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The Effect of Biochar, Biofertilization, and Mineral Fertilization on the Growth and Yield of Okra (Abelmoschus esculentus L.)

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Abstract

In 2024, a field experiment in the Zafaraniya area was conducted on silty loam soils to assess the effects of using biochar, biofertilizers, and mineral fertilizers on soil fertility, okra pod quality, and yield. The factorial design was composed of three treatment combinations: 0 tons/ha or 4 tons/ha of biochar; 0 tons/ha or 4 tons/ha of nitrogen-fixing, phosphate-solubilizing and potassium-solubilizing bacteria; and 0, 50%, or 100% of the recommended rate of mineral fertilizer applied. The design was performed within a completely randomized block design (CRBD) with three replicates for each treatment combination. The results indicated that the use of biochar, biofertilizers, and the different mineral fertilizer application rates had significant increases in soil N, P, and K levels. By the end of the study, the soil nutrient levels increased to 32.51 mg N/kg, 15.48 mg P/kg, and 210.03 mg K/kg, respectively. The nutrient content of the okra pods also increased; the levels of nitrogen, phosphorus, and potassium were 1.61, 0.48, and 1.52, respectively. The total yield of okra for the CRBD was 9.69 tons/ha; the average protein content was 10.10% and the total soluble solids (T.S.S.) were 7.30%. These results show that by improving soil characteristics, biochar, biofertilizers, and mineral fertilizers greatly increased the amount and quality of okra produced. The study emphasizes the necessity for more investigation into organic and biofertilizers in organic farming. In order to promote sustainability, boost farm profitability, and lessen pollution, farmers should be encouraged to use less expensive, ecologically friendly fertilizers instead of chemical ones.

Keywords:

Biochar, biofertilization, mineral fertilization, growth, okra, abelmoschus esculentus l., organic fertilizers, sustainable agriculture.

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Introduction

Okra (Abelmoschus esculentus L.) is a vegetable product of global importance due to its high nutritional value, as it contains essential protein (2.1%), carbohydrates (8%), and other vitamins and minerals, making its effective cultivation crucial for achieving food security (Mustapha et al., 2017; Tufaro et al., 2022; Nadeem Haider et al., 2017). To maximize productivity, it is important to control soil fertility and plant nutrition (Huang et al., 2020; Rahim et al., 2023). This need compels agricultural scientists to explore sustainable procedures that could increase yield and quality while reducing the environmental effects of high chemical fertilizer application (Hammadi & Alwan, 2023; Fasusi et al., 2021; Almamori & Abdul-Ratha, 2020; Mahmoud et al., 2009; Peech, 1947). As an increasing number of environmentally friendly alternatives, both biochar and biofertilizers have gained prominence in recent years. (Hassan, 2018; Mohsen et al., 2025; Almudhafar et al., 2024). Biological charcoal originates as charred organic matter through thermal decomposition processes involving plant residues; it significantly improves soil composition, moisture absorption capabilities, and fertility levels according to studies cited in reference number twenty-two (Zhang et al., 2012). Biological fertilizers facilitate plant development through activities like nitrogen fixing, phosphorus dissolution, and potassium release, thus increasing nutrient accessibility for plants. (Kartina et al., 2019; Mohsen & Alwan, 2019; Singh et al., 2020). The research was designed to examine the interaction and individual impacts of implementing these novel inputs alongside different proportions of conventional mineral fertilizers (N, P, K) (Mohsen et al., 2017; Al-Mawsili, 2018). The trial was conducted in the Zafaraniya region in 2024 with silty loam soil, employing a factorial design as part of a Completely Randomized Block Design (CRBD). The three factors included: Biochar (B0: 0 tons/ha vs. B1: 4 tons/ha), Biofertilizer (O0: control vs. O1: nitrogen-fixing, phosphate-solubilizing, and potassium-solubilizing bacteria), and Mineral Fertilizer (M0: 0%, M1: half the recommended dose, and M2: full recommended dose (Poornimadarshini, 2024; Lehmann et al., 2011).

The study obtained conclusive findings on the best fertilization plan for okra in this soil type. The most significant finding was the better performance of the triple interaction treatment (B1O1M2).

Key Contributions

- Maximized Total Yield and Quality: The B1O1M2 treatment (Biochar at 4 tons/ha + Biofertilizer + 100% Mineral Fertilizer) resulted in the highest total okra yield value of 9.69 tons/ha, significantly higher than the control yield value of 6.27 tons/ha. This treatment also maximized quality parameters such as protein content (10.10%) and total soluble solids (T.S.S.) at 7.30%.
- Improved Soil Fertility: The joint application of these inputs led to high levels of residual nutrient enrichment in the soil, with the B1O1M2 treatment having the highest levels of available nitrogen (32.51 mg N/kg), phosphorus (22.03 mg P/kg), and potassium (210.03 mg K/kg).
- Sustainability of Practices: The research confirms the effectiveness of combining biochar and biofertilizers with mineral fertilizers. This practice encourages the use of environmentally friendly fertilizers, promoting farm profitability, sustaining high yields, and minimizing environmental pollution from strictly chemical fertilization regimes.

The paper is organized in the following way: Introduction: Gives an overview of the significance of okra (Abelmoschus esculentus) and how biochar, biofertilizers, and mineral fertilizers can increase the productivity of the soils and crops. The rationale of the study and the importance of incorporating these inputs to achieve sustainable agriculture is identified. Materials and Methods: This section gives a description of the experimental design which includes the field site, soil properties and the treatments (biochar, biofertilizer and mineral fertilizers). The ways of collecting data such as measuring yields and analyzing the nutrients are elaborated. Results and Discussion: Reports the findings of the experiment of the effects of various treatments on soil nutrients, okra pod quality and yield. Interpretation of the interactions between biochar and biofertilizers and in relation to mineral fertilizers is done in statistical form. The results are compared to the past researches to comment on what they mean to the agricultural practices. Conclusion: Provides the summary of the main results with the focus on the most effective combinations of treatments in order to achieve the best okra production and enhance the soil health. The possibility of such treatments leading to sustainable agriculture is pointed out (Mustapha et al., 2016).

