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RESEARCH ARTICLE

Effect of humic acid and vermicompost levels on agronomic performance and soil nutrient dynamics in Pearl millet (*Pennisetum glaucum* (L.) R.Br.)

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Abstract

A field experiment was conducted during the kharif season of 2024 at Lovely Professional University, Phagwara, Punjab, to evaluate the effects of humic acid (HA) and vermicompost (VC) on the growth, yield and soil nutrient status of Bajra (*Pennisetum glaucum* (L.) R.Br.). The trial followed a randomized block design (RBD) with nine treatments and three replications, including combinations of HA (5 and 10 L ha^{-1}) and VC (2 and 4 t ha^{-1}), along with a control. The treatment combining HA at 10 L ha^{-1} and VC at 4 t ha^{-1} showed a significantly improvement in plant height (198.4 cm), tiller number (3.2 per plant) and yield-related traits. It produced the highest grain yield (2065.8 kg ha^{-1}) and stover yield (2706.2 kg ha^{-1}). Nutrient uptake was also maximized under this treatment, with nitrogen (67.8 kg ha^{-1}), phosphorus (14.2 kg ha^{-1}) and potassium (66.4 kg ha^{-1}) uptake being highest. Post-harvest soil analysis revealed improved fertility, with increased available N, P, K and organic carbon. These findings suggest that the combined application of HA and VC substantially enhances crop performance and soil health, offering a sustainable approach for Bajra cultivation in Typic Haplustept soils.

Keywords: bajra; humic acid; millets; soil fertility; sustainable agriculture; vermicompost

Introduction

Pearl Millet (*Pennisetum glaucum* (L.) R.Br.), often referred to as Bajra, stands out as a significant cereal crop cultivated in arid and semi-arid regions globally, due to its remarkable ability to thrive in drought conditions and marginal soils. It is believed to have originated in Africa and it is classified within the Poaceae family. Pearl Millet, recognized by several names including cat tail millet, candle millet and spiked millet, is regarded as a significant coarse grain crop and is frequently termed the "poor man's food" (1).

Due to its brief growing season and strong capacity to thrive in water-scarce environments, it serves as a fundamental food source for countless individuals, especially in tropical and subtropical regions. India is the leading global producer of pearl millet, representing a substantial portion of both the cultivated area and overall production. The primary states contributing to production in India are Rajasthan, Maharashtra, Gujarat, Uttar Pradesh and Haryana. Together, these states account for more than 87 % of the total cultivated area and 78 % of the national production. Rajasthan encompasses an area of 45 lakh ha^{-1}, with Uttar Pradesh at 9.8 lakh ha^{-1} and Haryana at 3.99 lakh ha^{-1} following closely behind. Recent production data reveal fluctuations in yields, showing outputs of 108.63 lakh tonnes for 2020–21, 97.81 lakh tonnes for 2021–22 and 111.66 lakh tonnes for 2022–23, with an estimated potential reaching up to 130 lakh tonnes (2).

Although it holds considerable importance, bajra cultivation in Punjab is minimal, occupying merely 0.01 lakh hectares, with yield levels approximately 650 kg ha^{-1} in 2021–22. This difference is primarily shaped by climatic conditions, soil quality and the implementation of contemporary agricultural techniques (2). Although the crop gains from light showers in the vegetative stage, rainfall during flowering can adversely affect fertilization by compromising pollen viability. Nonetheless, the excessive application of synthetic fertilizers has resulted in numerous environmental issues, such as soil degradation, water contamination and greenhouse gas emissions (1).

Consequently, attention has turned to organic and sustainable approaches for nutrient management. Organic amendments like humic acid (HA) and vermicompost (VC) are increasingly recognized for their potential to improve soil structure, enhance nutrient uptake and stimulate plant growth (1). HA resulting from the breakdown of organic matter and it contains an extensive number of bioactive molecules that enhance root development, increase cation exchange capacity and promote microbial activity in soil. It affects plant metabolism by enhancing nutrient absorption and serving as a stimulant for growth (3). Furthermore, VC generated through the biological breakdown of organic matter by earthworms serves as a powerful organic fertilizer, rich in macronutrients and micronutrients as well as calcium and magnesium, which are essential for plant physiology and soil fertility (4).

