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# Effect of the Interaction Between Humic Acid-enriched Biochar, and Chemical Fertilization on the Growth and Yield of Zucchini Squash (Cucurbita Pepo L.)

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## Abstract

This study assesses the impact of chemical fertilizers and biochar enriched with humic acid on the growth, yield, and quality of zucchini squash (Cucurbita pepo L.) in field conditions. The study was conducted in Zafaraniya, Iraq, in the autumn of 2023, employing a completely randomized block design (CRBD) with three replications and 18 treatments. The experiment used three levels of mineral fertilizers (0, 50, and 100 percent of the prescribed amount), three levels of biochar (0, 5, and 10 tonnes per acre), and two amounts of humic acid (0 and 4 mL per liter). All authors participated in the writing, evaluated, and sanctioned the final paper for publication. The zucchini plants were transplanted on 22 /8 / 2022, and the last harvesting was done on 30/10/2023. The results demonstrated that the mixture of mineral fertilizers, biochar, and humic acid would be applicable in enhancing nutrient uptake, soil fertility, and yield. The best results in terms of absorption of nutrients, content of fruit proteins (3.01 percent), and yield (22.83 kg per hectare) were observed with the M2B2H1 (100 percent mineral fertilizer, 10 tons biochar, and 4 mL/L humic acid) treatment. As has been established in this paper, biochar and humic acid work with chemical fertilizers, resulting in improved soil health, reduced fertilizer reliance, and sustainable farming. The findings will be very useful in integrated nutrient management programs that enhance the quality of crops and environmental sustainability.

## Keywords:

*Biochar, humic acid, mineral fertilizer, soil fertility, zucchini squash.*

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## Introduction

Plants rely on soil as the basic foundation of their development, which is the determining factor that maintains agricultural production and food security. The health of soil has become a modern concern in agriculture since using too many chemical fertilizers or using them in ways that don't make sense has had a huge impact on the environment and health. Because of this, farmers throughout the world are moving towards greener and more sustainable ways to fertilize their crops that don't rely on mineral fertilizers and still produce the same amount of food. Chemical fertilizers only have one advantage in that they yield large crop production, but they are costly to buy and carry, and have a second disadvantage of not being environmentally friendly.

This heightened realization of these negative effects has led to the application of modern scientific practices that involve minimal quantities of fertilizers being applied, and best practices that are in line with sustainable farming are encouraged. Unlike the negative consequences of industrial chemicals on the environment and human health, sustainable agriculture pays much attention to natural and organic resources, using them to cultivate crops and produce them in large amounts (Karagöz, 2021; Giri et al., 2019).

Agricultural experts have enforced environmentally friendly methods, especially those that incorporate organic and mineral fertilizers, in an attempt to reduce the adverse effects of mineral fertilization. This combined methodology seeks to maintain the productivity, quality, and reduce the ecological impairment. One of the most promising natural materials to be used to replace or supplement chemical fertilizers is Humus, an organic compound that is environmentally safe and has no harm to humans (Hernandez et al., 2021; de Andrade Bonetti et al., 2023). In this context, humic substances, especially humic acid, have become very prominent agents in the sustainable agricultural arena. The HAA can help in enhancing soil fertility and plant growth by enhancing nutrient absorption and soil structure in constantly cultivated soils, which undergo depletion. The ionic content of significant macro- and micronutrients is increased via various mechanisms by humic acid, and this is by chelation, pH regulation, and the development of complexes, therefore increasing the availability and ease of absorption of nutrients (Song et al., 2022).

Research has shown that using humic acid can help crops grow. The use of humic acid at a concentration of 2.5 cm $L^{-1}$ throughout the 15 and 30 days of maize planting has significantly improved growth metrics. These include growth in height, an increase in the area of the leaves, and an overall increase in the plant's productivity, all of which are caused by physiological processes and nutrient uptake (Oliwi et al., 2021). The concentration of humic acid in this supplement can explain it (Leiby et al., 2025). Humic acid is made up of crucial parts of plant growth and trace elements that are important for metabolism (Avery, 2021). Humic acid is a major source of carbon and is very important for the growth of microorganisms in soil (Shahrajabian et al., 2024; Khaled & Fawy, 2011). By chelating trace elements and keeping nutritional ions, it gives crops more nutrients (Abdel-Razzak, 2010; Fageria et al., 2009).

