sustainability

Article

Biochar Integrated Nutrient Application Improves Crop Productivity, Sustainability and Profitability of Maize–Wheat Cropping System

Naeem Sarwar [1,*], Naseem Abbas [1], Omer Farooq [1], Muhammad Akram [2], Muhammad Waqar Hassan [3], Khuram Mubeen [4], Atique-ur Rehman [1], Muhammad Shehzad [5], Matlob Ahmad [6] and Abdul Khaliq [7]

1 Department of Agronomy, Bahauddin Zakariya University, Multan 60800, Pakistan
2 Department of Environmental Sciences, COMSATS University Islamabad, Vehari Campus Pakistan, Vehari 61100, Pakistan
3 Department of Entomology, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan
4 Department of Agronomy, MNS University of Agriculture, Multan 66000, Pakistan
5 Department of Agronomy, University of Poonch Rawalakot, Rawalakot 12350, Pakistan
6 Department of Agricultural Engineering and Technology, Ghazi University, Dera Ghazi Khan 32200, Pakistan
7 Soil and Water Testing Laboratory, Kotla Ahmad Road, Rajanpur 33500, Pakistan
* Correspondence: naeemsarwar@bzu.edu.pk

Abstract: Enhancing cereal crop production to feed the largely growing population is an important approach towards maintaining food security. Fertilizer management is the major component of crop production requiring special attention for sustainable application. Integrated nutrient management (INM) is an evolving idea, which appears to contribute to sustainable nutrient management. A field study was designed to see the impact of INM on a maize–wheat cropping system during winter (wheat) and summer (maize) season at Agronomic Research Farm, Bahauddin Zakariya University Multan, Pakistan. Both wheat and maize crops were grown consecutively along with full inorganic fertilizer (NPK) as well as with partial dose of fertilizer (25%, 50%, 75% NPK) supplemented with or without the addition of biochar (5 ton/ha). Data were collected regarding crop growth, yield and quality and further analyzed using MSTAT-C statistics software. Results revealed that the INM approach (75% of NPK + Biochar) enabled crops to improve dry matter production and its translocation towards sink which in turn boosted the crop productivity. This treatment improved dry matter (19%, 57%), grain weight (44%, 54%), grain yield (60%, 63%) and harvest index (30%, 29%) over the control in maize and wheat crops. It also improved the nutrient uptake in the plants which in turn improved the nutrient contents in the grains. Similarly, crops recorded higher system productivity (USD 790, USD 830) in both years and were found to be economically sustainable under INM. It was concluded that an INM strategy (75% of NPK + Biochar) can improve the productivity and sustainability of a maize–wheat cropping system to maintain the food security.

Keywords: food security; sustainable crop production; integrated soil fertility; cropping system; biochar; dry matter partitioning; crop yield

check for updates

Citation: Sarwar, N.; Abbas, N.; Farooq, O.; Akram, M.; Hassan, M.W.; Mubeen, K.; Rehman, A.-u.; Shehzad, M.; Ahmad, M.; Khaliq, A. Biochar Integrated Nutrient Application Improves Crop Productivity, Sustainability and Profitability of Maize–Wheat Cropping System. *Sustainability* **2023**, *15*, 2232. https://doi.org/10.3390/su15032232

Academic Editors: Othmane Merah, Hailin Zhang, Purushothaman Chirakkuzhyil Abhilash, Magdi T. Abdelhamid and Bachar Zebib

Received: 13 November 2022
Revised: 13 January 2023
Accepted: 21 January 2023
Published: 25 January 2023

1. Introduction

Food security is a key concern, with the aim of feeding the fast-growing world's population. However, decreasing availability of fresh water due to global climate change has forced farmers to grow water saving crops. Due to climate change, water resources are depleting all over the world so water-saving cropping systems are being promoted [1]. Poor and unsustainable soil fertility management are the main constraints for lower fertilizer use efficiency in crop production [2,3], which not only enhance the cost of production but also can pollute natural resources [4]. In the Indo-Gangetic plains, a rice–wheat cropping system covers nearly 85% of the area and is a life line for billions of people. This system requires intensive nutrient application along with irrigation and energy, all which increase environmental footprints [3]. Currently, a maize–wheat cropping system provides staple foods for more than 20% of the population of South Asia and China [5]. In northern China, a winter wheat–summer maize double cropping system has been successful in intensifying the agricultural systems [1]. In this system, two crops are produced in a year, cultivating wheat from October to June and maize from June to October.

Maize (*Zea mays* L.) is an important cereal crop grown as a staple food for millions of people around the world. In Pakistan, maize is grown as the fourth major crop after wheat, rice and cotton. In recent years, demand for maize has increased due to its usage as human food as well as its utilization in poultry feed [6]. The current estimated maize production in the world is 1026 million tones with the USA as the main contributor, followed by China [7]. In Pakistan, the average maize yield is very low compared to the other countries because of improper and imbalanced soil nutrient management along with significant insect pest problems [2,8].

Wheat is another key cereal crop which has great significance in maintaining food security [9] as it is grown as a staple food in many countries, and provides protein, carbohydrates and other trace nutrients [10]. Wheat crops are produced on almost all continents with Asia having the highest share (44.7%) compared to Europe (31.6%), North America (16.5%) and Africa (3.9%) in total world production [11,12]. In Pakistan, it is grown as a staple food, contributing 9.6% in value added and a 1.9% share in the GDP [6]. In comparison to the world's producers, average yield is very low in Pakistan due to the inefficient nutrient management approaches and less soil organic matter status [2].

Biochar is a pyrolyzed material produced from organic biomass or feedstocks at varying temperatures in the absence of oxygen [13,14]. Biochar has high potential to increase soil porosity, bulk density, water contents, soil fertility and soil microbial activity, mitigating the adverse effects of various stresses and consequently increasing plant growth [10]. Many studies have explained that biochar improves the physical and chemical characteristics of the soil which favor plant growth [14]. Biochar increases soil organic matter which in turn improves soil fertility after mineralization. Most biochar has a higher surface area and absorption capacity and can be used for the development of slow releasing fertilizer. Moreover, biochar is recalcitrant in nature and takes hundreds of years to be fully decomposed [15]. Studies have indicated that soil amendment with biochar increased plant growth and yield in various crops, such as wheat, rice, maize and sunflower [16,17]. In addition, biochar application ameliorates the acidic soil and improves the availability of K and P to plants [18]. It has been shown that biochar derived from animal manures, chicken manures and plant residues have high nutrients than wood-based biochar [14]. Biochar modifies the soil characteristics and reduces nutrient losses through leaching or volatilization [19] and improving the soil fertility [20]. Depending on the root stock, biochar is a source of different essential nutrients such as N, P, K, Ca, Mg and S, and makes the conditions favorable for microorganisms that break down plant residues and organic matter in the soil [14,21]. Moreover, it is further elaborated that biochar application has shown beneficial effects on microbial activity and water retention in the soil [22].

In integrated nutrient management (INM), organic and inorganic fertilizers are applied in combination to meet crop demand in a sustainable manner [2,23]. This practice not only enhances soil fertility but also improves soil health [24], which in turn triggers crop productivity [25,26]. In Pakistan, farmers are totally dependent on inorganic fertilizer application, which is not a sustainable manner of crop production as it pollutes natural resources. Organic matter in the soil is very low due to high temperatures, which also reduces the nutrient use efficiency and crop yield. Among organic fertilizers, biochar looks to be a good option which can stay for a longer time in the soil due to its slow decomposition process even under high temperatures. In this experiment, we used biochar along with inorganic fertilizer in different combinations with a maize–wheat cropping system to see its impact on crop productivity and sustainability.

2. Materials and Methods

2.1. Location of Study

The field experiment of maize crop was carried out at the Agronomic Research Farm, Department of Agronomy, Bahauddin Zakariya University, Multan (30.2705° N, 71.5024° E) during 2018–2019 and 2019–2020.

