of the application of biochar, produced from wheat straws, and a nitrification inhibitor, sourced from neem (*Azadirachta indica*), in combinition with the recommended synthetic fertilizer on soil properties, maize (*Zea mays* L.) plant growth characteristics, and maize grain yield and quality paramters. The nitrification inhibitor was used with the concentrations of 5 and 10 mL pot^{-1} (N_1 and N_2, respectively) with four levels of biochar (B_0 = 0 g, B_1 = 35 g, B_2 = 70 g, B_3 = 105 g, B_4 = 140 g pot^{-1}), one recommended nitrogen, phosphorous, and potassium syntactic fertilizer (250, 125, and 100 kg ha^{-1}, respectively) treatment, and one control treatment. The results showed that the nitrification inhibitor enhanced crop growth while the application of biochar significantly improved soil fertility. The application of biochar significantly enhanced soil organic matter and soil nitrogen as compared with nitrogen–phosphorus–potassium treatment. The highest root length (65.43 cm) and root weight (50.25 g) were observed in the maize plants treated with B_4 and N_2 combinedly. The grain yield, total biomass production, protein content from biochar's $B_{4,}$ and nitrogen–phosphorus–potassium treatments were not significantly different from each other. The application of 140 g biochar pot^{-1} (B_4) with nitrification inhibitor (10 mL pot^{-1}) resulted in higher crop yield and the highest protein contents in maize grains as compared to the control treatments. Therefore, the potential of biochar application in combination with nitrification inhibitor may be used as the best nutrient management practice after verifying these findings at a large-scale field study. Based on the experimental findings, the applied potential of the study treatments, and results of economic analysis, it can be said that biochar has an important role to play in the circular bioeconomy.

Keywords: bioresources; circular bioeconomy; economic analysis; Nitrification inhibitor; smog; wheat straw

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Citation: Abbas, F.; Hammad, H.M.; Anwar, F.; Farooque, A.A.; Jawad, R.; Bakhat, H.F.; Naeem, M.A.; Ahmad, S.; Qaisrani, S.A. Transforming a Valuable Bioresource to Biochar, Its Environmental Importance, and Potential Applications in Boosting Circular Bioeconomy While Promoting Sustainable Agriculture. *Sustainability* **2021**, *13*, 2599. https://doi.org/10.3390/su13052599

Academic Editor: Elio Dinuccio

Received: 29 January 2021
Accepted: 25 February 2021
Published: 1 March 2021

1. Introduction

Developing countries in South Asia face serious environmental problems from poor management of waste materials such as the burning of crop residues [1]. The antienvironmental burning of crop residues takes place to get ready for the next cropping cycle.

Through such burning, although agricultural fields are cleared and get quickly ready for next sowing yet the adverse impacts of the release of greenhouse gases [2] on public health offsets the personal gains of individual farmers. Avoiding the burning of crop residues can help reduce smog-based public issues originating from poor air quality (including diseases and traffic accidents) that have been reported for more than 2 decades in India and Pakistan particularly between October and November every year [3]. The circular bioeconomy finds the best place to play its role in such conditions with options for transforming crop residues through recycling this valuable bioresource to biochar for sustainable agriculture [4]. Circular bioeconomy benefits from the enhanced circularity of bioresources (wheat and/or rice straws) as its agriculture-based waste feedstock [1].

Biochar application to agricultural soils has been identified as a low-cost approach with an environmentally sound option in the wake of the global depletion of clean environment. It has attracted attentiveness in recent years mainly due to importance of soil carbon sequestration [4,5]. Biochar application is viable in enhancing crop growth [6–8] through improving soil chemical and physical properties [9,10] such as its extremely porous interior structure [11,12]. It acts as a soil conditioning mediator thereby improving soil water holding capacity by altering the soil pore size distribution [13] thus preventing nutrient loss from agricultural fields [14–16].

Feedstock for biochar ranges from a variety of raw materials including agricultural waste. Figueredo et al. [17] reported that the raw material and the pyrolysis temperature impact the nutrient concentration of biochar. They characterized and reported the release of nutrients and contaminants from types of biochar made from sugarcane bagasse, eucalyptus bark, and sewage sludge on 350–500 °C pyrolysis temperature. Biochar is an enriched carbon-based material and is the product of biomass pyrolysis and has profound impacts on improving soil carbon storage [18]. An important attribute of biochar is its cation exchange capacity (CEC) due to its large surface area and porosity which impact the soil biota and nutrient dynamics [6,19]. It enhances the soil nutrient availability to plants [20,21], flourishes the soil microbial population [19,22,23], and reduces greenhouse gas emissions through carbon sequestration [24]. Eventually, it increases the crop yield [25]. For example, Peng et al. [26] stated that 1% application of biochar increased 64% total biomass (above and below ground) of the maize in ultisol soils. Henceforth, it might play a positive role against climate change [27–29]. By active carbon sequestration, biochar has the potential to gain carbon credits [4]. The positive response of crop productivity against biochar application is attributed to its nutrients such as Ca, mg, K, and unintended fertility. These indirect and direct fertility aspects of biochar are categorized as a soil conditioner and soil fertilizer, respectively [6,26,30] that improve soil fertility [31]. The soil pH is also improved by the alkalinity of biochar [12] and it also facilitates the availability of phosphorous [32].