Zucchini (*Cucurbita pepo* L.), belonging to the Cucurbitaceae family, ranks third in global significance after cucumber and watermelon. The vegetable crop is of interest in that it is a high-nutritional and economic crop since it contains essential mineral salts, proteins, and compounds that aid in the digestive system. It has a variety of varieties which are helpful in the human diet as well as in the agricultural profitability. Nonetheless, even though Zucchini responds to chemical fertilization, there is overuse of fertilizer, causing a lot of pollution in the environment (Bhoyar et al., 2025). Biochar is now a popular soil amendment and a remedy to soil problem which can maproblems, more fertile and reduce the adverse effects of chemical fertilisers. The biofertilizersracterized by its specific architecture of negatively charged functional groups, namely, hydroxyl (–OH), amino (–NH2), ketone (-OR), ester (C=O -OR), nitro (-NO2), aldehyde (C=O -H), and carboxyl (C=O -OH). They contribute to the cation exchange by keeping anions in the biochar and preventing leaching of the nutrients (Roozbahani & Ghafari, 2014). In general, it enhances the nutrient retention capacity, brings more essential nutrients, and even increases the productivity of soil (Mohsen & Alwan, 2019). The purpose of this study is to analyze the combined effects of humic acid, biochar, and fertilizers on the zucchini growth, yield, and quality (de Oliveira et al., 2024). This is how the object of the study originates. This project is mainly motivated by the critical requirement to reconcile agricultural production with environmental preservation (Smihunova et al., 2024). The research issue of the paper is whether the use of humic acid and biochar can decrease the need for chemical fertilizers without affecting product quality and yield, in order to prevent environmental deterioration (Githinji, 2014; Phooi et al., 2022). The proposed study posits that the efficient utilization of humic acid and biochar in equivalent quantities will result in a reduction in chemical fertilizer applications, with enhancements in soil quality and nutrient availability, as well as increased production potential (Uzakbaeva & Ajiev, 2022; Nair et al., 2014).

The best contribution of the research is that it explores the interactive action of biochar, humic acid, and chemical fertilizer, which represents empirical evidence in discovering an ecologically friendly model of fertilization (Boghori & Tabatabai, 2017). The study can be converted into better incorporation of soil management activities, which will be consistent with the sustainable world agricultural objectives, by assessing the quantitative and qualitative measurements of Zucchini under different conditions of fertilization.

The article includes the overall understanding of soil health and fertilization methods, the discussion of the importance of humic acid and biochar as sustainable alternatives, the description of an experimental design of the combined application of the two materials to zucchini growth and yield, and the interpretation of environmental and agronomic implications of the findings. This research endeavors to establish through the study that environmentally friendly soil amendments can be used to reduce the number of chemicals employed, enhance the quality of crops, and also make farming more sustainable in the future.

## Materials and Methods

The field experiment was carried out with clay loam soil during the 2023 growing season in Zafaraniya, Iraq, which is situated at latitude 33°24'120.9 N and longitude 44°52'350.87 E. Prior to planting, a randomized soil sample was taken from the field. A large sample was created by fully combining, air-drying, crushing into a fine powder, and sifting through a 2 mm mesh in order to create a composite sample of the soil samples that were collected. The physical, chemical, and fertility characteristics of the soil were ascertained using the general analytical methods of (Page et al., 1982). Leveling and field correction were completed concurrently with the perpendicular plowing. The trial field was partitioned into three main blocks, each consisting of 18 bed sectors. Patients within each block were randomized for treatments in accordance with the rules of a randomized complete block design (RCBD), which kept the beds 1.0 m apart and the blocks 1.5 m apart. Each experimental unit, measuring 9 m² (Figure 1), consisted of three rows, each 3 m long, with a gap of 0.75 m between the rows.

On August 22, 2022, the Zucchini (Cucurbita pepo L., cv. Ghada) seedlings were first raised in a nursery and then transplanted to the field when they were about two weeks old. The seedlings were placed in each planting hole, and in total, 21 plants were placed in each unit of the experiment. A drip irrigation system was utilized to maintain uniform water levels across all treatments. The field was planned to be irrigated to be up to capacity after 35% of the accessible soil water was used. All agronomic and crop maintenance practices were performed uniformly for all treatments throughout the experiment. On October 30, 2023, the yield was calculated after harvesting. To evaluate the effects of fertilization and the input of nitrogen (N), phosphorus (P), and Potassium (K), the protein content of the fruits was determined at the time of harvest. The experiment, consisting of 54 experimental units in three replications, was conducted using the Randomized Complete Block

Design (RCBD). The data were statistically analyzed using GenStat Discovery Edition 4 (2012) and the least significant difference (LSD) test at a 0.05 probability threshold to compare the treatment means.

## Experimental Treatments

Three main components made up the experiment's design: the amounts of humic acid, biochar, and fertilizer minerals. $M_0$ (no fertilizer application), $M_1$ (50 percent of the recommended dose), and M2 (100 percent of the recommended dose) were the three mineral fertilizer levels that comprised the former. 110 kg N ha$^{-1}$ of urea (46% N), 75 kg P ha$^{-1}$ of calcium superphosphate, and 60 kg K ha$^{-1}$ of potassium sulfate (41.5 K) made up the complete fertilizer prescription for courgette. Two weeks after planting and thirty-five days after germination, fertilizers were applied in two equal applications.

Three amounts of biochar application were included in the second factor: $B_0$ (0 t ha$^{-1}$), $B_1$ (5 t ha$^{-1}$), and $B_2$ (10 t ha$^{-1}$). Table 2 displays the results of the analysis of the biochar's chemical makeup and nutrient content. The third was the application of the humic acid concentration levels, H0 (0 mL/L) and H1 (4 mL/L). Before their field use, humic acid was combined with biochar and left overnight to allow better interaction with nutrients and microorganisms before adding the mixture to the soil. The randomization of line items was based on their treatment schedule allocated at each block, as reflected in Figure 1. The experiment design had 18 treatments, including replication and statistical balance.

