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Sustainable Soil Management in Alkaline Soils: The Role of Biochar and Organic Nitrogen in Enhancing Soil Fertility

Mushtaq Ahmad Khan [1], Abdul Basir [1], Syed Tanveer Shah [2], Monsif Ur Rehman [2], Mehmood ul Hassan [2], Hongbing Zheng [3], Abdul Basit [4], Árpád Székely [5], Aftab Jamal [6,*], Emanuele Radicetti [7], Yaser Hassan Dewir [8] and Roberto Mancinelli [9,*]

[1] Department of Agriculture, University of Swabi Anbar Swabi, Swabi 23561, Pakistan; mushtaq@uoswabi.edu.pk (M.A.K.); a.basir@uoswabi.edu.pk (A.B.)
[2] Department of Agriculture, Hazara University Mansehra, Mansehra 23100, Pakistan; dr.syedtanveershah@hu.edu.pk (S.T.S.); drmonsif@hu.edu.pk (M.U.R.); mehmoodagri@hu.edu.pk (M.u.H.)
[3] College of Agronomy, Jinlin Agricultural University, Changchun 130118, China; hongbingzheng@126.com
[4] Floricultural Biotechnology Laboratory, Department of Horticultural Science, Kyungpook National University, Deagu 41566, Republic of Korea; abdulbasit97_lily@knu.ac.kr
[5] Research Center for Irrigation and Water Management, Institute of Environmental Sciences, Hungarian University of Agriculture and Life Sciences, Anna-Liget Str. 35, 5540 Szarvas, Hungary; szekely.arpad@uni-mate.hu
[6] Department of Soil and Environmental Sciences, Faculty of Crop Production Sciences, The University of Agriculture, Peshawar 25130, Pakistan
[7] Department of Chemical, Pharmaceutical and Agricultural Sciences (DOCPAS), University of Ferrara, 44121 Ferrara, Italy; rdcmnl@unife.it
[8] Department of Plant Production, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia; ydewir@ksu.edu.sa
[9] Department of Agricultural and Forestry Sciences, University of Tuscia, Via San Camillo de Lellis SNC, 01100 Viterbo, Italy
* Correspondence: aftabses98@gmail.com (A.J.); mancinel@unitus.it (R.M.)

Abstract: Biochar (BC) serves a vital function in sequestering carbon, improving nutrient cycles, and boosting overall soil quality. This research explored the enhancement of the chemical and physical properties of soil (alkaline) using nitrogen and biochar (from organic and inorganic sources) in a semi-arid climate during the autumn seasons of 2015–2016 and 2016–2017. The study involved applying biochar at various rates (0, 10, 20, and 30 t ha^{-1}) and nitrogen at different levels (0, 90, 120, and 150 kg ha^{-1}) using urea, poultry manure (PM), and farmyard manure (FYM) as nitrogen sources, which were applied to the field in a randomized complete block design with split-plot arrangement. The application of biochar at the highest rate (30 t ha^{-1}) resulted in a significant increase of over 120% in soil organic matter (SOM), soil organic carbon (SOC), and soil moisture content (SMC). Additionally, it increased total soil nitrogen (STN) by 14.16% and mineral nitrogen (SMN) by 9.09%. In contrast, applying biochar at this rate reduced soil bulk density (SBD), pH, and electrical conductivity (EC) by 28.52%, 3.38%, and 2.27%, respectively, compared to the control. Similarly, applying nitrogen at 150 kg ha^{-1} using FYM significantly improved SOC, SOM, SMC, and SBD. At the same rate, using PM as a nitrogen source enhanced STN and SMN while reducing soil pH and EC. In conclusion, this study shows that applying biochar at 30 t ha^{-1} combined with nitrogen at 150 kg ha^{-1}, sourced from either PM or FYM, offers great potential for improving soil fertility and promoting carbon sequestration in alkaline soils of semi-arid regions. These findings highlight the value of integrating BC and organic N sources for enhancing agroecosystem sustainability. Thus, this study provides a promising pathway to enhance soil quality, improve crop productivity, and support sustainable agricultural practices in challenging environments.

Keywords: soil fertility; electrical conductivity; soil organic carbon; farmyard manure; poultry manure

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1. Introduction

Inorganic fertilizer application is widely regarded as one of the most effective methods for enhancing soil fertility among various agricultural practices [1]. Nevertheless, the persistent application of synthetic fertilizers causes significant negative impacts on soil characteristics (synthetic and physical), including a reduction in soil organic matter (SOM) [2]. Harmful factors associated with the use of conventional fertilizers include the prolific leaching of nutrients into groundwater and eutrophication, significant fossil fuel consumption during fertilizer production, and the ever-increasing costs associated with these fertilizers [3]. Consequently, there would be strong support for fertilization methods that are both efficient and eco-friendly. The main suppliers of nutrients are organic fertilizers, which are generally derived from animal manure, poultry droppings, etc. [4]. It has been reported that organic manure can modify the physical and chemical properties of soil due to its comprehensive nutrient content [5]. Furthermore, organic fertilizers are more efficient than mineral fertilizers [6]. Consequently, the use of organic manure presents an ideal method for recycling nutrients in the soil and minimizing environmental contamination [7]. The unpredictable and slow release of nutrients from organic fertilizers limits their widespread use [8]. Additionally, the benefits of organic fertilizers are often short-term in soil with the rapid degradation of SOM at high temperatures [9]. Therefore, additional organic matter that mineralizes within a few days after application should be applied [10].

Hence, there is a need to explore alternative methods of sustainable soil management to boost the current yield potential of soils. The sustainable management of soil requires techniques that improve soil's physical and chemical properties while ensuring optimal crop yields over time. Therefore, to boost soil fertility, there is an urgent need to use highly stable and nutrient-retentive organic materials such as biochar (BC) [11]. BC is a porous, carbon-based material obtained from the decomposition of organic matter under high temperatures and in low-oxygen conditions. Its unique physiochemical characteristics make it well suited for carbon storage for longer periods of time in the environment and offer promising potential for enhancing soil properties [12]. The utilization of biochar for soil fertility improvement is receiving growing interest because of its capability to enhance soil structure and texture, increase crop productivity, and sequester carbon [13]. The addition of BC can enhance water availability in the soil [14]; improve water-holding capacity [15]; increase soil aeration [16]; and boost soil organic carbon (SOC) [17], soil microbial activity, and biomass [18]. It also enhances enzyme activity [19] and nutrient retention and availability [20], resulting in reduced fertilizer requirements and decreased nutrient loss [21]. Published research indicates that BC can enhance soil nutrient levels, cation exchange capacity, soil structure, and nutrient use efficiency while also reducing soil acidity [22]. It has been demonstrated that the application of BC alters N dynamics within the soil [23]. Due to its high adsorption capacity, BC effectively retains nitrate and ammonium, making it beneficial for both water treatment and soil applications [24]. This characteristic allows for the enhanced storage of ammonium-N in the soil [25]. To address the issue of potentially inaccessible nitrogen, research has shown that combining BC with N fertilizer can yield positive results by enhancing the efficiency of mineral nitrogen fertilizers, decreasing reliance on inorganic fertilizers, and reducing costs [26]. Research has shown that incorporating biochar produced from materials like wood, maize straw, and rice husks can significantly increase soil nitrogen content. A study conducted by Varela Milla et al. [27] revealed that, after two years, this practice increased soil total nitrogen (STN) by 63% and soil mineral nitrogen (SMN) by 40%. Similarly, Wu et al. [28] reported improvements in STN levels following the application of wood biochar. Additionally, Major et al. [29] found that the incorporation of biochar derived from wood could either raise or lower soil pH, depending on the type of feedstock used for biochar production and the specific soil type. Wood biochar typically has a much lower bulk density (BD) compared to soil, and it also reduces the BD of the soil when incorporated [30]. The availability of plant nutrients and ash in biochar, along with its high surface area, porous structure, and ability to provide a habitat for microorganisms, is crucial for enhancing soil characteristics and improving nutrient uptake by plants in biochar-amended soils [31].