Biochar had a major and significant effect on different characters like a seedling, stem girth, number of roots, length of roots, and percentage germination [33]. Among the positive effects of biochar on plant development, the nitrogen use efficiency (NUE) has also been moderately recognized [10,34]. Laird et al. [35] found better N retention in soil hence, preventing approximately 11% N loss following 2% biochar application. Similarly, Clough et al. [36] reported that the biochar amendment had great agronomic advantages including changes soil nitrogen dynamics.

Nitrogen losses, precisely in agricultural soils are a widespread problem and are categorized into denitrification, leaching down with water as well as transformations into gaseous components [37]. In the case of anthropogenic N supplementation to agricultural soils, Zhang et al. [38] and others [39] found that about 30–80% of this N is taken up and incorporated by crops with loss of the remaining N proportion. Reactive N is effectively conserved through intrinsic soil N dynamics within natural environments [40–42]. Nitrate ($NO_3{}^-$) losses in soils of subtropical regions are more characterized by the leaching or runoff due to high rainfall patterns [40]. Nitrogen losses through nitrification are common in unsaturated N soils particularly upon the application of ammonium sulfate;

nonetheless, in saturated agricultural soils, N immobilization and mineralization into NH_4 are more frequent [43].

Nitrification inhibitors (NIs) are commonly employed in agricultural soils for enhancing the N retention by preventing its loss in the N_2O form and reducing the leaching of N [44–46]. Hence, to overcome N losses, NIs are distinguished in cropping systems [45,47] for enhancing crop production and decreasing the N_2O emission [46] hence improving the NUE in agricultural soils [48,49]. The NIs have shown a reduction in leaching of ammonium and urea-based fertilizers [50]. These inhibitors encourage the N retention in the soil in NH_4 by inhibiting the activity of ammonium monooxygenase (AMO). This AMO is recognized as a broad-spectrum efficiency for substrates [51]. The NIs compete with the active sites of this enzyme and aids in preventing the NH_4-enzyme complex and in this way, delay the rate-limiting step of nitrification [52]. A variety of NIs are used in agricultural biochar-amended soils. For example, 3,4-dimethyl pyrazole phosphate is viable for reducing N losses even at low application rates [53] with little adverse effects on soil ecology [48]. Another important NI is the dicyandiamide that is useful in reducing soil N losses [54]. These NIs have profoundly reduced N losses for example potassium thiosulfate is also characterized as a good NI [55]. Moreover, Cai et al. [56] in a laboratory experiment, found that dicyandiamide can reduce N_2O emissions up to 70% and predicted that these substances might be performed excellently at field scale as well [57,58].

Besides, recent studies have suggested that NIs correlate with biochar, explaining that the sorption of NIs is influenced by applied biochar [36,59–63]. The soil amendment of biochar, regardless of its feedstock, adds up new binding sites, thereby altering soil attributes such as pH and hydrophobicity and ultimately affecting the sorption of applied NIs resulting in the high productivity of cropping systems [64–66].

We hypothesized that the wheat crop residues would make nutrient-rich biochar and that such a soil amendment (biochar mixed with NI and NPK) will benefit soil health, plant growth, and crop yield and quality leading a way to circular bioeconomy. The hypothesis was tested by evaluating the effect of the application of biochar, produced from wheat straws, and NI, sourced from neem (*Azadirachta indica*), in combinition with recommended doeses of NPK on soil properties, maize (*Zea mays* L.) plant growth characteristics and maize grain yield and quality paramters. The use of neem as a NI in combination with NPK and biochar produced from wheat crop residues accounts for novelty of this work. Another novelty component of this work is the economic analysis that could not be found in biochar mixed with other fertilizers literature.

2. Materials and Methods

This experimental study was carried out at COMSATS University Islamabad, Vehari Campus Pakistan located at latitude 32°03′ N longitude 72°31′ E and with an altitude of 184 m. Long-term mean annual rainfall and reference evapotranspiration were approximately 231 mm and 1790 mm, respectively, while the annual mean daily maximum and minimum temperature were 28.0 °C and 13.7 °C, respectively as the experiment (Figure 1).

2.1. Preparation of Biochar, Neem Extract, and Experimental Pots

Biochar for this study was prepared with wheat straw via the pyrolysis method, which is also known as the thermal decomposition under oxygen-free conditions. The feedstock (wheat straw) of biochar were first heated at 105 °C for 30 min to remove the moisture from the raw materials. During the processing of biochar production, the temperature of the biochar pyrolysis apparatus was between 450 and 550 °C in a perpendicular oven. The gas produced from biochar preparation was condensed in the plant and collected as a liquid bio-oil for the safety of environmental pollution. The final biochar product was milled to pass through a 1 mm filter before its use. Selective properties of the produced biochar are given in Table 1.