Materials and Methods

Biochar is the ash of crops or farm refuse, leaves, plant stems, woody trunks, the husks of some grains and possibly some wild meadow and lake plants. All these materials are gathered and burnt, with soil over them, and they burn slowly until the majority or all the elements disintegrate, and hence a black powder or tiny particles are formed which are applied to the soil and plants to make them grow (Keeney & Nelson, 1982; Al-Azzawi, 2018). It is the production of the biochar process. It may be made at a small scale using specialized but of low-cost furnaces, or at a large scale by much more expensive large-scale production by large pyrolysis plants and large quantities of the aforementioned raw materials. Biochar is a form of organic additive and is a fixed organic carbon compound 1. Moreover, 2 has reported that application of Biochar to silty loam soil at the rate of 4 µg/ha increased the increase in grain yield of mung bean by 35.92 percent over the control treatment. Biofertilizers are living microorganisms which are mostly bacteria and fungi that enhance the growth of plants by several processes and one of them is by producing plant hormones (Boghori & Tabatabai, 2017). The main functions of biofertilizers include to retain the soil fertility because biofertilizers are a renewable source of the necessary nutrients essential to the plants as well as to restart the functioning and cells of the plant within the crop growing period. Microorganisms of the soil are important in the conversion of nutrients in either complex or inaccessible forms into absorbable forms that can be absorbed by plants 3 (Oliwi et al., 2021). As indicated by source 4 the application of biofertilizer technologies in agricultural activities facilitates the development of symbiotic relationships between advantageous microorganisms and plants. and also contributes to increasing the growth of plants by supplying them with the nutrients the plant requires (Ali, 2016). Biofertilizers in agriculture cause a better vegetative growth because they provide nutrients available to the plant which consequently results into an increase in production and quality or type of crop product 5 (Alkobaisy & Mutlag, 2021; Larramendy & Soloneski, 2019). There should be more awareness especially to the farmers on how to handle the fertilizers, because this is what will see them use the fertilizers properly to ensure that they achieve desired objectives of improving the soil properties and providing the plants with the necessary nutrients. Some of the most significant agricultural inputs in order to boost and maintain agricultural output include the mineral fertilizers (Al-Lami et al., 2023; Ali et al., 2022; Alwan & Mohsen, 2024). Some of the most significant fertilizers are those that provide the necessary macronutrients (N, P, and K), which are required by plants in high amounts to fulfill their valuable purpose of forming proteins, enzyme activation, energy, nucleic acid, and other cell membranes, and it regulates the process of water absorption in the plants 6. The nutrient requirements of every plant will be different based on the kind of plant or the medium in which the plant grows, the nature and kind of soil, productive ability of the plant, and the ecology around the plant. The productive ability of crops in general is connected to the maintenance processes of crops, which are applied on the basis of the good scientific principles. To enhance the productivity of new varieties, the agricultural specialists are obliged to invest in the means that are needed to reach this objective (Al-Dulaimi, 2022; Humod Al-Ogaidi & Alwan, 2024). Among the most significant approaches that can be employed with the purpose of reaching this objective, the emphasis on nutrition must be mentioned as one of them, because the importance of this measure cannot be overstated in stimulating the growth and enhancing the productivity and quality of any sort of crops 7. Due to the nutritional value of okra, its intake has been on the rise. A 100g of fresh okra pods has a: 88% of water, 2.1% of protein, 0.21% of fat, 8% of carbohydrates, 1.7% of fiber, 0.2% of ash 8, and 50.6kcal/100g of energy. In addition to that, vitamins (vitamin A, B, C, H), nutrients (K and Ca) and some compounds, including quercetin, polyphenols, unsaturated fatty acids, essential amino acids, antioxidants, antimicrobials, and some anti-nutritional compounds are present in okra pods. This is the reason why okra is occasionally applied in the treatment of cardiovascular diseases 9. Thus, this study aims at examining the influence of biochar, biofertilizer and mineral fertilizer on the levels of the major essential nutrients in the okra fruits, as well as their interrelations. The objectives of the study are also to assess the concentration of the chosen nutrients, some quality characteristics of okra fruits, and early and total yield of okra. The experiment was carried out in the Zafaraniya area in 2024 using silty loam soil with the following latitude 33 24 120.97 and longitude 44 52 350.87. Soil samples were obtained randomly in the field and mixed thoroughly to obtain a composite sample, air dried, ground and sieved using a 2 mm mesh. Then, before planting, some physical, chemical, and fertility characteristics of the study soil were estimated based on the above-mentioned analysis techniques 10, 11 as shown in Table 1. Plowing and soil leveling was done. The field was subdivided to three blocks, each of which had 12 experimental units. The size of each experimental unit was 6 m 2 (1.5 m x 4 m) while the spacing between two experimental units was 1 m. Then a factorial experiment was planned via a totally randomized design (RCBD) with the total number of experiment units being 36. There were two lines 75 cm apart in the experimental unit, and each line had 10 plants, or 20 plants in one experimental unit. There was planting of batra okra seeds. The consumers like this variety since the pods do not make woody easily. Irrigation: Drip irrigation system was deployed, and irrigation was done up to the field capacity ending up using 35 percent of available water to the okra plants. Crop Service: The entire crop service operations were performed (Sahoo et al., 2014). Experimental Design: Data analysis was done with Genstat (Discovery Edition 4) program, where the least significant difference L.S.D at the 0.05 level was used, and a comparison of the arithmetic means of the treatments was done. The nutrient content of soil (nitrogen, phosphorus, and potassium) was determined at harvest and early yield was calculated as the sum of the first three harvests of each experimental unit. The yield of fruits was computed at the cumulative end of the experiment and taken to be the total yield. Regarding quality, certain fruit characteristics were put under study, such as obtaining the concentration of specific nutrients in the fruit, the percentage of protein, and the percentage of total soluble solids (T.S.S.%). Three major factors and their treatments were used in the experiment as follows: Soil treatment and the use of three levels of mineral fertilizers: (a) no addition which was the control treatment (M0), (b) 50 percent of the recommended fertilization rate (M1) and (c) 100 percent of the recommended fertilization rate of okra (M2). The recommended dose of okra was 120 kg of N. ha -1, 60 kg of P. ha -1 and 75 kg of K. ha -1. As a source of nitrogen, urea was employed, phosphorus source- triple superphosphate, and potassium source- potassium sulfate 12. Fertilizer was separated into four portions and at one week after the seeding process, the first application was made. Follow-up applications had been made after 15 days.

1. Biochar: The biochar was put in at two levels:

Without addition designated (B0)

Some of the properties of biochar are revealed in added at a level of 4 tons/ha designated (B1) (Table 2). A longitudinal cut was done, and biochar treatments were incorporated into the soil and then soil was planted. The addition was followed by immediate irrigation of the field.