Although HA and VC have been examined separately for their positive impacts on soil health and crop productivity, there is a scarcity of information regarding their combined application. Understanding their interactive effects is essential, as synergistic or antagonistic relationships may impact their efficacy in promoting crop growth and nutrient absorption. Furthermore, there is limited understanding of the specific mechanisms through, which pearl millet takes up nutrients from these organic inputs. Examining their functions in nutrient availability, uptake pathways and transport mechanisms can yield valuable insights into sustainable millet cultivation practices (5). This study aims to investigate the synergistic effects of HA and VC on the growth and yield performance of pearl millet, considering its nutritional, ecological and agronomic importance.

Material and Methods

Location, weather and soil

The experimental trail was conducted at Agricultural farms of Lovely Professional University, Phagwara, Punjab in the season of kharif (2024–25). The Agricultural Farm is located at latitude 31.242108° and longitude 75.696344° (Fig. 1). The data displays monthly weather from July to October, highlighting critical parameters including temperature, dew point, humidity, wind speed and precipitation (Fig. 2). The average temperature decreases from 31.35 °C in July to 25.62 °C in October, with a corresponding decline in the dew point from 27.10 °C to 20.97 °C, reflecting a reduction in air moisture. Humidity peaks in August at 87.31 % and gradually declines to 74.72 % by October. Precipitation peaks in August at 9.20 mm and decreases markedly, with no rainfall observed in October. The soil at the experimental site was classified as coarse sandy loam. The initial soil status indicated medium levels of organic carbon, available phosphorus and available nitrogen, while available nitrogen was low.

Experiment details

The experiment carried out during the kharif season 2024. The experiment was comprised in a randomized block design with three replications and nine treatments. The treatments used in experiment was as follows:

T_0- HA_0+VC (0 t ha^{-1}),

T_1- HA_0+ VC (2 t ha^{-1}),

T_2- HA_0 + VC (4 t ha^{-1}),

T_3- HA (5 L ha^{-1}) + VC (0 t ha^{-1}),

T_4- HA (5 L ha^{-1}) + VC (2 t ha^{-1}),

T_5- HA (5 L ha^{-1}) + VC (4 t ha^{-1}),

T_6- HA (10 L ha^{-1}) + VC (0 t ha^{-1}),

T_7- HA (10 L ha^{-1}) + VC (2 t ha^{-1}),

T_8- HA (10 L ha^{-1}) + VC (4 t ha^{-1}).

This experiment utilized the PBH-09 variety of bajra. This variety is characterized by its early maturation, medium height ranging from 120 to 130 cm, grey grain colour, erect plant type, bold seed size, head weight between 15 to 20 g and head length measuring 20 to 25 cm. This variety reaches maturity in 80–85 days. Bajra seeds were sown using the line sowing method, adhering to a spacing of 45 cm × 15 cm. VC applied as soil application at the time of land preparation and HA applied as foliar application at 30 and 45 days after sowing (DAS). Urea, single super phosphate, di-ammonium phosphate and murate of potash are used as sources of nitrogen, phosphorus and potash for bajra. All the intercultural operations were done as per the package and practices of Punjab Agriculture University, Ludhiana, for the normal growth of crops.

Data recording

Plant data such as height, stem girth, number of leaves, leaf area, chlorophyll index, dry weight and crop growth rate (CGR) was recorded (5). The SPAD meter was used to measure chlorophyll index and was calibrated before each measurement session by performing zero calibration with no leaf inserted and verifying accuracy using the standard calibration plate. Data related to yield attributes-number of ears per plant, length of ears, number of seeds per ear, test weight, grain yield, stover yield and harvest index were collected following established protocols (6, 7). The crop was harvested when the heads had dried and contained 10–15 % moisture. Threshing was done by beating the heads with sticks and subsequently the grain yield was determined. The straw yield was calculated by deducting the grain yield from the total biological yield. All recorded yields, including grain, stover yield, were converted to kg ha^{-1}.

