Enhancing Soil Quality and Maize Yield with the Combination of *Acacia*-Biochar, NPK Fertilizer and Compost

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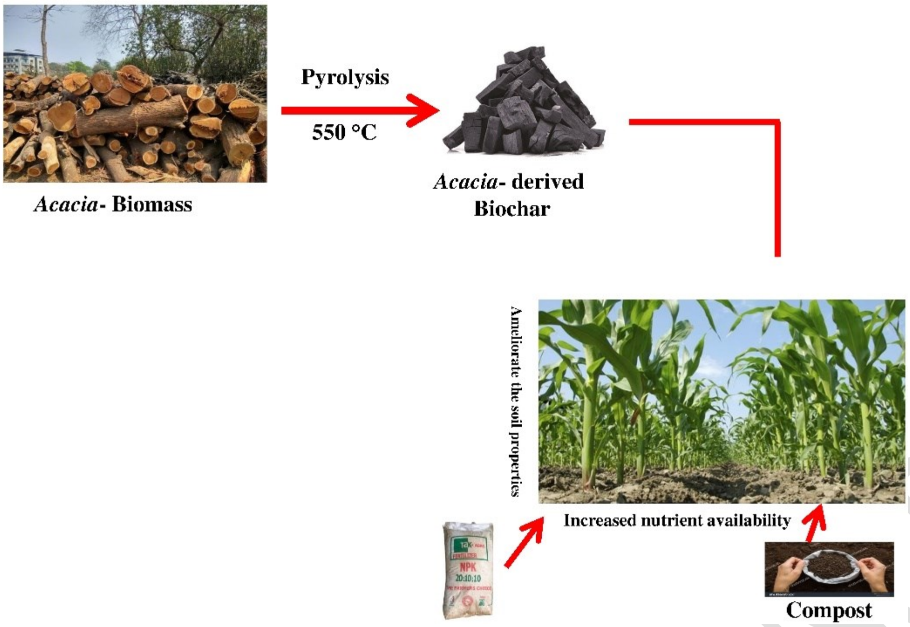
Graphical Abstract



Abstract

Pakistan's agricultural soils exhibit a high tendency for leaching, low quantities of organic matter, and minimal microbial activity. The situation is aggravated by human activities such as bush burning, mining, sand extraction, and ongoing conventional methods of farming. These methods, together with the naturally low amounts of organic matter, result in the soil being deprived of essential nutrients. These nutrients are necessary for the optimal growth and yield of crops. Enhancing crop production such as maize and other crops on nutrient-deficient soils has the potential to improve household food security in Pakistan, necessitating the implementation of appropriate measures. Various techniques have been devised to mitigate the deleterious impacts on plants. The use of biochar, an organic substance produced through pyrolysis with limited oxygen supply, as a soil amendment is currently attracting significant attention globally. This study aimed to assess the effectiveness of a mixture of Acacia-biochar, NPK fertilizer, and compost in improving soil quality and boosting yields of crops. The first variable examined in the study was the biochar dosage, which was divided into four levels: no biochar, a biochar dosage of 5, 10, and 15 t ha^{-1}. Additionally, it is important to take into account the selection of fertilizer, which consists of four different types: non-fertilizer, NPK, compost, and NPK + compost. The results showed that applying biochar at a rate of 10 t ha^{-1}, along with NPK + compost, improved the availability of phosphorus and potassium, and significantly enhanced soil quality, as indicated by a soil quality rating value of 18. Applying a rate of 10 t ha^{-1} of biochar, along with NPK + compost, led to the highest dry weight of seed maize, achieving 12.80 t ha^{-1}. This represents a 40% augmentation in relation to the conditions without biochar and with the addition of NPK + compost. When the seed maize is weighed without any moisture content, the yield of 12.80 t ha^{-1} results in the highest level of efficient agronomic value, which is 120.31%. Additionally, the feasibility value for growing maize in drylands is 1.28.

Keywords: Biochar, compost, NPK-fertilizer, maize, microbial population.

1. Introduction

Dryland conditions are typically distinguished by a range of constraints, including inadequate soil structure, significantly low carbon-organic content, and limited capacity to store water and nutrients. The emergence of dry-land agriculture is hindered by several limitations (Sufardi, 2024). The lack of attention to water and soil conservation principles in dryland management has resulted in the degradation of land and reduced production (Sofia et al., 2024). Rehabilitation can enhance dryland production by improving the soil quality, including its physicochemical and biological properties. One potential approach to enhance soil quality in arid regions is the utilization of diverse elements such as soil ameliorants or conditioners (Sazali et al., 2024).

Inorganic fertilizers and farmyard manures are being used to restore the degraded soils in the tropics. However, the continuous use of the inorganic fertilizers to restore degraded soil may increase soil acidification, decline microbial abundance and population, affect both the soil biota and biogeochemical processes thus posing an environmental risk and decreasing crop yield (Tusar et al., 2023). Also, soil amendments such as manure or compost have proven to enhance the physical environment and supply the soil with macro and micronutrients. Still, the high rapid decomposition and mineralization of organic resources make it ineffective for the reclamation of highly weathered soils on a long-term basis (Al-Swadi et al., 2014). Given that healthy soils will help feed the ever-growing world population, innovative agriculture technologies and practices are needed to prevent healthy soil from degradation (Maqbool et al., 2024). Sustainable agricultural intensification (SAI) has been proposed as a climate-smart approach for remediation of degraded soil. One of the major aims of SAI practices is to enhance soil storage of black carbon on degraded soils, which can be derived by incorporating biochar into the degraded soil (Nie et al., 2021). Different strategies have been developed to reduce the toxic effects of heavy metals and salt stresses in plants (Lee and Kasote, 2024). The application of biochar pyrolyzed organic material under a limited supply of oxygen, as a soil amendment is currently gaining considerable interest worldwide (Amalina et al., 2023; Ghorbani et al., 2024). . Biochar supplementation is linked to a diverse range of beneficial effects, including enhanced soil microbial activity, improved soil nutrient absorption through plants, higher nutrient availability in soil, and reduced nutrient leaching (Maniraj et al., 2023). In addition, it enhances soil aeration, bulk density, porosity, infiltration rate, water holding capacity, aggregate stability, and hydraulic conductivity, heavy metals stabilization, and restricts their bioavailability to plants cultivated in unfavourable or low-quality soils (Elkhalifa et al., 2022). Several studies have reported the positive effects of BC under either heavy metal or salt stress (Shoudho et al., 2024). The addition of biochar in the soil increased the soil pH and decreased the bioavailability and uptake by plants (Dutta et al. 2024). It has been reported that biochar was more effective in reducing heavy metal uptake by wheat plants compared to other organic amendments (Yadav and Ramakrishna, 2023). Similarly, applying biochar to potatoes under metal stress boosted their growth, photosynthetic rate, and yield while also causing a decrease in Na^+ and an increase in K^+ in the xylem (Gusiatin and Rouhani, 2023). In addition to increasing maize biomass and growth, the biochar and bacteria that promote plant growth also reduced the Na^+ and raised the K^+ level of the maize xylem sap (Gusiatin and Rouhani, 2023). Applying biochar boosted bean development under stress soil and decreased oxidative stress (Mukhopadhyay et al., 2024). Biochar additionally facilitates the proliferation of microorganisms and mitigates the adverse impacts of heat, salinity, and drought stress on crops. It promotes the growth and production of crops, accelerates the process of biological nitrogen fixation in legumes, and aids in the sequestration of carbon (Garcia et al., 2022).