### *Soil Properties Before Planting*

The physical, chemical, and fertility properties of the soil before planting are shown in Table 1. The soil had a pH of 7.21 and a conductivity of 2.81 dS m$^{-1}$, indicating that it was slightly alkaline and moderately saline. The quantity of mineral carbonates was 285.00 g kg$^{-1}$, and the soil contained 7.23 g kg$^{-1}$ of organic matter. The same soil had 153.31 mg kg$^{-1}$ of Potassium, 12.00 mg kg$^{-1}$ of phosphorus, and 30.55 mg kg$^{-1}$ of nitrogen, which were the amounts of macronutrients present. The corresponding values for calcium ($Ca^{2}$), potassium ($K^{2-}$), sodium ($Na^{2+}$), and magnesium ($Mg^{2+}$) were 8.30 mmol/L$^{-1}$, 1.10 mmol/L, 3.30 mmol/L, and 5.21 mmol/L$^{-1}$, respectively. Carbonate ions ($CO_3^{2-}$) were not detected, while sulfate ($SO_4^{2-}$), chloride ($Cl^{2-}$), and bicarbonate ($HCO_3^{2-}$) ions were negative. The results of the soil texture analysis showed that the soil was clay loam, with a sand texture of 534 g kg-1, a silt texture of 88 g kg-1, and a clay texture of 378 g kg-1.

Table 1. Some of the physical, chemical, and fertility properties of the experimental soil before planting

| Property | | Value |
|---|---|---|
| pH (1:1) | | 7.21 |
| Electrical conductivity (dS m$^{-}$1) | | 2.81 |
| Organic matter (g kg$^{-1}$) | | 7.23 |
| Mineral carbonates (g kg$^{-1}$) | | 285.00 |
| (mgkg$^{-1}$) | Available nitrogen | 30.55 |
| | Available phosphorus | 12.00 |
| | Available Potassium | 153.31 |
| Positive ions MmolL-1 | $Ca^{++}$ | 8.30 |
| | $K^{+}$ | 1.10 |
| | $Na^{+}$ | 3.30 |
| | $Mg^{++}$ | 5.21 |
| Negative ions mmolL-1 | $SO_4^{=}$ | 4.30 |
| | $Cl^{-}$ | 21.10 |
| | $HCO_3^{-}$ | 1.12 |
| | $CO_3^{=}$ | ———— |
| Soil separates (gkg$^{-1}$) | Sand | 534 |
| | Silt | 88 |
| | Clay | 378 |
| Texture class | Clay loam | |

### *Biochar and Humic Acid Characterization*

The chemical characteristics and the mineral composition of the humic acid and biochar used in this study are presented in Table 2. The biochar contained 324 mg of carbon and 11.01 mg of nitrogen and had an EC of 3.53 dS $m^{-1}$, a pH of 7.71, and a C: N ratio of 29.47. Furthermore, it had 2.31 mg of phosphorus, 9.60 mg of Potassium, 0.63 mg of sodium, 8.21 mg of calcium, and 2.66 mg of magnesium. The richness of the humic acid in vital plant nutrients was confirmed by its pH of 6.75, which included 32.10 mg $g^{-1}$ nitrogen, 2.83 mg $g^{-1}$ phosphorus, 60.10 mg $g^{-1}$ potassium, 0.81 mg $g^{-1}$ sodium, 12.21 mg $g^{-1}$ calcium, and 9.25 mg $g^{-1}$ magnesium.

Table 2. Mineral content of biochar and humic acid

| Material | EC (1:5 ds.$m^{-1}$) | pH | Mineral content (mg $g^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | C (mg $g^{-1}$) | N (mg $g^{-1}$) | C: N ratio | P (mg $g^{-1}$) | K (mg $g^{-1}$) | Na (mg $g^{-1}$) | Ca (mg $g^{-1}$) | Mg (mg $g^{-1}$) |
| biochar | 3.53 | 7.71 | 324 | 11.01 | 29.47 | 2.31 | 9.60 | 0.63 | 8.21 | 2.66 |
| Humic acid | - | 6.75 | - | 32.10 | - | 2.83 | 60.10 | 0.81 | 12.21 | 9.25 |