Soil samples from each plot were obtained before and after crop harvest at 0–15 cm depth to ascertain the available nutrients and were subsequently dried at room temperature for 72 hr. The soil organic carbon (OC) was determined (8). To evaluate available phosphorus (P) and potassium (K) standard methods were applied (9). The amounts of phosphorus and potassium were assessed using a visible spectrophotometer and a flame photometer. The Kjeldahl method was employed to ascertain the available nitrogen in the soil (10).

To determine nutrient contents and the uptake by plant samples, shoot and grain samples were collected and desiccated in a hot air oven at 70 °C for 24 to 48 hr. Upon drying, the materials were thoroughly crushed. The micro Kjeldahl method determined the nitrogen concentration in the plant and seed samples. The di-acid digestion method was utilized for the determination of P and K (11). A visible spectrophotometer and a flame photometer were employed to quantify the amounts of phosphorus, potassium and sulfur.

Statistical analysis

The recorded data was tabulated treatment-wise under three replications. The differences between the mean values were estimated by one-way ANOVA (analysis of variance) with the Grapes software (General R-based Analysis Platform empowered by statistics) launched in 2020. The significant differences among the means were calculated on the basis of LSD (least significant difference) at a 5 % level of significance.

Results and Discussion

Effect of humic acid and vermicompost on growth attributes of bajra

The findings from the experiment assessing the impacts of various treatments on plant height, stem girth, leaf area, number of leaves per plant, chlorophyll index (SPAD), dry weight and crop growth rate (CGR) presented in Table 1.