Subsequently, little information is available in the literature regarding the effect of the woody-biochar amendment on stressed soil maize grown even though maize is facing environmental stresses simultaneously. There is currently a scarcity of research on the advantages of biochar in enhancing soil quality on dry land for different crops, particularly maize. Enhancing soil quality on dry land is crucial for advancing corn production in Bahawalpur. We hypothesized that biochar, NPK, and compost may alleviate environmental stress in maize by enhancing the soil health and quality. In this study, we examined the importance of *Acacia*-biochar in enhancing the efficacy of NPK and compost fertilizer to enhance soil quality and boost maize production in dryland environments. The present work contends that the addition of *Acacia*-biochar with NPK and compost has the potential to enhance soil quality and increase maize yield in arid regions.

2. Materials and Methods

The experiment was carried out at Islamia University of Bahawalpur located in Bahawalpur, Punjab, Pakistan (29° 23’ 44.5956’’ N and 71° 41’ 0.0024’’ E). The climate in District Bahawalpur is characterized by extremely hot and dry summers, along with cold and dry winters. The maximum temperature rises to 48ºC, but the minimum temperature drops to 7ºC. Summer frequently experiences a multitude of wind and dust storms. The area experiences a mean yearly precipitation of 200 mm. The study used biochar obtained from Acacia bark, compost made from poultry litter, hybrid maize seeds Gohar-19, and NPK fertilizer. Biochar production involved heating the material to pyrolysis at a temperature of 550 °C for 2 h. The physico-chemical characteristics of biochar have been examined after its manufacture and are presented in Table 1. The present study employs a field-scale experimental methodology, specifically utilizing an Randomized Block Design (RBD) comprising pattern two factors. The treatments examined in this study were determined using the optimal dose of biochar (10 t/ha^{-1}), NPK-Repsol (313.81 kg/ha^{-1}), and compost (20.14 t/ha^{-1}) as determined from previous research findings (Rombel et al., 2022). The treatments that were examined included the dose of biochar and the type of fertilizers used. The first factor considered in the study was the dose of biochar (B), which was categorized into four levels: B_0 (no biochar/control), B_1 (5 t/ ha^{-1}), B_2 (10 t/ ha^{-1}), and B_3 (15 t/ ha^{-1}). The second factor pertains to the type of fertilizer (F), which encompasses four different types: without fertilizer/control (F_0), compost (F_1), NPK (F_2), and NPK + compost (F_3). The experimental procedure was replicated three times to achieve a total of 48 units.

The variables examined in this study encompass soil conditions and maize plant characteristics. The analyzed soil exhibits a range of variables, including soil water content, bulk density, soil texture, pH, porosity, C-organic content, total N content, K available content, available P content, CEC, Base Saturation, total microbial presence, and Soil Quality Rating (SQR). The detected variability in plants can be attributed to the dry seed grain water content of 15% per hectare, as well as the analysis of Incremental Benefit Cost Ratio (IBCR), and Relative Agronomic Effectiveness (RAE). An analysis of variance (ANOVA) was employed to ascertain the impact of the therapy on the assessed variables. The least significant difference (LSD) test, conducted at a level of significance of 5%, is employed to assess the difference in the mean values of each variable. The optimal dose of application was determined using regression analysis.

Table 1 Physicochemical characteristics of biochar

Parameters	Attributes
pH	9.13 ± 0.02
Surface area (m^2g^{-1})	132.11 ± 2.49
Electrical conductivity (dSm^{-1})	4.12 ± 0.05
Organic matter %	30.32 ± 1.02
Nitrogen %	0.24 ± 0.02
Phosphorus %	0.20 ± 0.02
Potassium %	0.87 ± 0.02
Calcium %	0.60 ± 0.02
Moisture %	4.21 ± 0.02
Ash %	24.21 ± 0.21

3. Results and Discussion

The findings from the statistical evaluation of soil physical characteristics indicate that there was no significant correlation between fertilizer type and biochar dose, as well as the application of the type of fertilizer. However, biochar dose was found to have a highly significant effect ($P<0.01$) on the water content, soil porosity, and bulk density. Table 1 displays the mean water content, soil porosity, and bulk density after being treated with fertilizer and biochar, which may be related to the biochar properties such as particle size, active surface area, and porosity as well as properties of the soil. Further, the ability of biochar to form the soil aggregates in combination with soil particles leading to a decrease in bulk density could also play a role. This was confirmed in the research of An et al. (2023). The surface of biochar particles after oxidation may contain the hydroxyl and carboxyl groups that are able to associate with the mineral and other organic soil particles to form soil aggregates. Biochar supplied to the soil is a substrate for soil fauna. Its particles can be mixed with the soil particles in a digestive tract of the earthworms creating coprolites that are agronomically valuable soil aggregates (Zanutel et al., 2024). Due to its inert nature, biochar is often combined with other organic and mineral fertilizers to improve its effect in the soil (Younas et al., 2024). Fertilization-especially with nitrogen is a significant factor influencing bulk density. Mineral nitrogen applied to the soil can act as an accelerator speeding up the mineralization of organic matter (Yang et al., 2019), which can result in an increase of bulk density values. However, application of biochar in combination with N fertilization has a positive effect on the incorporation of biochar-especially into larger aggregates (Ahmed et al., 2024) which helps to improve the soil structure (Sobuz et al., 2024) and ultimately reduce the bulk density values as was also confirmed in the results obtained by Shao et al. (2024). Based on the soil texture measurements (Table 2) indicating the proportions of clay, silt, and sand in response to fertilizer and different doses of biochar, the soil texture was classified as sandy loam. The treatment containing ten times as much biochar as ha^{-1} yielded the maximum water content (10.41%), which increased by 15% in comparison to the control treatment (9.20%).

Table 2 Effects of biochar dosage and fertilizer type on the average water content, porosity, bulk density, clay, silt, and sand at treatment

Treatment	**Bulk density g.cm^3**	**Water content %**	**Porosity %**	**Clay%**	**Silt %**	**Sand %**
Control (without biochar)	0.97a	8.35b	64.01b	12.29a	23.01a	63.14a
BC 5 t ha^{-1}	0.94ab	9.01ab	64.9ab	10.88a	23.90a	64.71a
BC 10 t ha^{-1}	0.88b	9.81a	65.21ab	10.65a	23.90a	64.14a
BC 15 t ha^{-1}	0.86b	9.50a	66.31a	12.12a	22.31a	64.03a
LSD 5%	0.05	0.83	0.05	-	-	-
Without fertilizer	0.93a	8.60a	65.14b	11.30a	25.10a	63.16b
NPK	0.91a	9.40a	66.10a	12.14a	23.40ab	64.17b
Compost	0.93a	9.20a	65.74a	12.03a	22.41b	65.74a
NPK+ compost	0.92a	9.50a	65.78a	11.a	25.14a	65.14b
LSD 5%	-	-	-	-	2.76	1.29

The best bulk density was achieved at a biochar dose of 10 t ha^{-1}, which corresponds to 0.88 g cm^3. This value was reduced by 7.31% in comparison to the highest bulk density found without biochar, which was 0.97 g cm^3. The application of 10 to 15 t ha-1 biochar resulted in enhancements to several physical characteristics of the examined soil, including soil texture, bulk density, water content, and porosity (Table 2). As stated by Murtaza et al. (2024), the utilization of biochar has been found to decrease soil bulk density while simultaneously increasing water content and soil porosity. One direct correlation exists between soil porosity and the utmost power savings that can be derived from soil water. The application of biochar resulted in a substantial increase in the water concentration in the field capacity (Murtaza et al., 2021). The bulk density achieved at the rate of biochar 10 t ha^{-1} exhibited a reduction in comparison to the greatest bulk density observed in the absence of biochar (control). The porosity of the soil reached its maximum at a biochar dose of 15 t ha^{-1}, indicating an increase relative to control. The decrease in soil volume resulting from the soil aggregates formation is facilitated by the presence of aromatic ring compounds (C=C) and a high concentration of carboxylic groups (OH) in biochar (Hua et al., 2021). According to the study conducted by Mandal et al. (2020), the process of soil aggregate formation involves the incorporation of organo-mineral components into the biochar framework, which in turn generates an aromatic carboxylic acid group. According to Murtaza et al. (2023), the application of biochar has the potential to decrease the bulk density of various soil types.