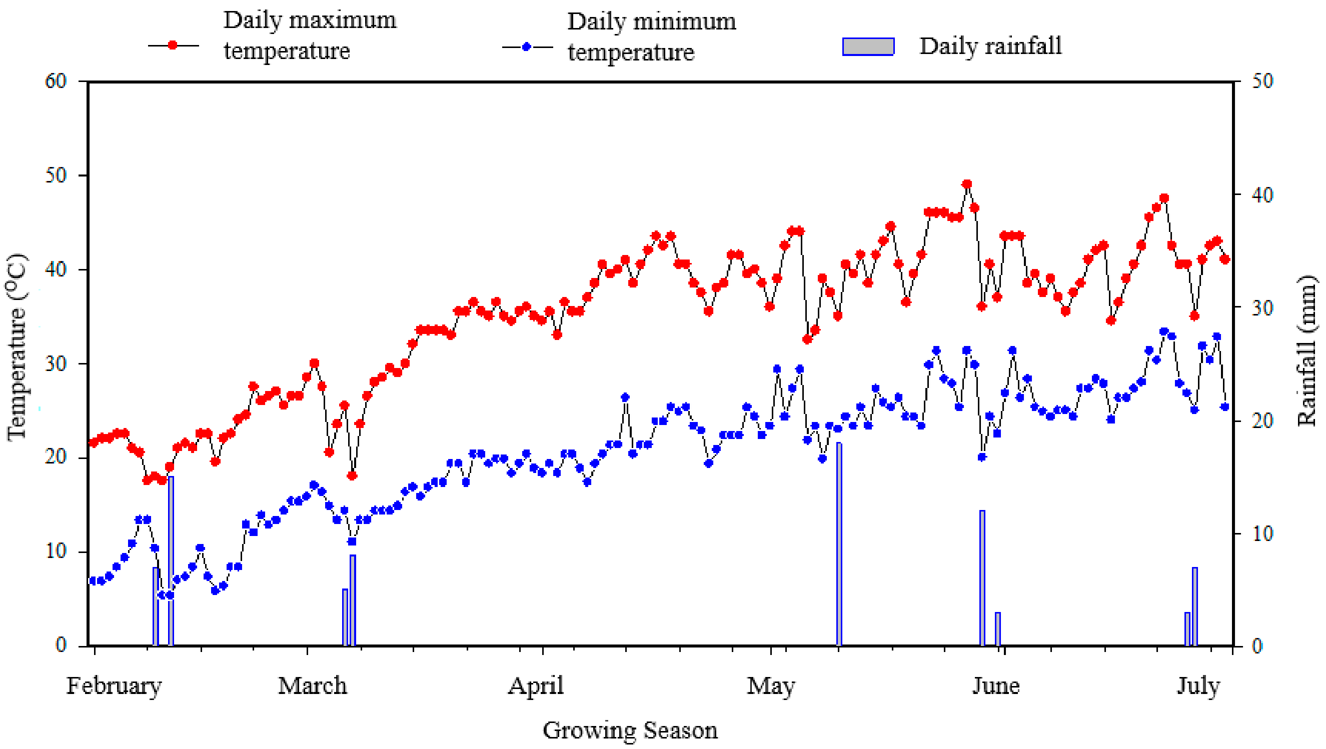

Figure 1. Daily temperature and rainfall data of experimental site during the growing season.

Table 1. Physio-chemical characteristics of biochar and soil used in the experiment.

Characteristics	Biochar	Soil
Organic matter (%)	45.5	0.74
Total nitrogen (g kg^{-1})	0.35	0.04
Total phosphorous (g kg^{-1})	1.34	6.5
Total potassium (g kg^{-1})	9.40	14.0
Electrical conductivity (dSm^{-1})	—	1.41
pH	8.8	7.5
Ash content (g kg^{-1})	120	—
Moisture (%)	31	—
Cation exchange capacity (cmolc kg^{-1})	93	6.5

As per local practice of preparing neem extract for kitchen/backyard gardening, the neem leaves plus seeds were soaked in water overnight with 1:2 neem to water ratio (5 kg of neem leaves/seeds in 10 L of water). The same material was then boiled on the next day to the point when approximately 50% of the water was evaporated and/or left in the boiling pan. The boiled solution was then sieved to collect neem extract to be used as NI in this experiment.

The soil made pots (30-cm height, 15-cm radius from the bottom, and 20-cm radius from the neck) were used during this experiment to grow maize under the experimental treatments. Each pot had a filling capacity of 15 kg of soil. All the pots were filled with 5 kg of non-sterilized soil collected from a nearby agricultural field that was sieved by using a 4.5-mm sieve to remove plant roots and other debris. A small hole was permitted at the bottom of each pot to let the excess water drain out in case of excessive rain. The properties of experimental soil are given in Table 1.

2.2. *Experimental Design and Treatments*

The experimental design for this was a factorial split-plot design with three replications. Four levels of biochar (B_0 = 0 g, B_1 = 35 g, B_2 = 70 g, B_3 = 105 g, B_4 = 140 g per pot), one treatment of recommended the N, P, and K (250, 125 and 100 kg ha^{-1}, respectively) and one control treatment were used to make the experimental treatments. A treatment of one selected NI (neem extract solution; N_1 = 5 mL, N_2 = 10 mL pot^{-1}) was applied to each of the four biochar levels, one NPK level, and one control. Resultantly, the set of four biochar treatments separately existed with 5 mL NI and with 10 mL NI. Therefore, the total experimental units were twelve as given below.