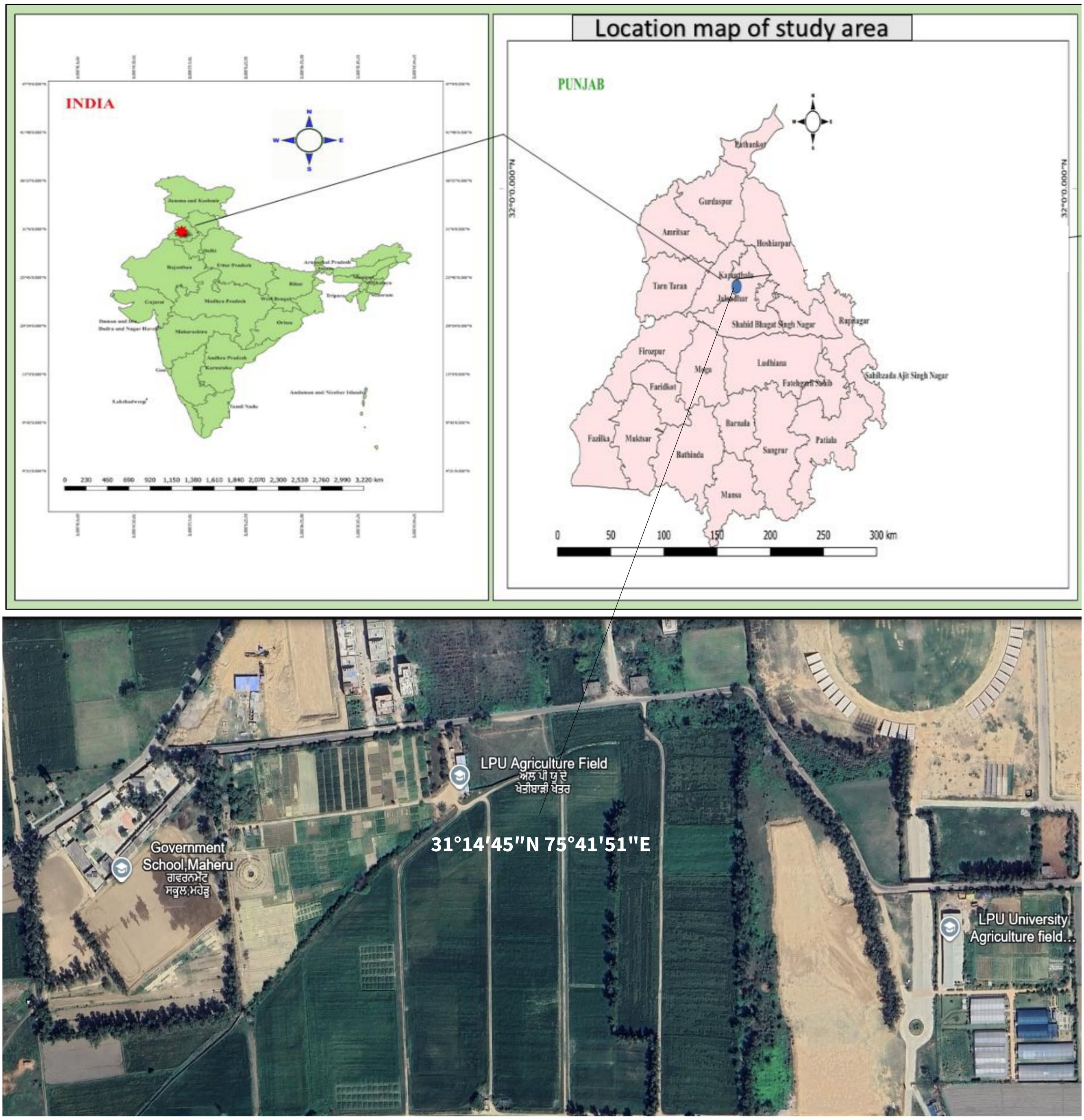

Fig. 1. Experimental location map.

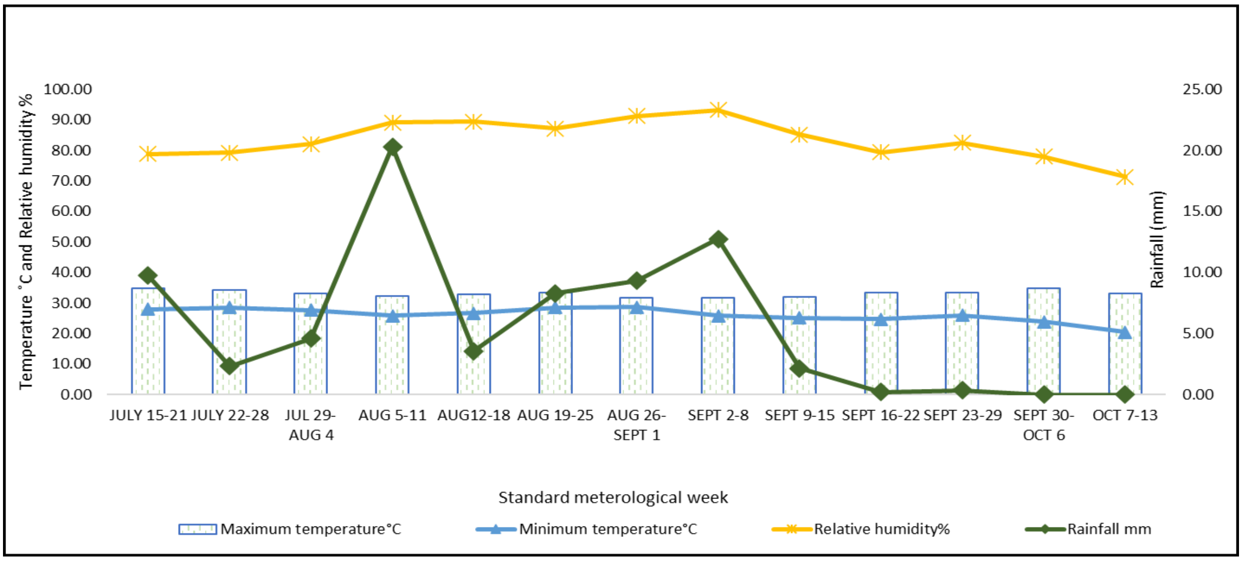

Fig. 2. Mean weekly meteorological data from July to October 2024.

Table 1. Effect of different levels of humic acid and vermicompost on the growth attributes of pearl millet