Organic Matter, pH, Total N, C/N, and C-organic

The statistical evaluation revealed that there was no significant interaction between fertilizer type and dosage of biochar on pH, C/N, total N, C-organic, and organic matter. The impact of biochar dosage on soil parameters such as pH, C/N, total N, C-organic, and organic matter was shown to be highly significant ($P<0.01$). The application of fertilizer had a statistically significant impact ($P<0.01$) on organic matter, total N, and C-organic. However, the effect on pH and C/N was not statistically significant ($P<0.05$). The total N content reached a high value of 0.217% when the biochar dose was 15 t/ ha^{-1}. The biochar dosage of 5 t/ ha^{-1} resulted in the greatest pH value of 6.76, organic matter content of 6.89%, C-organic content of 4.01%, and C/N content of 23.40. These values are significantly different from the lowest yield observed control (Table 3). The rise of the soil pH could be attributed to the high pH of the biochar (7.5) as alkaline substances were released from the biochar into the acidic soil during the remediation process (Riyad et al., 2023). The increase of the soil pH during the liming process is attributed to the substitution of hydrogen and aluminum iron on the colloidal surface of the soil with the cation oxides, thereby decreasing the exchangeable acidity (H^+ and Al^{3+}) in the soil environment (Brekalo et al., 2023). However, the possibility of biochar to increase the soil pH depends on the ash content, basic oxide cations and the absorbent nature of the biochar (Kaljunen et al., 2023). The lower soil pH obtained by the biochar and NPK addition compared to the biochar and manure addition plots was because of the acidic nature of the NPK, which could probably contribute to the less pH. Besides increasing the soil pH by the biochar in the biochar and manure addition plot, manure contributes to raising the soil pH through the complexation of its organic anion released into the soil exchange site (Anand and Kumar, 2022).

Table 3 Values of pH, organic matter (OM), C-organic, total nitrogen (N), and C/N after application of fertilizer type and biochar dosage

Treatment	**pH**	**Organic matter %**	**C-organic %**	**Total N %**	**C/N**
Control (without biochar)	6.58c	6.30b	3.64b	0.17b	21.88a
BC 5 t ha^{-1}	6.76ab	6.89a	4.01a	0.17b	23.40a
BC 10 t ha^{-1}	6.69a	6.39b	3.69b	1.8b	21.21a
BC 15 t ha^{-1}	6.66bc	6.30b	3.64b	0.21a	18.39b
LSD 5%	0.07	0.25	0.14	0.027	3.19
Without fertilizer	6.60a	6.02b	3.49b	0.16b	21.89a
Compost	6.64a	6.64a	3.84a	0.17b	22.69a
NPK	6.70a	6.57a	3.80a	0.20a	19.30a
NPK+ compost	6.67a	6.63a	3.85a	0.207a	19.13a
LSD 5%	-	0.25	0.14	0.027	-

The combined application of compost and NPK fertilizer results in the highest total Nitrogen soil value of 0.207%, which is significantly higher than the low yield of 0.166% observed in the treatment control (without fertilizer). The addition of compost resulted in the highest levels of organic matter and C-organic, with values of 6.64% and 3.84% respectively. These values are significantly different from the lowest levels seen in the absence of fertilizer, which was 6.02% and 3.49% respectively (Table 3). The high total nitrogen content in the manure could probably be attributed to manure functions to improve acidic soil, increase ECEC and supplement the soil with nutrients being released from their organic matter. The biochar and NPK addition recorded higher total nitrogen than the biochar and the manure addition (0.36%) since the 15-15-15 NPK fertilizer contains more nitrogen than the manure. The addition of the biochar to the NPK fertilizer and manure decreased the apparent ammonification and ammonium loss because of the temporary adsorption of NH_4^+ onto the biochar surface (Zhong et al., 2024). Biochar can release a small amount of nitrogen add up to the total nitrogen pool, as reported by Islam et al. (2024).

Available (P) and available (K)

The statistical analysis findings indicate that there was a significant interaction ($P<0.01$) between the dose of biochar and the kind of fertilizer on the availability of phosphorus (P) and potassium (K). The application of biochar has a considerable impact ($P<0.05$) on the availability of phosphorus (P) and a highly significant impact ($P<0.01$) on the availability of potassium (K). The application of fertilizer had a statistically significant impact ($P<0.01$) on the availability of phosphorus (P) and potassium (K). Tables 3 and 4 display the mean P available and K available values for the interactions between biochar and different types of fertilizers. The highest content of available phosphorus (P) was observed in the interactions between biochar at a rate of 10 t ha^{-1} and compost, with a recorded value of 69.10 ppm. This value is significantly different from the lowest yield observed in the interactions between compost, control, and biochar, as well as the interactions between $10tha^{-1}$ without fertilizer, which resulted in P-available values of 38.20 ppm and 30.25 ppm, respectively (Table 4). The maximum K-available content observed in the interactions between biochar and NPK + compost was 1250.31 ppm, which differed significantly from the lowest yield reported in Table 5. The biochar and NPK addition differ significantly as compared to biochar and manure addition. Biochar and NPK addition obtained available phosphorus of 9 % higher than the biochar and manure addition. The addition of biochar to the weathered soil increased soil pH, leading to the alteration of P complexation with Al^{3+} that occurs in highly weathered acidic soils, increasing soil P availability for plant uptake (Pandian al., 2024). The high available phosphorus in the combined biochar and NPK plots was because of the high phosphorus concentration in the inorganic NPK fertilizer (Mujtaba et al., 2021). Hence this could explain the higher available P in the combined biochar and NPK plot than the co-applied biochar with manure. The phosphorus availability could also be attributed to the P concentration in the biochar ash, manure and the inorganic fertilizer, which adds up to the soil phosphorus pool, as reported by Mood (2024). Particularly, it has been demonstrated that biochar enhances potassium availability through various mechanisms mainly based on the increased potassium retention capacity associated with a high porosity, surface area, and cation exchange capacity of the biochar, ultimately resulting in higher potassium absorbance by plants (Mujtaba et al., 2021).