- T1 = N_1B_0 *(control)*: 5 mL neam + 0 g biochar
- T2 = N_1NPK: 5 mL neam + N, P, and K added @ 250, 125 and 100 kg ha^{-1}, respectively
- T3 = N_1B_1: 5 mL neam + 35 g biochar
- T4 = N_1B_2: 5 mL neam + 70 g biochar
- T5 = N_1B_3: 5 mL neam + 105 g biochar
- T6 = N_1 B_4: 5 mL neam + 140 g biochar
- T7 = N_2B_0 *(control)*: 10 mL neam + 0 g biochar
- T8 = N_2NPK: 5 mL neam + N, P, and K added @ 250, 125 and 100 kg ha^{-1}, respectively
- T9 = N_2 B_1: 10 mL neam + 35 g biochar
- T10 = N_2 B_2: 10 mL neam + 70 g biochar
- T11 = N_2 B_3: 10 mL neam + 105 g biochar
- T12 = N_2 B_4: 10 mL neam + 140 g biochar

2.3. Sample Analysis

The experimental soil (collected from the field) and soils from each experimental pot were analyzed for various soil properties. Soil organic matter was determined by the dichromate oxidation method [67]. Soil electrical conductivity (EC) and pH were determined in a 1:5 soil/water extract. Plant available-N in the soil was determined by the methods defined by Hesse [68] and available-P was determined by using the method as described by Olsen [69]. Available soil potassium (K) was determined by the method described by Junsomboon and Jakmunee [70].

The experiment started on February 12, 2018 and the maize variety Pioneer 31R88 was sown in experimental pots on the same day right after fertilization and crop sowing. At maturity, one plant was randomly extracted from each replication and washed with water. Root length was measured from plant base to root tip with the help of scale. The plant roots were oven-dried separately at 70 °C till constant weight and their dry weight was recorded. The number of days to tasseling, silking, and maturity were noted in each plant and the mean number of days taken to tasseling, silking, and crop maturity was calculated from the sowing date. A sample for thousand grains was taken from each pot and sun-dried up to standard moisture content in the grains and weighed by an electrical balance. At maturity, grain yield was calculated. The harvested plants were threshed manually, and grain yield was recorded on a g plant^{-1} basis. For biological yield whole plant was harvested and weighed. At harvest, the grains were taken from each plant and nitrogen contents of the seeds were calculated by using the micro-Kjeldahl method [71], and then crude protein contents were calculated by using the following formula.

$$\text{Crude protein} = \text{Nitrogen} \times 6.25$$

2.4. Statistical and Economic Analysis

The treatment effects on the studied variables were analyzed by constructing an analysis of variance (ANOVA) using SAS [72]. When F-values were significant, the least significant difference test was used for comparing means of treatments. The difference in treatment means was considered significant at $p < 0.05$. An economic analysis of the crop inputs (expenses) and output was performed on the basis of costs that varied in different treatments and by adding fixed cost following the procedure devised by Byerlee [73]. For economic analysis, the yeild was converted from plant pot^{-1} to Ton ha^{-1} by considering 666,666 plants per ha as reported by Hammad et al. [74]. All the input and output prices were made based on numbers obtained from consulting growers and the 2018 Economic Survey of Pakistan.

3. Results

Basis for presenting the study findings were made from the ANOVA results for the study variables. Sample ANOVA results for selective variables (root length, grain yield, total biomass, and protein content) are presented in Table 2. If the interaction of NIs and biochar levels were non-significant, the results were presented individually for each treatment. For example, the interaction of NIs and biochar levels were non-significant for root length (p = 0.9343). Therefore, results of such variables are discussed separately (see Tables 3 and 4). However, if interactions of the NIs and biochar levels were significant; for example, for grain yield (p = 0.0029), total biomass (p = 0.0031), and protein contents (p = 0.0030), the results of these variables are discussed for the combined effects of experimental treatments (see Table 5).

Table 2. Sample analysis of variance (ANOVA) values for selective variables (root length, grain yield, total biomass, and protein content) to base method for presenting study results.

Source of Variation	DF	SS	MS	F	p
Root Length					
Replication	2	12.77	6.384		
NI	1	81.60	81.601	42.2	0.0229
Error Replication×NI	2	3.87	1.934		
Biochar	5	2547.1	509.420	61.39	0.0000
NI×Biochar	5	10.42	2.084	0.25	0.9343
Error Replication×NI×Biochar	20	165.97	8.299		
Total	35	2821.73			
Grain Yield					
Replication	2	4.39	2.19		
NI	1	348.44	348.44	33.1	0.0289
Error Replication×NI	2	21.06	10.53		
Biochar	5	6050.56	1210.11	89.45	0.0000
NI× Biochar	5	358.22	71.64	5.3	0.0029
Error Replication×NI×Biochar	20	270.56	13.53		
Total	35	7053.22			
Total Biomass					
Replication	2	30.2	15.08		
NI	1	584	584.03	1617.31	0.0006
Error Replication×NI	2	0.7	0.36		
Biochar	5	34,868.3	6973.65	124.04	0.0000
NI×Biochar	5	1477.1	295.43	5.25	0.0031
Error Replication×NI×Biochar	20	1124.4	56.22		
Total	35	38,084.8			
Protein Content					
Replication	2	0.574	0.2869		
NI	1	6.588	6.5878	765.03	0.0013
Error Replication×NI	2	0.017	0.0086		
Biochar	5	280.939	56.1878	213.55	0.0000
NI×Biochar	5	6.922	1.3844	5.26	0.0030
Error Replication×NI×Biochar	20	5.262	0.2631		
Total	35	300.302			

DF: Degree of freedom, SS: Some of squares, MS: Mean squares, NI: Nitrification inhibitor.