This study hypothesized that the combination of BC and N from organic sources, such as FYM and PM, would significantly enhance both the chemical and physical characteristics of soil, including organic matter content, nitrogen availability, and soil structure, compared to the use of either biochar or nitrogen alone in alkaline soils in a semi-arid environment. The main objectives of this study were to assess the individual and combined effects of nitrogen and biochar from different organic and inorganic origins on key soil health indicators over a two-year period. Additionally, the study aimed to evaluate the carryover effects of biochar on soil properties and nitrogen dynamics beyond the initial application period.

2. Materials and Methods

2.1. Description and Treatments at the Site of Experiment

The Field trials were conducted at the Agriculture Research Station (ARS) in Swabi, Khyber Pakhtunkhwa (KP), Pakistan, during the autumn seasons of 2015–2016 and 2016–2017. The study area is located at latitude 34°7′48″ N and longitude 72°28′11″ E, between the Indus and Kabul Rivers in KP, Pakistan. During the experimental period, the total monthly rainfall ranged from 0 to 188 mm, while the mean monthly air temperatures varied between 11.78 °C and 34.68 °C. Prior to the experiment, the field had been cropped with wheat and maize.

In both years, the experiment included four wood biochar (BC) application rates (0, 10, 20, and 30 t ha^{-1}) and three nitrogen (N) management levels (90, 120, and 150 kg ha^{-1}), along with a control treatment. The required nitrogen was supplied through various sources, including farmyard manure (FYM), urea, and poultry manure (PM), at different concentrations (control; 90, 120, 150 kg ha^{-1} urea; 90, 150 kg ha^{-1} N FYM; and 90, 120, and 150 kg ha^{-1} N PM) using a randomized complete block design with a split-plot arrangement and three replicates. In total, there were 40 treatments in each replicate, and they were repeated thrice. Each main plot comprised 10 subplots, and each subplot was 3×4 m^2. Row-to-row and plant-to-plant distances between the main plots and subplots were maintained at 1 m and 0.5 m, respectively. The same procedure was followed for the second-year experiment in 2016–2017.

2.2. Application of Biochar, Urea, FYM, and PM, and Sowing of Wheat Seeds

Biochar, derived from Acacia tree prunings, was obtained from the Agriculture Research Farm, The University of Agriculture Peshawar, Pakistan, following the detailed procedure of Arif et al. [32]. Farmyard manure (FYM) was obtained from a local dairy, and poultry manure (PM) was obtained from nearby poultry farms. The manures were stored under cover for three weeks before being used in the field experiments.

Following land preparation, the experimental field was organized into plots measuring 3×4 m^2. Biochar (BC) was sieved using 2 mm mesh, weighed, and then applied to the main plots according to the specified rates. Additionally, BC was mixed into the soil at a depth of 15 cm using a rotavator. Nitrogen content in PM and FYM was analyzed in the laboratory and then carefully incorporated into the subplots by hoeing, ensuring no cross-contamination occurred with neighboring subplots. The nitrogen content from urea was accurately calculated based on the 46% stated on the packaging and was applied at the time of sowing and during the tillering stage. Furthermore, both PM and FYM were incorporated into the field soil one week prior to sowing, while BC was incorporated during seedbed preparation. BC was applied once, while urea, FYM, and PM were applied in both seasons. Each subplot received a basal application of phosphorus (90 kg ha^{-1}) as a single application of superphosphate and potassium (60 kg ha^{-1}) in the form of potassium sulfate. Wheat cultivar 'Pirsabak 2013' was obtained from Cereal Crops Research Institute (CCRI) Pirsabak Nowshera, Pakistan, and was sown at a seed rate of 120 kg ha^{-1} in 3×4 m^2 plots, maintaining a row spacing of 30 cm. Broad-spectrum herbicide 'Atlantus' was used to control weeds in wheat crops. Crops were irrigated as needed using canal water. Normal cultural practices were carried out throughout the crop's growing period.

2.3. Determination of the Post-Harvest, Soil Physicochemical Properties

Tillage was performed using a cultivator that plowed the soil up to 15 cm depth for soil preparation. Soil samples were then randomly collected from 0 to 15 cm depth from various locations of the site with the help of soil auger before the start of the experiment in 2015. After drying, the soil samples were passed through a 2 mm sieve and subjected to various soil physicochemical analyses.

The soil of the experimental site belongs to the Gulyana soil series. The soil type was classified as Calcisols based on the World Reference Base (WRB) system of soil taxonomy, and the soil exhibited a silt loam texture, comprising 19.4% sand, 71.6% silt, and 8.96% clay. Additionally, soil samples were collected after the harvest of wheat in both years (2015 and 2017) from each subplot and analyzed for soil physicochemical properties. For soil moisture at harvest, the soil sample was collected, put in a moisture cane, weighed, and dried at 105 °C; further calculations were performed using the formula of Reeb [33]. Soil BD was determined using the procedure outlined by Blake et al. [34]. SOC was calculated using the dichromate wet oxidation method by Walkley and Black [35]. Soil OM was determined by multiplying C content by factor 1.724. The pH and electrical conductivity (EC) of the soil were measured using the methods developed by McLean [36] and Rhoades [37]. In this method, suspension consisting of a soil-to-water ratio of 1:5 was analyzed for pH and electrical conductivity (EC) using a pH meter and an EC meter, respectively. The total soil nitrogen (STN) was determined calorimetrically for each treatment, following the Kjeldahl procedure outlined by Bremner et al. [38]. For the determination of SMN, the steam distillation procedure described by Keeney and Nelson [39] was used.

2.4. Composition of Biochar, FYM, and PM

In this study, biochar (BC) was generated from the prunings of Acacia trees. FYM had a pH of 8.57; an EC of 2.39 dS m^{-1}; 46.4% C; and concentrations of 0.34% P, 0.87% N, and 0.6% K. PM had a pH of 6.82; an EC of 2.48 dS m^{-1}; 34.7% C; and concentrations of 0.97% P, 1.53% N, and 0.9% K. The biochar used in the experiment contained 0.08% nitrogen and 0.112% phosphorus, with a pH of 7.05 and an EC of 1.49 dS m^{-1} [4].

2.5. Statistical Analysis

Data collected from each year, as well as the combined data, were statistically analyzed using SPSS version 20, following a randomized complete block design with a split-plot arrangement. Mean comparisons were performed using the least significant difference (LSD) test at $p \leq 0.05$ [40].

3. Results

3.1. Soil Organic Carbon, Organic Matter, Bulk Density, and Moisture Content

Biochar (BC) application and nitrogen levels significantly affected soil organic carbon (SOC), organic matter (SOM), bulk density (BD), and soil moisture content (SMC) (Figure 1A–D). Across both years, BC application alone had a significant ($p < 0.05$) influence on these attributes. Increasing BC from 0 to 30 t ha^{-1} significantly increased SOC (Figure 1A), SOM (Figure 1B), and SMC (Figure 1D); however, it reduced BD (Figure 1C). The combined data over the two years showed that BC applied at 10, 20, and 30 t ha^{-1} increased SOC by 27.62, 47.86, and 121.38%; SOM by 27.54, 47.76, and 121.24%; and moisture content by 27.58%, 47.80%, and 121.30% but reduced BD by 2.30%, 18.27%, and 39.90%, respectively, compared to the control (Table 1).