Treatments	Plant height (cm)	Number of leaves plant^{-1}	Leaf area (cm^2)	Stem girth (mm)	Dry weight (g)	Chlorophyll index (SPAD)	CGR (g g^{-1} m^{-2})
T_0 - HA0 +VC (control)	132.1^f ± 1.47	6.0^i ± 0.34	307.20^f ± 3.91	26.83^g ± 0.34	74.12^e ± 3.12	23.6^f ± 0.74	1.08^f ± 0.01
T_1 - HA0 + VC (2 t ha^{-1})	135.45^{ef} ± 2.59	7.4^h ± 0.43	321.45^{ef} ± 1.65	25.17^g ± 0.43	77.1^e ± 1.67	24.87^{ef} ± 0.36	1.19^e ± 0.02
T_2 - HA0 + VC (4 t ha^{-1})	138.4^{def} ± 0.20	8.6^g ± 1.18	348.20^{def} ± 9.99	28.5^f ± 1.18	82.19^d ± 0.52	25.33^e ± 0.18	1.26^e ± 0.05
T_3 - HA (5 L ha^{-1}) + VC (0 t ha^{-1})	140.2^{cde} ± 4.95	10.0^f ± 0.98	389.50^{cde} ± 11.75	32.1^e ± 0.98	92.44^c ± 3.08	26.2^{de} ± 0.21	1.52^d ± 0.07
T_4 - HA (5 L ha^{-1}) + VC (2t ha^{-1})	145.1^{abc} ± 1.28	11.5^e ± 0.03	435.70^{abc} ± 12.19	38.1^c ± 0.03	95.53^c ± 1.38	30.97^c ± 0.17	2.06^c ± 0.07
T_5 - HA (5L ha^{-1}) + VC (4t ha^{-1})	147.17^{ab} ± 1.73	12.78^c ± 0.84	455.20^{ab} ± 6.70	40.5^{ab} ± 0.84	99.87^{ab} ± 0.45	32.03^c ± 0.66	2.15^c ± 0.08
T_6 - HA (10 L ha^{-1}) + VC (0 t ha^{-1})	143.13^{bcd} ± 3.16	12.0^d ± 1.25	416.70^{bcd} ± 5.52	35.5^c ± 1.25	94.08^c ± 3.31	27.13^d ± 1.13	1.44^d ± 0.03
T_7 - HA (10 L ha^{-1}) + VC (2 t ha^{-1})	148.4^{ab} ± 5.02	13.34^b ± 0.99	481.10^{ab} ± 7.44	42.3^b ± 0.99	117.03^b ± 1.48	33.77^b ± 1.34	2.50^b ± 0.04
T_8 - HA (10 L ha^{-1}) + VC (4 t ha^{-1})	151.2^a ± 3.78	14.21^a ± 1.10	490.60^a ± 6.50	43.7^a ± 1.10	119.06^a ± 0.64	35.17^a ± 0.76	2.61^a ± 0.05
CD ($p < 0.05$)	5.830	0.409	6.32	1.583	3.715	1.340	0.092
SE(m)	1.945	0.102	2.1	0.528	1.239	0.432	0.031

HA- humic acid, VC- vermicompost. Values within a column followed by the same superscript letters are not significantly different and different letters are significantly different according to Duncan's multiple range test (DMRT) at $p < 0.05$.

Plant height

The height of bajra (cm) as affected by different concentrations of HA and the application of VC. The height of the plants exhibited a significant ($p < 0.05$) positive correlation with the increasing concentrations of HA and VC. The highest plants were observed under HA at 10 L ha^{-1} + VC at 4 t ha^{-1}, attaining a height of 151.2 cm, which was significantly superior to all other treatments. The control treatment exhibited the minimum plant height (132.1 cm). The increase in plant height can be attributed to enhanced nutrient absorption, more efficient root development and hormonal processes promoted by humic substances along with the organic nutrient provided VC (11).

Number of leaves plant^{-1} and leaf area

A progressive increase in the number of leaves per plant was recorded with the synergistic application of HA and VC. HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} yielded the highest leaf count of 14.21, demonstrating statistical superiority over all other treatments. The control showed the lowest leaf number. The observed increase could be attributed to increased cytokinin activity and better nutrient availability resulting from the application of VC and HA, which encourages high vegetative growth (12).

The leaf area shows a significant improvement across the various treatments, with the highest measures recorded in the combination of HA at 10 L ha^{-1} and VC at 4 t ha^{-1}, reaching 490.60 cm^{2}. The control showed the lowest leaf area, measuring 370.20 cm^{2}. The expansion of leaf area is essential for the process of photosynthesis and is associated with the synergistic interaction of HA and VC in enhancing the metabolic functions of plants (13).