| | Block3 | | Block2 | | Block1 | |
|---|---|---|---|---|---|---|
| Main stream | | | | | | |
| Guard area | $M_0B_0H_0$ | Sub-sowary | $M_0B_1H_1$ | Sub-sowary | $M_1B_1H_1$ | Guard area |
| | $M_1B_0H_0$- | | $M_2B_0H_1$ | | $M_1B_2H_1$ | |
| | $M_0B_0H_1$ | | $M_0B_1H_0$ | | $M_2B_2H_1$ | |
| | $M_0B_1H_0$ | | $M_2B_2H_1$ | | $M_0B_2H_1$ | |
| | $M_1B_1H_1$ | | $M_0B_2H_0$ | | $M_0B_1H_1$ | |
| | $M_2B_0H_0$ | | $M_1B_2H_1$ | | $M_2B_0H_1$ | |
| | $M_2B_2H_1$ | | $M_0B_2H_1$ | | $M_1B_0H_1$ | |
| | $M_1B_2H_0$ | | $M_2B_0H_0$ | | $M_2B_2H_0$ | |
| | $M_2B_1H_0$ | | $M_2B_2H_0$ | | $M_2B_1H_0$ | |
| | $M_2B_2H_0$ | | $M_1B_0H_1$ | | $M_1B_2H_0$ | |
| | $M_1B_0H_1$ | | $M_0B_0H_1$ | | $M_1B_1H_0$ | |
| | $M_0B_2H_1$ | | $M_1B_2H_0$ | | $M_0B_0H_1$ | |
| | $M_0B_1H_1$ | | $M_2B_1H_0$ | | $M_0B_2H_0$ | |
| | $M_2B_0H_1$ | | $M_1B_1H_0$ | | $M_0B_1H_0$ | |
| | $M_1B_1H_0$ | | $M_2B_1H_1$ | | $M_2B_0H_0$ | |

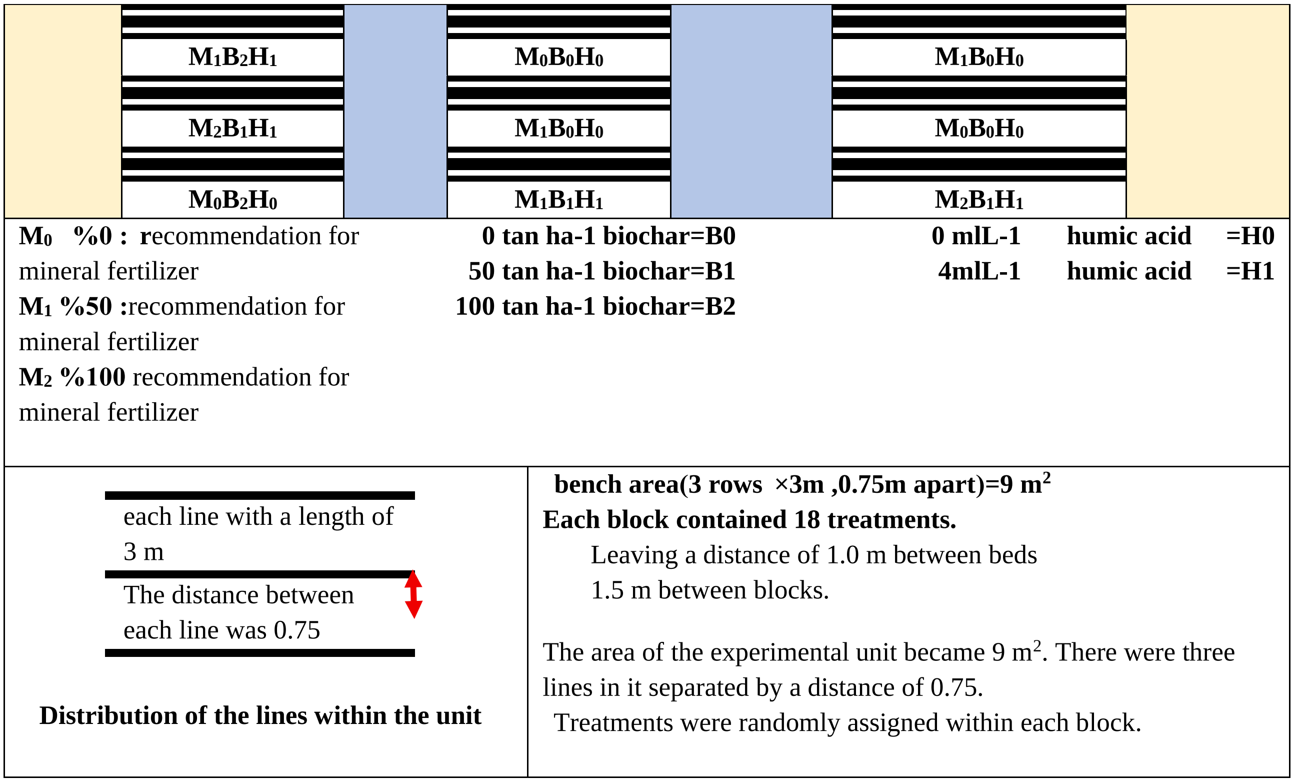


Figure 1. Schematic layout of the randomized complete block design (RCBD) used in the experiment

## Results and Discussion

The overall effects of chemical fertilizers, biochar, and humic acid were found to have significant effects ($P \leq 0.05$) on the nutrient absorption, nutrient residuals in the soil, the protein content, and the overall yield of the Zucchini *(Cucurbita pepo* L.) fruits. The results of the obtained data show clearly that the integration of these inputs will enhance the efficiency of nutrient uptake by plants, as well as their status in the soil, in general, as shown in Tables 3-10.