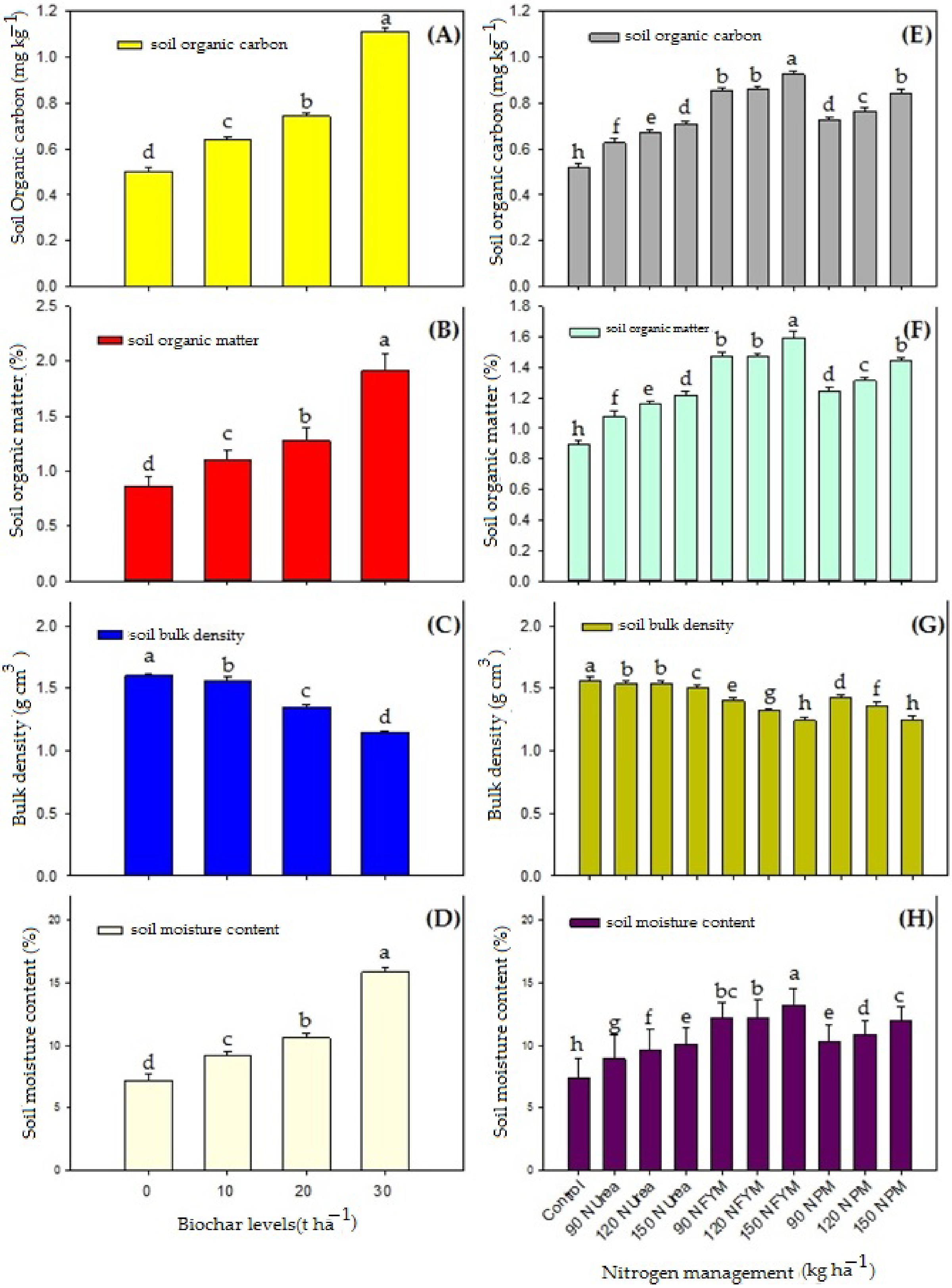

Figure 1. Effect of biochar levels and nitrogen management on (**A**,**E**) soil organic carbon, (**B**,**F**) soil organic matter, (**C**,**G**) soil bulk density, and (**D**,**H**) soil moisture content, respectively. Different lowercase letters indicate significant variations among treatments ($p \leq 0.05$). The error bars indicate the standard error.

Table 1. Year-wise effect of biochar and nitrogen management on soil organic carbon, organic matter, bulk density, moisture content, total nitrogen, mineral nitrogen, pH, and EC.

Attributes	2015–2016	2016–2017	Significance (α at 5%)
Soil organic carbon	0.721 b	0.777 a	**
Soil organic matter	1.240 b	1.337 a	**
Soil bulk density	1.445 a	1.383 b	**
Soil moisture content	10.302 b	11.101 a	**
Soil total nitrogen	0.074 b	0.079 a	*
Soil mineral nitrogen	29.2 b	31.1 a	*
Soil pH	7.49	7.52	NS
Soil EC	0.734	0.735	NS

*, ** indicate significant data at 5%; NS: non-significant. Different lowercase letters denote significant variations among treatments ($p \leq 0.05$).

Similarly, N management in both years and as an individual factor also significantly improved SOC, SOM, BD, and SMC as compared to control treatment. Nitrogen management significantly increased SOC (Figure 1E), SOM (Figure 1F), and SMC (Figure 1H); however, it reduced BD (Figure 1G) when compared with the control. In general, the management of N led to an increase in SOC with an increase in N levels from 90 to 150 kg N ha^{-1}, regardless of whether the sources were organic or inorganic. Specifically, applying 150 kg N ha^{-1} from FYM led to an increase in SOC (Figure 1E) and SOM (Figure 1F) by 78.16% and 78.24%, respectively, when compared with plots where nitrogen was not applied. Furthermore, N management reduced soil BD and increased SMC with an increase in N levels. The addition of 150 kg N ha^{-1} from organic sources resulted in the lowest BD (Figure 1G) and the highest SMC (Figure 1H). Specifically, applying 150 kg N ha^{-1} exclusively from organic sources, such as FYM, led to a 20.48% reduction in BD. Additionally, this application increased SMC by 78.29% compared to the N control treatment. In the case of BC $\times$ N interaction for SOC and SOM, the highest SOC and SOM were observed in plants supplied with 30 t BC and FYM at 150 kg as the source of N (Figures 2 and 3). Similarly, the interaction of BC $\times$ N showed that SMC was improved and recorded as the highest with the combined application of 30 t h^{-1} biochar and 150 kg ha^{-1} N from the FYM source. This increase was 18.53% higher than that of the control treatment (Figure 4).