Biochar Production and Characterization

Harvested cotton sticks were kept in an open space for sun drying and then were cut into small pieces of about 5 mm. The copped cotton sticks were pyrolyzed in an airtight stainless-steel furnace of 10 kg capacity at 400 °C using natural gas. The pyrolysis was completed in such a way that fire did not directly contact copped material. A constant temperature of 400 °C was maintained for 2 h to complete the pyrolysis. The prepared biochar was stored for application in pot experiments. The volatile matter, fixed carbon contents and ash contents were measured using the method followed by [27]. Filtered aliquots of biochar and distilled water were used with a 1:10 ratio for determination of EC and pH [28]. Elemental analysis method was used for the determination of total carbon in cotton sticks biochar (CSB). For determination of nitrogen in CSB, samples were digested in concentrated H_2SO_4 following the Kjeldhal method [29]. Samples of CSB were prepared through digestion in HNO_3-$HClO_4$ for determination of P and K within biochar [30]. After digestion, potassium was analyzed using a flame photometer while phosphorus was determined using a spectrophotometer.

2.2. Treatment Detail

Different maize hybrids (H1: YH 5394, H2: YH 1898 and H3: FH 1046) and wheat cultivars (V1: Millat-2011, V2: Punjab-2011 and V3: Galaxy-2013) were evaluated under an integrated nutrient management (INM) system. All fertilizers containing major nutrients were applied as per treatment plan, i.e., M0: control, M1: Recommended NPK (220-140-90 kg ha^{-1}), M2: 25% NPK + 5 t ha^{-1} biochar, M3: 50% NPK + 5 t ha^{-1} biochar, M4: 75% NPK + 5 t ha^{-1} biochar, M5: 100% NPK + 5 t ha^{-1}. A randomized complete block design (RCBD) with factorial arrangement was used for field experiment. The biochar dose was optimized in the pot experiment and the best dose (5 t ha^{-1}) was selected for the field experiment.

2.3. Edaphic Factors and Sowing of the Crop

For good soil tilth and seed bed preparation, the soil was ploughed and cultivated three times, followed by planking each time, to break the clods. Irrigation was provided after preparing the field, and biochar at 5 t ha^{-1} was mixed manually in the soil at the field capacity. Maize crop was sown in the field using a seed rate of 25 kg ha^{-1}. Net plot size for each treatment unit was 6 m × 1.8 m, keeping 75 cm space between rows and 25 cm between plants. The crop seed was sown manually in the first week of August in 2018–2019 and 2019–2020, respectively. Similarly, wheat crop was sown using 125 kg ha^{-1} with the help of a hand drill in the first week of November in both years. Net plot size of each treatment unit was 6 m × 1.8 m, keeping row spacing of 22.5 cm.

2.4. Crop Management Practices and Measurement

Pre-sowing soil analysis was done which revealed that soil was alkaline in nature and categorized as silty clay. Soil contained 0.42% organic carbon, 0.109% total nitrogen (N), 7.92 mg/kg phosphorus (P) and 185 mg/kg available potassium (K). Recommended doses of N, P and K were utilized (220, 140, 90 kg ha^{-1}, respectively) in maize crop. DAP (46% P and 18% N), urea (46% N) and muriate of potash (60% K2O) were used for phosphorus (P), nitrogen (N) and potassium (K). The full quantities of P and K and half the quantity of N were consumed during the crop sowing, and the remaining N was given in two equal doses at knee height and at the tasseling stage. All the plots were kept weed free, following manual weeding. The crops were irrigated as per crop need by visual observation and protected from the root borer or top borer by applying Furadon at the threshold level. After maturity, the crops were harvested manually and placed in the representative treatment plots for sun drying up to the one week.

For the wheat crop, recommended dose of fertilizer (120-80-60 kg/ha) for NPK was used while the nitrogen dose was decreased as per treatment plan. All the P and K, and 1/3 of the nitrogen, were consumed during the sowing of the crop, while the rest of the N was given to the crop in two equal splits at the tillering and booting stages. Manual weeding was done to keep the crops weed free, and the crops were irrigated as per need by visual observation. A total of four irrigations were provided, and the crops were harvested in early May for both years. The crops were harvested manually and sun dried up to one week.

2.4.1. Dry Matter Accumulation (g)

Two plants from the wheat crop were selected randomly and harvested to separate the leaves, stems and spikes, and sun dried followed by oven dried at 70 °C until the achievement of constant weight. The average dry weight of the leaf, stem and spike was noted then expressed in grams. A similar procedure was used for the maize crop. One maize plant was randomly selected from each treatment and harvested. Leaves, stems and cobs were separated afterward. All plant material was sun dried followed by oven dried. Dry weight for each treatment was noted by using laboratory balance.

2.4.2. Yield Parameters

Dried plants were weighed for biological weight for each treatment. For grain weight, 1000 grains were counted from each treatment and their weight was recorded on a digital balance. After the sun-dried crop was threshed, the grains were separated, collected in small jute bags and their weight was noted in "kg" and then converted in ton ha^{-1}.

Harvest index was measured by following formula:

$$\text{Harvest Index (HI)} = \frac{\text{Grain yield}}{\text{Biological yeild}} \times 100$$

2.4.3. System Productivity

Market price for grains and straw of both crops was noted by using prevailing market price to calculate the gross income. All expenses for the crop production were also noted and subtracted from the gross income to calculate the net return. System productivity was calculated on the basis of net income of maize and wheat using following formula:

$$\text{System productivity} = \text{maize net returns} + \text{wheat net returns}$$

2.4.4. Economic Analysis

Economic analysis was conducted separately for each crop following standard methodology [31] and then average values were drawn. All expenses incurred on crop production, including land rent, seed, land preparation, fertilizer, plant protection, were combined for both crops to get the total expenses. Similarly, the gross income was calculated as per market price of grain and straw. Lastly, the net income was computed with a difference of gross income and total expenses. The benefits–cost ratio (BCR) of treatments was determined by following formula:

$$\text{BCR} = \frac{\text{Gross income}}{\text{Total cost}}$$

2.4.5. Statistical Analysis

The collected data were analyzed through statistical software, MSTAT-C. One-way ANOVA was used to test the significance in the dataset [32]. The difference among the treatments was calculated by LSD (least significant difference) test at 5% probability level, and was used as post-hoc test to separate the means where ANOVA indicated the significance.

2.5. Analytical Procedure

2.5.1. Grain Protein and Carbohydrate Content (%)

Each treatment samples were brought to laboratory for chemical analysis. The grain protein and carbohydrates were measured through near infrared (NIR) apparatus (Omega Analyzer G™ Bruins Instruments, Puchheim, Germany).

2.5.2. Nutrient Analysis

Nutrients analysis for N, P, K, Ca, Mg and Zn contents was performed in the laboratory for each treatment. Sample material (grain/leave) was ground using a grinding mill and digested following wet digestion method with the use of concentrated NHO_3. Following the digestion, the Ca, Mg and Zn concentrations were detected through the flame atomic absorption spectroscopy method [33]. Similarly, K content was measured using a flame photometer whereas P was determined using a spectrophotometer. Samples were digested under concentrated H_2SO_4 and nitrogen contents were measured following Kjeldahl distillation [29].

3. Results

3.1. Dry Matter Accumulation

Table data showed that in maize crop, integrated nutrient management (INM) significantly improved the dry matter as compared to the control or sole application of inorganic fertilizer, while treatment M4 produced the highest dry matter of stem (81.15 g), leaves (51.88 g) and cob (108.57) in YH-1898 hybrid (H2), which was 38%, 4% and 16% higher than control plants (M0H1), respectively. Maize plant accumulated the highest dry matter to cob followed by stem and leaves. Similarly, the M5 treatment combinations also enhanced dry matter significantly over other treatments but was found to be statistically similar with M4 treatment combinations. The lowest dry matter was observed in control (50 g, 49 g, 91 g in stem, leaves and cob, respectively) (M0H1). In comparison with control, almost similar results for dry matter production and its partition were observed in the second year of experimentation (Table 1).

Table 1. The physicochemical properties of cotton sticks and biochar material.