Table 4 Average phosphorus availability in the interaction between biochar dosage and fertilizer type

Treatment	**Fertilizer Type**			
	Without fertilizer	**Compost**	**NPK**	**NPK + Compost**
Biochar dosage	--------------------------ppm---			
0 t ha^{-1}	30.50a	40.59b	35.89b	50.41ab
5 t ha^{-1}	32.96a	43.54b	64.69a	37.13b
10 t ha^{-1}	25.68a	69.10a	39.0b	64.40a
15 t ha^{-1}	38.20a	41.64b	43.14b	42.12b
LSD 5%	13.15			

Table 5 Average potassium availability obtained from the interaction between biochar dosage and fertilizer type

Treatment	**Fertilizer Type**			
	Without fertilizer	**Compost**	**NPK**	**NPK + Compost**
Biochar dosage	--------------------------ppm---			
0 t ha^{-1}	445.12d	749.14b	329.24c	612.24d
5 t ha^{-1}	667.34c	998.17a	721.41b	927.12c
10 t ha^{-1}	978.32b	1020.14a	700.23b	1250.31a
15 t ha^{-1}	1032.14a	1051.19a	1027342a	1124.37b
LSD 5%	57.12			

Base Saturation and Cation Exchange Capacity

The statistical evaluation revealed that there was no significant interaction (P≦0.05) between the biochar dose and fertilizer type about the base saturation and cation exchange capacity. The biochar dose had a significant impact ($P<0.05$) on both the base saturation and CEC. Additionally, fertilizer type had a significant influence ($P<0.05$) on both the base saturation and CEC, with the CEC having a very significant effect ($P<0.01$). Table 6 displays the mean values of base saturation and cation exchange capacity. Table 6 demonstrates that the application of biochar at a dose of 15 t ha^{-1} resulted in a significantly higher CEC of 19.20 cmolc kg^{-1} compared to the lowest CEC of 15.89 cmolc kg^{-1} observed in the treatment control (without biochar). Similarly, the maximum base saturation achieved at a biochar dose of 10 t ha^{-1} was significantly different from the lowest biochar dose of 15 t ha^{-1}, which was 35.78%. The increased CEC in the biochar amended soil was because of the slow oxidation of biochar to oxygenate the functional groups of biochar surface and enhance the formation of organo-mineral (Quan et al., 2020). According to Pace (2018), biochar in the soil can have larger negative charges on their surface, attributed to the formation of the phenolic group by abiotic oxidation, contributing to the increase of the CEC in the soil environment. Therefore, biochar and manure addition differs significantly as compared with biochar and NPK addition. The combined biochar and manure plots obtained higher CEC (5.97 cmol/kg) more than the biochar and NPK addition (5.73 cmol/kg) because of the organic matter derived from the farmyard manure. The organic matter entails large numbers of charged functional groups, which contribute significantly to the increase of CEC (Kumar et al., 2018). Also, due to the high surface area of the biochar, it adsorbed the organic matter derived from the manure and the soil environment on its surface, causing the release of carboxylic and phenolic acid groups into the soil environment (Nkoh et al., 2021). At the same time, the biochar and NPK addition depend much on the biochar to increase the CEC (Jing et al., 2022)

Table 6 Average capacity for cation exchange and the saturation of the base at different doses of biochar and types of fertilizers

Treatment	**CEC (cmolc kg^{-1})**	**Base saturation (%)**
Biochar dose		
Without biochar	15.89b	42.79ab
5 t ha^{-1}	17.01b	45.47ab
10 t ha^{-1}	17.51ab	54.36a

15 t ha^{-1}	19.20a	35.78b
LSD 5%	2.10	12.69
Fertilizer Type		
Without fertilizer	16.09b	31.74b
Compost	19.11a	45.54a
NPK	17.60ab	45.97a
NPK+ compost	16.80b	55.78a
LSD 5%	2.10	12.69

Total Soil Microbial

Changes in soil microbial communities may impact soil fertility and stability because microbial communities are key to soil functioning by supporting soil ecological quality and agricultural production (Purakayastha et al., 2023). The statistical evaluation of the total soil microbial population revealed that the interaction between biochar dose and type of fertilizer, and the biochar dose alone, had a highly significant effect ($P<0.01$). Additionally, the fertilizer type had a significant influence ($P<0.05$) on the total soil microbial population. Table 7 displays the average soil microbial population about the interactions between the biochar dose and different types of fertilizers. According to Table 6, the highest total microbial yield was observed when using a biochar dose of 15t ha^{-1} with a compost type of 4.19 x 10^{6} cfu ml^{-1}. In contrast, the lowest yield was obtained when using without biochar 15 t/ ha^{-1} and without fertilizer, with yields of 2.18 x10^{6}cfu ml^{-1} and 2.39x10^{6}cfu ml^{-1}, respectively. The maximum microbial total of 3.69x10^{6} cfu ml^{-1} was seen when a dose of 10 t ha^{-1} of biochar was combined with NPK + compost. The study found that the combination of the without and the without of fertilizer resulted in the lowest total microbial count, which was measured at 2.18x10^{6} cfu ml^{-1}. The addition of NPK fertilizer to the soil improves the microbial activity (Gryta et al., 2023) which in turn can intensify the mineralization of biochar in the soil leading to a subsequent increase in biochar's active surface and cation exchange capacity (Rizwan et al., 2023), resulting in increased soil aggregation capacity and lower bulk density (Gusiatin and Rouhani, 2023). The pH and pyrolysis temperature of biochar also had significant effects on the soil microbial community. Kumar et al. (2024) found that the application of biochar increased the soil pH, resulting in a significant increase in the abundance of the bacterial community. Biochar sorption properties also increase soil porosity, its cation exchange capacity (CEC), and water-holding capacity (Tang et al., 2024).

Such changes in the soil matrix may affect soil microbial communities that are central for soil quality. The extreme abundance (up to 1 billion cells per gram of soil) and diversity (up to 1 million species per gram of soil) of soil microbial communities indeed make them pivotal for functions of interest supporting the soil ecological quality and agricultural production: organic matter mineralization, soil structure, pesticide degradation, or competitive exclusion of pathogenic species (Mubeen et al., 2023). Changes in soil microbial communities may affect these processes.

Table 7 Average soil microbial count in the presence of biochar when mixed with different types of fertilizers

Treatment	**Fertilizer Type**			
	Without fertilizer	**Compost**	**NPK**	**NPK + Compost**
Biochar dosage	**--------------------------10^6 x cfu ml^{-1}--**			
0 t ha^{-1}	2.18c	2.29c	3.19b	3.62a
5 t ha^{-1}	3.28b	3.49b	3.88a	3.39ab
10 t ha^{-1}	3.99a	3.61b	3.48ab	3.69a
15 t ha^{-1}	2.39c	4.19a	2.87b	2.86b
LSD 5%	0.69			

Impact of *Acacia*-derived Biochar dose and type of Fertilizer on Soil Health

Biochar can improve soil fertility by inducing changes in soil chemical and physical properties. The alkaline pH of biochar, the presence of carbonates and negatively charged phenolic, carboxyl and hydroxyl groups on its surface can increase the soil pH, while soil acidity is associated to low fertility (Mandal et al., 2024). The present study used the soil quality rating (SQR) as a means of assessing the state of the soil. The SQR is determined by calculating the cumulative weight of soil indicators of quality, which have been chosen as the minimum set of data (Mueller et al., 2013). Table 8 displays the SQR assessment findings for each treatment dose combination involving the type of fertilizer (BF) and biochar on soil. Table 8 indicates that the SQR values varied from 18 to 23. The biochar dose of 10 t ha^{-1} with NPK + compost (B_2F_3) resulted in the lowest value of SQR 18, indicating a high level of sustainability. On the other hand, the treatment fertilizer (B_0F_0) and without biochar and the addition with biochar dose of 10 t ha^{-1} and no fertilizer (B_2F_0) yielded the highest SQR 23, indicating a good sustainability level. According to the data presented in Table 7, it can be observed that the treatment fertilizer and control (B_0F_0, B_1F_0, B_2F_0, and B_3F_0) yields the highest soil quality rating. However, when biochar is mixed with different kinds of compost (F_1), NPK (F_2), and NPK and compost (F_3), the soil quality rating value gradually declines. The low rating of soil quality in the mixture of biochar 10 t ha^{-1} combined with NPK + compost (B_2F_3) is attributed to the enhancement of soil characteristics resulting from the application of B_2F_3, which ensures a balanced supply of essential nutrients for maize plants.