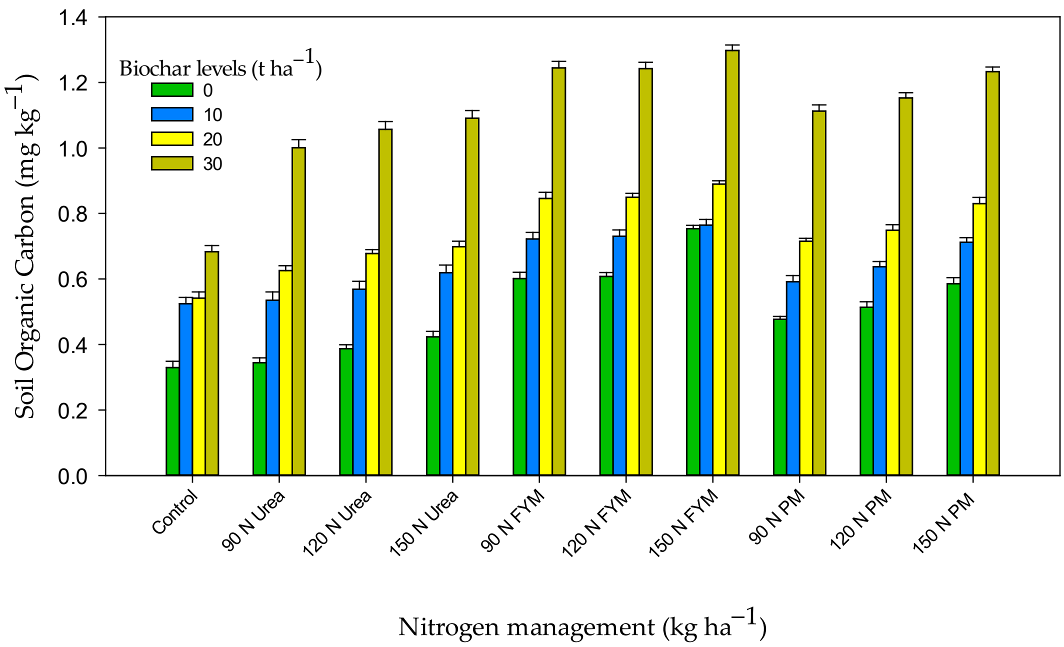

Figure 2. The interaction between BC and N over the years for soil organic carbon content. The error bars indicate the standard error.

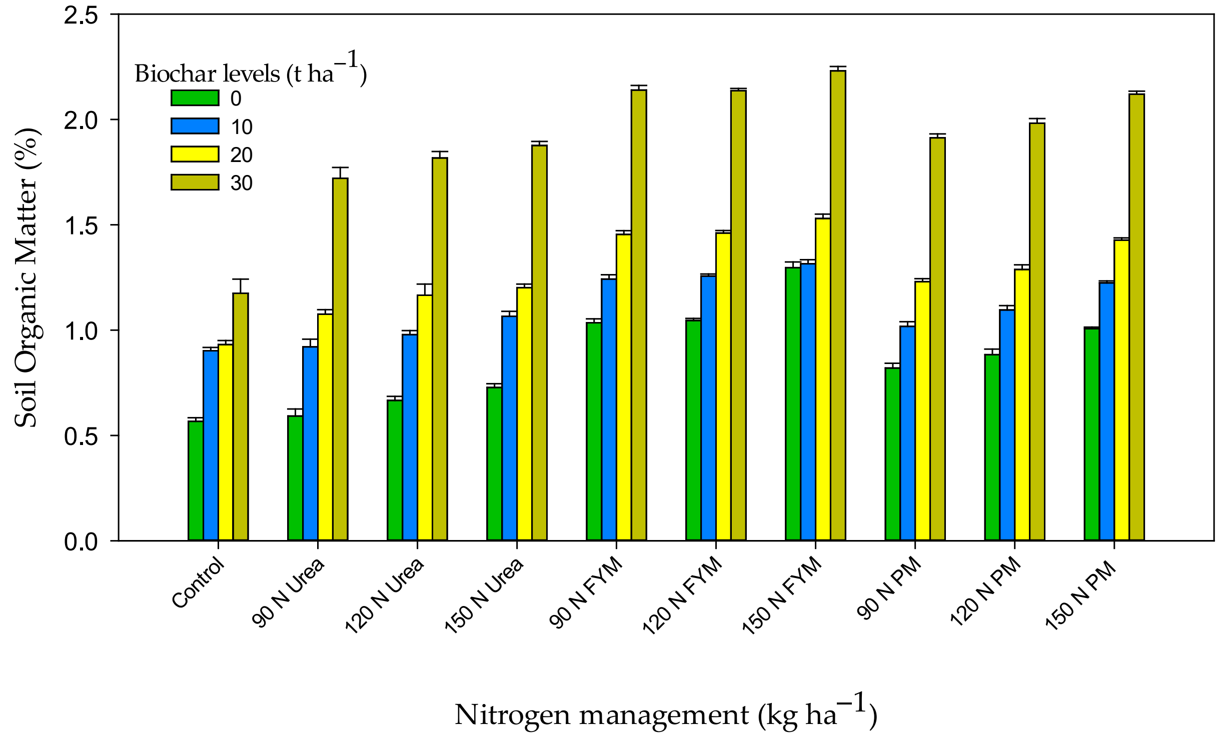

Figure 3. The interaction between BC and N over the years relative to soil organic matter.

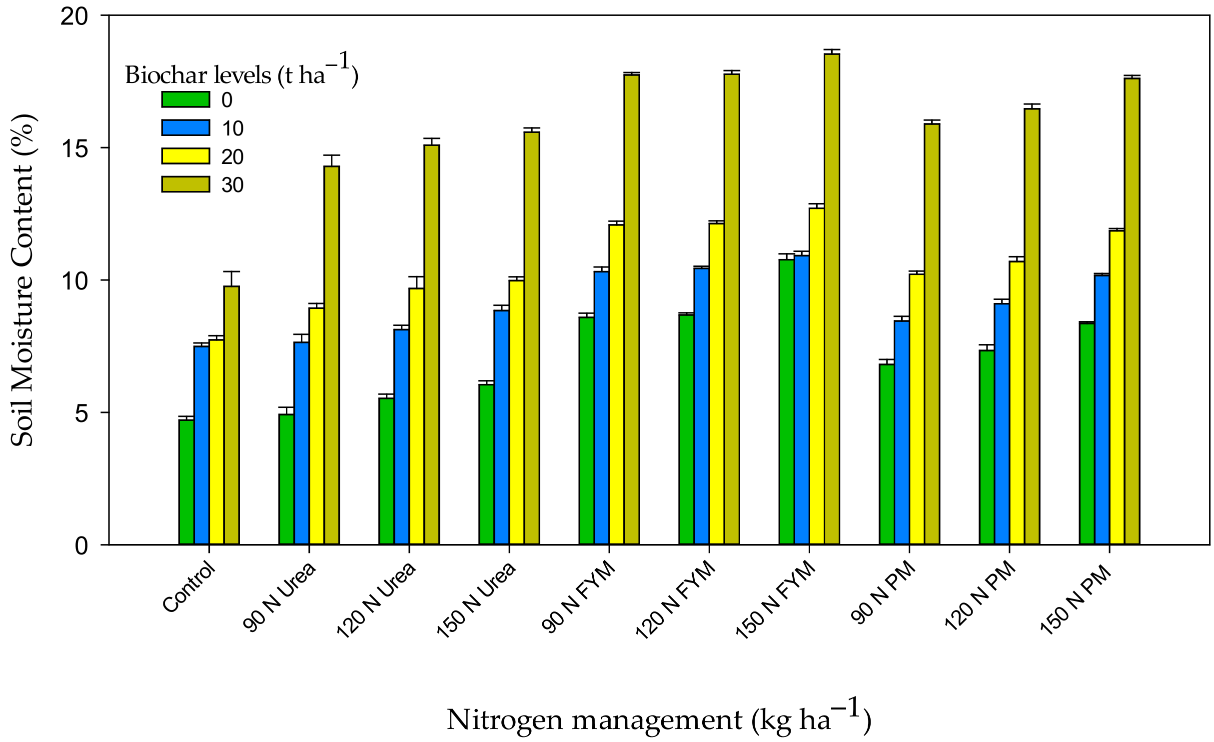

Figure 4. The interaction between BC and N over the years relative to soil moisture content.