2. Biofertilizer: Biofertilizer was used in two quantities:

Without addition (O0)

Incorporating components(O1) such as Azotobacter chroococcum for nitrogen fixation, Pseudomonas fluorescens for phosphate solubility enhancement, and Bacillus spp. for potash mobilization contributes to this formulation. The statement can be restated as follows: Biofertilizers were applied as seed treatments prior to sowing (AL-Obaidi, 2020).

Table 1. Selected physical, chemical, and fertility properties of the field soil before planting

Property		Value	Unit of measurement
EC 1:1		2.23	dS.m-1
pH 1:1		7.83	
Cation exchange capacity (CEC)		18.53	Cmol.kg-1 soil
Organic matter (OM)		15.81	g.kg-1
Carbonate minerals		28.15	
Gypsum (2H2O.CaSO4)		1.72	
Soluble positive ions	Calcium (Ca+2)	10.96	mEq/L
	Magnesium (Mg+2)	8.87	
	Sodium (Na+)	3.11	
	Potassium (K+)	1.12	
Soluble negative ions	Chloride (Cl-)	16.25	
	Sulfate (SO4=)	5.22	
	Bicarbonate (HCO3-)	2.27	
Some of the major elements	Available nitrogen	20.14	mg.kg-1 soil
	available phosphorus	8.17	
	available potassium	90.30	
Some physical properties	Bulk Density	1.34	mg/m^3
	Volumetric Moisture Content (1/3 bar)	0.284	cm3.cm-3
	Volumetric Moisture Content (15 bar)	0.151	
	Available Water (A.W)	0.133	
	Sand	352.10	g.kg-1 soil
	Silt	522.10	
	Clay	125.80	
Texture is Silty Loam			

Table 2. Chemical and physical properties of biochar (eucalyptus plant)

Property	The value of Biochar is its type (eucalyptus tree).	Unit
pH (1:5)	16.79	/
EC (1:5)	11.61	ds.m-1
Total Nitrogen	21.95	%
Total Phosphorus	89.82	%
Total Potassium	50.21	%
Organic Carbon	432.22	%
Organic Matter	658.64	%
C/N	31.10	-

Results and Discussion

In this experiment, Genstat (Discovery Edition 4) software was used to conduct the data analysis. A discussion of the experiment data was carried out through the use of this statistical software. Least Significant Difference (LSD) of 0.05 was used to compare the arithmetic means of the treatment combinations. The practice aided in determining the impact of the various treatments (Biochar, Biofertilizer, and Mineral Fertilizer) on the various parameters that included the soil nutrients, plant growth, yield, and fine features of the okra pods.

Data Set Description of Okra Fertilization Study:

The data used in the paper was related to a field experiment that was held in the Zafaraniya region in the year 2024 to test the effects of biochar, biofertilizers, and mineral fertilizers on silty loam soils. The experiment used in the study was a factorial design within a completely randomized block design (CRBD) having three replicates, resulting in 36 experimental units. The data is compiled using the initial soil characteristics, the variables that have been manipulated (independent variables), and the conclusive measurements (dependent variables) made on the soil and okra pods.

E1: Housing type, age, and daycare experience duration: E1 designed to assess the effects of these three variables on the dependent variable (TV watching).

The factors used in the experiment were three, and a total of 12 combinations of treatment were used.

Mineral Fertilization (M):

This is used at three levels:

- no addition (M_0),
- 50% (M_1), or
- 100% (M_2) of the recommended rate (120 kg N ha^{-1}, 60 kg P ha^{-1}, and 75 kg K ha^{-1}).

Biochar (B): Biochar is spread at two levels:

- without addition (B_0) or
- 4 tons/ha (B_1).

Biofertilizer (O): Used in two amounts:

- without addition (O_0) or
- addition (O_1) that involved nitrogen-fixing (Azotobacter chroococcum), phosphorus-solubilizing (Pseudomonas fluorescens), and potassium-solubilizing (Bacillus spp.) bacteria.

Dependent Variables: Soil and Crop Response Data

The measured data set includes the data on the performance of okra at harvest and soil fertility.

- Residual Soil Nutrients: The amount of remaining available nitrogen (N), available phosphorus (P), and available potassium (K) in the soil (mg N kg^{-1} soil, mg P kg^{-1} soil, and mg K kg^{-1} soil) at harvest were measured.

- Yield Metrics: Early yield (adding the first three harvests) and final yield (calculated at the cumulative completion of the experiment in tons per hectare).
- Okra Pod Quality: Specific nutrient (Nitrogen, Phosphorus, and Potassium percentage) concentration in the fruit, percentage protein, and the percentage T.S.S. (Total Soluble Solids) percentage.

Initial Conditions Data

The field soil initial data and the biochar used prior to planting were also put in the paper. These tables are a measure of baseline properties, which include:

- soil texture (Silty Loam),
- pH (7.83),
- Organic matter (15.81 g·kg^{-1}), and
- available nutrient initial (e.g., 20.14 mg/kg - available nitrogen).

Other properties of biochar that belong to the descriptive dataset include the pH (16.79), total nitrogen (21.95%), and phosphorus (89.82%).

Effect of biochar, biofertilizer, and mineral fertilizer on the residual quantity of major essential nutrients in soil at the end of the experiment

Tables three findings indicate that the application of biochars resulted in notable improvements, as it led to an increased availability of nitrogen within the soil environment by achieving its highest mean concentration towards the conclusion of the study period. Treatment B1 had an exceptionally high dosage yielding a score of twenty-five units. At concentrations ranging from 06 mg per kilogram of soil, the minimal level observed corresponds specifically to treatment B0, which exhibited an uptake rate of 23 units. Thirty milligrams per kilogram of soil weight. The biofertilizer grade O1 exhibited superior qualities, delivering an exceptional worth of 26 units. Eighty-two milligrams of nitrogen per kilogram in soil content. Despite having the least median value of 22 across all treatments, Treatment O0 stood out as it had the minimum score. Treatment M2 exhibited an elevated concentration at 54 mg/kg compared to other fertilizer-based treatments which resulted in its maximum value being recorded as 29 units. The dosage of N per kilogram in treated area was higher at 16 mg/kg than in untreated control group M0's level of 21 mg/kg. Zero milligrams per kilogram of dry weight in soil. The triad involving biochar, biostimulants, and chemical fertilizers reveals significant variations within its interactions as shown by Table 3.