Parameters	Cotton Sticks	Biochar
pH	7.06	8.1
EC (dS/m)	1.40	1.46
N (%)	1.22	0.57
P (%)	1.17	1.06
K (%)	0.89	0.80
Zn (ppm)	11.88	7.79
Cu (ppm)	2.0	0.84
Fe (ppm)	270	230
Mn (ppm)	11.5	6.45
Volatile matter (%)	39	22
Ash (%)	40	70
Fixed carbon (%)	15	28

In the case of the wheat crop, plants produced under INM excelled in dry matter in stem, leaves and spike. Maximum and statistically similar dry matter was produced in treatment combination of M5V3 and M4V3 in stem (590.32 g, 589.24 g) and spike (604.31 g, 598 g), while in case of leaves higher dry matter was observed in M5V3 (286.20 g) followed by M4V3 (275.40 g). It was noted that plants transferred higher dry matter in the stem followed by spike and leaves. Treatments M4 and M5 also resulted similarly in different cultivars. Plants produced without fertilizer (M0) or with 25% inorganic fertilizer (M1) in each hybrid reduced plant dry matter as compared with other INM application. In comparison with the control (M0H1), treatment M4V3 produced 53%, 60% and 58.90% higher dry matter in stem, spike and leaves. Similar results for dry matter production and its partition was observed in the second year of experimentation (Table 2).

Table 2. Impact of biochar-integrated application on dry matter accumulation and its distribution in maize–wheat cropping system.

	Maize (2018–2019)			Wheat (2018–2019)			Maize (2018–2019)			Wheat (2018–2019)		
Treat.	**Stem DW (g)**	**Leaves DW (g)**	**Cobs DW(g)**	**Stem DW (g m^{-2})**	**Leaves DW (g m^{-2})**	**Spike DW (g m^{-2})**	**Stem DW (g)**	**Leaves DW (g)**	**Cobs DW(g)**	**Stem DW (g m^{-2})**	**Leaves DW (g m^{-2})**	**Spike DW (g m^{-2})**
M_0H_1	50.31 ^{i}	49.76 ^{e}	91.34 ^{i}	277.86 ^{l}	113.40 ^{k}	238.82 ^{i}	50.25 ^{k}	38.52 ^{k}	91.12 ^{k}	275.40 ^{k}	154.05 ^{j}	247.52 ^{k}
M_1H_1	76.63 ^{e}	42.65 $_{g}$	106.05^{e}	470.31 ^{f}	255.96 ^{e}	546.16 ^{e}	75.87 ^{e}	49.30 ^{e}	105.20 ^{e}	460.08 ^{e}	255.81 ^{d}	416.00 ^{e}
M_2H_1	59.87 ^{g}	44.54 ^{f}	106.68 ^{g}	365.44 ^{j}	156.60 ^{i}	348.88 ^{g}	58.20 ^{i}	41.87 ^{i}	95.49 ^{i}	356.40 ^{i}	199.28 ^{h}	324.48 ^{i}
M_3H_1	64.32 ^{f}	51.00 ^{c}	99.17 ^{f}	406.52 ^{i}	179.28 ^{g}	400.80 ^{f}	62.18 ^{g}	43.54 ^{g}	97.68 ^{g}	401.76 ^{h}	224.72 ^{g}	361.92 ^{h}
M_4H_1	79.58 $_{c}$	51.35 ^{bc}	107.70 ^{c}	484.36 ^{e}	275.40 ^{bc}	581.47 ^{c}	79.28 ^{bc}	50.74^{bc}	107.07^{bc}	476.28 ^{d}	267.12 ^{c}	430.56 ^{d}
M_5H_1	80.38 ^{bc}	39.26 ^{h}	108.15^{bc}	501.66 ^{c}	277.56 ^{bc}	591.85 ^{bc}	79.80 ^{bc}	50.95^{bc}	107.36^{bc}	489.24 ^{c}	271.36 ^{c}	443.04 ^{c}
M_0H_2	51.86 ^{h}	50.22 ^{d}	92.21 ^{h}	276.78 ^{l}	113.40 ^{k}	240.89 ^{i}	52.29 ^{j}	39.38 ^{j}	92.25 ^{j}	275.40 ^{k}	154.05 ^{j}	247.52 ^{k}
M_1H_2	77.72 ^{d}	42.94 ^{g}	106.66 ^{d}	467.06 ^{f}	259.20 ^{de}	554.47 ^{de}	77.35 ^{d}	49.93 ^{d}	106.02 ^{d}	456.84 ^{e}	254.40 ^{d}	411.84 ^{ef}
M_2H_2	60.54 ^{g}	44.36 ^{f}	97.06 ^{g}	366.52 ^{j}	152.28 ^{i}	353.03 ^{g}	59.84 ^{h}	42.56 ^{h}	96.40 ^{h}	356.40 ^{i}	199.28 ^{h}	324.48 ^{i}
M_3H_2	63.91 ^{f}	51.67 ^{ab}	98.94 ^{f}	404.36 ^{i}	192.24 ^{f}	404.95 ^{f}	63.35 ^{fg}	44.03 ^{fg}	98.32^{fg}	401.76 ^{h}	224.72 ^{g}	361.92 ^{h}
M_4H_2	81.15 ^{ab}	51.88 ^{a}	108.57^{ab}	489.77 ^{de}	271.08 ^{c}	581.47 ^{c}	79.41^{bc}	50.79 ^{bc}	107.14^{bc}	476.28 ^{d}	267.12 ^{c}	430.56 ^{d}
M_5H_2	81.63 ^{a}	38.69 ^{i}	108.84 ^{a}	497.34 ^{cd}	279.72 ^{ab}	589.77 ^{bc}	81.22 ^{a}	51.55 ^{a}	108.14 ^{a}	489.24 ^{c}	271.36 ^{c}	443.04 ^{c}
M_0H_3	50.51 i	38.69 ^{i}	91.46 ^{i}	323.27 ^{k}	124.20 ^{j}	257.51 ^{h}	50.17 ^{k}	38.49 ^{k}	91.08 ^{k}	317.52 ^{j}	176.67 ^{i}	289.12 ^{j}
M_1H_3	77.27 ^{de}	50.03 ^{de}	106.41 ^{de}	535.18 ^{b}	263.52 ^{d}	558.62 ^{d}	76.51 ^{de}	49.57 ^{de}	105.56 ^{de}	521.64 ^{b}	288.32 ^{b}	474.24 ^{b}
M_2H_3	60.12 ^{g}	42.76 ^{g}	96.83 ^{g}	420.57 ^{h}	165.24 ^{h}	357.19 ^{g}	57.26 ^{i}	41.47 ^{i}	94.98 ^{i}	412.56 ^{g}	230.37 ^{f}	372.32 ^{g}
M_3H_3	64.39 ^{f}	44.57 ^{f}	99.21 ^{f}	458.41 ^{g}	185.76 ^{fg}	398.72 ^{f}	64.44 ^{f}	44.49 ^{f}	98.92 f	443.88 ^{f}	245.92 ^{e}	405.60 ^{f}
M_4H_3	79.61 ^{c}	51.02 ^{c}	107.71 ^{c}	589.24 ^{a}	275.40 ^{bc}	598.08 ^{ab}	78.72 ^{c}	50.50 ^{c}	106.77 c	573.48 ^{a}	318.00 ^{a}	524.16 ^{a}
M_5H_3	80.35 ^{bc}	51.34 ^{bc}	108.13 ^{bc}	590.32 ^{a}	286.20 ^{a}	604.31 ^{a}	80.27 ^{ab}	51.15 ^{ab}	107.62ab	573.48 ^{a}	318.00 ^{a}	524.16 ^{a}
$LSD_{0.05}$	0.86	0.37	0.49	0.024	6.84	10.50	1.17	0.49	0.64	8.51	4.58	4.27

M_0: control, M_1: Recommended NPK (220-140-90 kg ha^{-1}), M_2: 25% NPK + 5 t ha^{-1} biochar, M_3: 50% NPK + 5 t ha^{-1} biochar, M_4: 75% NPK + 5 t ha^{-1} biochar, M_5: 100% NPK + 5 t ha^{-1} biochar, H_1: YH 5394, H_2: YH 1898, H_3: FH 1046, DW: dry weight. For wheat crop: H1 = V1, H2 = V2, H3 = V3. Different letters show statistically similar results.