Table 8 Impact of combining biochar dosage with fertilizer type (BF) on soil quality rating (SQR)

	Soil quality indicators										
Treatment	**Water content**	**Soil texture**	**Bulk density**	**Soil porosity**	**pH**	**C**	**cation exchange capacity**	**NPK**	**Base saturation**	**Total microbial**	**SQR**
B_0F_0	4	3	1	1	1	2	4	2	4	1	23
B_0F_1	3	3	1	1	1	2	3	2	4	1	21
B_0F_2	3	3	1	1	1	2	3	2	3	1	20
B_0F_3	3	3	1	1	1	2	4	2	2	1	20
B_1F_0	3	3	1	1	1	2	4	2	3	1	21
B_1F_1	3	3	1	1	1	2	3	2	3	1	20
B_1F_2	3	3	1	1	1	2	3	2	3	1	20
B_1F_3	3	3	1	1	1	2	4	2	2	1	20
B_2F_0	3	3	1	1	1	2	4	2	4	1	23
B_2F_1	3	3	1	1	1	2	3	2	2	1	19
B_2F_2	3	3	1	1	1	2	3	2	1	1	20
B_2F_3	3	3	1	1	1	2	3	2	4	1	18
B_3F_0	3	3	1	1	1	2	4	2	3	1	22
B_3F_1	3	3	1	1	1	2	3	2	3	1	20
B_3F_2	3	3	1	1	1	2	3	2	3	1	20
B_3F_3	3	3	1	1	1	2	3	2	4	1	21

Note: B0 (without biochar), B1 (5 t ha-1), B2 (10 t ha-1), B3 (15 t ha-1), F0 (without fertilizer), F1 (compost), F2 (NPK), F3 (compost + NPK), Soil Quality Rating (SQR): < 20 = very good, 20- 25 = good, 25-30 = moderate, 30-40 = bad, >40 = very bad

The measurement findings obtained from the application of soil quality rating single-dose biochar treatment (B) and fertilizers treatment (F) on the soil are displayed in Table 9. The findings indicated that the biochar soil quality index varied between doses of 19 to 21. The soil quality is great, with a minimum value of 19 soil quality rating biochar attained at a dose of 10 t ha^{-1} (B$_2$), and a higher value of soil quality rating of 21 at both the biochar dose of 15 t ha^{-1} (B$_3$) and the control (B$_0$). Evaluating the soil quality in relation to the application of various kinds of fertilizer, using a scale ranging from 20 to 22 quality rating of soil. The soil quality rating level was as low as 20 for the compost (F$_1$), the type of NPK fertilizer (F$_2$), and the NPK + compost (F$_3$), all of which were in good condition. The maximum soil quality rating value of 22 was observed for the compost with no fertilizer (F$_0$). Assess the condition of the soil before the research. A value of SQR 26 indicated a moderate quality, indicating that substantial inputs are required for land use. However, following the experimentation with different dosages of biochar and fertilizer, this rating dropped to SQR 18 and 19, signifying an excellent quality.

Table 9 Impact of biochar dose and fertilizer type on soil quality rating (SQR)

	Soil quality indicators										
Treatment	**Water content**	**Soil texture**	**Bulk density**	**Soil porosity**	**pH**	**C**	**cation exchange capacity**	**NPK**	**Base saturation**	**Total microbial**	**SQR**
	Biochar dosage										
0 t ha^{-1}	3	3	1	1	1	2	4	2	3	1	21
5 t ha^{-1}	3	3	1	1	1	2	3	2	3	1	20
10 t ha^{-1}	3	3	1	1	1	2	3	2	2	1	19
15 t ha^{-1}	3	3	1	1	1	2	3	2	4	1	21
	Fertilizer Type										
Without fertilizer	3	3	1	1	1	2	4	2	4	1	22
Compost	3	3	1	1	1	2	3	2	3	1	20
NPK	3	3	1	1	1	2	3	2	3	1	20
NPK + compost	3	3	1	1	1	2	4	2	2	1	20

Impact of varying fertilizer type and biochar dose on the dry weight of seed maize per hectare, with a water content of 15%

The maximum dry weight of seed-maize per hectare, with a water level of 15% t ha^{-1}, was 12.79 tons when using a biochar dose of 10 t ha^{-1} in combination with NPK + compost. This was significantly different from the dry seed weight of 8.59 tons achieved when using a biochar dose of 15 t ha^{-1} in combination with NPK + compost, with a water level of 15% t ha^{-1} (Table 10). According to the data shown in Table 9, it can be observed that the dry weight of seed-maize t ha-1, with a water content of 15%, varied between 5.80 and 12.79 tons. The application with a biochar rate of 10 t ha^{-1} in combination with NPK + compost resulted in a maximum yield of 12.79 tons. Conversely, the treatment of fertilizer and without biochar yielded the lowest dry-weight seed-maize t ha-1, with a water level of 15%, yielding 5.79 tons. When different dose levels of biochar were applied to the same kind of fertilizer, it was seen that the best yield was achieved when the biochar dose of 10 t ha^{-1} was combined with NPK + compost. This interaction was found to be statistically different from the other treatments. The application of biochar at a dose of 10 t ha^{-1}, combined with NPK + compost, resulted in a significant 40% rise in the dry weight of seed-maize t ha^{-1}. The highest dry weight of 12.79 tons was achieved, compared to the 9.27 tons obtained when biochar was not used in combination with NPK + compost. The application of biochar at several doses on different types of fertilizers resulted in the highest yield. Specifically, the interaction between biochar dose of 10 t ha-1 and NPK + compost exhibited a substantially different outcome compared to the other treatments. The application of biochar at a dosage of 10 tons per hectare, in combination with NPK + compost, resulted in a high dry weight of seed-maize per hectare with a water content of 15%. This yield was 12.79 tons, representing a significant increase of 48.31% compared to the lowest dry weight observed when using a biochar dosage of 10 tons per hectare with or without fertilizer, which was 8.59 tons.

Table 10 The combination of biochar dosage and fertilizer type resulted in an average dry weight seed-corn water content of 15% per hectare

Treatment	**Fertilizer Type**			
	Without fertilizer	Compost	NPK	NPK + compost
Without biochar	5.80c	7.73b	8.50b	9.27bc
5 t ha^{-1}	7.11bc	8.10bc	9.60ab	10.22b
10 t ha^{-1}	8.59a	9.60a	10.30a	12.79a
15 t ha^{-1}	8.19ab	9.18ab	9.18ab	8.59c
LSD 5%	1.50			

* The presence of a number followed by the same little letter in the vertical direction, with capitalization equivalent to the horizontal way, does not exhibit a statistically significant difference at a significance level of 5%.