Table 3. Effect of biochar, biofertilizer, and mineral fertilizer on the remaining available nitrogen in the soil (mg N. kg-1 soil)

<table>
<tr><th rowspan="2">Biofertilizer O</th><th rowspan="2">Biochar B</th><th colspan="3">Chemical fertilization M</th><th rowspan="2" colspan="2">Average B</th><th rowspan="2" colspan="2">Average O</th></tr>
<tr><td>M0</td><td>1 M</td><td>M2</td></tr>
<tr><td rowspan="2">O0</td><td>B0</td><td>17.61</td><td>21.01</td><td>26.12</td><td rowspan="2">B0</td><td rowspan="2">23.30</td><td rowspan="2">22.54</td><td rowspan="2">O0</td></tr>
<tr><td>B1</td><td>19.00</td><td>22.80</td><td>2727.</td></tr>
<tr><td rowspan="2">O1</td><td>B0</td><td>21.10</td><td>24.01</td><td>29.02</td><td rowspan="2">B1</td><td rowspan="2">25.06</td><td rowspan="2">26.82</td><td rowspan="2">O1</td></tr>
<tr><td>B1</td><td>25.31</td><td>27.70</td><td>32.51</td></tr>
<tr><td rowspan="2" colspan="2">LSD 0.05</td><td>M</td><td>B</td><td>O</td><td colspan="2">MBO</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>4.93</td><td>4.30</td><td>4.30</td><td colspan="2">5.10</td></tr>
<tr><td colspan="2">Average M</td><td>21.00</td><td>23.88</td><td>29.16</td><td colspan="2"></td></tr>
</table>

Treatment B101M2 demonstrated the greatest accumulation rate of available soil nitrogen towards its conclusion phase due to this intervention achieving an overall mean value of thirty-two units. A concentration of 0. 51 milligrams per kilogram in soil is being referred to here. The outcome surpassed the baseline comparison (Control Treatment B0O0M0), yielding an observed score of 17. Sixty-one milligrams of nitrogen per kilogram in soil content.

Effect of biochar, biofertilizer, and mineral fertilizer on available phosphorus in the soil (mg p.kg-1 soil) for okra and their interactions

Table 4 statistical analysis results indicate that biochar was a significant influence in the experiment since it offered the most average quantity of available phosphorus in the soil at the experiment conclusion. Treatment (B1) was far better and gave a value of 12.18mg P.kg -1 soil as opposed to treatment (B0) which gave a value of 9.68mg P.kg -1 soil. The sample (O1) of the biofertilizer was shown to be much higher with the highest value of 13.02 mg P. kg-1 soil and the lowest average was in O0 which had the value of 8.90 mg P. kg-1 soil. Regarding mineral fertilizer, the treatment M2 was far much higher than the other treatments getting the highest value of 14.78 mg P. kg-1 soil, which was not the same as the treatment M0 which had a value of 7.98 mg P. kg-1 soil. In the case of the triple interaction between biochar, biofertilizers and mineral fertilizer, Table (3) indicates that there are great differences in this interaction. The largest mean in the amount of available phosphorus in the soil at the final stage of the experiment was in the treatment (B1O1M2) which had the value of 22.03 mg P. kg-1 soil, whereas the treatment (B0O0M0) had the value of 3.82 mg P. kg-1 soil.

Table 4. Effect of biochar, biofertilizer, and mineral fertilizer on the remaining available Phosphorus in the soil (mg P.kg-1 soil)

Biofertilizer O	**Biochar B**	**Chemical fertilization M**			**Average B**		**Average O**	
		M0	**1 M**	**M2**				
O0	B0	3.82	5.15	8.98	B0	9.68	8.90	O0
	B1	5.07	7.11	12.64				
O1	B0	8.98	11.95	15.48	B1	12.18	13.02	O1
	B1	14.00	18.23	22.03				
LSD 0.05		M	B	O	MBO			
		5.11	4.30	4.30	6.01			
Average M		7.98	10.61	14.78				

Effect of biochar, biofertilizer, and mineral fertilizer on available potassium in the soil (mg K. kg-1 soil) for okra plant and their interactions

The Table 5 presented indicate that there was a significant influence of biochar since it offered the highest average of available potassium into the soil at the experiment end. Treatment (B1) was more remarkably better and presented a value of 162.68 mg K. kg-1 soil as compared to treatment (B0) that presented a value of 128.73 mg K. kg-1 soil. O1 level of biofertilizer was also very high and this was the highest of the other treatments and this had the highest value of 165.76 mg K.kg-1 soil and the lowest average was recorded at 124.32 mg K. kg-1 soil at treatment O0 level. In the case of mineral fertilizer, treatment M2 was well ahead of the rest of the treatments as it had the highest value at 167.66 mg K. kg-1 soil as compared to treatment M0 with a value of 127.98 mg K. kg-1 soil. Regarding triple interaction between biochar, biofertilizer and mineral fertilizer, Table (3) indicates that there are significant fluctuations in the triple interaction. The treatment (B1O1M2) recorded the highest average amount of available potassium in the soil and had a value of 210.03 mg K. kg-1 soil as compared to the treatment (B0O0M0) (the comparison treatment), which had a value of 80.11 mg K. kg-1 soil in the end of the experiment.

Table 5. Effect of biochar, biofertilizer, and mineral fertilizer on the remaining available potassium in the soil (mg K. kg-1 soil)

<table>
<tr><th rowspan="2">Biofertilizer O</th><th rowspan="2">Biochar B</th><th colspan="3">Chemical fertilization M</th><th rowspan="2" colspan="2">Average B</th><th rowspan="2" colspan="2">Average O</th></tr>
<tr><th>M0</th><th>1 M</th><th>M2</th></tr>
<tr><td rowspan="2">O0</td><td>B0</td><td>80.11</td><td>113.30</td><td>136.32</td><td rowspan="2">B0</td><td rowspan="2">128.73</td><td rowspan="2">124.32</td><td rowspan="2">O0</td></tr>
<tr><td>B1</td><td>120.24</td><td>151.46</td><td>162.44</td></tr>
<tr><td rowspan="2">O1</td><td>B0</td><td>132.56</td><td>165.57</td><td>184.54</td><td rowspan="2">B1</td><td rowspan="2">162.68</td><td rowspan="2">165.76</td><td rowspan="2">O1</td></tr>
<tr><td>B1</td><td>157.24</td><td>200.24</td><td>210.03</td></tr>
<tr><td rowspan="2" colspan="2">LSD 0.05</td><td>M</td><td>B</td><td>O</td><td colspan="2">MBO</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>9.60</td><td>5.30</td><td>5.30</td><td colspan="2">10.01</td></tr>
<tr><td colspan="2">Average M</td><td>127.98</td><td>137.17</td><td>167.66</td><td colspan="2"></td></tr>
</table>