3.2. Soil Total Nitrogen, Mineral Nitrogen, pH, and EC

The individual application of BC (Figure 5A–D) and N (Figure 5E–H) significantly influenced STN, SMN, soil pH, and soil EC. The combined data over the two years showed that increasing biochar levels to 10, 20, and 30 t BC ha^{-1} also improved STN (Figure 5A) by 7.41, 11.03, and 14.16, and SMN (Figure 5B) by 2.68, 5.91, and 9.09%, compared to the control treatment. Moreover, BC application significantly ($p < 0.05$) decreased soil pH from control to 30 t ha^{-1} (Figure 5C). The average of two-year data indicated that the addition of 20 t ha^{-1} of BC considerably reduced soil pH compared to other BC levels and the control treatment. In contrast, the pH levels of soils amended with 10 t ha^{-1} and 30 t ha^{-1} of BC, as well as the control treatment, did not show any significant differences (Figure 5C). Similarly, the application of BC significantly ($p < 0.05$) reduced soil EC when compared to BC-untreated soil. Across years, a reduced soil EC was observed for soil amended with 30 t BC ha^{-1} as compared to the control treatment (Figure 5D).

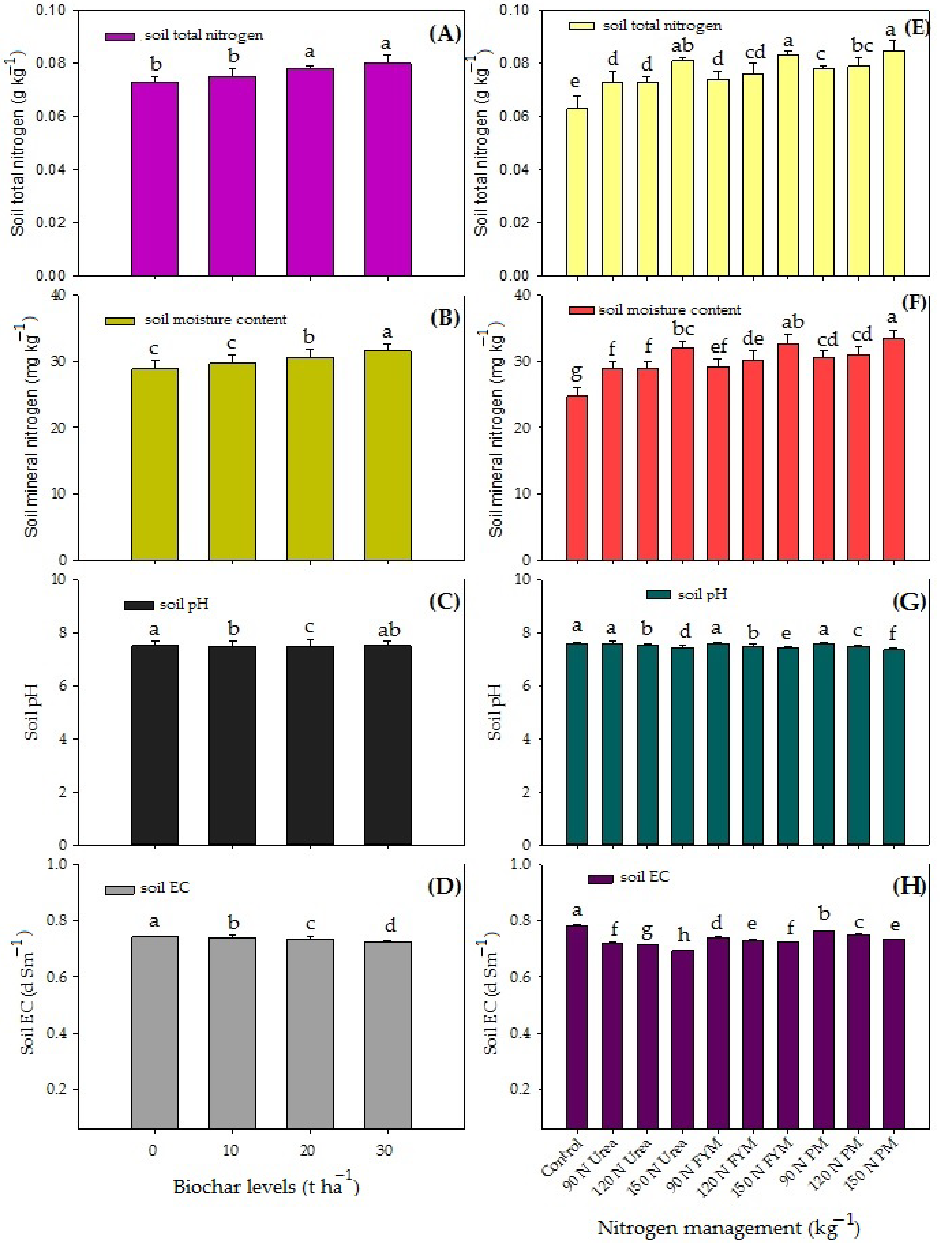

Figure 5. Effect of biochar levels and nitrogen management on (**A**,**E**) soil total nitrogen, (**B**,**F**) soil mineral nitrogen, (**C**,**G**) soil pH, and (**D**,**H**) soil electrical conductivity. Different lowercase letters indicate significant variations among treatments ($p \leq 0.05$). The error bars indicate the standard error.

Similarly, the application of N from different sources (organic and inorganic) considerably enhanced STN and SMN. In terms of STN (Figure 5E) and SMN (Figure 5F), both attributes showed improvement as N application levels increased from 90 to 150 kg N ha^{-1}, irrespective of whether the sources were organic or inorganic. In particular, the sole application of 150 kg N ha^{-1} from organic sources, such as FYM and PM, led to increased STN and SMN by 18.37% and 20.88%, respectively, over the control treatment. Similarly, soil pH reduced significantly with N management when compared with the control treatment. It has been observed that irrespective of the source of N (organic or inorganic), it generally reduced soil pH when N levels increased from 90 to 150 kg N ha^{-1}. However, the application of 150 kg N ha^{-1} solely from PM significantly lowered soil pH compared to other N levels and the control soil. The pH levels were recorded as the highest in the control soil and soils fertilized with 90 kg N ha^{-1} solely from urea, PM, and FYM (Figure 5G). Similarly, a combined analysis of variance also revealed significant differences in soil EC among N treatments. Generally, the soil with controlled N had the maximum EC, followed by soil amended with PM, FYM, and urea (Figure 5H). BC × N interaction indicated that the highest STN and SMN were observed with the combined application of 30 t BC and 150 kg N ha^{-1} from the PM source (Figures 6 and 7). Moreover, the lowest soil pH (7.28) was observed in plots where 20 t BC and 150 kg N ha^{-1} from the PM source were applied (Figure 8). BC × N interaction indicated that the maximum soil EC (0.240 dS m^{-1}) was recorded in the sample with 30 t BC and 90 kg N applied solely from urea. However, there were no significant changes among different levels of N applied from organic sources (Figure 9).

The year effect was also found to be significant for all the studied attributes, except soil pH and soil EC. The results showed that 2016–2017 was the best year in terms of improvement in SOC, SOM, BD, SOM, STN, and SMN, as compared with 2015–2016 (Table 1).