The formulation of 10 t ha^{-1} biochar with NPK + compost resulted in a significant increase in soil characteristics on dry land. Specifically, the available P increased from 30.50% to 64.40%, the available K increased from 445.12 ppm to 1250.31 ppm, and the total microbial population increased from 2.18x10^{6}cfu ml^{-1} to 3.69 x 106 cfu ml^{-1}. The maximum yield on B_2F_3 is usually justified by the enhancement of soil characteristics when using 10 t ha^{-1} of biochar. The dose of biochar with 10 t ha^{-1} has been found to enhance soil aggregation by transforming micro-aggregates into larger aggregates. This process leads to a reduction in soil bulk density and enhancement of soil porosity, which in turn improves the soil's capacity to retain nutrients and water, as well as the total soil microbes. The condition under consideration is distinguished by a decrease in the bulk density of the soil from 0.97 g cm^{-3} to 0.86 g cm^{-3}, an increase in soil porosity from 64.01% to 66.31%, a rise in soil water content from 8.35% to 9.81%, an increase in soil pH from 6.58 to 6.76, a decrease in total N from 0.17% to 0.21%, a decrease in C-organic from 3.64% to 4.01%, a decrease in CEC from 15.89 to 19.20 cmolckg^{-1}, and a decrease in base saturation from 42.79% to 55.78%. The high yield seen in B_2F_3 can be attributed to its surface form, which exhibits a distribution of micropores and a more favourable mix of constituent elements. The enhancement of soil qualities concerning the augmentation of maize crop yields is commonly observed in the evaluation of soil quality. The application of biochar at a dose of 10 t ha^{-1} in combination with NPK + compost resulted in a good soil quality status, as seen in Table 8. The utilization of Acacia-biochar has been found to enhance various soil qualities, including aggregation, CEC, pH, and soil water holding capacity. Additionally, it has been observed to promote an increase in soil population and microbial activity (Li et al., 2024). Biochar plays a crucial role in enhancing the soil's capacity to sequester carbon, enhance soil fertility, stabilize soil, and promote crop growth and production by supplying and retaining soil nutrients (Lusizi et al., 2024). The utilization of biochar exhibits significant promise in enhancing the fertility of the soil and facilitating the growth of plants. Biochar has the potential to serve as an innovative and viable fertilizer directly. The reasons for this phenomenon extend beyond the fertility of biochar, including its economic and environmental advantages (Chen et al., 2023).

Exploration of IBCR and RAE

Table 11 displays the findings of the Relative Agronomic Effectiveness (RAE) evaluation, which aims to assess the agronomic efficacy of biochar when combined with different fertilizers. Additionally, the results of the Incremental Benefit Cost Ratio (IBCR) evaluation, which evaluates the economic benefits in terms of maize yield in dryland conditions, are also presented. The addition of biochar 10 t ha^{-1} with NPK + compost resulted in a maximum yield of 12.80 tonnes. This combination had a high RAE value of 120.31% and an IBCR of 1.28, making it highly efficient, practical, and favourable for maize plants in dry land. In contrast, the biochar application of 15 t ha^{-1} combined with NPK and compost resulted in the lowest RAE value of 12.71% and an IBCR value of 0.45. These values were deemed inefficient and unsuitable for cultivating maize plants in dryland conditions, as indicated in Table 11.

Table 11 Findings from the study of hybrid corn cultivation

Treatment	**Dry weight of maize-seed WC 15% (t ha$^{-1)}$**	**Cost (Rp)**	**Acceptance (Rp)**	**RAE (%)**	**IBCR**
B_0F_0	5.70	4,275,000	17,194,108	-	-
B_0F_1	7.69	14,385,000	23,090,808	-	0.59
B_0F_2	8.50	5,747,839	25,484,912	-	5.64
B_0F_3	9.30	15,857,839	27,792,494	-	0.93
B_1F_0	7.21	6,905,000	21,220,004	-	1.54
B_1F_1	8.10	17,015,000	24,214,056	51.77	0.56
B_1F_2	9.60	8,377,839	28,766,193	92.03	2.92
B_1F_3	10.12	18,487,839	30,687,440	90.34	0.96
B_2F_0	8.59	9,535,000	25,836,980	-	1.65
B_2F_1	9.60	19,645,000	28,773,659	50.81	0.76
B_2F_2	10.29	11,007,839	30,826,800	61.21	2.03
B_2F_3	12.80	21,117,839	38,522, 248	120.31	1.28
B_3F_0	8.19	12,165,000	24,609,344	-	0.95
B_3F_1	9.21	22,275,000	27,518,059	50.64	0.58
B_3F_2	9.20	13,637,839	27,491,262	35.54	1.11
B_3F_3	8.58	23,747,839	25,814,896	12.71	0.45

The Relative Agronomic Effectiveness (RAE) of Acacia-biochar combined with different types of fertilizers exhibited a range of 12.71% to 120.31%, as seen in Table 11. The application of a biochar dose of 10 t ha^{-1} and NPK + compost resulted in the greatest RAE rating of 120.31%. On the other hand, the biochar application at the dose of 15 t ha^{-1} and fertilizers NPK + compost had the lowest RAE level of 12.71%. The treatment that involves an association of B_2F_3 is shown to be highly efficient (RAE 120.31%) and profitable (IBCR 1.28), resulting in a significantly higher maize plant yield than other treatments. The profitability of growing maize in dryland farming is found to be higher when chemical fertilizers, specifically NPK, are utilized compared to compost and biochar, as seen in Table 10. Table 10 provides insights into the viability and profitability of different biochar dosages, ranging from 5 to 10 t ha^{-1} when treated without fertilizer and supplemented with varying dosages of NPK and biochar. Biochar dose with an IBCR value greater than 1 are considered viable and profitable. Conversely, combinations of compost with biochar or NPK with compost, with an IBCR value less than 1, are classified as unsuitable, unless the B_2F_3 is considered.

The application of biochar at a rate of 10 t ha^{-1}, in combination with NPK and compost, results in an IBCR scale of 1.28. This formulation is considered to be a feasible and financially advantageous approach for enhancing the yield of maize crops. The low value of IBCR on compost is attributed to the substantial expenditures associated with its procurement, which have a negligible impact on the initial maize production. The utilization of biochar and compost has the potential to significantly impact soil fertility, particularly in cases of low fertility. Additionally, the inclusion of compost in the biochar-compost mixture may lead to an increase in deficiencies in nutrients within the soil, hence impacting the direct economic value of the crop. In contrast, the utilization of biochar showed efficacy in medium-fertility soils for water and nutrient storage, plant production, and sequestration of carbon. Long-term field studies using biochar to absorb carbon dioxide from the atmosphere; the function of microbes in oxidizing the surface of the biochar and releasing nutrients; the characteristics of the carbon surface of the soil environment; the ratio of biochar nutrition to compost-biochar; and the biochar rate and type of applications. Future study lines should consider evaluating compost and biochar made from the same raw materials, as long- and short-term long-term assessments of biochar should be complementary to one another.

4. Conclusion

The addition of 10 t ha^{-1} of *Acacia* biochar, 20 t ha^{-1} of compost, and 313 kg ha^{-1} of NPK can raise the K and P availability, increase the total amount of soil microbes, enhance the micropores distribution, and improve the soil quality to very good with a value of SQR 18. The application of Acacia biochar at a dose of 10 t ha^{-1}, when combined with NPK and compost, resulted in the maximum yield of 12.80 tonnes of dry weight seed maize per hectare. This yield was observed to increase by 40% compared to the scenario where biochar was not used in conjunction with compost and NPK. The combination of biochar 10 t ha^{-1} with NPK + compost resulted in a maximum yield of 12.80 tonnes. This combination had a high RAE value of 120.31% and an IBCR of 1.28, making it very effective, practical, and favourable for corn crops in dryland.