The implication of the findings of Table 3, 4 and 5 implies that the effect of biochar is indirect, which is mainly by improving the water retention capacity of the soil. This is related to a higher soil stability (aggregate stability) and a lower compaction. The applied biochar also brings about contact with the minerals, microorganisms and soil organic matter. This is primarily because of the charge existing on the surface of the biochar and the surface created due to bonding which is a result of the interaction between biochar and other substances in the soil. On the one hand, biochar is able to inhibit or diminish the conversion of added fertilizers of nitrogen in the soil to nitrate and consequent loss of soil nitrate. It, therefore, is left available to the plant to be absorbed, and decreased in its concentration in the soil 13, 14, 2, 15. Concerning the effect of biofertilizers, it is influential in enhancing nutrient concentration. They have been regarded as some of the most significant fertilizers and are added into the soil in the form of materials, and they are made up of microorganisms that are helpful to plants, or referred to as microbial vaccines. The microorganisms help in production increase and quality enhancement as they supply the necessary nutrients to the plant and transform them into a form easily accessible to the plant. They also contribute to the mitigation of the damaging impacts of mineral fertilizer on the environment. Their application in mitigating the ill impacts of mineral fertilizers in the environment 16, 17, 18. Furthermore, the level of mineral fertilizers greatly boosted the nutrient content of the soil like nitrogen, phosphorus and potassium. The elevation of the remaining nutrients (nitrogen, potassium, and phosphorus) in the soil in chemical fertilizer treatments could be explained by the nutrients that these fertilizers introduce in the soil and enriched it with nutrients. This can be explained by the fact that, when urea, a nitrogenous fertilizer, is applied to the soil, it has an acidic impact on the root zone particularly the rhizosphere. The acidity can also be attributed to the existence of the urease enzyme that lowers the reaction rate of the soil hence enhancing the presence of major nutrients in the soil 19. In the case of phosphorus, the levels of phosphorus added to the soil increased tremendously with the level of phosphorus added to the soil, even though the phosphorus element was subjected to adsorption and soil precipitation. Likewise, an upward shift in the amount of potassium added contributed to an upward shift in the concentration of available potassium in soil 7. The rise in the amounts of other nutrients in the soil (nitrogen, potassium and phosphorus) under the chemical fertilization treatments is attributed to the fact that the treatments supplement the soil with vital elements which the plant requires over the growing season 20, 21.

Effect of biochar, biofertilizer, and mineral fertilizer on the concentration of major essential nutrients in okra pods and their interactions at the end of the experiment.

Results presented in Table 6 demonstrate that biochar was a very influential factor since it presented the highest mean value of nitrogen level in okra pods at the conclusion of the experiment. The value (T1) of 1.4 was even better than that of treatment (T0) which was 1.38. Regarding the (O1) level of the biofertilizer, it was much better, as it provided the greatest value of 1.42. The median average was lowest in treatment O0 which was equivalent to 1.36, but treatment M2 had a considerably high average of 1.52 against the treatment M0 with an average of 1.20. In the case of triple interaction of biochar, biofertilization, and mineral fertilization. Table (6) indicates that there were strong differences in this interaction. The average nitrogen content in the (B1O1M2) treatment of the plant pods of okra at the end of the experiment was the highest as the average nitrogen content in (B1O1M2) treatment was 1.61 percent as compared to the (B0O0M0) treatment (the comparison treatment) which had an average nitrogen content of 1.15 percent.

Table 6. Effect of biochar, biofertilizer, and mineral fertilizer on nitrogen concentration in okra pods

Biofertilizer O	Biochar B	Chemical fertilization M			Average B		Average O	
		M0	1 M	M2				
O0	B0	1.15	1.30	1.41	B0	1.38	1.36	O0
	B1	1.20	1.37	1.49				
O1	B0	1.23	1.45	1.55	B1	1.40	1.42	O1
	B1	1.26	1.51	1.61				
LSD 0.05		M	B	O	MBO			
		0.10	0.07	0.07	0.11			
Average M		1.20	1.33	1.52				

Effect of biochar, biofertilizer, and mineral fertilizer on phosphorus concentration in okra pods and their interactions after harvest

As can be observed in Table 7, biochar was very influential because it gave the highest average of phosphorus level in okra pods at the end of the experiment. Treatment (B1) was by far better which offered a value of 0.34 compared to treatment (B0), offering a value of 0.31. The level (O 1) of biofertilizer was also much better as it provided the highest value of 0.36. Although the least average was in the treatment O0, which was 0.29 percent, treatment M2 was significantly high than other treatments, and it had the highest average of 0.42 percent as compared to the treatment M0, which had 0.25 percent. The tri-productive interaction between biochar, biofertilizers and mineral fertilizers.

Table 7. Effect of biochar, biofertilizer, and mineral fertilizer on phosphorus concentration in okra pods

Biofertilizer O	Biochar B	Chemical fertilization M			Average B		Average O	
		M0	1 M	M2				
O0	B0	0.22	0.28	0.35	B0	0.31	0.29	O0
	B1	0.24	0.30	0.39				
O1	B0	0.26	0.32	0.45	B1	0.34	0.36	O1
	B1	0.30	0.35	0.48				
LSD 0.05		M	B	O	MBO			
		0.1	0.08	0.08	0.12			
Average M		0.25	0.31	0.42				

Table (7) demonstrates that there are large variations in this interaction. The treatment with the highest average phosphorus concentration in okra pods at the conclusion of the experiment was the (B1O1M2) treatment with an average phosphorus content of 0.48_ as compared to the (B0O0M0) treatment (control treatment) which contained an average phosphorus content of 0.22%.

Effect of biochar, biofertilizer, and mineral fertilizer on potassium concentration in okra pods and their interactions after harvest

Table 8 results showed that the biochar had a strong effect as it demonstrated the best average potassium level in okra pods after the experiment. In the case of treatment (B1) a value of 1.35 was far much better than that of treatment (B0) which was 1.32. The level (O1) of biofertilizer was much better because it produced the greatest value of 1.37. Although all average readings were the lowest in treatment O0, which had 1.30, treatment M2 had very high average readings than the rest of the treatments where mineral fertilization was applied with an average value of 1.45 being the highest compared to 1.22 in treatment M0. The tri-productive interaction between biochar, biofertilizers and mineral fertilizers. Table (8) demonstrates that there are considerable differences in this interaction. The average potassium concentration of okra pods was highest in (B1O1M2) treatment followed by the (B0O0M0) whereby the treatment of (B1O1M2) had a value of 1.52 and (B0O0M0) had a value of 1.18.