3.1. Soil Properties

Soil organic matter is an important characteristic that plays a key role in maize grain yield. The result showed that the maximum soil organic matter (1.03%) was observed in the N_2 treatment of NI (Table 3). The soil organic matter increased with increase of biochar application levels. The application of biochar level B_4 (140 g pot^{-1}) resulted in soil organic matter of 1.30% for this treatment, which was 65% (0.84 vs. 1.30) greater from the soil organic matter content of control treatment.

Table 3. Effect of biochar and nitrogen inhibitor application on soil physic-chemical properties.

Treatments	Soil Organic Matter (%)	Soil pH	Soil EC (dSm^{-1})	N in the Soil (mg g^{-1})	P in the Soil (mg kg^{-1})	K in the Soil (mg kg^{-1})
N_1	1.02 a	7.61 a	1.58 a	0.046 b	6.96 a	15.60 b
N_2	1.03 a	7.59 a	1.56 a	0.049 a	6.97 a	15.83 a
Significance	<0.07	<0.03	<0.08	<0.001	<0.01	<0.01
LSD 5%	0.05	0.15	0.053	0.0011	0.56	0.15
Control	0.74 c	7.51 a	1.41 b	0.045 b	6.48 c	13.97 b
NPK (Recommended)	0.83 c	7.65 a	1.54 ab	0.045 b	4.46 a	16.73 a
B_1	0.92 bc	7.51 a	1.50 ab	0.046 ab	6.68 bc	14.96 ab
B_2	0.98 b	7.61 a	1.59 ab	0.046 ab	6.82 abc	15.18 ab
B_3	1.26 a	7.63 a	1.66 a	0.047 ab	7.05 abc	16.27 a
B_4	1.30 a	7.69 a	1.69 a	0.049 a	7.26 ab	16.88 a
Mean	1.02	7.60	1.57	0.046	6.96	15.67
Significance	<0.02	<0.3	<0.03	<0.021	<0.03	<0.01
LSD 5%	0.13	0.64	0.20	0.003	0.67	1.97
CV	7.45	4.65	7.02	3.57	5.28	6.96

EC: Electrical conductivity, N: Nitrogen, P: Phosphorous, K: Potassium, NPK: Nitrogen–phosphorus–potassium treatment. Means values that share different homogeneous group letters (a, b, or c) in a column vary significantly at $p \leq 0.05$, CV: coefficient of variance, LSD: Least significance difference, N_1 and N_2 are neem extract solutions (5 mL, 10 mL pot^{-1}, respectively) B_1 = 35, B_2 = 70, B_3 = 105, B_4 = 140 g biochar pot^{-1}.

The maximum soil pH (7.59) was observed in the N_2 of NI treatment, which was was improved with biochar applications; however, the effect biochar levels on soil pH was non-significance. The application of biochar level B_4 at the rate of 140 g pot^{-1} resulted in the highest soil pH 7.69. The lowest soil pH (7.51) was observed in unfertilized treatment; i.e., control treatment. Soil electrical conductivity (EC) is another important characteristic that plays a key role in plant growth. The result showed that the maximum soil EC was attained at the N_1 of NI which was 1.58 dSm^{-1}. The results showed that soil EC was improved with increasing of the biochar application rate. The application of biochar level B_4 resulted in the highest soil EC (1.69 dSm^{-1}). The lowest soil EC (1.41 dSm^{-1}) was observed in control treatment.

The result showed that the maximum N in the soil was observed at the N_2 level of NI which was 0.049 mg N g^{-1} (Table 3) and it increased with increase in biochar application reaching to its higest value of 0.049 mg g^{-1} in B_4 treatment and the lowest value (i.e., 0.045 mg N g^{-1}) in the soil of control treatment. Similarly, the highest P concentration (6.97 mg kg^{-1}) was deterined in the soil of N_2 application (Table 3). Like N, the concentraiton of P also increased with increasing biochar application rate. The application of biochar at the rate of 140 g pot^{-1} (level B_4) resulted in the highest P (7.26 mg kg^{-1}) concentration in the soil of B_4 treatment and the lowest concentration of P (6.48 mg kg^{-1}) was observed in the soil of control treatment. In addition to N and P, the K in the soil is also an important characteristic that plays a key role in growth and yield quality. The concentration of K was the highest in soil of the N_2 level of NI (15.83 mg kg^{-1}). Its concentration was significantly affected by levels of biochar application (Table 3). The K had the increasing trends with increasing the biochar application rate also as its highest value (16.88 mg kg^{-1}) was from the biochar application at the 140 g pot^{-1} (B_4) and the lowest value was (13.97 mg kg^{-1}) in the soil of control treatment.