3.2. Yield Parameters

Yield parameters, like 1000 grain weight, grain yield and harvest index, were noted during the study period for maize and wheat crop. In the case of maize grain weight, significantly heavier grains were observed in treatment combinations of M5H2 (317 g), M4H2 (317 g) and M5H3 (313 g), which were 44.16% and 43.45% higher than the control treatment (M0H1). Crops grown under INM (M4H2, M5H2) also produced maximum grain yield (6.04, 6.06 t/ha) which was almost 60% higher than control (M0H1) and 9% higher than sole inorganic fertilization. The harvest index was also statistically higher in treatments M5H2 and M4H2 (35.95%, 36.22%), which was almost 30% higher than the control. Crops grown without fertilization (M0) produced the lightest grains and so exhibited the lowest grain yield and harvest index (Table 3).

In the case of wheat crops, for the year 2018–2019, the treatment combinations of M4V3 (39.85 g) and M5V3 (39.97 g) produced statistically heaviest grains as compared to other treatments. These treatments enhanced almost 54% grain weight over control and 20% over sole inorganic fertilization. Similarly, the grain yield was also higher in the treatment combinations of M4V3 (5119 kg/ha) and M5V3 (5134 kg/ha), which were almost 63% higher than control and 24% higher than sole inorganic fertilization treatment. Moreover, these treatments enhanced harvest index as well in the same pattern as observed in grain weight and overall grain yield. Treatments M4V3 and M5V3 recorded the highest harvest index (37.99, 38.04), which was about 29% higher than control and 11% higher than sole inorganic fertilization. Both crops behaved similarly for the next growing period in 2019–2020 (Table 2).

Table 3. Impact of biochar-integrated application on crop yield and yield attributing factors in maize–wheat cropping system.

	Maize (2018–2019)			Wheat (2018–2019)			Maize (2018–2019)			Wheat (2018–2019)		
Treat.	**1000-GW (g)**	**GY (t/ha)**	**HI (%)**	**1000-GW (g)**	**GY (t/ha)**	**HI (%)**	**1000-GW (g)**	**GY (t/ha)**	**HI (%)**	**1000-GW (g)**	**GY (t/ha)**	**HI (%)**
M_0H_1	177 ^{i}	2.37 ^{k}	25.91 ^{d}	18.81 ^{k}	1855 ^{k}	26.97 ^{j}	172 +	2.13 ^{j}	22.84 ^{e}	18.73 ^{k}	2007 ^{j}	29.08 ^{hi}
M_1H_1	294 ^{d}	5.45 ^{e}	35.81 ^{a}	31.84 ^{e}	3664 ^{e}	34.13 ^{de}	290 ^{e}	5.33 ^{e}	35.23 ^{a}	31.73 ^{e}	3762 ^{d}	34.91 ^{c}
M_2H_1	234 ^{g}	3.00 ^{i}	24.73 ^{fg}	24.73 ^{i}	2432 ^{i}	28.62 ^{i}	233 ^{h}	2.98 ^{g}	24.48 ^{d}	24.64 ^{i}	2462 ^{h}	28.87 ^{i}
M_3H_1	258 ^{e}	3.65 ^{g}	27.27 ^{c}	27.57 ^{h}	3114 ^{g}	29.76 ^{h}	257 ^{f}	3.79 ^{f}	28.77 ^{b}	27.47 ^{h}	3121 ^{f}	29.73 ^{ghi}
M_4H_1	309 ^{b}	5.86^{bc}	36.22 ^{a}	32.79 ^{d}	4247 ^{d}	33.71 ^{e}	311 ^{ab}	5.78 ^{c}	35.54 ^{a}	32.67 ^{d}	4280 ^{c}	33.85 ^{d}
M_5H_1	311^{ab}	5.91 ^{b}	35.94 ^{a}	34.00 ^{c}	4401 ^{b}	34.92 ^{cd}	311 ^{ab}	5.89^{bc}	35.83 ^{a}	33.87 ^{c}	4431 ^{b}	35.05 ^{c}
M_0H_2	190 ^{h}	2.53 ^{j}	25.71 ^{de}	18.74 ^{k}	1920 ^{k}	29.39 ^{hi}	187 ^{i}	2.46 ^{h}	25.81 ^{c}	18.66 ^{k}	1937 ^{k}	29.54 ^{hi}
M_1H_2	300 ^{c}	5.57 ^{d}	35.79 ^{a}	31.63 ^{e}	3704 ^{e}	35.60 ^{bc}	302 ^{cd}	5.56 ^{d}	35.66 ^{a}	31.52 +	3736 ^{d}	35.76 ^{bc}
M_2H_2	241 ^{f}	3.15 ^{h}	25.26d^{ef}	24.84 ^{i}	2436 ^{i}	29.61 ^{h}	242 ^{g}	3.05 ^{g}	24.48 ^{d}	24.75 ^{i}	2472 ^{h}	29.93 ^{gh}
M_3H_2	256 ^{e}	3.78 ^{f}	28.50 ^{b}	27.39 ^{h}	3115 ^{g}	30.85 ^{g}	254 ^{f}	3.81 ^{f}	28.68 ^{b}	27.29 ^{h}	3139 ^{f}	30.98 ^{f}
M_4H_2	317 ^{a}	6.04 ^{a}	36.22 ^{a}	33.15 ^{d}	4292 ^{cd}	35.33 ^{bc}	317 ^{a}	5.92^{ab}	35.75 ^{a}	33.03 ^{d}	4325 ^{c}	35.48 ^{bc}
M_5H_2	317 ^{a}	6.06 ^{a}	35.95 ^{a}	33.67 ^{c}	4356 ^{bc}	35.80 ^{b}	316 ^{ab}	6.01 ^{a}	35.91 ^{a}	33.54 ^{c}	4390 ^{b}	35.94 ^{b}
M_0H_3	178 ^{i}	2.33 ^{k}	25.20^{ef}	21.88 ^{j}	2267 ^{j}	29.91 ^{h}	178 ^{j}	2.27 ^{i}	25.00^{cd}	21.81 ^{j}	2323 ^{i}	30.53 ^{fg}
M_1H_3	297 ^{cd}	5.52 ^{d}	35.82 ^{a}	36.21 ^{b}	4270 ^{d}	35.50 ^{bc}	297 ^{de}	5.46 ^{d}	35.72 ^{a}	36.07 ^{b}	4306 ^{c}	35.66 ^{bc}
M_2H_3	240 ^{fg}	3.01 ^{i}	24.21 ^{g}	28.53 ^{g}	2833 ^{h}	31.88 ^{f}	240 ^{gh}	3.02 ^{g}	24.52 ^{d}	28.42 ^{g}	2928 ^{g}	32.81 ^{e}
M_3H_3	259 ^{e}	3.71^{fg}	27.67 ^{c}	31.03 ^{f}	3470 ^{f}	32.04 ^{f}	257 ^{f}	3.86 ^{f}	28.97 ^{b}	30.93 ^{f}	3562 ^{e}	32.76 ^{e}
M_4H_3	308 ^{b}	5.80 ^{c}	35.83 ^{a}	39.85 ^{a}	5119 ^{a}	37.99 ^{a}	309 ^{bc}	5.81 ^{c}	35.64 ^{a}	39.71 ^{a}	5166 ^{a}	38.19 ^{a}
M_5H_3	313 ^{ab}	5.91 ^{b}	35.96 ^{a}	39.97 ^{a}	5134 ^{a}	38.04 ^{a}	311 ^{ab}	5.86^{bc}	35.63 ^{a}	39.83 ^{a}	5171 ^{a}	38.16 ^{a}
$LSD_{0.05}$	6.60	0.07	0.71	0.49	69	0.81	7.24	0.10	0.94	0.48	54	0.88

M_0: control, M_1: Recommended NPK (220-140-90 kg ha^{-1}), M_2: 25% NPK + 5 t ha^{-1} biochar, M_3: 50% NPK + 5 t ha^{-1} biochar, M_4: 75% NPK + 5 t ha^{-1} biochar, M_5: 100% NPK + 5 t ha^{-1} biochar, H_1: YH 5394, H_2: YH 1898, H_3: FH 1046, GW: grain weight, GY: grain yield, HI: harvest index. For wheat crop: H1 = V1, H2 = V2, H3 = V3. Different letters show statistically similar results.