Table 8. Effect of biochar, biofertilizer, and mineral fertilizer on potassium concentration in okra pods

Biofertilizer O	**Biochar B**	**Chemical fertilization M**			**Average B**		**Average O**	
		M0	**1 M**	**M2**				
O0	B0	1.18	1.26	1.37	B0	1.32	1.30	O0
	B1	1.20	1.30	1.41				
O1	B0	1.22	1.35	1.49	B1	1.35	1.37	O1
	B1	1.24	1.40	1.52				
LSD 0.05		M	B	O	MBO			
		0.09	0.08	0.08	0.10			
Average M		1.22	1.30	1.45				

As can be seen in Tables 6, 7, and 8, the concentration of the nutrients in okra pods was favourable. This loss can be explained by the fact that the plant absorbs nutrients in the course of its development. This could be as a result of the use of biochar which has a high surface area that holds the soil particles together to create soil aggregates and enhance its stability. This is quite successful in enhancing the water holding capacity of soil, because biochar has internal structure, size of the particle, large population of fine pores and it is capable of absorption and trapping water over long periods. This is in line with the results of 22. The addition of biochar made by charring organic matter to soil is seen to bring some positive changes to the soils, such as being capable of holding water, making their particles hold together, and be able to hold the fertilisers added to them as long as possible. Further, 23 showed that the soil content of certain of the available elements e.g. phosphorus, potassium, magnesium and calcium in soils that received biochar was significantly higher than that of soils that received no biochar. The phosphorus content of the soils in the biochar treatment was three times more than the phosphorus content of the soils in the control treatment, which was in line with the results of 15 who observed that biochar in treatment ratios of 1.5% resulted in increased resistance of the plants and significant growth parameters were noted with a salinity level of 8 dS.m -1. They came to a conclusion that biochar could be scientifically used as a technique to mitigate the adverse impacts of salinity on maize plants. The effect of biofertilizers could be attributed to the joint action of biofertilizers obtained as a result of bio-isolates isolated in the rhizosphere of various soils, which contributes to the safe and environmentally friendly release of vital nutrients-nitrogen, phosphorus, and potassium-, as well as to the pod weight increase. Also, some species of Bacillus bacteria have their contribution by the release of organic acids like citric, lactic, and propionic acids, which reduce the pH and therefore aid in nutrient availability. The application of such a combination of these nitrogen-fixing, phosphate-solubilizing and potassium-releasing bacterial isolates might also promote a notable rise in the concentrations of these vital nutrients in the plant and its pods and a notable rise in the availability of these nutrients in the soil. This holds in line with the results of 24, 5, 25. Concerning the contribution of mineral fertilization, such amounts can be in terms of nitrogen fertilization procedure through usage of DAP fertilizer prior to planting and urea fertilizer by use of two applications. The low harvest values could be because of the plant uptake and nitrogen loss in the soil, particularly through its volatilization since the soil is alkaline in reaction 19, 20, 26, 27, 28.

Effect of Biochar, Biofertilizer, and Mineral Fertilizer on Early and Total Yield of Okra Plants at The End of The Experiment

As can be seen in Table 9, biochar had a major impact in that given the highest average early yield where the treatment (B1) has a significant impact as it gave a value of 536.55 kg. ha-1 which is much higher than the one given by the treatment (B0) which is 535.34 kg. ha-1. With the level (O1) of biofertilizer, it was improved greatly as it provided the greatest value that is 537.37 kg. ha-1. With regards to treatment of mineral fertilization, the lowest average was in treatment O0, which yielded the lowest of 534.98 kg. ha-1, but when it comes to treatment M2 the amount yielded 548.62 kg. ha-1 which is significantly higher than that of treatment M0, which yielded 527.30 kg. ha-1. Concerning the triple interaction between biochar, biofertilizers and mineral fertilizer, Table (9) reveals that there are very strong differences between the interaction. The biggest mean was in the amount of early yield in the treatment (B1O1M2), which amounted to 564.10 kg. ha-1 as compared to the treatment (B0O0M0) (the comparison treatment), which amounted 521.21 kg. ha-1.

Table 9. Effect of biochar, biofertilizer, and mineral fertilizer on early yield of okra plants (kg. ha-1)

<table>
<tr><th rowspan="2">Biofertilizer O</th><th rowspan="2">Biochar B</th><th colspan="3">Chemical fertilization M</th><th rowspan="2" colspan="2">Average B</th><th rowspan="2" colspan="2">Average O</th></tr>
<tr><th>M0</th><th>1 M</th><th>M2</th></tr>
<tr><td rowspan="2">O0</td><td>B0</td><td>521.21</td><td>530.22</td><td>537.23</td><td rowspan="2">B0</td><td rowspan="2">535.34</td><td rowspan="2">534.98</td><td rowspan="2">O0</td></tr>
<tr><td>B1</td><td>523.11</td><td>535.10</td><td>541.45</td></tr>
<tr><td rowspan="2">O1</td><td>B0</td><td>525.90</td><td>541.21</td><td>550.31</td><td rowspan="2">B1</td><td rowspan="2">536.55</td><td rowspan="2">537.37</td><td rowspan="2">O1</td></tr>
<tr><td>B1</td><td>531.01</td><td>559.99</td><td>564.10</td></tr>
<tr><td rowspan="2" colspan="2">LSD 0.05</td><td>M</td><td>B</td><td>O</td><td colspan="2">MBO</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>3.21</td><td>2.60</td><td>2.60</td><td colspan="2">3.98</td></tr>
<tr><td colspan="2">Average M</td><td>527.99</td><td>531.10</td><td>548.62</td><td colspan="2"></td></tr>
</table>

Effect of biochar, biofertilizer, and mineral fertilizer on total yield at the end of the experiment

Table 10 results indicate that biochar had a bearing difference as it provided the largest average final total yield at the culmination of the experiment. The treatment (B1) performed much better with a value of 7.87 tons. ha-1 as compared to treatment (B0) with the value of 7.39 tons. ha-1. The concentration O1 exhibited superior performance by delivering an impressive yield of eight units in economic terms. Nine metric tonnes. The ha-1 is an abbreviation for human immunodeficiency virus type 1. Despite being at its minimum value of seven, Treatment O0 stood out as having the least favorable outcome among all options examined. A load weighing 37 metric tonnes is being transported by this vehicle. Treatment H-1 exhibited notably greater efficacy compared to other interventions involving mineral fertilizer through observation of an increase in yield measurement at eight units. A load weighing 31 metric tonnes is being transported by the vehicle. The ha-1 was evaluated against Treatment M0, whose efficacy score was six points lower. Sixty-nine metric tonnes. The ha-1 refers to an identifier in biological classification systems used for categorizing organisms based on their genetic makeup. Table 10 highlights significant variations in how biochar interacts when combined with both biofertilizers and minerals compared to their individual effects. Treatment B101M2 yielded an exceptionally high overall production rate concluding the study session, achieving a mean output figure of nine units. Sixty-nine metric tonnes. The ha-1 was evaluated against B0O0M0; however, its performance metric equaled 6. Twenty-seven metric tonnes. The ha-1 is an abbreviation for hemoglobin A1c, which measures blood sugar levels over time in diabetics.

