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RESEARCH ARTICLE

# Efficiency of biochar and compost on soil bio-chemical properties and yield of knol-khol (*Brassica oleracea* L.)

**Peeyush Sharma, Vikas Abrol*, Satesh Kumar, Reetika Sharma, Maanik, Haziq Shabir & Stanzin Khenrab**

Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu, Jammu & Kashmir 180 009, India

*Email: abrolvics@rediffmail.com

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## Abstract

A field experiment was conducted to assess how the combined application of biochar with various organic amendments affects the soil biochemical properties and the yield characteristics of knol-khol (*Brassica oleracea* var. *gongyloides* L.). The outcomes showed that biochar with organic amendments substantially enhanced the biological characteristics of the soil as compared to the control treatment. There was a notable increment in soil microbial biomass carbon by 33.27 % and dehydrogenase activity by 5.68 % following the integrated application of farmyard manure, vermicompost and biochar ($T_8$). In addition, several knol-khol growth metrics showed significant improvement in $T_8$ compared to the control, including leaf number (1.36 times), plant height (1.38 times) and knob diameter (2.3 times). In $T_8$, the knolkhol production increased by a remarkable 3 times, demonstrating the beneficial effects of the combined treatment . The results of the experiment showed that $T_8$ had significantly higher levels of accessible nitrogen (12.38 %), available potassium (8.54 %), available phosphorus (24.19 %) and organic carbon (9.5 %) than the control. According to this, the concurrent application of farmyard manure, vermicompost and biochar enhanced soil fertility and boosted plant and microbial nutrient availability, which in turn led to higher profitability.

## Keywords

biochar; compost; microbial biomass; soil properties

## Introduction

Since the "green revolution," inorganic fertilizers have been instrumental in increasing agricultural yields. However, its continued usage puts soil health at risk since it may hasten soil acidification and negatively impact soil biota and biochemical processes. The overuse of mineral fertilizers has led to a move towards organic farming methods, accentuate using biochar to increase plant production and soil fertility (1). Although organic farming has historically relied on manures and composts, concerns have emerged regarding their potential to introduce pathogens, heavy metals and pharmaceutical residues into the environment. These contaminants can pose health risks to consumers and accumulate in the soil, disrupting ecosystems (2). Additionally, the decomposition of organic materials releases methane and ammonia, potent greenhouse gases that exacerbate global warming. Nutrient runoff from these materials can also create streams and groundwater pollution, causing eutrophication and harming aquatic life. Moreover, the labour-intensive process of managing and applying these organic amendments can be costly and time-consuming for farmers, adding to the challenges of sustainable organic farming (3). Furthermore, the breakdown of these organic compounds can emit methane and ammonia, which can worsen global warming and contaminate streams and groundwater with nutrients. On the other hand, when combined with mineral fertilizers, biochar has shown promising as an amendment that can increase crop yields without having a negative impact on the environment and soil health (4). As a byproduct of biomass pyrolysis, biochar is heated at low oxygen levels to transform plant biomass into a kind of charcoal that may be used in agriculture. Biochar has become well-known for its many advantages after being inspired by Amazonian terra preta soils, where the purposeful use of charcoal enhanced the chemical and physical qualities of heavily worn soils (5).

Biochar's porous structure creates a network of microscopic holes that hold water and serve as a home for microorganisms (6). Char makes a good soil supplement because it improves the ability of the soil to absorb water as well as nutrients. Moreover, biochar increases the amount of organic carbon in soil, promotes microbial activity and aids in the carbon sequestration (7-10). Compared to the addition of fresh organic matter, biochar application to soils is known to have different impacts on the soil microbiota, affecting the variety, activity and abundance of microbial communities present in the soil-root zone (11). Biochar has the vast surface area and porous characteristics that allow it to absorb inorganic nutrients and soluble organic stuff, making it a perfect home for microorganisms. As a result, biochar and soil bacteria can work together more harmoniously, improving nutrient cycling and the mineralization of organic materials (12). The microbial growth-promoting properties of biochar. Freshly added biochar contains substrates that support microbial growth in the soil and its impact on microbial communities evolves, influencing ecosystem services crucial for agriculture, such as nutrient cycling and organic matter mineralization. The rise in soil pH associated with biochar addition has been linked to an increase in microbial biomass carbon and microbial biomass ninhydrin-N (13). It was demonstrated that as soil pH increased from 3.7 to 8.3, microbial biomass carbon increased from about 20 to 180 μg biomass C $g^{-1}$ soil, indicating a positive correlation between rising pH and microbial biomass (14). many researches proved that biochar has a lot of potential for improving soil health and raising agricultural yield. There are numerous advantages of biochar such as the ability to retain nutrients and water, sequester carbon and provide microbial habitat making it an invaluable material in sustainable agriculture. Research is needed to better understand the long-term effects of biochar on soil biota, microbial communities and ecosystem dynamics as the agricultural community investigates and uses biochar. Biochar is included in organic farming methods as part of a comprehensive strategy for sustainable agriculture that takes environmental and productivity issues into account.