3.2. *Plant Growth Characteristics*

The results showed that the maximum root length (55.35 cm) was observed at N_2 level (Table 4). Besides, root length was significantly also affected by levels of biochar application

($p < 0.0001$). Among the biochar treatment levels, maximum root length (65.43 cm) was noted at B_4 treatment (140 g biochar pot^{-1}) followed by NPK treatment which had the root length equavalent to 61.36 cm that was 38% greater (40.7 vs. 65.4) than the root length of plants of control treatment. The lowest root length (40.70 cm) was observed in the control treatment. Like root length, there was also a substantial difference between the root weight of maize treated with two different treatment levels of NIs. The maximum root weight (42.13 g plant^{-1}) was observed for N_2 level that was significantly different from N_1 treatment ($p < 0.01$).

Table 4. Effect of biochar and nitrogen inhibitor applications on maize growth parameters.

Treatments	Root Length (cm)	Root Weight (g)	Days to Tasseling (Day)	Days to Silking (Day)
N_1	52.34 b	38.51 b	45 a	51 a
N_2	55.35 a	42.13 a	47 a	52 a
Significance (P)	<0.022	<0.02	<0.10	<0.09
LSD 5%	1.99	3.58	2.53	1.95
Control	40.70 d	30.60 d	42 c	47 c
NPK (Recommended)	61.36 ab	41.83 b	47 ab	53 ab
B_1	47.15 c	35.25 cd	44 bc	49 bc
B_2	51.40 c	39.90 bc	46 ab	52 abc
B_3	57.01 b	44.13 b	48 a	54 a
B_4	65.43 a	50.25 a	50 a	56 a
Mean	53.84	40.33	46	52
Significance (P)	<0.01	<0.01	<0.01	<0.02
LSD 5%	5.22	5.57	3.99	4.88
CV	5.35	7.62	4.78	5.23

Means values that share different homogeneous group letters (a, b, c, or d) in a column vary significantly at $p \leq 0.05$, CV: coefficient of variance, LSD: Least significance difference, Control: A treatment without fertilizer, N_1 and N_2 are Neem extract solutions (5 mL, 10 mL pot^{-1}, respectively) and B1: 35, B2: 70, B3: 105, and B4: 140 g biochar pot^{-1}.

Similarly, maize treated with N_2 took non-significantly lesser days (47 days) for tasselling and silking (52 days) as compared to N_1 treatment in which the tasselling and silking took place after 45 and 51 days, respectively (Table 4). However, there was significant differences in the tasselling and silking days of maize treated with different biochar levels ($p < 0.05$). Maximum days to tasselling (50 days) and silking (56 days) were reported at biochar level B_4 while tasselling occurred after 42 days and silking after 47 days in the control treatment. The onset of tasselling (47 days) and silking (53 days) was also a bit earlier in maize treated with NPK. Furthermore, the results from B_4 were statistically similar to the NPK treatment level while silking in B_4 treatment was statistically at par with NPK application treatment. In both NI treatment levels; i.e., N_1 and N_2, crop maturity occured after 102 days and maturity during N_1 and N_2 was statistically similar. However, maturity was significantly affected by different levels of biochar application; i.e., maturity was delayed with increasing level of biochar application. Maize treated with B_4 reached maturity after 108 days which was 11 days later than that in B_1 (97 days). Maturity in B_4 was statistically at par with NPK application treatment and the mean number of days to maturity was 102 days.

3.3. Yield and Quality Parameters

Grain yield and total biomass were also significantly affected by levels of biochar and NPK applications and significantly ($p < 0.01$) increased with an increasing level of biochar application (Table 5). The maximum grain yield (84.00 g plant^{-1}) and biomass (266.67 g plant^{-1}) were resulted from the application of recommended NPK with the combination of N_2. However, the application of biochar level B_4 with N_1 resulted in grain yield of 76.67 g plant^{-1} and total biomass of 256 g plant^{-1}. The highest grain yield (43.00 g plant^{-1}) and the lowest total biomass (172. 33 g plant^{-1}) were observed in N_2B_0. In the case of total biomass, N_1B_4 and N_2B_4 were statistically similar to NPK treatment as represented by similar LSD letters. In the case of protein content, the highest protein content (14.3%) in maize grain was observed in the grains of NPK treatment in combination with N_2. Besides, significantly increasing protein content percentage with increasing biochar applications was also observed. At the largest biochar application level, the protein content was 12.37%, which was slightly lower than that of N_1NPK treatment (12.97%). The lowest protein content was observed in the N_2B_1 treatment (4.90%).

Table 5. Effect of biochar and nitrogen inhibitor application on maize yields and quality.