3.3. Nutrients Uptake and Grain Quality

It is evident from the average data of both years (Figures 1 and 2) that maize plants grown under biochar integrated nutrient application treatment (M4 and M5) uptake a higher amount of macro and micro nutrients (N, P, K, Ca, Mg, Zn) in all hybrids, while hybrids H2 and H3 gave more pronounced responses and recorded higher values under M4 and M5. Plants (H2/H3) uptake more nutrients (68%, 39%, 44.41%, 39.87, 54% and 26% more N, P, K, Ca, Mg and Zn, respectively) under these treatment combinations as compared to the control (M0H1). All other treatment combinations were found statistically inferior to these aforementioned combinations. Similarly, the protein and carbohydrates were also enhanced under M4 and M5. Hybrids H1 and H2 improved protein content (3.14%) and carbohydrate (3.18%) content while grown under treatments M4 and M5 as compared to the control combined with hybrid-1 (M0H1).

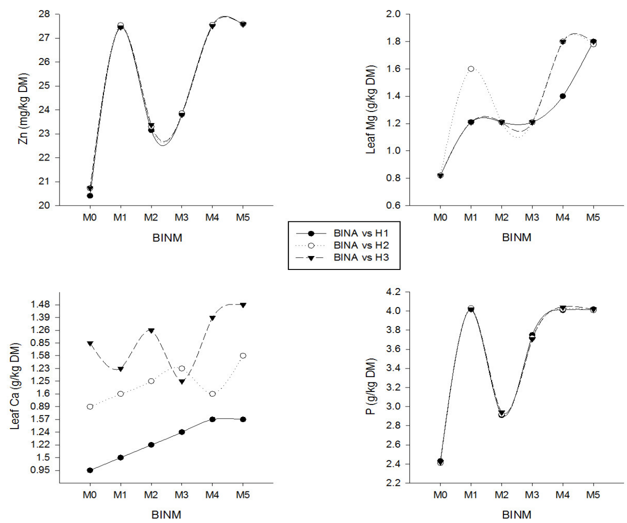

Figure 1. Zinc (Zn), Leaf-Magnesium (Mg), Leaf-Calcium (Ca) and Phosphorus (P) contents under biochar integrated nutrient application (BINA) in different maize hybrids.

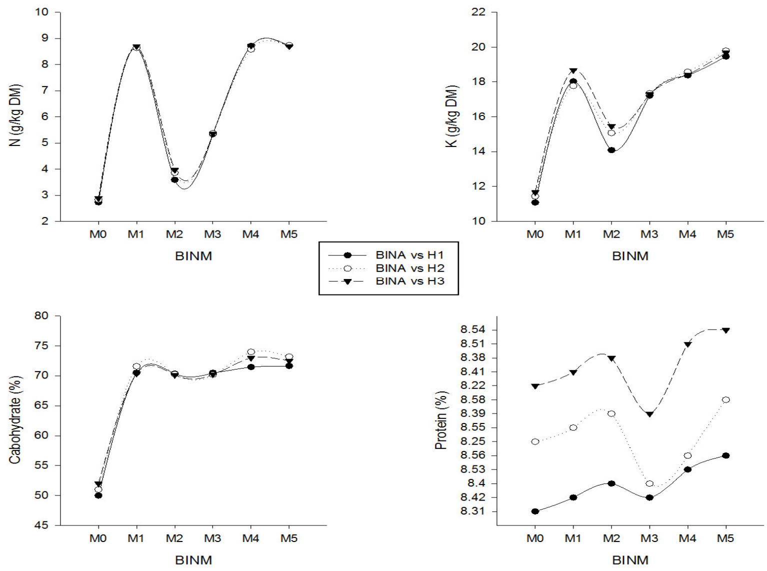

Figure 2. Nitrogen (N), Potassium (K), carbohydrates and protein contents under biochar integrated nutrient application (BINA) in different maize hybrids.

Data explained in Figures 3 and 4 depict that all wheat varieties were found to be responsive to integrated nutrient application with biochar. Treatment combinations: M4V1, M5V1, M4V2, M5V2, M4V3 and M5V3 recorded higher nutrient accumulations (N, P, K, Ca, Mg, Zn) in wheat plants and resulted as statistically at par with each other. The highest value (M5V3) in comparison with control treatment revealed that wheat plants improved (67%, 72%, 71%, 42%, 55%, 26%) these nutrient accumulations respectively. Similarly, the wheat crop also improved grain quality in the sense of protein and carbohydrate concentration in the aforementioned combinations. The highest protein and carbohydrate contents were recorded in M4 and M5 treatments.

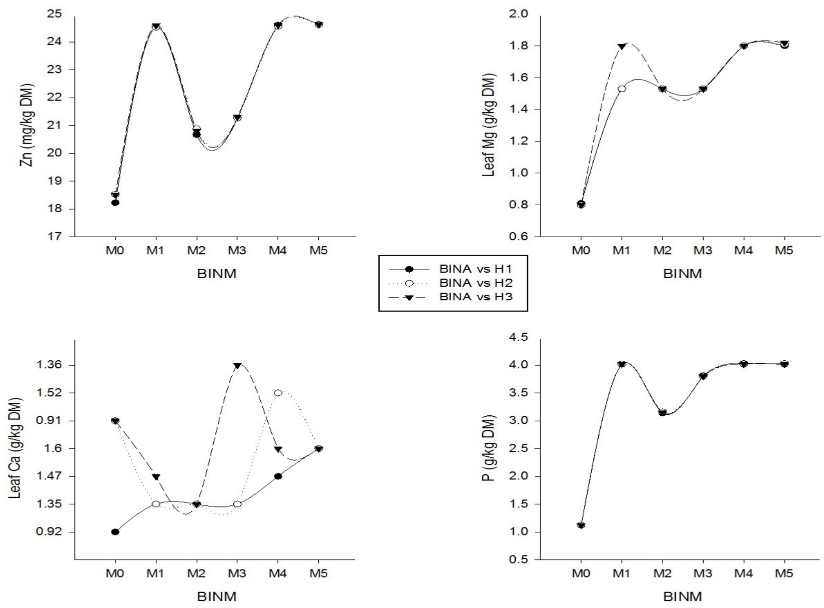

Figure 3. Zinc (Zn), Leaf-Magnesium (Mg), Leaf-Calcium (Ca) and Phosphorus (P) contents under biochar integrated nutrient application (BINA) in different wheat verities (H1 = V1, H2 = V2, H3 = V3).