Study aimed to ascertain the beneficial impacts of organic amendments and BC (Biochar) on crop productivity and soil characteristics. The deliberate choice of treatments, which includes biochar made from plentiful rice husk in the area has opted to demonstrate a context-specific approach to sustainable agriculture. Another aspect was to determine the potential of biochar and organic farming techniques to improve the general health of agroecosystems. Further, the study's aims to provide insightful information to farmers, scholars and decision-makers in similar agroclimatic zones who are looking for ecologically friendly and sustainable agricultural practices. Thus, achieving resilient and sustainable agricultural systems.

## Materials and Methods

### Study area

The experiment was conducted at the Organic Farm Research Centre, SKUAST–J, Chatha, Jammu and Kashmir during the year 2018–19. The objective of the field experiment was to assess the effects of several treatments, including biochar, on crop yield and soil parameters. At 293 metres above sea level, the experimental site represents the subtropical region of Jammu province, situated at latitude 32° 40′ N and longitude 78° 48′ E. The Jammu area, which is located in agroclimatic zone 1 (Western Himalayan), has favourable weather during the cropping season, allowing for normal growth and development.

### Soil characteristics

The sandy clay loam soil at the experimental site exhibited specific characteristics, including a pH of 7.6, electrical conductivity (EC) of 0.24, organic carbon content of 6.4 g $kg^{-1}$, available nitrogen of 196.7 kg $ha^{-1}$, available phosphorus ($P_2O_5$) of 19.28 kg $ha^{-1}$ and available potassium ($K_2O$) of 175.62 kg $ha^{-1}$.

### Treatment details

Using a Randomised Block Design (RBD) and three replications of each of the eight treatment combinations, the experiment was conducted. A control group ($T_1$), 100 % nitrogen (N) via farmyard manure (FM) ($T_2$), 100 % N via VC (Vermicompost) ($T_3$), 50 % N via FM (Farm Yard Manure) + 50 % N via VC (Vermicompost) ($T_4$) and 2 t $ha^{-1}$ BC (Biochar) ($T_5$), 2 t $ha^{-1}$BC (Biochar) + 100 % N via FM (Farm Yard Manure) ($T_6$), 2 t $ha^{-1}$BC (Biochar) + 100 % N via VC (Vermicompost) ($T_7$) and 2 t $ha^{-1}$BC (Biochar) + 50 % N via FM (Farm Yard Manure) + 50 % via VC (Vermicompost) ($T_8$) were among the treatments implemented.

### Soil microbial parameters

#### *Dehydrogenase activity (DHA) determination*

Dehydrogenase activity (DHA) determination is a critical assay castoff to assess the overall microbial activity and soil health. Dehydrogenases are intracellular enzymes involved in the biological oxidation of soil organic matter through the transfer of hydrogen ions from substrates to acceptors. Their activity is indicative of the metabolic potential of the soil microbial community. DHA is typically measured by the reduction of tetrazolium salt, such as 2,3,5-triphenyl tetrazolium chloride (TTC), to its corresponding formazan, which can be quantitatively detected through colorimetric analysis. This reduction process reflects the electron transport system activity in soil microbes, making DHA a sensitive indicator of microbial oxidative activity. High DHA values usually correlate with high microbial biomass and activity, suggesting fertile and biologically active soil. Conversely, low DHA can indicate poor soil health, possibly due to contamination or nutrient depletion. The DHA assay is favoured for its simplicity and the valuable insights it provides into the biological functioning of soils, thus serving as an essential tool in soil science for monitoring soil quality, the impacts of agricultural practices and the efficacy of soil amendments in both conventional and organic farming systems (15).