### *Nutrient Uptake by Zucchini Fruits*

The simultaneous application of chemical fertilizers, biochar, and humic acid significantly enhanced the absorption of the macronutrients by zucchini fruits. The interaction of the three factors illustrated that there was a high difference in nutrient absorption at $P \leq 0.05$ (Tables 3–5).

Table 3 illustrates that the absorption of nitrogen was slowly increasing as chemical fertilization, biochar, and humic acid were increasing. The control ($M_0B_0H_0$) experienced the lowest nitrogen uptake (18.23 kg ha$^{-1}$), and the highest uptake (55.20 kg ha$^{-1}$) was experienced under full fertilization ($M_2$) and 10 t ha$^{-1}$ of biochar ($B_2$) and 4 mL L$^{-1}$ of humic acid ($H_1$). The mean nitrogen uptake increased at M0 to 23.68 kg ha$^{-1}$, to 45.39 kg ha$^{-1}$ at $M_2$, thereby showing an improvement of 91.8 %. This implies that there is a powerful synergistic interaction between humic acid and biochar in increasing the use of nitrogen by raising soil aeration and retention of nitrogen, insofar as previous research findings indicated (Ryan et al., 2009).

Table 3. Effect of chemical fertilizers, biochar, and humic acid on the amount of nitrogen absorbed by zucchini fruits (kg ha-1)

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 18.23 | 26.00 | 39.35 | $B_0$ | 29.89 | 44.23 | $H_0$ |
| | $B_1$ | 20.45 | 30.80 | 40.21 | | | | |
| | $B_2$ | 26.01 | 32.10 | 45.70 | $B_1$ | 33.84 | | |
| $H_1$ | $B_0$ | 23.10 | 31.32 | 41.34 | | | | |
| | $B_1$ | 25.31 | 35.70 | 50.54 | $B_2$ | 39.42 | 51.65 | $H_1$ |
| | $B_2$ | 29.00 | 48.39 | 55.20 | | | | |
| LSD at P≤ 0.05 | | M | B | H | MBH | | | |
| | | 4.99 | 4.99 | 2.69 | 5.11 | | | |
| Average M | | 23.68 | 34.05 | 45.39 | | | | |

Note: differences are significant at P≤ 0.05 according to the LSD test.

Table 4. Impact of chemical fertilization, biochar, and humic acid on the amount of phosphorus absorbed by zucchini fruits (kg ha⁻¹)

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 4.03 | 5.20 | 8.32 | $B_0$ | 5.99 | | |
| | $B_1$ | 4.45 | 5.80 | 9.22 | | | 9.64 | $H_0$ |
| | $B_2$ | 5.01 | 6.11 | 9.70 | $B_1$ | 6.89 | | |
| $H_1$ | $B_0$ | 4.55 | 5.30 | 8.54 | | | | |
| | $B_1$ | 5.31 | 6.70 | 9.84 | $B_2$ | 7.74 | 10.97 | $H_1$ |
| | $B_2$ | 6.00 | 8.39 | 11.20 | | | | |
| LSD at P≤ 0.05 | | M | B | H | MBH | | | |
| | | 1.1 | 1.1 | 1.01 | 2.00 | | | |
| Average M | | 4.94 | 6.25 | 11.11 | | | | |

Note: differences are significant at P≤ 0.05 according to the LSD test.

Table 4 shows that the uptake of phosphorus increased significantly when both fertilizers and high concentrations of biochar and humic acid were used. The maximum phosphorus uptake (11.20 kg $ha^{-1}$) occurred under M2B2H1, more than double that of the control. Average phosphorus uptake rose from 4.94 kg $ha^{-1}$ ($M_0$) to 11.11 kg $ha^{-1}$ ($M_2$). Biochar enhanced phosphorus availability by reducing soil fixation, while humic acid improved phosphate solubility through chelation and organic complex formation. These results agree with (Xu et al., 2021), who reported increased P availability with organic–mineral integrations.

According to Table 5, potassium uptake in zucchini fruits significantly increased under integrated treatments. The highest uptake was 26.29 kg $ha^{-1}$ at $M_2B_2H_1$ and 16.03 kg ha-1 at $M_0B_0H_0$ (control) uptake. It also elevated the mean potassium uptake by an estimated 26 % in $M_0$ and $M_2$ because of growing nutrient supply and uptake by the root. Biochar increased the exchange of cations and water retention of the soils, and made the $K^{2+}$ more available, yet humic acid could have facilitated the membrane permeability of potassium ions. Combined treatment ($M_2B_2H_1$) was always the most effective in the uptake of macronutrients among all three elements, proving its better agronomic efficiency ($P \leq 0.05$).