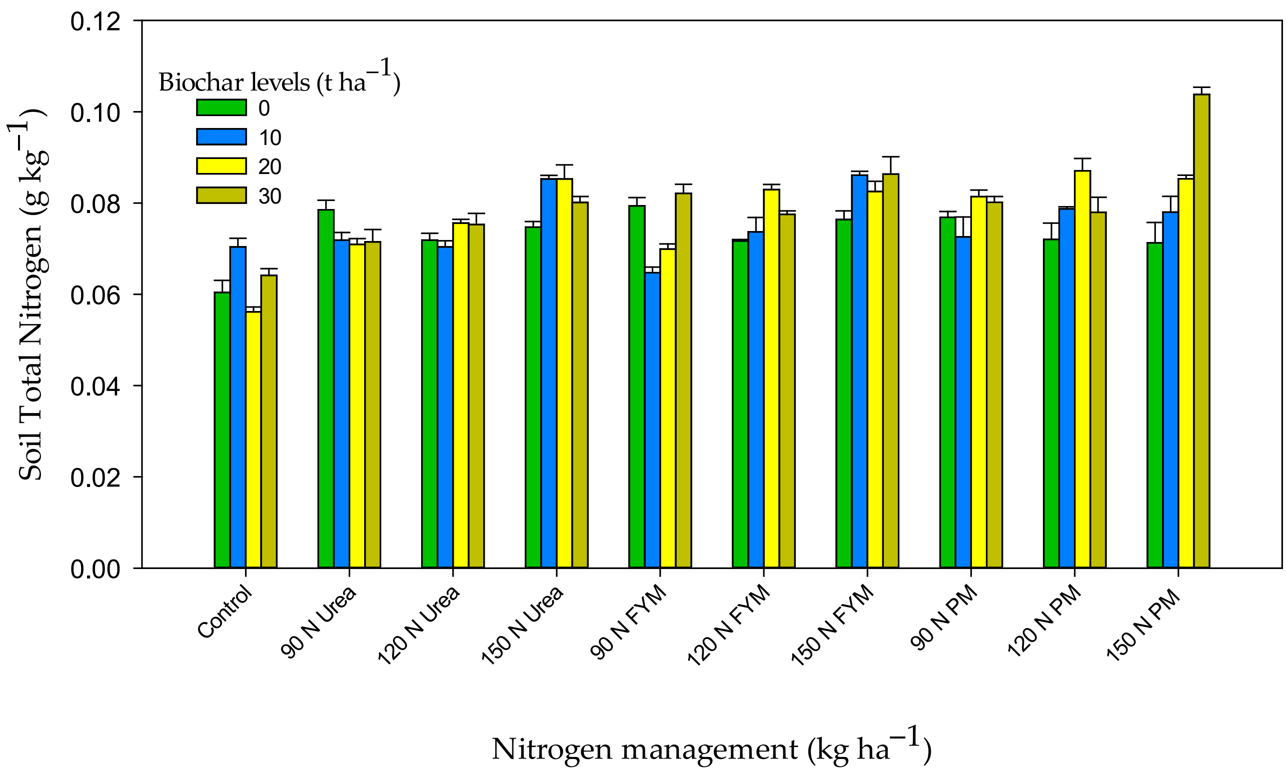

Figure 6. The interaction between BC and N over the years relative to soil total nitrogen content.

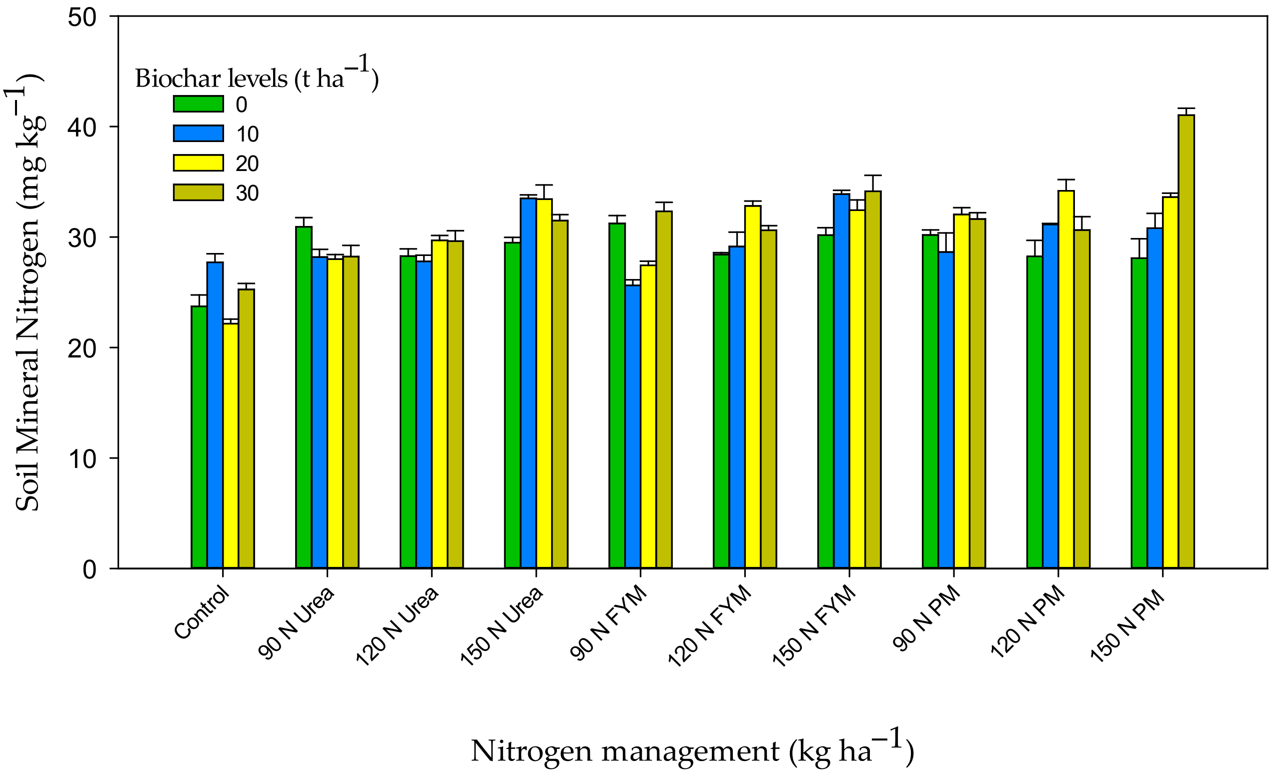

Figure 7. The interaction between BC and N over the years relative to soil mineral nitrogen content.