### *Soil Microbial Biomass carbon (SMBC)*

Soil microbial biomass carbon (SMBC) is a key indicator of soil health and fertility, representing the living component of soil organic matter, excluding plant roots and soil animals larger than 5 x 10^-3 mm. SMBC is a measure of the amount of carbon present within the microorganisms in the soil, serving as an essential proxy for microbial activity and the potential for nutrient cycling. This biomass is a dynamic reservoir of nutrients, particularly nitrogen and phosphorus, which can be rapidly mineralized and made available to plants. Methods for determining SMBC often involve chloroform fumigation-extraction, where soil samples are fumigated to kill the microbes and then extracted to measure the carbon released. High levels of SMBC generally indicate a rich, active microbial community, which enhances soil structure, promotes nutrient availability and supports plant growth. Conversely, low SMBC values can signal poor soil conditions, such as low organic matter content, compaction or contamination. Monitoring SMBC provides valuable insights into the effects of agricultural practices, land management, and environmental changes on soil ecosystems, aiding in the development of strategies for sustainable soil management and the conservation of soil health (16). Rice husk biochar enhances soil health and mitigates climate change, but its effectiveness depends on pyrolysis temperature and characteristics of rice husk used (17). Further modifying soil structure can significantly influence the soil fertility and microbial biomass (18). As rice husk is widely available in the Jammu region, it was chosen for the production of the biochar employed in the study. FYM and vermicompost were taken from the Organic Farm Research Centre. Locally grown variety *gongyloides* of knol-khol was selected. During the experiment, a variety of data were measured, including dehydrogenase activity (DHA) and soil microbial biomass carbon (SMBC), in addition to growth characteristics such as plant height, number of leaves and knob diameter. The entire weight of the plants was used to compute the yields; yields/ha were calculated in quintals and yields per plot were estimated in kg.

Standard techniques were used to analyse the soil's chemical qualities (19). Soil pH was measured using a pH meter at a soil-to-water ratio of 1:2.5. A 1:2.5 soil-water suspension was used to test EC, which was reported in $dSm^{-1}$. The wet digestion technique was employed to quantify the organic carbon content. (20). Olsen's technique (21) was used to measure the available phosphorus content and 1N ammonium ethanoate was used as an extractant. The available nitrogen content was calculated by using the alkali potassium permanganate method (22). For the randomised block design, statistical analysis was performed using the analysis of variance approach (23), with treatment differences assessed at a 5 % level of significance (P= 0.05).

## Results and Discussion

A field experiment at the Organic Farm Research Centre in Jammu and Kashmir in 2018–19 examined the effects of biochar and organic amendments on soil microbial biomass carbon (SMBC) and dehydrogenase activity. In comparison to the control ($T_1$), the study's results showed substantial impacts on SMBC and dehydrogenase activity, used a Randomised Block Design (RBD) with eight treatment combinations.

### Soil microbial biomass carbon

The use of farmyard manure (FM), vermicompost (VC) and biochar ($T_8$) in combination was shown to significantly increase SMBC when compared to the control (Table 1). Additionally, there were notable improvements in SMBC in treatments including combinations of FM, biochar ($T_6$), VC, biochar ($T_7$) and FM, VC and biochar ($T_8$) by 7.4 %, 8.02 % and 11.10 % respectively, compared to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$). The noted SMBC values ranged from 95.05 mg $kg^{-1}$ to 71.32 mg $kg^{-1}$. The highest soil microbial biomass carbon (SMBC) of 95.05 mg $kg^{-1}$ was observed in treatment $T_8$, which involved the application of 2 t $ha^{-1}$ biochar, with 50 % of nitrogen sourced from farmyard manure (FM) and the remaining 50 % from vermicompost. Following closely was treatment $T_7$, with an SMBC of 87.23 mg $kg^{-1}$, utilizing 2 t $ha^{-1}$ biochar and 100 % nitrogen from vermicompost. Conversely, the control ($T_1$) exhibited the lowest SMBC (71.32 mg $kg^{-1}$). The sequential decrease in SMBC was $T_8 > T_7 > T_4 > T_6 > T_3 > T_2 > T_5 > T_1$ as per Table 1. The rise in microbial biomass under comparable circumstances is