Table 5. Effect of chemical fertilization, biochar, and humic acid on the amount of Potassium absorbed by zucchini fruits (kg ha$^{-1}$)

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 16.03 | 18.32 | 19.89 | $B_0$ | 18.40 | 18.89 | $H_0$ |
| | $B_1$ | 16.66 | 19.80 | 20.22 | | | | |
| | $B_2$ | 17.39 | 20.11 | 21.66 | $B_1$ | 20.25 | | |
| $H_1$ | $B_0$ | 16.77 | 18.47 | 20.88 | | | | |
| | $B_1$ | 18.43 | 21.89 | 24.50 | $B_2$ | 21.61 | 21.27 | $H_1$ |
| | $B_2$ | 20.31 | 23.90 | 26.29 | | | | |
| LSD at P≤ 0.05 | | M | B | H | MBH | | | |
| | | 1.22 | 1.22 | 1.00 | 2.21 | | | |
| Average M | | 17.60 | 20.42 | 22.24 | | | | |

Note: differences are significant at P≤ 0.05 according to the LSD test.

***Residual Macronutrients in the Soil***

The combined application of chemical fertilizers, biochar, and humic acid had a substantial impact on the residual concentrations of nitrogen, phosphate, and Potassium in the soil after zucchini fruits were harvested (Tables 6–8). Applying humic acid and biochar together with chemical fertilizers improved the soil's capacity to retain nutrients and reduced the amount of nutrients that leached out, which increased soil fertility after harvest. These findings suggest that organic amendments not only increase instant nutrient intake by plants, but they also help in the sustainability of soil nutrient management that will be available in later cropping phases.

Table 6. Effect of chemical fertilizer, biochar, and humic acid on available nitrogen residual in the soil( mg N kg$^{-1}$ ).

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 20.61 | 21.02 | 26.10 | $B_0$ | 23.64 | 25.28 | $H_0$ |
| | $B_1$ | 22.02 | 24.80 | 29.21 | | | | |
| | $B_2$ | 26.01 | 27.10 | 30.70 | $B_1$ | 26.17 | | |
| $H_1$ | $B_0$ | 21.10 | 24.010 | 29.00 | | | | |
| | $B_1$ | 23.31 | 26.70 | 33.80 | $B_2$ | 29.37 | 27.50 | $H_1$ |
| | $B_2$ | 25.00 | 32.20 | 35.20 | | | | |
| LSD at P≤ 0.05 | | M | B | H | MBH | | | |
| | | 1.65 | 1.65 | 1.35 | 4.00 | | | |
| Average M | | 23.00 | 25.97 | 30.20 | | | | |

Note: differences are significant at P≤ 0.05 according to the LSD test.

This table displays the amount of nitrogen that remains in the soil after applying humic acid, charcoal, and chemical fertilizer in various combinations. As can be seen, the largest nitrogen residual values were experienced in mixed application of humic acid and biochar at full fertilizer rates ($M_2$), which indicates that organic and inorganic amendments have a synergistic response in the improvement of nitrogen availability. The LSD test demonstrated that all components and their interactions (M, B, H, and MBH) impact the difference, and it was also discovered that there are significant differences (P≤ 0.05) between the treatments.

Table 7. Effect of chemical fertilization, biochar, and humic acid on the amount of residual phosphorus in the soil mg P kg$^{-1}$ soil

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 4.40 | 6.87 | 8.67 | $B_0$ | 9.67 | 11.05 | $H_0$ |
| | $B_1$ | 8.57 | 10.0 | 12.66 | | | | |
| | $B_2$ | 14.37 | 16.47 | 17.41 | $B_1$ | 13.59 | | |
| $H_1$ | $B_0$ | 8.99 | 13.66 | 15.44 | | | | |
| | $B_1$ | 15.10 | 16.88 | 18.30 | $B_2$ | 17.24 | 15.55 | $H_1$ |
| | $B_2$ | 16.00 | 18.20 | 21.00 | | | | |
| LSD at $P \leq 0.05$ | | M | B | H | MBH | | | |
| | | 1.90 | 1.90 | 1.55 | 3.30 | | | |
| Average M | | 11.24 | 13.68 | 16.10 | | | | |

Note: differences are significant at $P \leq 0.05$ according to the LSD test.

The amount of phosphorus in the soil following harvest in different treatment combinations is shown in this table. According to the data, the largest phosphorus residues were found in the combined application of biochar, humic acid, and the optimal fertilizer rate ($M_2$). Such results reveal the importance of biochar in the reduction of phosphorus fixation and its availability, and the efficacy of humic acid in increasing phosphorus mobility and uptake. The significant treatment effects and interactions are supported by additional LSD test results ($P < 0.05$).