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References

Ahmed, N., Deng, L., Wang, C., Shah, Z. U. H., Deng, L., Li, Y., ... & Tu, P. (2024). Advancements in Biochar Modification for Enhanced Phosphorus Utilization in Agriculture. Land, 13(5), 644.

An, X., Liu, Q., Pan, F., Yao, Y., Luo, X., Chen, C., ... & Liu, X. (2023). Research Advances in the Impacts of Biochar on the Physicochemical Properties and Microbial Communities of Saline Soils. Sustainability, 15(19), 14439.

Chen, W., Wu, Z., Liu, C., Zhang, Z., & Liu, X. (2023). Biochar combined with Bacillus subtilis SL-44 as an eco-friendly strategy to improve soil fertility, reduce Fusarium wilt, and promote radish growth. Ecotoxicology and Environmental Safety, 251, 114509.

Elkhalifa, S., Mackey, H. R., Al-Ansari, T., & McKay, G. (2022). Pyrolysis of biosolids to produce biochars: a review. Sustainability, 14(15), 9626.

Garcia, B., Alves, O., Rijo, B., Lourinho, G., & Nobre, C. (2022). Biochar: production, applications, and market prospects in Portugal. Environments, 9(8), 95.

Ghorbani, M., Konvalina, P., Neugschwandtner, R. W., Soja, G., Bárta, J., Chen, W. H., & Amirahmadi, E. (2024). How do different feedstocks and pyrolysis conditions effectively change biochar modification scenarios? A critical analysis of engineered biochars under H_2O_2 oxidation. Energy Conversion and Management, 300, 117924.

Hua, L., Wu, C., Zhang, H., Cao, L., Wei, T., & Guo, J. (2021). Biochar-induced changes in soil microbial affect species of antimony in contaminated soils. Chemosphere, 263, 127795.

Li, Z., Wu, S., Liu, Y., You, F., Hall, M., & Huang, L. (2024). Natural nodulation and nitrogen fixation of Acacia Auriculiformis grown in technosol eco-engineered from Fe ore tailings. Plant and Soil, 497(1), 25-41.

Lusizi, Z., Motsi, H., Nyambo, P., & Elephant, D. (2024). Black (*Acacia mearnsii*) and silver wattle (Acacia dealbata) invasive tree species impact on soil physicochemical properties in South Africa: A systematic literature review. Heliyon.

Mandal, S., Pu, S., He, L., Ma, H., & Hou, D. (2020). Biochar induced modification of graphene oxide & nZVI and its impact on immobilization of toxic copper in soil. Environmental pollution, 259, 113851.

Maniraj, J., Ramesh, M., Kumar, S. G., & Sahayaraj, A. F. (2023). Introduction of Biochar: Sources, Composition, and Recent Updates. In Biochar and its Composites: Fundamentals and Applications (pp. 1-17). Singapore: Springer Nature Singapore.

Mubeen, B., Hasnain, A., Wang, J., Zheng, H., Naqvi, S. A. H., Prasad, R., ... & Moustafa, M. (2023). Current progress and open challenges for combined toxic effects of manufactured nano-sized objects (MNO’s) on soil biota and microbial community. Coatings, 13(1), 212.

Mueller, L., Shepherd, G., Schindler, U., Ball, B. C., Munkholm, L. J., Hennings, V., ... & Hu, C. (2013). Evaluation of soil structure in the framework of an overall soil quality rating. Soil and Tillage Research, 127, 74-84.

Murtaza, G., Ahmed, Z., Eldin, S. M., Ali, B., Bawazeer, S., Usman, M., ... & Tariq, A. (2023). Biochar-Soil-Plant interactions: A cross talk for sustainable agriculture under changing climate. Frontiers in Environmental Science, 11, 1059449.

Murtaza, G., Ahmed, Z., Usman, M., Tariq, W., Ullah, Z., Shareef, M., ... & Ditta, A. (2021). Biochar induced modifications in soil properties and its impacts on crop growth and production. Journal of plant nutrition, 44(11), 1677-1691.

Murtaza, G., Ahmed, Z., Valipour, M., Ali, I., Usman, M., Iqbal, R., ... & Tariq, A. (2024). Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants. Scientific Reports, 14(1), 217.

Rombel, A., Krasucka, P., & Oleszczuk, P. (2022). Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. *Science of the total environment*, *816*, 151588.

Sazali, N., Harun, Z., & Sazali, N. (2024). Additional of Organic Amendments in the Soil to Increase the Various Crop Yield: A Review. Journal of Advanced Research in Applied Sciences and Engineering Technology, 35(2), 158-174.

Shao, F., Zeng, S., Wang, Q., Tao, W., Wu, J., Su, L., ... & Lin, S. (2023). Synergistic effects of biochar and carboxymethyl cellulose sodium (CMC) applications on improving water retention and aggregate stability in desert soils. Journal of Environmental Management, 331, 117305.

Sobuz, M. H. R., Khan, M. H., Kabbo, M. K. I., Alhamami, A. H., Aditto, F. S., Sajib, M. S., ... & Alam, A. (2024). Assessment of mechanical properties with machine learning modeling and durability, and microstructural characteristics of a biochar-cement mortar composite. Construction and Building Materials, 411, 134281.

Sofia, G., Zaccone, C., & Tarolli, P. (2024). Agricultural drought severity in NE Italy: Variability, bias, and future scenarios. International Soil and Water Conservation Research, 12(2), 403-418.

Sufardi, S. (2024, February). How to enhance soil quality in dryland farming systems in Indonesia. In IOP Conference Series: Earth and Environmental Science (Vol. 1297, No. 1, p. 012071). IOP Publishing.

Tang, S., Gong, J., Song, B., Cao, W., & Li, J. (2024). Remediation of biochar-supported effective microorganisms and microplastics on multiple forms of heavy metals in eutrophic lake. Journal of Hazardous Materials, 465, 133098.

Yang, X., Tsibart, A., Nam, H., Hur, J., El-Naggar, A., Tack, F. M., ... & Ok, Y. S. (2019). Effect of gasification biochar application on soil quality: Trace metal behavior, microbial community, and soil dissolved organic matter. Journal of hazardous materials, 365, 684-694.

Younas, Z., Tanveer, K., Ikram, M., & Raja, N. I. (2024). Characterization and evaluation of different biochars as soil amendment under a polluted environment. In Biochar-assisted Remediation of Contaminated Soils Under Changing Climate (pp. 277-304). Elsevier.

Zanutel, M., Garré, S., Sanglier, P., & Bielders, C. (2024). Biochar modifies soil physical properties mostly through changes in soil structure rather than through its internal porosity. Vadose Zone Journal, 23(1), e20301.

Gusiatin, M. Z., & Rouhani, A. (2023). Application of selected methods to modify pyrolyzed biochar for the immobilization of metals in soil: A review. Materials, 16(23), 7342.

Gryta, A., Skic, K., Adamczuk, A., Skic, A., Marciniak, M., Józefaciuk, G., & Boguta, P. (2023). The Importance of the Targeted Design of Biochar Physicochemical Properties in Microbial Inoculation for Improved Agricultural Productivity—A Review. Agriculture, 14(1), 37.