**Table 1.** Impact of utilizing biochar in conjunction with various organic amendments on the soil microbial biomass carbon and soil dehydrogenase activity

| Treatments | SMBC (mg $kg^{-1}$) | DHA (µg TPF $g^{-1}$) |
|---|---|---|
| $T_1$ - Control | 71.32a ± 7.32 | 202.5a ± 10.51 |
| $T_2$ - 100 % N via FM | 78.62ab ± 6.99 | 207.4b ± 9.50 |
| $T_3$ - 100 % N via V | 80.75b ± 7.28 | 207.9b ± 8.46 |
| $T_4$ - 50 % N via FM + 50 % N via VC | 85.55b ± 6.73 | 210.8c ± 9.22 |
| $T_5$ - 2 t $ha^{-1}$ BC | 78.19a ± 2.71 | 204.1a ± 9.07 |
| $T_6$ - 2 t $ha^{-1}$ BC + 100 % N via FM | 84.40b ± 6.10 | 212.2cd ± 8.44 |
| $T_7$ - 2 t $ha^{-1}$ BC + 100 % N via VC | 87.23bc ± 6.97 | 212.0cd ± 9.18 |
| $T_8$ - 2 t $ha^{-1}$ BC + 50 % N via FM + 50 % via VC | 95.05c ± 5.67 | 214.0d ± 8.78 |
| **CD (0.05)** | 8.63 | 2.28 |
| **SE(m±)** | 2.82 | 0.74 |
| **CV (%)** | 5.97 | 0.62 |

**N**: Nitrogen, **FM**: Farm Yard Manure, **VC**: Vermicompost, **BC**: Biochar

consistent with the observed improvement in SMBC. The formation of habitat, protection against hyphal grazers and variations in nutrient availability are all responsible for the rise in SMBC. Studies also emphasized how biochar may improve soil microbial biomass C. Furthermore, the impact of humidity on the quantity of microorganisms was recognized, with recurring drying causing stress or dormancy in microbes (12, 24). These impacts could be reduced by the high water-holding capacity of biochar, which would encourage microbial development and depends on the feedstocks and temperature of biochar production process (25).

## Dehydrogenase activity

The soil's dehydrogenase activity, is a vital indicator of soil respiration and organic matter decomposition, exhibited significant responsiveness to the applied treatments (Table 1). The range of dehydrogenase activity among the treatments varied from 214.0 µg TPF $g^{-1}$ soil 24 $h^{-1}$ to 202.5 µg TPF $g^{-1}$ soil 24 $h^{-1}$. Treatment $T_8$ recorded the highest dehydrogenase activity at 214.0 µg TPF $g^{-1}$ soil 24 $h^{-1}$, followed by $T_6$ at 212.2 µg TPF $g^{-1}$ soil 24 $h^{-1}$, while the control ($T_1$) displayed the lowest activity at 202.5 µg TPF $g^{-1}$ soil 24 $h^{-1}$. The concurrent use of biochar in combination with FM and VC resulted in a significant change in dehydrogenase activity compared to the control. Treatments $T_6$, $T_7$ and $T_8$ displayed increases in dehydrogenase activity by 2.31 %, 2.0 % and 1.5 % respectively, compared to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$) as shown in Table 1. Dehydrogenase activity decreased in the following order: $T_8 > T_6 > T_7 > T_4 > T_3 > T_2 > T_5 > T_1$. The enhanced dehydrogenase activity that has been seen can be ascribed to the amplified enzyme activity that has been enabled by the incorporation of organic carbon into the soil via FM and biochar. Microbes and enzymes find the perfect home in biochar because of its porous porosity, significant surface area and capacity to absorb dissolvable organic materials and inorganic nutrients. Organic amended soils exhibited higher dehydrogenase activity, attributed to the improved microbial biomass and enhanced soil pH conditions and also showed that acidic soils raised the pH and subsequently increased phosphatase activity, facilitating better phosphorus availability for plants. This is consistent with the research conducted earlier (26-28). Additionally, it was also observed that applying biochar improve soil microbial diversity and can prevent heavy metals from leaching (29).