Table 10. Effect of biochar, biofertilizer, and mineral fertilizer on total yield (tons. ha-1) at the end of the experiment

Biofertilizer O	Biochar B	Chemical fertilization M			Average B		Average O	
		M0	1 M	M2				
O0	B0	6.27	6.80	7.10	B0	7.39	7.37	O0
	B1	6.50	7.20	7.98				
O1	B0	6.70	7.80	8.50	B1	7.87	8.09	O1
	B1	7.30	8.60	9.69				
LSD 0.05		M	B	O	MBO			
		0.96	0.75	0.75	1.03			
Average M		6.69	7.60	8.31				

Effect of biochar, biofertilizer, and mineral fertilizer on some qualitative traits in okra pods at the end of the experiment

Table 11 results show that the inclusion of biochar was not insignificant because it provided the largest average percentage of protein in okra pods in treatment (B1), which was 8.92 percent as compared to treatment (B0), which resulted in 8.70 percent. The degree (O1) of biofertilizer was the best since it recorded the highest average of 8.98, and the lowest average was recorded in treatment O0 that measured 8.53. With regards to mineral fertilization, M2 treatment was significantly higher than the rest, which had a value of 9.48% over treatment M0 with 7.57%. In relation to the triple interaction of biochar, biofertilizer and mineral fertilizer, Table (11) indicates that there is a significant difference in interaction. The mean percentage of the proteins in the okra pods was highest in the treatment (B1O1M2) as it registered 10.10% against the control treatment (B0O0M0), which registered 7.19%.

Table 11. Effect of biochar, biofertilizer, and mineral fertilizer on protein percentage in okra pods

Biofertilizer O	Biochar B	Chemical fertilization M			Average B		Average O	
		M0	1 M	M2				
O0	B0	7.19	8.13	8.82	B0	8.70	8.53	O0
	B1	7.50	8.56	9.31				
O1	B0	7.69	9.06	9.69	B1	8.92	8.98	O1
	B1	7.88	9.44	10.10				
LSD 0.05		M	B	O	MBO			
		0.48	0.46	0.46	0.55			
Average M		7.57	8.03	9.48				

Effect of biochar, biofertilizer, and mineral fertilizer on the total soluble solid's percentage (T.S.S.%) in okra pods and their interactions

Table 12 results suggested that biochar affected the results significantly because it produced the highest mean percentage of T.S.S. in okra pods at the conclusion of the experiment. The treatment (B1) showed a significant improvement in value, that is, 6.18, whereas treatment (B0) was 6.06. On the same note, the level (O1) of biofertilizer was greatly excellent because it provided topmost value of 6.20, whereas minimum average was in O0 treatment of 5.95. On mineral fertilization, treatment (M2) was very effective as it had the highest value of 6.43, unlike treatment (M0) whose value was 5.26. In the case of the triple interaction between biochar, biofertilizer and mineral fertilizer, Table (12) shows that there are significant changes brought about by the interaction. The average percentage of the total soluble solids in okra pods at the end of the experiment were the highest in (B1O1M2) treatment (7.30) than in (B0O0M0) treatment (the control treatment) (5.12).

Table 12. The effect of biochar, biofertilizer, and mineral fertilizer on the percentage of total soluble solids (T.S.S%) in okra pods

Biofertilizer O	**Biochar B**	**Chemical fertilization M**			**Average B**		**Average O**	
		M0	**1 M**	**M2**				
O0	B0	5.12	5.25	6.36	B0	6.06	5.95	O0
	B1	5.16	6.27	6.58				
O1	B0	5.23	6.31	7.10	B1	6.18	6.20	O1
	B1	5.35	6.39	7.30				
LSD 0.05		M	B	O	MBO			
		0.77	0.30	0.30	0.85			
Average M		5.26	6.00	6.43				

As shown in table (11 and 12), there was an increase in the percentage of protein and the percentage of solids in okra pods. It might be explained by the usage of biochar that helps to increase the various properties of the soil (physical and chemical). In addition to that of nutrient availability, especially nitrogen, leading to increase in nitrogen and its uptake by the plant, there are other more essential and physiological processes, food production, seed storage, and increased protein levels 1, 2. With regards to the role of biofertilization, the nitrogen-fixing, phosphate-solubilizing and potassium-releasing bacteria isolates could assist in increasing the quantity of these nutrients in the plant, in addition to increasing the quantity of these nutrients in the soil, substantially. It is as per findings of 24. Regarding the role of mineral fertilization, in particular, nitrogen, phosphorus, and potassium, Tables (3, 4 and 5) demonstrate that the levels of the available elements were moderately high at the end of the experiment. These components have the role of fostering formation and production of components that are involved in the photosynthesis process such as pigments and sugars which in turn lead to increase in carbohydrates and amino acids, increased vegetative growth, and consequently increase in metabolic compounds, which are involved in protein synthesis. This may also be potentially due to the fact that the concentrations of the available nitrogen were not very high as the initially available nitrogen was rather abundant in the soil (Table 1). These levels exhibit the procedure of fertilization of the soil with nitrogen, since it involved the use of DAP fertilizer before the planting process and urea in two applications. The reduced values of the harvest phase was credited to the absorption of plants and nitrogen loss in the soil particularly by volatilization because the soil is alkaline reaction in the reaction 29. The chemical fertilization patterns of okra growth explain the concentration of the protein levels of the okra pods in the patterns that lead to the development of the vegetables and result in the increase of the nutrients and increase of photosynthetic products 7. The results indicate that early and total yield was increased by biochar, biofertilizer, and mineral fertilization. This may be explained by the fact that the nutrients are supplied through application of chemical fertilizers that improves the nutritional condition of the plant and hence yield is better. In the growth and development of roots, phosphorus and nitrogen play a significant role and stimulate photosynthesis, respiration, and other metabolic activities. Potassium influences the enzyme activity as well, and it promotes the ATP growth and improves a loading of sieve tubes with products of photosynthesis with high molecular weight and their transport by the water to the fruits 27. It is agreeable that such findings are comparable to the findings of 30, 15.