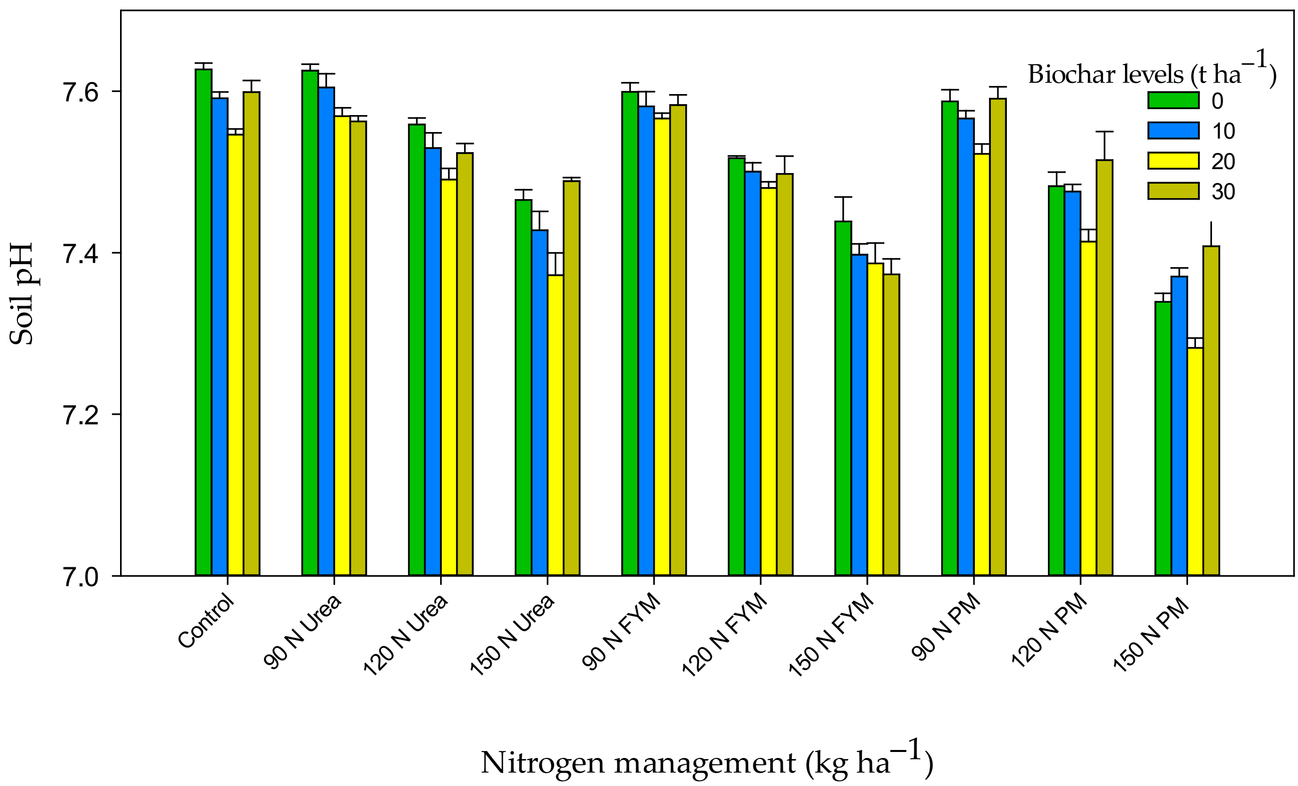

Figure 8. The interaction between BC and N over the years relative to soil pH.

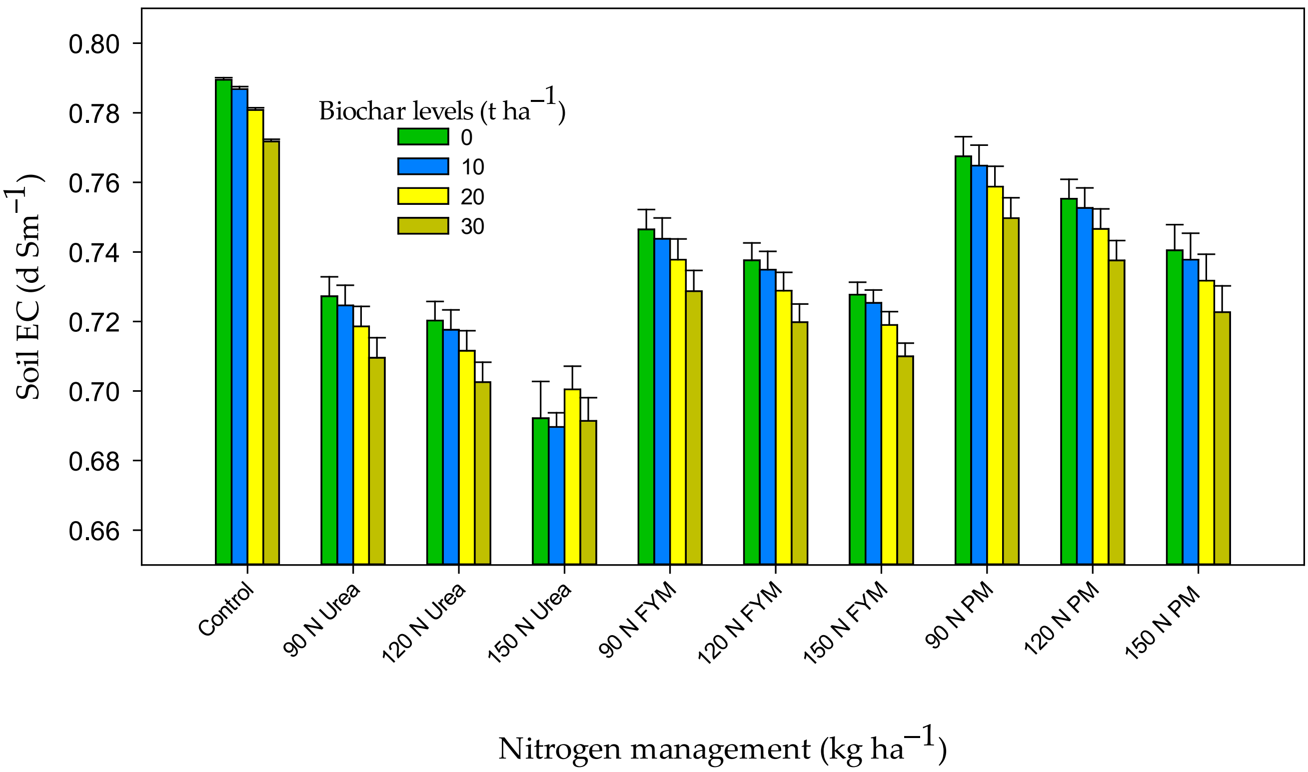

Figure 9. The interaction between BC and N over the years relative to soil electrical conductivity.

4. Discussion

In our study, the reduced bulk density (BD) in biochar (BC)-amended soil is due to the porous nature of BC, and it promotes the activity of soil faunas. The increased activity of soil faunas increases the soil pore volume. This aids in maintaining optimal soil structure, aeration, and water movement, which further leads to a reduction in soil BD. Burrell et al. [41] and Verheijen et al. [42] also reported similar findings in their studies. They reported that the BD of biochar is lower than soil BD, thereby reducing the BD of soil when incorporated in the soil. According to our study, the enhancement in SMC is mainly due to the presence of water in the pore spaces of applied BC, which has comparatively high porosity. This can be further explained by the existence of variations in soil BD among the treatments, as differences were observed in SMC among the plots modified with BC and the control. Previous studies also reported that the water retention of soil can be influenced by the addition of biochar, which modifies the BD of soil, as revealed by Castellini et al. [43]. Similarly, according to Laird et al. [44], soil amended with biochar retained 15% more moisture than control soil with no BC application. Furthermore, the high water-holding capacity of BC brought about by the presence of small pores that can retain more water also helps in withstanding water stress conditions [45,46].