## Number of leaves per plant

In Table 2, the results showed that applying biochar and organic amendments together significantly increased the number of leaves per plant. In comparison to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$), treatments $T_6$ (FM + Biochar), $T_7$ (VC + Biochar) and $T_8$ (FM + VC + Biochar) showed increases of 7.9 %, 5.3 % and 9.48 % respectively. With 15.0 leaves, $T_8$ has the most leaves, followed by $T_7$ with 14.0 leaves. In the control ($T_1$), the fewest leaves (11.0) were seen. The number of leaves was slightly different from the control when biochar and organic amendments were applied. When these amendments are used, like farm manure (FM) and vermicompost (VC), they can further boost soil fertility and microbial activity and supply essential nutrients and organic matter that enhance soil structure and fertility. While biochar supports these amendments by providing a habitat for beneficial microbes and improving soil physical properties (30).

## Plant height

When biochar and organic amendments were applied together, plant height increased significantly (Table 2). Compared to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$), treatments $T_6$, $T_7$ and $T_8$ increased plant height by 8.7 %, 10.7 % and 12.4 % respectively, as shown in Table 2. $T_8$ had more height (49.2 cm), whereas $T_7$ had the second-highest plant (45.4 cm). In the control group ($T_1$), the lowest plant height (36.0 cm) was noted. A significant alteration in the height of knol-khol plants was seen when using biochar either alone or in conjunction with organic inputs. The current study's results, which show that the plants with more height were produced by applying biochar and organic amendments together, are consistent with the earlier findings (29, 30). Organic amendments contribute organic matter and essential nutrients to the soil and promote microbial activity, which in turn helps in the decomposition of organic materials and the release of nutrients in plant-available forms. The combination of biochar and organic amendments synergistically enhances these effects, like height of the plant.

**Table 2.** Impact of utilizing biochar in conjunction with various organic amendments on plant growth parameters

| Treatments | No. of leaves plant $^{-1}$ | Plant height (cm) | Knob diameter (cm) | Yield ( q $ha^{-1}$) |
|---|---|---|---|---|
| $T_1$ - Control | 11.0a ± 1.16 | 36.0a ± 4.77 | 4.2a ± 0.66 | 70.40a ± 32.45 |
| $T_2$ - 100 % N via FM | 12.7ab ± 0.88 | 41.6abc ± 4.85 | 4.7a ± 0.15 | 167.62c ± 34.81 |
| $T_3$ - 100 % N via VC | 13.3bc ± 0.67 | 41.0abc ± 4.29 | 5.6ab ± 0.56 | 166.30c ± 30.00 |
| $T_4$ - 50 % N via FM + 50 % N via VC | 13.7bc ± 0.88 | 44.4bcd ± 5.61 | 7.7c ± 0.55 | 173.64c ± 32.55 |
| $T_5$ - 2 t $ha^{-1}$ BC | 11.0a ± 0.58 | 38.1ab ± 4.21 | 5.4ab ± 1.31 | 92.65b ± 30.29 |
| $T_6$ - 2 t $ha^{-1}$ BC + 100 % N via FM | 13.7bc ± 0.88 | 45.2cd ± 4.87 | 6.3bc ± 1.01 | 203.73d ± 28.47 |
| $T_7$ - 2 t $ha^{-1}$ BC + 100 % N via VC | 14.0bc ± 0.58 | 45.4cd ± 5.57 | 6.7bc ± 1.10 | 208.60 ± 26.99 |
| $T_8$ - 2 t $ha^{-1}$ BC + 50 % N via FM + 50 % via VC | 15.0c ± 0.58 | 49.9d ± 2.76 | 9.7d ± 0.15 | 216.44d ± 42.70 |
| **CD (0.05)** | 1.81 | 6.23 | 1.45 | 16.41 |
| **SE(m±)** | 0.59 | 2.04 | 0.48 | 5.36 |
| **CV (%)** | 7.83 | 8.25 | 13.03 | 5.71 |