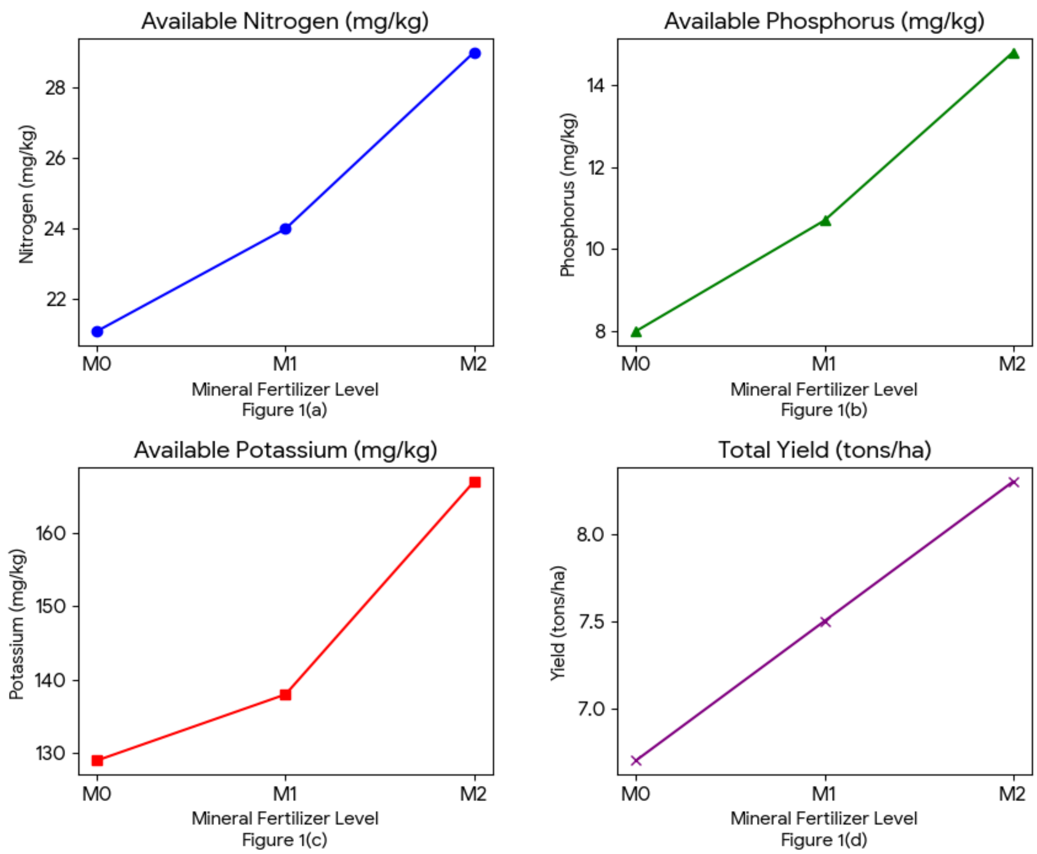

Figure 1. Effect of mineral fertilizer levels on soil nutrients and okra yield

Here the four-line graphs that show how different quantities of mineral fertilizer (M0, M1, and M2) affect important soil nutrients and okra yield. The levels of accessible nitrogen in the soil are shown in Figure 1(a) for various fertilizer treatments. There is a strong correlation between the amount of mineral fertilizer and the soil's nitrogen content, according to the research. Figure 1(b) shows how mineral fertilizer affects accessible phosphorus, and it shows the same pattern: more fertilizer means more phosphorus in the soil. Similarly, the available potassium levels exhibit a linear relationship with increasing fertilizer application leading to larger potassium content (Figure 1(c)). Figure 1(d) concludes with the overall okra production as a function of the various fertilizer treatments. The results show that the maximum yield of okra is obtained by applying the prescribed dose of mineral fertilizer (M2), which supports the idea that fertilizer actually increases crop output. These figures highlight the importance of mineral fertilizer in improving soil nutrient availability and raising agricultural yields. The research shows that adding more mineral fertilizer to the soil increases the levels of nitrogen, phosphate, and potassium, which in turn leads to better okra harvests. The results highlight how crucial it is to use the right fertilizer methods to maximize crop growth and harvest.

Discussion

The development and yield of okra (Abelmoschus esculentus L.) cultivated in silty loam soil are examined in this research by examining the impacts of biochar, biofertilizers, and mineral fertilizers. An experiment was carried out in Zafaraniya, Iraq, using a factorial design within a Completely Randomized Block Design (CRBD). The experiment aimed to investigate the interaction between biochar (0 tons/ha vs. 4 tons/ha), biofertilizer (control vs. a mixture of bacteria that fix nitrogen, phosphate, and potassium), and different levels of mineral fertilizers (0%, 50%, and 100% of the recommended dose). The study found that combining biochar, biofertilizers, and complete mineral fertilizer resulted in the highest soil nutrient levels and okra output, suggesting the potential for these organic and environmentally friendly inputs to boost crop quantity and quality. The study highlights the significance of environmentally conscious farming methods, recommending the use of biochar and biofertilizers in conjunction with chemical fertilizers to increase yields while decreasing pollutants.

Conclusion

This field study's findings unequivocally show that combining biochar and biofertilizers with mineral fertilizers offers a better way to increase okra yields in silty loam soils. The triple interaction (B1O1M2) produced 9.69 tons·ha^{-1} of okra and had the highest values for pod protein (10.10%) and T.S.S. (7.30%). Importantly, the considerable increases in residual accessible N, P, and K show how successful this integrated approach was at enhancing soil health. The study suggests using 4 tons·ha^{-1} of biochar, a biofertilizer consortia, and 100% of the prescribed mineral fertilizer rate to maximize okra yield. Furthermore, these findings underscore the importance of ongoing research into organic and biological inputs to facilitate the development of sustainable, profitable, and environmentally friendly agricultural systems.

Author Contributions

Wajdan Talib Kadhim and Bushra Mahmoud Alwan contributed equally to the research and writing of this paper. Wajdan Talib Kadhim designed the experiment, performed data collection, analyzed the results, and drafted the manuscript. Bushra Mahmoud Alwan assisted with the experimental design, provided statistical analysis support, and contributed to the interpretation of results. Both authors reviewed and revised the manuscript for intellectual content and approved the final version for submission.

Conflict of Interest

The authors declare no conflict of interest related to this study. There are no financial or personal relationships that could influence the work described in this paper.

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