Table 8. Effect of chemical fertilizer, biochar, and humic acid on the available residual Potassium in the soil, mg K kg$^{-1}$ soil

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 98.10 | 114.30 | 137.32 | $B_0$ | 130.74 | | |
| | $B_1$ | 132.21 | 157.46 | 162.43 | | | 145.51 | $H_0$ |
| | $B_2$ | 161.36 | 170.11 | 175.35 | $B_1$ | 165.30 | | |
| $H_1$ | $B_0$ | 122.56 | 150.56 | 170.58 | | | | |
| | $B_1$ | 158.25 | 188.36 | 193.33 | $B_2$ | 179.80 | 171.73 | $H_1$ |
| | $B_2$ | 180.44 | 191.55 | 199.95 | | | | |
| LSD at $P \leq 0.05$ | | M | B | H | MBH | | | |
| | | 4.24 | 4.24 | 3.98 | 8.85 | | | |
| Average M | | 142.31 | 162.10 | 183.16 | | | | |

Note: differences are significant at $P \leq 0.05$ according to the LSD test.

An overview of the effects of the treatments on the soil's remaining potassium levels may be found in the following table. The addition of biochar to humic acid significantly enhanced the amount of Potassium available, and the combined organic and inorganic ($M_2 \times B_2 \times H_1$) scenario had the highest residual K level value. These synergistic impacts are probably due to the enhanced capacity for cation exchange (CEC) and retaining water of biochar and humic materials that serve to sustain available forms of Potassium to be taken up by plants. All treatment combinations exhibit significant differences, according to the LSD test ($P < 0.05$).

***Protein Content in Fruits***

The generation of protein in zucchini fruits was significantly impacted by the combined application of humic acid, charcoal, and chemical fertilizer (Table 9). Chemical fertilizers did enhance the protein composition significantly, and the maximum was recorded with the $M_2$ treatment (2.67%). Similarly, the fruits' higher protein accumulation was largely due to the application of humic acid and biochar. $B_2$ had the highest protein content at 2.04 %, whereas humic acid treatment $H_1$ had 2.08 %. The greatest impact was observed in the triple interaction ($M_2B_2H_1$), where the protein content of 3.01% was achieved, which showed that there is a great synergistic interaction between the chemical and organic inputs.

Table 9. Effect of chemical fertilization, biochar, and humic acid on the protein content of zucchini fruits (%)

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 1.03 | 1.25 | 2.37 | $B_0$ | 1.69 | 1.73 | $H_0$ |
| | $B_1$ | 1.30 | 1.40 | 2.61 | | | | |
| | $B_2$ | 1.43 | 1.53 | 2.65 | $B_1$ | 1.86 | | |
| $H_1$ | $B_0$ | 1.29 | 1.56 | 2.63 | | | | |
| | $B_1$ | 1.41 | 1.67 | 2.71 | $B_2$ | 2.04 | 2.08 | $H_1$ |
| | $B_2$ | 1.60 | 2.85 | 3.01 | | | | |
| LSD at $P \leq 0.05$ | | M | B | H | MBH | | | |
| | | 0.30 | 0.30 | 0.21 | 0.37 | | | |
| Average M | | 1.36 | 1.71 | 2.67 | | | | |

Note: differences are significant at $P \leq 0.05$ according to the LSD test.

The effects of different fertilizers, biochar, and humic acid treatments on the protein content of zucchini fruits are shown in this table. The results indicate that using chemical fertilizer ($M_2$) in combination with biochar ($B_2$) and humic acid ($H_1$) produced the highest protein percentage (3.01%). The obtained improvement is explained by the better vegetative development, nutrient uptake, and photosynthetic performance because the nutrient availability was sufficient (Wiley, 1908). Biochar also helped in this enhancement by either enriching the rhizosphere with nutrients and enhancing water retention, and humic acid enhanced soil structure and nutrient availability (Zhang et al., 2012; Pettit, 2004; Huang et al., 2020). All the main factors and their interactions significantly influenced the effects that were confirmed by the LSD test ($P \leq 0.05$). All of these complementary qualities show how biochar and humic acid play significant roles in the nutrient cycle, which ultimately helps the metabolic pathways that are involved in protein synthesis (Alwan & Mohsen, 2024; Verheijen et al., 2010; Hammabi & Alwan, 2023).

***Total Yield Per Experimental Unit***

The data presented in Table 10 indicate that the application of humic acid, biochar, and chemical fertilizer significantly increased the overall production of zucchini fruits ($P \leq 0.05$). Chemical fertilization had the strongest influence, with the $M_2$ treatment achieving the highest total yield of 16.66 kg per experimental unit. All of this was also influenced by the application of biochar, and B2 recorded a total yield of 15.30 kg, as opposed to a yield of 13.16 kg registered by the treatment that was using humic acid $H_1$. The total productivity of the triple interaction ($M_2B_2H_1$) was highest at 22.83 kg per unit of the experiment, and this showed the positive synergism of the three inputs.

The table above summarizes the effects of different treatment combinations on the total amount of zucchini fruits produced. The results show that the chemical fertilization developed relevant improvement in the overall and early yields because it improved the frequency of chemical compounds, particularly nitrogen and phosphorus, which help to improve the growth of roots and biomass. Additionally, Potassium has a major role in photosynthesis, enzyme activation, and the translocation of carbohydrates, all of which improve fruit output and weight (Dosjanova, 2025; Humod Al-Ogaidi & Alwan, 2024). The greater surface area, increased soil aggregation, and improved water-retaining qualities of biochar, which support root growth and nutrient retention, can be used to explain this increase in production (Mohsen & Alwan, 2019). Further, biochar in combination with humic acid and fertilizers minimized nitrogen leaching, enhanced nutrient-use efficiency, and additionally, enhanced yield quality (Almamori & Abdul-Ratha, 2020; Hammadi & Alwan, 2023; Janghel et al., 2023; El-Zehery, 2019; Hafez et al., 2021). The LSD test has verified that there are significant differences between all factors.