**N**: Nitrogen, **FM**: Farm Yard Manure, **VC**: Vermicompost, **BC**: Biochar

### Knob diameter

The knob's diameter, a critical knol-khol development indicator, responded significantly to the combined application of organic fertilizers and biochar (Table 2). In comparison to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$), treatments $T_6$, $T_7$ and $T_8$ increased knob diameter by 34.04 %, 19.64 % and 25.97 % respectively. $T_8$ has the largest knob diameter (9.7 cm), followed by $T_4$ (7.7 cm). The control group ($T_1$) had the smallest knob diameter, at 4.2 cm. Combining biochar with manures has a significant impact on the knob diameter of knol-khol. When biochar is combined with organic fertilizers, it acts synergistically to enhance nutrient availability and uptake efficiency by adsorbing and stabilizing nutrients, thereby reducing nutrient losses through leaching and runoff. This combined effect supports robust plant growth, leading to larger and more developed knobs in knol-khol plants (31, 32).

### Soil pH

There are no significant variations in soil pH reported among different treatments, with values varying from 7.73 to 7.81 (Table 3). The highest pH value (7.81) was observed in treatment $T_5$, which received 2 t ha$^{-1}$ biochar, closely followed by $T_6$ with 2 t ha$^{-1}$ biochar and 100 % nitrogen from farmyard manure (FM) (pH 7.8). Treatment $T_4$, which received 50 % nitrogen from FM and 50 % from vermicompost, displayed the lowest pH value (7.73). Since the biochar used had a slightly alkaline pH, the assimilation of FM, vermicompost (VC) and biochar (B) did not significantly alter the pH. Comparable results were reported earlier (33), linking the formation of ash—primarily carbonates and alkali metals in soil modified with biochar to elevated soil pH. The findings are consistent with research showing that the liming action of biochar raises soil pH and that decomposition of organic matter lowers pH (34). The incorporation of organic amendments did not significantly alter pH because these amendments can have a buffering effect on soil pH. Organic matter decomposition processes release organic acids, which tend to slightly acidify the soil. This acidity can counterbalance the alkaline effect of biochar to some extent, resulting in overall pH values that remain within a relatively narrow range (35).

### Electrical conductivity

No significant variations in soil electrical conductivity (EC) were observed among treatments, with values ranging from 0.24 dS m$^{-1}$ to 0.31 dS m$^{-1}$ (Table 3). The highest EC (0.31 dS m$^{-1}$) was recorded in $T_8$, which received 2 t ha$^{-1}$ biochar, 50 % nitrogen from farmyard manure (FM) and 50 % nitrogen from vermicompost, followed by $T_6$ (2 t ha$^{-1}$ biochar, 100 % nitrogen from FM) with 0.30 dS m$^{-1}$. The lowest EC (0.24 dS m$^{-1}$) was observed in the control group. Organic amendments typically have a low electrical conductivity due to their carbonaceous nature. When applied to soil, biochar can act as a buffer, stabilizing EC levels by absorbing excess ions and preventing drastic changes in soil salinity (36).

### Organic carbon

As seen in Table 3, significant variations in the organic carbon content were seen when biochar and organic amendments (FM + VC) were applied together. The range of organic carbon in each treatment was 6.9 g kg$^{-1}$ to 6.3 g kg$^{-1}$. $T_8$, which got 2 t ha$^{-1}$ BC (Biochar) + 50 % N through FM (Farm Yard Manure) + 50 % N through VC (Vermicompost), had the largest amount of organic carbon (6.9 g kg$^{-1}$), followed by $T_7$, i.e., 2 t ha$^{-1}$ BC (Biochar) + 100 % N by VC (Vermicompost), with 6.8 g kg$^{-1}$ and 6.3 g kg$^{-1}$ of organic carbon found in the control group ($T_1$). The organic carbon contents were $T_8 > T_7 > T_6 = T_4 > T_3 > T_2 > T_5 > T_1$ observed in this sequence and this variance may be because of the refractory organic carbon in biochar and the labile and recalcitrant fractions contributing to the total organic carbon levels. These results were found to be similar to the study conducted earlier (37, 38). Organic amendments supply labile organic carbon fractions to the soil and when these materials decompose over time, releasing nutrients and contribute to short-term increases in soil organic carbon content. Treatments combining biochar with organic amendments benefit from both the stable carbon of biochar and the readily available carbon from organic amendments, leading to enhanced organic similar carbon levels compared to treatments using organic inputs alone (39).