Treatments	Grain Yield (g Plant^{-1})	Total Biomass (g Plant^{-1})	Protein Content (%)
N_1B_0 *(control)*	43.33 f	183.33 de	5.67 g
N_1NPK	73.33 b	252.67 a	12.97 ab
N_1B_1	44.67 f	181.00 de	6.27 fg
N_1B_2	51.33 e	198.00 cd	7.77 ef
N_1B_3	59.67 cd	221.33 b	9.80 cd
N_1 B_4	76.67 b	256.00 a	10.30 c
N_2B_0 *(control)*	43.00 f	172.33 e	4.90 g
N_2NPK	84.00 a	266.67 a	14.30 a
N_2B_1	53.00 de	193.67 cde	7.53 ef
N_2B_2	61.33 c	214.67 bc	8.43 de
N_2B_3	72.67 b	245.00 a	10.37 c
N_2 B_4	72.33 b	248.33 a	12.37 b
Mean	61.27	219.42	9.22
Significance (P)	<0.003	<0.003	<0.003
LSD 5%	6.26	22.45	1.54
CV	6.00	3.42	5.56

Means values that share different homogeneous group letters (a–g) in a column vary significantly at $p \leq 0.05$, CV: Coefficient of variance, LSD: Least significance difference, Control: A treatment without fertilizer, N_1 and N_2 are Neem extract solutions (5 mL, 10 mL pot^{-1}, respectively) and B_1: 35, B_2: 70, B_3: 105, and B_4: 140 g biochar pot^{-1}.

3.4. Economic Analysis Results

The highest net returns were calculated for N_2NPK treatment (\$759.4 ha^{-1}) followed by N_2B_3 (\$664.7 ha^{-1}) and N_1B_4 (\$587.7 ha^{-1}) treatments (Table 6). Although the NPK treatment had the highest returns but it is argued that the difference between its and biochars treatments' profit may be traded of with the long-term treasure of soil health with a wealth of sequestered soil organic carbon and the bioremediation role of biochar for soil health [4]. With improvements in biochar production technologies, inclusion of biochar in the best nutrient management pracitces, and reduction of its cost due to higher commercial production, circulation, and demand, its market price is anticipated to drop down. Hence, the economical availability of biochar will reduce the costs of crop inputs and will increase the farm profitability. The mixed use of biochar with compost or with synthetic fertilizers can also be argued for its importance in farmer's income. Numerous studies have highlighted [75,76] that the crop growth is affected precisely due to biochar made changes in soil nutrient cycles, specifically the cycling of P and K.

Table 6. Economic analysis of input and output costs on maize cultivated with the experimental treatments.

Treatment	Total Yield, Ton ha^{-1}	Adjusted Yield after Considering 10% Yield Lost during Field Harvest, Ton ha^{-1}	Gross Income Based on Maize Grain Price in Pakistan (\$360 ton^{-1})	Biochar Cost Based on Biochar Price (\$140 ton^{-1})	Fertilizer per Hectare Cost, \$ ton^{-1}	Variable Cost, \$ ha^{-1}	Fixed Cost, \$ ha^{-1}	Net Benefit, \$ ha^{-1}
N_0B_0	2.389	2.15	773.9	—	—	0	415	358.9
N_1NPK	4.889	4.4	1583.9	—	694.0	640.0	415	528.9
N_1B_1	2.978	2.68	964.9	163.3	—	163.33	415	386.5
N_1B_2	3.422	3.08	1108.7	326.7	—	326.66	415	367.1
N_1B_3	3.978	3.58	1288.9	490.0	—	490.0	415	383.7
N_1B_4	5.111	4.60	1656.1	653.3	—	653.33	415	587.7
N_0B_0	2.367	2.13	766.8	—	—	0	415	351.8
N_2NPK	5.600	5.04	1814.4	—	694.0	640.0	415	759.4
N_2B_1	3.533	3.18	1144.8	163.3	—	163.33	415	566.5
N_2B_2	4.089	3.68	1324.7	326.7	—	326.66	415	583.1
N_2B_3	4.845	4.36	1569.7	490.0	—	490	415	664.7
N_2 B_4	4.822	4.34	1562.3	653.3	—	653.33	415	494.0

All calculations are based on numbers obtained from consulting growers and the 2018 Economic Survey of Pakistan.

4. Discussion

The role of biochar and NIs on growth and yield of maize has been reported in literature [7,26]. Among the direct and indirect effects of biochar, the latter are more distinguished as reported by Glaser et al. [6]. According to Genesio et al. [77] the biochar application to the soils changes the natural state and thermal dynamics of the soil thereby promoting crop growth. They further reported that biochar supplementation with the NI had a promising role in the germination and phenology of plants.

Slow-release of N from synthetic fertilizers is achieved by coating the fertilizer grains with hydrophobic chemicals to provide a physical barrier against water for minimizing N losses and improving N uptake by crops; however, such alternatives may harm the soil health and crop growth [78]. In contrast, the natural NIs are soil environment friendly and plant growth stimulators. The nature-based inhibitors have been exhaustively investigated as alternatives [79]; these include powder of *Azadirachta indica* seed [62] and bark of *Acacia* caven [63]. Such alternatives promote the slow release of N to soil solution [80]. In our experimentl treatments involving higher concentration of NI sourced from naturally occurig neem significantly reduced N loss from soil. These reults are in agreement with the finding of Mohanty et al. [62] who used neem seed powder, and found that the difference in urea content of treated and untreated samples was less significant at the start but became more profound with time, pointing to an inhibitory mechanism of neem whereby it takes some time for the bio inhibitor to be activated [78].