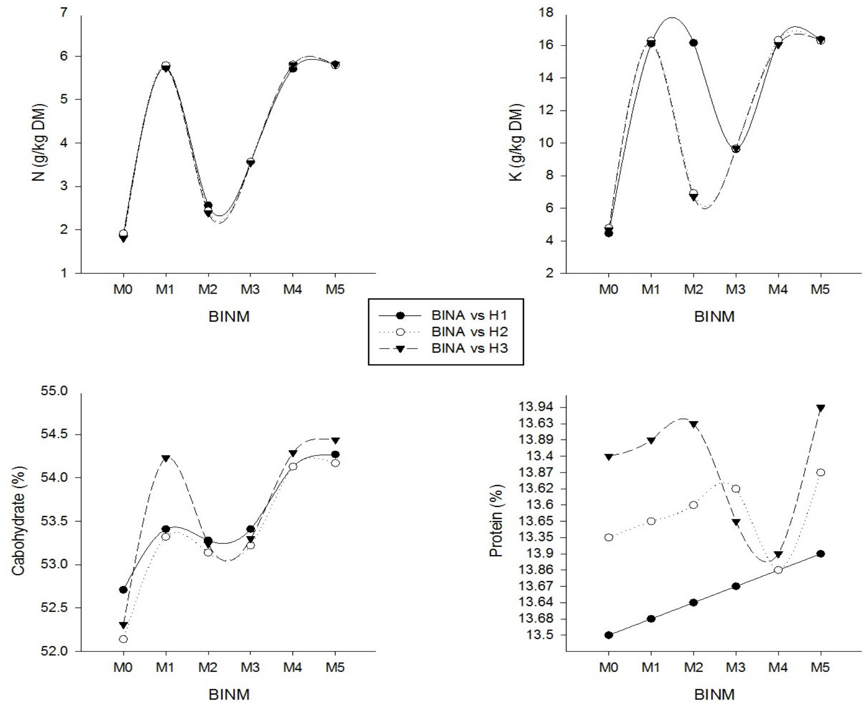

Figure 4. Nitrogen (N), Potassium (K), carbohydrates and protein contents under biochar integrated nutrient application (BINA) in different wheat varieties (H1 = V1, H2 = V2, H3 = V3).

3.4. Economic Analysis

Economic analysis was also carried out for both seasons and for both crops separately. Average values for the crops were drawn from both growing seasons, and are given in Table 3. Analysis revealed that the maximum (2.10) benefit–cost ratio (BCR) was calculated in treatment M4 (75% NPK + 5 t ha^{-1} biochar), followed by M1 (sole inorganic fertilizer) and M5 (100% NPK + 5 t ha^{-1} biochar). A higher benefit under treatment M4 further explained that under this treatment the crop was matured with less expense compared with M5. Similarly, the lowest values were recorded in M2 (25% NPK + 5 t ha^{-1} biochar) and M3 (50% NPK + 5 t ha^{-1} biochar) treatments (Table 4).

Table 4. Economic analysis of maize and wheat under biochar integrated nutrient application (average of both years).

Parameters	No NPK	Recommended NPK (220-140-90 kg ha^{-1})	25% NPK + 5 t ha^{-1} Biochar	50% NPK + 5 t ha^{-1} Biochar	75% NPK + 5 t ha^{-1} Biochar	100% NPK + 5 t ha^{-1} Biochar	Remarks
Maize crop							
Total earning	92,785	21,2135	117,425	142,835	227,150	229,460	Rs.1540/40 kg
Cost of cultivation	51,234	10,7212	80,229	94,223	108,219	122,212	Rs. ha^{-1}
Net Return	41,551	10,4923	37,196	48,612	118,931	107,248	Rs. ha^{-1}
BCR	1.81	1.98	1.46	1.52	2.10	1.88	
Wheat crop							
Total earning	57,903	11,1521	73,801	92,949	130,899	133,113	Rs.1150/40 kg
Cost of cultivation	35,461	6,9787	59,042	67,624	76,205	84,787	Rs. ha^{-1}
Net Return	22,442	4,1734	14,759	25,325	54,694	48,326	Rs. ha^{-1}
BCR	1.63	1.60	1.25	1.37	1.72	1.57	

BCR = Benefit–cost ratio, USD 1 = PKR 220.

In the case of wheat crop, M4 treatment was found to be more economically sound compared with other treatments. Treatment combinations combining application of biochar and inorganic fertilizer i.e., 75% NPK + 5 t ha^{-1} biochar (M4) recorded higher BCR relative to M5 (100% NPK + 5 t ha^{-1} biochar). This treatment exceeds to M5 due to having lower calculated expenses involved in the different crop inputs. Treatments M2 and M3, recorded the lowest BCR, which indicates that proper combinations matter while going for integrated application (Table 5).

Table 5. System productivity of wheat–maize under NPK + biochar during 2018–2019.

Treatments	No NPK	Recommended NPK (120-80-60 kg ha^{-1})	25% NPK + 5 t ha^{-1} Biochar	50% NPK + 5 t ha^{-1} Biochar	75% NPK + 5 t ha^{-1} Biochar	100% NPK + 5 t ha^{-1} Biochar	Remarks
Wheat	22,442	41,734	14,759	25,325	54,694	48,326	Rs. ha^{-1}
Maize	41,551	104,923	37,196	48,612	118,931	107,248	Rs. ha^{-1}
Total income	63,993	146,657	51,955	73,937	173,625	155,574	
			2019–2020				
Wheat	28,914	51,358	21,083	32,679	64,993	58,494	Rs. ha^{-1}
Maize	36,623	103,604	34,867	52,500	117,676	106,465	Rs. ha^{-1}
Total income	65,537	154,962	55,950	85,179	182,669	164,959	Rs. ha^{-1}

3.5. System Productivity

Data regarding the system productivity of wheat–maize under biochar integrated nutrient application (NPK + biochar) showed that maximum system productivity (Rs. 173625 in 2018–2019 and Rs. 182669) was recorded for 75% NPK + 5 t ha^{-1} biochar (M4) followed by 100% NPK + 5 t ha^{-1} biochar (M5) (Rs. 155574 in 2018–2019 and Rs. 164959 in 2019–2020). The lowest system productivity (Rs. 51955 in 2018–2019 and Rs. 55950 in 2019–2020) was observed for 25% NPK + 5 t ha^{-1} biochar, followed by control treatment (no NPK).

4. Discussion

In Pakistan, most of the soil is calcareous in nature, which can fix the applied phosphorus into undissolved compounds as calcium phosphate [34]. Aside from this factor, low organic matter in the soil due to high temperatures also reduces the fertilizer binding force in the soil [2,35]. These factors reduce nutrient use efficiency (NUE) due to higher losses in the form of leaching and volatilization [4,36]. Inorganic fertilizers are a very expensive input for crop production, which is going to be more expensive day by day and out of range for farmers especially in the developing countries. These factors may lead towards less fertilizer application, which may cause nutritional stress in the field crops and cause low productivity. Due to this, better or site specific sustainable nutrient management approaches are needed to meet the food security. Biochar is a pyrolyzed material that works as a soil conditioner to improve the soil characteristics for binding soil nutrients when applied with inorganic fertilizer [37,38]. It was further found that biochar application significantly reduced leaching of nitrate, ammonium, phosphate and other ionic solutes [39,40]. Thus, biochar incorporation could be an efficient technique to reduce nutrient leaching and increase their availability to plants, which results in higher growth and yield.

Experiment outputs exhibited that integrated application of fertilizer along with biochar under a specific percentage improved crop performance in the sense of dry matter production, crop yield and quality. Dry matter production and its distribution among plant parts has great significance, as grain yield is directly correlated with biomass. Although dry matter partitioning is a genetic factor, its optimum production is dependent on balanced nutrition, which improves the grain filling. Biochar has superiority relative to other organic sources due to its spongy structure which can absorb or bind the nutrients in the soil. Previous studies reported that biochar application in soil improved the plant growth by optimizing the uptake of essential nutrients [11,16]. Biochar not only improves the nutrient availability but also provides the nutrients after its mineralization, which is dependent on pyrolyzed material [41,42]. This factor is witnessed by the experiment results as an integrated application of biochar (5 t/ha) along with a reduced dose of inorganic fertilizer (75%) or a full dose of fertilizer produced higher plant dry matter among all the plant parts. Enhanced dry matter under INM improved the grain yield in the various field crops [26,36,43]. This might be due to the availability of essential nutrients in the soil for a longer time, as organic fertilizer provides nutrients in the soil after the mineralization process. There should be a balance between mineralization and immobilization of different nutrients in the soil for better nutrient availability which can be maintained by INM. Moreover, biochar also improves the soil physical, chemical and biological characteristics, which provides a favorable environment for plant growth and development [44,45].