Rizwan, M., Murtaza, G., Zulfiqar, F., Moosa, A., Iqbal, R., Ahmed, Z., ... & Li, H. (2023). Sustainable manufacture and application of biochar to improve soil properties and remediate soil contaminated with organic impurities: a systematic review. Frontiers in Environmental Science, 11, 1277240.

Kumar, P. (2024). Biochar Production from Marine Algae and Its Application in the Treatment of Industrial Effluent. Marine Biomass: Biorefinery, Bioproducts and Environmental Bioremediation, 57.

Purakayastha, T. J., Bhaduri, D., Kumar, D., Yadav, R., & Trivedi, A. (2023). Soil and Plant Nutrition. In Trajectory of 75 years of Indian agriculture after independence (pp. 365-411). Singapore: Springer Nature Singapore.

Mandal, J., Sharma, P. K., Mondal, D., Wood, M. D., Hutchinson, S. M., Kirby, J., & Srivastava, P. (2024). Meta-analysis of biochar as an amendment for arsenic mitigation in paddy soils. Current Pollution Reports, 10(1), 105-118.

Anand, R. S., & Kumar, P. (2022). Recent Developments in Energy Recovery from Sewage Treatment Plant Sludge via Anaerobic Digestion. Environmental Management in India: Waste to Wealth, 199-231.

Kaljunen, J. U., Al-Juboori, R. A., Mikola, A., Righetto, I., & Konola, I. (2021). Newly developed membrane contactor-based N and P recovery process: Pilot-scale field experiments and cost analysis. Journal of Cleaner Production, 281, 125288.

Brekalo, M., Rajs, B. B., Aladić, K., Jakobek, L., Šereš, Z., Krstović, S., ... & Strelec, I. (2023). Multistep extraction transformation of spent coffee grounds to the cellulose-based enzyme immobilization carrier. Sustainability, 15(17), 13142.

Riyad, Y. M., Elmorsi, T. M., Alam, M. G., & Abel, B. (2023). Surface functionalization of bioactive hybrid adsorbents for enhanced adsorption of organic dyes. International Journal of Environmental Research and Public Health, 20(9), 5750.

slam, M., Siddique, K. H., Padhye, L. P., Pang, J., Solaiman, Z. M., Hou, D., ... & Bolan, N. (2024). A critical review of soil phosphorus dynamics and biogeochemical processes for unlocking soil phosphorus reserves. Advances in Agronom, 185, 153-249.

Zhong, H., Feng, Z., Luo, Y., Zheng, Y., Luo, Z., Peng, T., ... & Song, B. (2024). When biochar meets iron mineral: An opportunity to achieve enhanced performance in treating toxic metal (loid) s and refractory organics. Separation and Purification Technology, 128022.

Jing, F., Sun, Y., Liu, Y., Wan, Z., Chen, J., & Tsang, D. C. (2022). Interactions between biochar and clay minerals in changing biochar carbon stability. Science of the Total Environment, 809, 151124.

Nkoh, J. N., Baquy, M. A. A., Mia, S., Shi, R., Kamran, M. A., Mehmood, K., & Xu, R. (2021). A critical-systematic review of the interactions of biochar with soils and the observable outcomes. Sustainability, 13(24), 13726.

Kumar, A., Joseph, S., Tsechansky, L., Privat, K., Schreiter, I. J., Schüth, C., & Graber, E. R. (2018). Biochar aging in contaminated soil promotes Zn immobilization due to changes in biochar surface structural and chemical properties. Science of the Total Environment, 626, 953-961.

Pace, B. (2018). Mineral enriched biochars for soil nutrient retention and enhanced microbial activity (Doctoral dissertation, UNSW Sydney).

Quan, G., Fan, Q., Sun, J., Cui, L., Wang, H., Gao, B., & Yan, J. (2020). Characteristics of organo-mineral complexes in contaminated soils with long-term biochar application. Journal of hazardous materials, 384, 121265.

Mood, S. H., Mainalis, K., Pelaez-Samaniego, M. R., & Garcia-Perez, M. (2024). Characteristics of biochar: Micro-and nano-chemical properties and interactions. In Biochar for Environmental Management (pp. 127-151). Routledge.

Mujtaba, G., Hayat, R., Hussain, Q., & Ahmed, M. (2021). Physio-chemical characterization of biochar, compost and co-composted biochar derived from green waste. Sustainability, 13(9), 4628.

Pandian, K., Vijayakumar, S., Mustaffa, M. R. A. F., Subramanian, P., & Chitraputhirapillai, S. (2024). Biochar–a sustainable soil conditioner for improving soil health, crop production and environment under changing climate: a review. Frontiers in Soil Science, 4, 1376159.

Nie, T., Yang, X., Chen, H., Müller, K., Shaheen, S. M., Rinklebe, J., ... & Wang, H. (2021). Effect of biochar aging and co-existence of diethyl phthalate on the mono-sorption of cadmium and zinc to biochar-treated soils. Journal of Hazardous Materials, 408, 124850.

Tusar, H. M., Uddin, M. K., Mia, S., Suhi, A. A., Wahid, S. B. A., Kasim, S., ... & Anwar, F. (2023). Biochar-acid soil interactions—a review. Sustainability, 15(18), 13366.

Al-Swadi, H. A., Al-Farraj, A. S., Al-Wabel, M. I., Ahmad, M., Usman, A. R., Ahmad, J., ... & Rafique, M. I. (2024). Impacts of kaolinite enrichment on biochar and hydrochar characterization, stability, toxicity, and maize germination and growth. Scientific Reports, 14(1), 1259.

Maqbool, Z., Farooq, M. S., Rafiq, A., Uzair, M., Yousuf, M., Khan, M. R., & Huo, S. (2024). Unlocking the potential of biochar in the remediation of soils contaminated with heavy metals for sustainable agriculture. Functional Plant Biology, 51(2).

Lee, J. H., & Kasote, D. M. (2024). Nano-Priming for Inducing Salinity Tolerance, Disease Resistance, Yield Attributes, and Alleviating Heavy Metal Toxicity in Plants. Plants, 13(3), 446.

Amalina, F., Krishnan, S., Zularisam, A. W., & Nasrullah, M. (2023). Recent advancement and applications of biochar technology as a multifunctional component towards sustainable environment. Environmental Development, 46, 100819.

Shoudho, K. N., Khan, T. H., Ara, U. R., Khan, M. R., Shawon, Z. B. Z., & Hoque, M. E. (2024). Biochar in global carbon cycle: Towards sustainable development goals. Current Research in Green and Sustainable Chemistry, 100409.

Dutta, A., Patra, A., Nain, P., Jatav, S. S., Meena, R. S., Mukharjee, S., ... & Pradhan, C. (2024). Engineered biochar: potential application toward agricultural and environmental sustainability. In Biochar Production for Green Economy (pp. 531-556). Academic Press.

Yadav, R., & Ramakrishna, W. (2023). Biochar as an environment-friendly alternative for multiple applications. Sustainability, 15(18), 13421.

Gusiatin, M. Z., & Rouhani, A. (2023). Application of selected methods to modify pyrolyzed biochar for the immobilization of metals in soil: A review. Materials, 16(23), 7342.

Mukhopadhyay, A., Misra, S., Manjanagouda, S. S., Singh, A. K., & Ghosh, A. (2024). Biochar aspects in the sustainability of agriculture and environment. In Waste Management for Sustainable and Restored Agricultural Soil (pp. 203-219). Academic Press.