In our study, better root length and root weight were reported for the application of 140 g biochar pot^{-1} that is linked with better nutrient accessibility to roots after the biochar application to soils [26,32]. Besides, maize root growth was increased with increasing biochar application because the biochar hold a slight ratio of labile carbon [5], which either improves root growth or facilitates the root contact to available P [81,82].

In the case of N, biochar application increased the quantity of N reserved in the soils that is not according to the earlier conclusions that biochar expands the absorption capacity of the soil but decreases leakage of nitrate and ammonium because of its great surface area and absorbent structure [35,83] as found in the soils tested by Zhang et al. [38] with biochar adjustment. The results of the current study showed K availability was also increased through the biochar amendment resulting in enhanced K content in the soil. This K content then increased the maize total biomass and grain yield in treatments that received greater biochar application. However, at this point, the fertilizing effect of biochar is more characterized because K availability to maize was increased due to the high content of K in biochar along with its reduced leaching [35,84]. Martinsen et al. [84] argued that K is the major nutrient supplied by biochar which helps in delaying the tasseling and silking days and also helps in alleviating the nutrient stress conditions.

The treatments with increasing level of biochar application also enhanced the P availability to maize, which also improved maize grain yield, total biomass, and protein content For example, the B_4 treatment relative to other treatments, made P available for plants by increasing the soil pH [13,85] that helps in reducing P sorption [86,87]. DeLuca et al. [88] further elucidated that the biochar amendment ensures better P availability to crops, with the ability of biochar to retain exchangeable P ions due to its positively charged sites. The increase in maize total biomass and grain yield in B_4 treatment is also attributed to biochar's role in increasing the total soil organic carbon as reported by Trupiano et al. [89]. Likewise, Pandit et al. [30] mentioned increased maize biomass production with increasing biochar supplementation.

Better soil water retention is governed by biochar amendments as found by Hagemann et al. [90] suggesting that biochar influences in forming organic coatings of soils by reducing pore spaces (resulting in increased capillary rise) and enhanced hydrophilicity. This leads to better soil health and enhanced crop yield [7,74,91]. From our study results, it can be assumed that the application of biochar to agricultural soils is thoughtful and can be used as an alternative option to lime materials in raising the pH, especially in acidic soils because it is noted that approximately 30% world's soils are acidic and 50% of them have the arable potential [92].

The impact of applying biochar as a soil amendment is for approximately 30% world's soils that are acidic and 50% of which have arable potential. The application of biochar to agricultural soils can alternate soil liming, which is used to raising the pH of acidic soils [93]. This leads to the potential of improving acidic soils of Atlantic Canada, to make them suitable for potato cultivation. Soil liming is a common practice in potato fields where the pH is either too acidic or too alkaline. The lime application in Canadian soils varies from province to province; as 11.3 and 20.2% of the croplands of New Brunswick and Prince Edward Island were treated with lime for making them suitable for potato cultivation [94]. Overall, the use of biochar improves soil health especially in poor soils of arid and semiarid regions [95]. Based on the experimental findings, the applied potential of the study treatments, and results of economic analysis, it can be said that biochar has an important role to play in the circular bioeconomy in future.

5. Conclusions

Biochar amendment to agricultural soils is environmentally safe and a sustainable approach relative to synthetic fertilization. Besides, it is also helpful in increasing the fertilizer use efficiency as well as reducing soil pollution. Like biochar supplementation, applying the nitrification inhibitor (neem extract) revealed better maize growth and yield. The maize had the best growth parameters namely the maximum root length, root weight, tasseling, silking, and crop maturity under the treatment of 140 g of biochar applied per pot/plant and 10 mL pot^{-1} application of neem extract. Therefore, the potential of biochar application in combination with nitrification inhibitors should be further exploited for sustainable crop production. It is therefore concluded that the circular bioeconomy seems one of the solutions to transform wheat straw biowastes into a useful bioproduct (biochar) that can ensure agricultural sustainability in terms of a closed-loop sustainability framework involving biomass. With attributes of success of circular bioeconomy at small as well as at large scales, farmers can recycle their crop residues and benefit from a circular resource economy. Biochar can be synthesized by farmers themselves at a low cost instead of spending on the purchase of commercially produced biochar that has the same fertility components. Waste to biochar is a sustainable partway to the circular bioeconomy.

Author Contributions: Conceptualization, F.A. (Farhat Abbas) and H.M.H.; methodology, F.A. (Farhat Abbas); H.M.H. and F.A. (Farhat Anwar); software, H.M.H.; validation, A.A.F.; formal analysis, F.A. (Farhat Anwar); investigation, H.M.H., and F.A. (Farhat Anwar); resources, H.M.H.; data curation, F.A. (Farhat Anwar); writing—original draft preparation, F.A. (Farhat Abbas); H.M.H.

and A.A.F.; writing—review and editing, R.J.; H.F.B.; M.A.N.; S.A.; and S.A.Q.; visualization, R.J.; H.F.B.; M.A.N.; S.A.; and S.A.Q.; supervision, H.M.H.; project administration, F.A. (Farhat Abbas); H.M.H.; funding acquisition, A.A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The Natural Sciences and Engineering Research Council of Canada (NSERC).

Conflicts of Interest: The authors declare no conflict of interest.

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