Slow releasing fertilizers are also getting attention due to having higher nutrient use efficiency (NUE) by reducing losses and improving crop yield. Many innovative strategies are being developed to improve the nutrient use efficiency, e.g., coated fertilizers and nano-fertilizer technologies with a similar theme to INM. Our experiment results also demonstrated that INM acts as a slow releasing fertilizer because, under sole application of inorganic fertilizer, crop performance was lower as compared to integrated application (M4 and M5). It might be due to the binding of nutrients in biochar which released slowly in the soil after the mineralization process [2,46]. It is also evident from the results that the highest nutrient accumulation was observed in the treatments where 75% or a full dose of inorganic fertilizer were applied along with biochar (M4 and M5). Previous research work also added that biochar works to bind the nutrients due to having a higher surface area which improves the NUE [41,47].

Under INM, plants get sufficient nutrients, which is evident from the plant analysis as integrated application enhanced the nutrients uptake. A balanced application of various macro and micro nutrients are needed for successful crop production. This strategy also showed that crops with balanced nutrition did not face nutritional stress and had enhanced crop productivity. It has also been reported previously that integrated application appeared as a sustainable technique to improve the crop yield in maize–wheat and rice–wheat cropping systems [2,4]. Improved yield is the cumulative result of various factors like better soil characteristics which enable the proper root growth that favors the nutrients uptake which participates in the various metabolic processes in the plants. Biochar addition has been reported to provide similar conditions to improve the soil characteristics in term of pH, CEC and availability of nutrients [37].

Furthermore, economic analysis is the major factor which decides what fertilizer is used, which is crucial in the developing countries like Pakistan where most of the farmers are hand to mouth. Integrated nutrient management not only improved the soil health but also resulted in improved benefits, which might be the most attractive factor for the farmers. These results also suggest that farmers can improve the productivity of a wheat–maize cropping system with integrated soil fertilizers and can save the precious inputs. Similar findings were also shown in some previous studies to improve the maize–wheat system productivity with integrated nutrient management [2,42]. Although farmers can get good crop yield with inorganic fertilizer application, this system have many drawbacks as it pollutes our natural resources, and so cannot be followed for a longer time. We should evaluate and suggest the sustainable practices by which we can get the yield goal without compromising natural resources. There is also the pressure of time as population is growing fast, requiring higher cereal production for ensuring food security. INM practice can also be environment friendly, as plant or animal wastes can also be consumed in a useful manner, or used for carbon sequestration. Biochar preparation also provides a better process for plant waste management, as it can squeeze carbon and also be included in soil fertility management practices.

5. Conclusions

Maize–wheat cropping system demands wise soil fertility management, which may help meet crop demand without compromising natural resources. Our results concluded that biochar integrated application with inorganic fertilizer (INM) proved to be a sustainable technique to enhance maize–wheat productivity. Further, treatment comparison revealed that the integrated nutrient approach (75% NPK + 5 ton/ha biochar) was the most economical and productive process for fertilizer application. This approach improved the nutrient availability in the soil, which enhanced its uptake in the crop plants. Crops grown under INM accumulated higher dry matter, which improved the grain yield in maize and wheat crop. Furthermore, this treatment combination also enhanced the system productivity and was observed as the most economical soil fertility management technique. The study also encourages to use biochar along with inorganic fertilizer, which may squeeze the carbon and work as a soil conditioner to improve soil characteristics for sustainable crop production.

Author Contributions: N.S.: experiment conceptualization, supervision, review and editing; N.A.: data collection, writing and preparation of initial draft; K.M.: plan layout and methodology; M.A. (Muhammad Akram) resources, M.W.H.: resources and investigation; O.F.: statistical analysis; A.-u.R.: review and editing; M.S.: investigation; M.A (Matloob Ahmad) and A.K.: visualization. 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: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the agronomy farm management who provided the labor as well as the inputs to complete this project. We also acknowledge the lab staff for their assistance in plant analysis. Moreover, we are also thankful to the soil science lab for their guidance and providing the biochar furnace for the preparation of biochar.

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

References

1. Wang, X.; Zhang, J.; Shamsuddin, S.; Xia, X.; He, R.; Shang, M. Catastrophe theory to assess water security and adaptation strategy in the context of environmental change. *Mitig. Adapt. Strateg. Glob. Chang.* **2014**, *19*, 463–477.
2. Sarwar, N.; Atique, R.; Omer, F.; Allah, W.; Mubshar, H.; Ahmed, S.; Shakeel, A.; Marian, B.; Samy, F.M.; Marek, Z.; et al. Integrated nitrogen management improves productivity and economic returns of wheat-maize cropping system. *J. King Saud Uni. Sci.* **2022**, *33*, 101475. [CrossRef]
3. Bhatt, R.; Singh, P.; Hossain, A.; Timsina, J. Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: Issues and technological interventions for increasing productivity and sustainability. *Paddy Water Environ.* **2021**, *19*, 345–365. [CrossRef]
4. He, H.; Li, D.; Pan, F.; Wang, F.; Wu, D.; Yang, S. Effects of Nitrogen Reduction and Optimized Fertilization Combined with Straw Return on Greenhouse Gas Emissions and Crop Yields of a Rice–Wheat Rotation System. *Int. J. Plant Prod.* **2022**, *16*, 669–679. [CrossRef]
5. Khalofah, A.; Khan, M.I.; Arif, M.; Hussain, A.; Ullah, R.; Irfan, M.; Mahpara, S.; Shah, R.U.; Ansari, M.J.; Kintl, A.; et al. Deep placement of nitrogen fertilizer improves yield, nitrogen use efficiency and economic returns of transplanted fine rice. *PLoS ONE* **2021**, *16*, e0247529. [CrossRef]
6. GOP. *Economic Survey of Pakistan*; Pakistan Bureau of Statistics: Islamabad, Pakistan, 2020.
7. Cerquiglini, C.; Claro, J.; Giusti, A.M.; Karumathy, G.; Mancini, D.; Marocco, E.; Mascianá, P.; Michetti, M.; Milo, M. *Food Outlook June 2016*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2016.
8. Tahir, M.; Ali, A.; Nadeem, M.; Hussain, A.; Khalid, F. Effect of different sowing dates on growth and yield of wheat (*Triticum aestivum* L.) varieties in district Jhang, Pakistan. *Pak. J. Life Soc. Sci.* **2009**, *7*, 66–69.
9. Shiferaw, B.; Smale, M.; Braun, H.J.; Duveiller, E.; Reynolds, M.; Muricho, G. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Secur.* **2013**, *5*, 291–317. [CrossRef]
10. Hussain, M.; Farooq, M.; Nawaz, A.; Al-Sadi, A.; Solaiman, Z.; Alghamdi, S.; Jawad, A.; Yong, S.; Siddique, K. Biochar for crop production: Potential benefits and risks. *J. Soils Sediments* **2017**, *17*, 685–716. [CrossRef]
11. FAO. *FAO Food Outlook 2013*; FAO: Rome, Italy, 2013.
12. Dixon, J.; Braun, H.-J.; Kosina, P.; Crouch, J.H. *Wheat Facts and Futures 2009*; Cimmyt: Mexico City, Mexico, 2009.
13. Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockaday, W.C.; Crowley, D. Biochar effects on soil biota—A review. *Soil Biol. Biochem.* **2011**, *43*, 1812–1836. [CrossRef]
14. Weber, K.; Quicker, P. Properties of biochar. *Fuel* **2018**, *217*, 240–261. [CrossRef]
15. Adekiya, A.O.; Agbede, T.M.; Olayanju, A.; Ejue, W.S.; Adekanye, T.A.; Adenusi, T.T.; Ayeni, J.F. Effect of Biochar on Soil Properties, Soil Loss, and Cocoyam Yield on a Tropical Sandy Loam Alfisol. *Sci. World J.* **2020**, *2020*, 9391630. [CrossRef]
16. Batool, A.; Taj, S.; Rashid, A.; Khalid, A.; Qadeer, S.; Saleem, A.; Ghufran, M. Potential of Soil Amendments (Biochar and Gypsum) in increasing Water Use Efficiency of Abelmoschus esculentus L. Moench. *Front. Plant Sci.* **2015**, *6*, 733. [CrossRef]