Table 10. Effect of chemical fertilization, biochar, and humic acid on the total yield (kg) per experimental unit

| Humic acid | Biochar B | Chemical fertilization M | | | Average B | | Average H | |
|---|---|---|---|---|---|---|---|---|
| | | $M_0$ | $M_1$ | $M_2$ | | | | |
| $H_0$ | $B_0$ | 4.22 | 9.58 | 13.74 | $B_0$ | 9.55 | 10.49 | $H_0$ |
| | $B_1$ | 5.10 | 9.97 | 14.73 | | | | |
| | $B_2$ | 6.10 | 13.20 | 17.77 | $B_1$ | 10.82 | | |
| $H_1$ | $B_0$ | 4.98 | 10.87 | 14.10 | | | | |
| | $B_1$ | 6.37 | 11.77 | 17.00 | $B_2$ | 15.30 | 13.16 | $H_1$ |
| | $B_2$ | 9.89 | 20.20 | 22.83 | | | | |
| LSD at $P \leq 0.05$ | | M | B | H | MBH | | | |
| | | 1.31 | 1.31 | 1.22 | 3.00 | | | |
| Average M | | 6.11 | 12.60 | 16.66 | | | | |

Note: differences are significant at $P \leq 0.05$ according to the LSD test.

## Discussion

On the growth rate, nutrient uptake, and the yield of zucchini plants, the results based on this are quite clear that the mixture of chemical fertilizers, charcoal, and humic acid was an effective enhancer. Synergistic interaction of inputs was an important requirement in improving the dynamics of nutrients and soil fertility. The large macro nutrients (N, P, K) were provided by chemical fertilizers to provide the plants with an instant supply of the nutrients. Losses in the form of leaching and fixation normally impair their efficiency. The addition of biochar, which has a high porosity and high carbon content on the surface, improved cation exchange capacity, water retention, and microbial activities in the soil, which further increased the nutrient retention brought out by fertilizers (Xu et al., 2021). Humic acid is a major organic molecule in humus, a chelating agent that increases the solubility of nutrients and uptake of nutrients by the root, increases enzyme activity, and photosynthesis (Ryan et al., 2009; Pettit, 2004).

Increased nutrient availability in the rhizosphere and better root-soil interaction are implied by the rise in nitrogen, phosphorus, and potassium nutrient uptake (Selladurai & Purakayastha, 2016). Moreover, biochar and humic acid aided in reducing the immobilization and leaching of nutrients, thereby leaving the residual nutrient content greater after harvest (Das et al., 2017). The protein content and its total yield indicate that not only did the amendments combined improve the growth of the plants in the vegetative aspect, but also in improving the metabolic efficiency of the plants. Because humic acid stimulated the production of protein and chlorophyll, it increased productivity, which is suggestive of a hormone-like effect (Zhang et al., 2011; Huang et al., 2020). The higher yield obtained by the $M_2B_2H_1$ treatment supports the idea that integrated nutrient management works better than chemical fertilizers (Mohsen & Alwan, 2019; Dosjanova, 2025). The consistency of such findings with the earlier experiments attests to the utility of the experimentation, which entails the employment of a combination of mineral and organic amendments to maintain soil fertility and achieve sustainable production in agriculture.

## Conclusion

This study shows that the addition of humic acid, charcoal, and chemical fertilizer significantly improved the intake of nutrients, their retention in the soil, their protein content, and the overall output of zucchini fruits. It was established that M2B2H1 (high chemical fertilizer + high biochar + humic acid) had the maximum values in all the parameters being tested. It has been determined that humic acid and biochar can be used as supplements to mineral fertilizers to enhance nutrient utilization, improve soil quality, and lessen environmental soil degradation. This type of nutrient management application on zucchini production may lead to high-quality production, which is sustainable and less dependent on chemical fertilizers.

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## Conflict of Interest

The authors testify to the lack of conflicts of interest of any nature.

## Author Contribution

Alwan B.M., Mohsen T.K., and Kadhim W.T. were the designers of the study, the field experimenters, and the analyzer of the study, respectively. The writing, review, and approval of the final manuscript have been done by all authors to be published.

## Data Availability Statement

The evidence behind the results of this research is not publicly available at the moment since the manuscript is still under review and has not been published yet. The relevant author can provide data on a sensible request.

## Ethical Considerations

There were neither human subjects nor animal experiments and no personal information was confidential in this study and hence there was no need to obtain ethical approval. The institutional, national and international procedures and methods will be the ethics standards and guidelines adhered to. According to the authors, this work does not present any ethical issues.

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