### Available nitrogen

The available nitrogen content of the soil was greatly affected by the combined application of biochar and

**Table 3.** Impact of utilizing biochar in conjunction with various organic amendments on pH, EC, OC, N, P, K and yield parameters

| Treatments | pH | EC ( dS m$^{-1}$) | OC (gkg$^{-1}$) | N (kgha$^{-1}$) | P (kgha$^{-1}$) | K (kgha$^{-1}$) |
|---|---|---|---|---|---|---|
| $T_1$ – Control | 7.79 | 0.24 | 6.3a ± 0.33 | 194.7a ± 9.56 | 18.68a ± 1.99 | 175.40a ± 14.93 |
| $T_2$ - 100 % N via FM | 7.74 | 0.29 | 6.5b ± 0.58 | 202.3ab ± 11.55 | 21.22b ± 2.02 | 181.10b ± 16.87 |
| $T_3$ - 100 % N via VC | 7.74 | 0.30 | 6.6c ± 0.33 | 204.3bc ± 8.72 | 21.25b ± 1.98 | 181.56b ± 18.12 |
| $T_4$ - 50 % N via FM + 50 % N via VC | 7.73 | 0.28 | 6.7c ± 0.33 | 210.0cd ± 8.67 | 22.21c ± 1.89 | 183.58b ± 17.10 |
| $T_5$ - 2 t ha$^{-1}$ BC | 7.81 | 0.26 | 6.4a ± 0.00 | 200.7ab ± 10.84 | 19.10a ± 1.71 | 179.33a ± 15.26 |
| $T_6$ - 2 t ha$^{-1}$ BC + 100 % N via FM | 7.80 | 0.30 | 6.7c ± 0.03 | 212.5de ± 6.95 | 22.71cd ± 1.61 | 182.34b ± 17.02 |
| $T_7$ - 2 t ha$^{-1}$ BC + 100 % N via VC | 7.79 | 0.29 | 6.8cd ± 0.03 | 212.8de ± 5.37 | 22.38cd ± 1.48 | 183.59b ± 17.53 |
| $T_8$ - 2 t ha$^{-1}$ BC + 50 % N via FM + 50 % via VC | 7.75 | 0.31 | 6.9d ± 0.67 | 218.8e ± 5.57 | 23.20d ± 1.85 | 190.30c ± 15.38 |
| **CD (0.05)** | NS | NS | 0.13 | 7.49 | 0.89 | 4.88 |
| **SE(m±)** | 0.07 | 0.01 | 0.04 | 2.45 | 0.29 | 1.59 |
| **CV (%)** | 1.52 | 2.36 | 1.07 | 2.05 | 2.35 | 1.51 |

**N**: Nitrogen, **FM**: Farm Yard Manure, **VC**: Vermicompost, **BC**: Biochar

organic amendments (Table 3). Across treatments, available nitrogen varied from 194.7 kg $ha^{-1}$ to 218.8 kg $ha^{-1}$. $T_8$, which got 2 t $ha^{-1}$ BC (Biochar) + 50 % N through FM (Farm Yard Manure) + 50 % N through VC (Vermicompost), had the greatest nitrogen content (218.8 kg $ha^{-1}$), followed by $T_7$, 2 t $ha^{-1}$ BC (Biochar) + 100 % N through VC (Vermicompost), with 212.8 kg $ha^{-1}$. The control had the lowest amount of accessible nitrogen (194.7 kg $ha^{-1}$). The order of available nitrogen content was $T_8 > T_7 = T_6 > T_4 > T_3 > T_2 > T_5 > T_1$. This was due to biochar's high adsorption capacity and influence on nitrogen dynamics in soil, leading to increased availability. Also, these findings were similar to results reported earlier (40). The presence of organic amendments alters nitrogen cycling processes in soil and promotes microbial activity, which enhances nitrogen mineralization (conversion of organic nitrogen to plant-available forms). Additionally, biochar's alkaline nature can influence soil pH, optimizing conditions for nitrogen transformations and reducing nitrogen losses through volatilization or denitrification (41).