17. Agegnehu, G.; Bass, A.M.; Nelson, P.N.; Bird, M.I. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Sci. Total Environ.* **2016**, *543*, 295–306. [CrossRef]
18. Pandit, N.R.; Mulder, J.; Hale, S.E.; Martinsen, V.; Schmidt, H.P.; Cornelissen, G. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil. *Sci. Total Environ.* **2018**, *625*, 1380–1389. [CrossRef]
19. Kammann, C.I.; Schmidt, H.P.; Messerschmidt, N.; Linsel, S.; Steffens, D.; Müller, C.; Joseph, S. Plant growth improvement mediated by nitrate capture in co-composted biochar. *Sci. Rep.* **2015**, *5*, 11080. [CrossRef]
20. Liang, B.; Lehmann, J.; Solomon, D.; Kinyangi, J.; Grossman, J.; O'neill, B.; Neves, E.G. Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* **2016**, *70*, 1719–1730. [CrossRef]
21. Martinsen, V.; Mulder, J.; Shitumbanuma, V.; Sparrevik, M.; Børresen, T.; Cornelissen, G. Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 681–695. [CrossRef]
22. Atkinson, C.J.; Fitzgerald, J.D.; Hipps, N.A. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant Soil* **2010**, *33*, 1–18. [CrossRef]
23. Bharti, N.; Barnawal, D.; Shukla, S.; Tewari, S.K.; Katiyar, R.S.; Kalra, A. Integrated application of Exiguobacterium oxidotolerans, Glomus fasciculatum, and vermicompost improves growth, yield and quality of Mentha arvensis in salt-stressed soils. *Ind. Crops Prod.* **2016**, *83*, 717–728. [CrossRef]
24. Ng, L.C.; Sariah, M.; Radziah, O.; Zainal Abidin, M.A.; Sariam, O. Development of microbial-fortified rice straw compost to improve plant growth, productivity, soil health, and rice blast disease management of aerobic rice. *Compost Sci. Util.* **2016**, *24*, 86–97. [CrossRef]
25. Keteku, A.K.; Yeboah, S.; Agyemang, K.; Amegbor, I.; Danquah, E.O.; Amankwaa-Yeboah, P.; Dormatey, R.; Brempong, M.B. Evaluation of Carrier- and Liquid-Based Bioinoculant as a Promising Approach to Sustain Black Gram (*Vigna mungo* L.) Productivity. *Int. J. Plant Prod.* **2022**, *16*, 741–754. [CrossRef]
26. Sarma, I.; Phookan, D.B.; Boruah, S. Influence of manures and biofertilizers oncarrot (*Daucus carota* L.) cv. early Nantes growth, yield and quality. *J. Ecofriendly Agric.* **2015**, *10*, 25–27.
27. McLaughlin, H.; Anderson, P.S.; Shields, F.E.; Reed, T.B. All Biochars Are Not Created Equal, and How to Tell Them Apart? In Proceedings of the North American Biochar Conference, Boulder, CO, USA, 9–12 August 2009.
28. Singh, B.; Singh, B.P.; Cowie, A.L. Characterization and evaluation of biochars for their application as a soil amendment. *Austr. J. Soil Res.* **2010**, *48*, 516–525. [CrossRef]
29. Schouwenberg, V.J.C.H.; Walinge, I. *Methods of Analysis for Plant Material*; Agriculture University: Wageningen, The Netherlands, 1973.
30. Chapman, H.D.; Pratt, P.F. *Methods of Analysis for Soils, Plants and Water*; University of California: Berkeley, CA, USA, 1961.
31. CIMMYT. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. Mexico. 1988. Available online: http://hdl.handle.net/10883/3842 (accessed on 1 January 2023).
32. Steel, R.; Torrei, J.; Dickey, D. *Principles and Procedures of Statistics— A Biometrical Approach*; McGraw-Hill Kogakusha, Ltd.: New York, NY, USA, 1997.
33. Wyszkowski, M.; Brodowska, M.S. Phytoextraction with Maize of Soil Contaminated with Copper after Application of Mineral and Organic Amendments. *Agronomy* **2020**, *10*, 1597. [CrossRef]
34. Kalayu, G. Phosphate Solubilizing Microorganisms: Promising Approach as Biofertilizers. *Int. J. Agron.* **2019**, *2019*, 4917256. [CrossRef]
35. Ghimire, R.; Bista, P.; Machado, S. Long-term Management Effects and Temperature Sensitivity of Soil Organic Carbon in Grassland and Agricultural Soils. *Sci. Rep.* **2019**, *9*, 12151. [CrossRef]
36. Sarwar, N.; Atique, R.; Shakeel, A.; Mirza, H. *Modern Techniques in Rice Crop Production*; Springer: Berlin/Heidelberg, Germany, 2022.
37. Jenberu, G. *Biochar, Compost and Biochar-Compost: Effects on Crop Performance, Soil Quality and Greenhouse Gas Emissions in Tropical Agricultural Soils*; James Cook University: Douglas, Australia, 2017.
38. Adekiya, A.O.; Agbede, T.M.; Ejue, W.S.; Aboyeji, C.M.; Dunsin, O.; Aremu, C.O.; Adesola, O.O. Biochar, poultry manure and NPK fertilizer: Sole and combine application effects on soil properties and ginger (Zingiber officinale Roscoe) performance in a tropical Alfisol. *Open Agric.* **2020**, *5*, 30–39. [CrossRef]
39. Karimi, A.; Moezzi, A.; Chorom, M.; Enayatizamir, N. Application of Biochar Changed the Status of Nutrients and Biological Activity in a Calcareous Soil. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 450–459. [CrossRef]
40. Rubin, R.L.; Anderson, T.R.; Ballantine, K.A. Biochar Simultaneously Reduces Nutrient Leaching and Greenhouse Gas Emissions in Restored Wetland Soils. *Wetlands* **2020**, *40*, 1981–1991. [CrossRef]
41. Rodríguez-Vila, A.; Forján, R.; Guedes, R.S.; Covelo, E.F. Changes on the phytoavailability of nutrients in a mine soil reclaimed with compost and biochar. *Water Air Soil Pollut.* **2016**, *227*, 453. [CrossRef]
42. Sahoo, G.; Wani, A.M.; Roul, P.K.; Dash, A.C. Effect of Integrated Nutrient Management on Dry Matter Accumulation and Nutrient Uptake by Maize (Variety-MS 2) under Poplar Agroforestry System. *Int. J. Pl. Soil Sci.* **2021**, *33*, 254–260. [CrossRef]
43. Shareef, T.; Zhao, B. Review Paper: The Fundamentals of Biochar as a Soil Amendment Tool and Management in Agriculture Scope: An Overview for Farmers and Gardeners. *J. Agricul. Chem. Environ.* **2017**, *6*, 38–61. [CrossRef]
44. Blanco-Canqui, H. Biochar and Soil Physical Properties. *Soil Sci. Soc. Am. J.* **2017**, *81*, 687–711. [CrossRef]
45. Lu, J.; Hu, T.; Zhang, B.; Wang, L.; Yang, S.; Fan, J.; Yan, S.; Zhang, F. Nitrogen fertilizer management effects on soil nitrate leaching, grain yield and economic benefit of summer maize in Northwest China. *Agric. Water Manag.* **2021**, *247*, 106739. [CrossRef]

46. Abbas, S.; Javed, M.T.; Ali, Q.; Chaudhary, H.J.; Rizwan, M. Alteration of Plant Physiology by the Application of Biochar for Remediation of Organic Pollutants. In *Handbook of Bioremediation*; Academic Press: Cambridge, MA, USA, 2021; pp. 475–492. [CrossRef]
47. Ding, Y.; Liu, Y.; Liu, S.; Li, Z.; Tan, X.; Zeng, G.; Zhou, L.; Zheng, B. Biochar to improve soil fertility. A review. *Agron. Sustain. Dev.* **2016**, *36*, 36. [CrossRef]