Soil quality is dependent on various factors, among which soil organic carbon (SOC) content is considered crucial. In our study, we observed that the fused aromatic ring structure and the high resistance in BC may support the increase in SOC by enhancing C sequestration in the soil. Wang et al. [47] reported that BC is stable in soil and exhibits a slow decomposition rate. Consequently, its high resistance significantly contributes to its effectiveness in improving soil carbon sequestration [48]. The incorporation of organic manure in the soil can increase the quantity of organic matter, which might be the cause of improvement in soil organic matter (SOM). Bista et al. [49] supported our result, as they also observed reduced plant growth in treatments without BC. This is because soil with no biochar application caused a reduction in shoot and root biomass and eventually resulted in lower SOM accumulation. Increased SOM in BC-amended soil was also observed by Rawat et al. [50]. The increase in the total nitrogen content (STN) of the soil treated with biochar (BC) is the result of the favorable properties of BC, which enhance the fertility of soil mainly in two significant aspects: firstly, BC can provide essential nutrients, including but not limited to NPK, and secondly, it effectively retains some nutrients not only those present in the soil (particularly N) but also from fertilizers (both organic and inorganic). In support of our results, Rawat et al. [50] noted that biochar facilitates the sustained availability of nutrients like N, C, P, and K to plants by gradually releasing them after absorption. The study conducted by Kameyama et al. [51] provides additional support for the results of this investigation. They stated that BC has a strong affinity for ammonium (NH_4^+) and nitrate (NO_3^-), which helps maximize their retention time in soil. This potentially leads to the improved retention of nitrogen fertilizer in the soil. The nutritional profile of the soil can be modified by the addition of biochar, primarily by enhancing the availability of nutrients that are directly accessible to plants. Consequently, the increase in soil mineral nitrogen (SMN) in soils modified with biochar application can be associated with biochar's multifunctional role. Yuan et al. [52] also reported results comparable to our findings. The incorporation of BC into soil resulted in a reduced rate of BC mineralization [53]. Various studies have reported differing effects: some observed a decline in net nitrogen (N) mineralization [54], while others noted an enhancement in net N mineralization [54]. Some findings indicated no significant changes in mineralization [55], while others suggested a slight influence on mineralization [56]. Additionally, in [57], the authors utilized 15N labeling to investigate N dynamics in plots amended with BC and found an increase in N mineralization associated with BC application. We also observed a reduction in soil pH in our study possibly due to the production of materials acidic in nature, which is the result of the oxidation and decomposition of BC in the soil. Cheng et al. [58] pointed out that biochar (BC) is not fully inert within the soil; it can oxidize, especially at its surface, due to chemical reactions and the activity of microorganisms. As a result, the generation of acidic functional groups can progressively decrease soil pH by counteracting soil alkalinity. This trend is reinforced by prior studies indicating that alkaline biochar application in soil decreases soil pH [59]. The decline in electrical conductivity (EC) in soil amended with BC could be linked to the reduced ash content present in wood-derived biochar. This result is consistent with Jalal's findings [60], which showed that EC in plots treated with BC decreased by 20% and 40% after two years. Similarly, Kawsar et al. [61] observed a 20% and 41% decrease in EC in plots that incorporated BC.

We observed an increase in the SMC in the soil amended with organic manures. Specifically, the highest SMC was observed in FYM-amended soil, followed by PM-amended soil; this might be due to manure application, which increases the content of soil organic matter. The organic matter present in FYM likely contributed to stabilizing the structure of the soil, thereby reducing the bulk density while improving the SMC. Zhang et al. [62] reported a similar effect of farmyard manure (FYM) on enhancing soil moisture content (SMC). In another study, Singh et al. [63] also found that the levels of soil moisture were higher in plots treated with FYM. Their explanation for this increase was that FYM's colloidal and hydrophobic properties probably improved the structure, aggregation, and soil water-retention ability. In the same vein, improvement in the physical structure of soil caused by the application of manure was also observed in this study. This may be caused by a high organic matter content (resulting from more organic matter through manure application), which increases soil aggregation (by bonding particles), causing the dilution of the soil. Mahmood et al. [64] also reported similar results. Consistent with our findings, Mbah et al. [65] reported a decrease in soil bulk density (BD), resulting from the incorporation of organic manures. According to Ahmad et al. [66], the application of organic manure individually or in combination with organic matter and inorganic fertilizers notably improved soil BD and increased porosity in soil. Furthermore, it also had a beneficial effect on soil conditions by mixing organic matter into the soil, which helped to reduce the overall soil mass.

The increment in the SOC as a result of FYM integration is because FYM is a rich source of organic carbon. Prior research has indicated that the application of manure is among the most effective methods to increase organic matter in soils and enhance carbon sequestration [67]. Similarly, Bhogal et al. [68] observed that organic manure leads to increased carbon accumulation across various soil types and climatic conditions. The rise in the SOC content in plots treated with organic manures may cause the accumulation of organic matter, which subsequently modifies soil properties, including its biological, physical, and chemical properties [69]. The role of organic manure in the accumulation of soil organic carbon (SOC) and carbon sequestration has been documented by Are et al. [70]. The enhancement in STN can be linked to the mineralization and residual effects of organic manure, which increases the nitrogen levels in the soil. Our findings are supported by Bhat [71], who noted that nitrogen from organic sources contributed to an increase in STN. Additionally, Iqbal et al. [5] demonstrated that organic manures positively influence soil quality compared to inorganic fertilizers, leading to increased nutrient release and availability (particularly nitrogen) for crop plants. Similarly, the results reported by Farid et al. [72] showed that the incorporation of organic nitrogen sources significantly enhanced chemical properties, including the soil total N and organic matter content, whereas there was minimal impact from artificial or mineral sources. The application of nitrogen from organic sources also significantly boosted SMN. The increased availability of nitrogen in plots with organic materials may result from enhanced nitrogen mineralization from these organic sources. Tabassum et al. [73] also reported elevated SMN levels due to the incorporation of organic amendments. Additionally, Alizadeh [74] observed that soil amended with PM exhibited significantly higher nitrogen mineralization compared to other organic sources. Furthermore, Cordovil et al. [75] pointed out that variations in nitrogen mineralization across different sources of organic manure may be due to differences in animal diets and the carbon-to-nitrogen (C/N) ratio of the organic materials. Poultry, which mainly feeds on grains and protein-rich cakes, generally exhibits a lower ratio of carbon-to-nitrogen ratio as compared to cattle, which mostly consume forages and straws that possess a higher C/N ratio [76]. Consequently, organic materials with a low C/N ratio encourage nitrogen mineralization [77], whereas those with a higher carbon-to-nitrogen ratio tend to promote the immobilization of N [78]. We observed that soil pH decreased when soil was amended with organic manure. The decomposition of these materials may have released organic acids and consequently caused a decrease in soil pH. Furthermore, the nitrification process results in fat accumulation with the application of more N, thereby producing more hydrogen ions that are subsequently added to the soil; this may be the cause for the observed decline in soil pH with more nitrogen application [79]. Furthermore, nitrogen management significantly influenced the electrical conductivity (EC) of the soil, with the highest EC recorded in the control group, followed by plots treated with poultry manure (PM), farmyard manure (FYM), and urea. Comparable results were also reported by Kawsar et al. [61].

The application of BC and N and their interaction improved soil chemical properties. This can be attributed to the fact that the surface oxidation of BC is supported by the incorporation of manures with BC at higher temperatures, predominantly at the start of the process. Further, it also modifies BC characteristics biotically due to the greater microbial activity during the decomposition of available carbon sources. Kuzyakov et al. [80] reported similar results, which support our findings.

5. Conclusions

This study demonstrates that integrating biochar and nitrogen can effectively enhance soil fertility under the specific conditions tested. Biochar application reduced soil bulk density, increased moisture content, and improved soil structure, while nitrogen application, especially from organic sources, enriched soil organic carbon and nitrogen, and moderated soil pH. The synergistic effects observed between biochar and nitrogen suggest a promising strategy for improving soil fertility and sustainable agricultural productivity. These findings provide valuable insights into soil amendment practices, but further research is required to validate these results under varying conditions and optimize the application of biochar and nitrogen for broader agricultural systems.

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