### Available phosphorus

Table 3 shows that the range of accessible phosphorus in treatments was 18.68 kg $ha^{-1}$ to 23.20 kg $ha^{-1}$. In comparison to the control, biochar and organic amendments (FM, vermicompost) increased the amount of phosphorus that was accessible. $T_8$ had the greatest phosphorus content (23.20 kg $ha^{-1}$) and $T_6$ had the second-highest (22.71 kg $ha^{-1}$) with 2 t $ha^{-1}$ BC (Biochar) + 100 % N via FM (Farm Yard Manure). In the control, the lowest amount of accessible phosphorus (18.68 kg $ha^{-1}$) was noted. The order of accessible phosphorus content was $T_8 > T_6 > T_7 > T_4 > T_3 > T_2 > T_5 > T_1$. According to the studies, the concentration of accessible P in biochar is responsible for the rise in available phosphorus (42, 43). These amendments have a high surface area and porosity, which enable the sorption of phosphorus from the soil solution. Phosphorus ions can bind to biochar surfaces through chemical interactions, reducing their leaching potential and increasing their availability to plants over time (44).

### Available potassium

Across treatments, the available potassium level varied from 175.40 kg $ha^{-1}$ to 190.30 kg $ha^{-1}$ (Table 3). $T_8$ had the greatest potassium content, 190.30 kg $ha^{-1}$, followed by $T_7$, which had 183.59 kg $ha^{-1}$in treatment having 2 t $ha^{-1}$ BC (Biochar) + 100 % N by VC (Vermicompost). The lowest potassium availability (175.40 kg $ha^{-1}$) was noted in control. The order of accessible potassium content was $T_8 > T_7 > T_4 > T_6 > T_3 > T_2 > T_5 > T_1$. It was emphasised the direct advantages of biochar on nutrient availability, especially potassium (44). The amendments can influence soil microbial activity and nutrient cycling processes, promoting the release of potassium from mineral sources and organic matter. This enhances the pool of plant-available potassium, supporting improved nutrient uptake by crops and contributing to better growth and yield. The findings show how biochar and organic additions significantly affect the pH, electrical conductivity, organic carbon content and availability of nutrients in soil. The study provides insights for sustainable agriculture practices by highlighting the impact of biochar on soil properties and nutrient dynamics.

### Yield

The yield of knol-khol was significantly affected by all the treatments compared to the control (Table 2). In comparison to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$) without biochar, the combined application of FM + Biochar ($T_6$), VC + Biochar ($T_7$) and FM + VC + Biochar ($T_8$) enhanced the yield by 21.54 %, 25.43 % and 24.64 % respectively as shown in Table 3. $T_8$ achieved the greatest output (216.44 q $ha^{-1}$), followed by $T_7$ with 208.60 q $ha^{-1}$. While yields in $T_8$, $T_7$ and $T_6$ were statistically equivalent, they were greater than in the other treatments. The control ($T_1$) had the lowest yield (70.40 q $ha^{-1}$). The use of biochar, either by itself or in conjunction with manures, showed a noteworthy improvement in knol-khol output. As shown in Table.1, the results show a substantial effect of all the treatments on knol-khol yield when compared to the control. In particular, compared to FM ($T_2$), VC ($T_3$) and FM + VC ($T_4$) without biochar, the combined application of FM + Biochar ($T_6$), vermicompost (VC) + B ($T_7$) and FM + VC + B ($T_8$) produced yield increases of 21.54 %, 25.43 % and 24.64 % respectively. Across treatments, the output varied from 70.40 q $ha^{-1}$ to 216.44 q $ha^{-1}$. The amendments contribute to soil fertility by enhancing nutrient retention and availability. Biochar has a porous structure with a high surface area that can adsorb and retain nutrients such as nitrogen, phosphorus and potassium, making them more accessible to plants (45).

## Conclusion

The integrated application of biochar with farmyard manure and vermicompost significantly enhanced soil biological properties and knol-khol yield parameters compared to the control group. This approach notably increased soil microbial biomass carbon and dehydrogenase activity, resulting in improved nutrient availability and enhanced crop productivity, thus indicating a promising strategy for sustainable agricultural practices.

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## Authors' contributions

PS and VA: conceptualization, methodology, formal analysis, investigation, writing-original draft; PS and SK: experiment, and methodology; RS, M,HS and SKh: editing, statistical analysis. All authors have read and agreed to the published version of the manuscript.

## Compliance with ethical standards

**Conflict of interest**: The authors declare that they have no conflict of interests concerning this work.

**Ethical issues**: None

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