Stem girth and dry weight

The treatments had a significant impact on stem girth. The highest significant stem girth was observed in HA at a rate of 10 L ha^{-1} combined with VC at 4 t ha^{-1}, measuring 43.7 mm, whereas the least significant stem girth was found in control. Treatments that integrated both HA and VC demonstrated superior performance compared to those utilizing individual applications, highlighting the significance of organic amendments in enhancing the structural components of plants.

The accumulation of dry matter exhibited a comparable pattern, with HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} achieving the highest dry weight of 119.06 g, which was significantly superior to all other treatments. The control exhibited the lowest dry weight (74.12 g). This trend suggests enhanced biomass accumulation resulting from improved nutrient and water uptake, which is facilitated by the application of HA and VC (14).

Chlorophyll index and CGR

The chlorophyll index, as examined by SPAD, showed a significant increase in plants treated with HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, observed a value of 35.17 SPAD. The control had the lowest chlorophyll index (23.6 SPAD). The observed increase indicates an improvement in nitrogen metabolism and an enhancement in photosynthetic efficiency among the treated plants, given that humic substances have been recognized for their role in promoting chlorophyll synthesis (15).

The highest CGR was observed in HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} (2.61 g g^{1} m^{-2}), indicating strong vegetative development under ideal organic nutrient conditions. The control treatment exhibited the minimal CGR, quantified at 1.08 g g^{1}m^{-2}. The improvement in CGR across treatments can be attributed to enhanced photosynthetic rates and the effective allocation of assimilates towards biomass production. The synergistic application of HA and VC, especially at elevated rates (HA at 10 L ha^{-1} + VC at 4 t ha^{-1}), significantly improved the growth, physiological characteristics and biomass accumulation of the crop. The combined influence of HA, functioning as a bio stimulant, with VC, serving as an organic nutrient source, has led to improved root development, enhanced nutrient uptake and optimized hormonal regulation, resulting in superior crop performance. The results are consistent with the findings of whom, documented substantial growth advantages resulting from the use of combined organic amendments (16, 17).

Effect of humic acid and vermicompost on yield attributes of bajra

The variation in the number of ears per plant was statistically significant ($p < 0.05$) among the different treatments presented in Table 2.

Ear number, length and weight

The highest number of ears (5.96) was observed with HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, demonstrating a significant advantage over all other treatments. The control treatment exhibited the lowest number of ears, recorded at 1.89. The significant increase in ear number resulting from the combined use of HA and VC indicates an increase in vegetative growth, nutrient absorption and reproduction that can be attributed to enhanced soil fertility and root activity (18, 19).

The treatments had a significant impact on ear length, with the combination of HA at 10 L ha^{-1} and VC at 4 t ha^{-1} resulting in a maximum ear length of 25.9 cm. The control showed the shortest ears, measuring 19.13 cm. The observed increase in ear length associated with organic treatments may be attributed to enhanced plant nutrition and the auxin-like effects of humic substances, which facilitate cell elongation and development (20).

Significant variations in ear weight have been observed across the different treatments. HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} resulted in the highest ear weight of 21.3 g, whereas the control group showed the lowest ear weight at 9.2 g. The gradual increase in ear weight associated with higher HA and VC levels shows a more effective translocation of assimilates to reproductive structures, which increases yield potential (21).

Number of seeds, test weight, seed yield and stover yield

The maximum number of seeds per ear recorded was 841.33, found with HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}. The control treatment showed the lowest seed count at 490.67. This increase can be attributed to the nutrient-rich conditions, improved floret development and enhanced pollen viability within the HA and VC treatments (22).

The test weight showed a notable enhancement with the combined applications. The maximum test weight of 13.43 g was observed in the treatment of HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}. The control group exhibited the lowest test weight at 8.4 g. The application of HA and VC appears to have positively influenced the duration of grain filling and the translocation of nutrients, which in turn has contributed to the enhancement of seed quality and weight (19).

Table 2. Effect of different levels of humic acid and vermicompost on the yield and yield attributes of pearl millet

Treatments	Number of ears plant^{-1}	Ear length (cm)	Ear weight (g)	Number of seeds ear^{-1}	Test weight (g)	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})
T_0 - HA0 +VC (control)	$1.89^{g} \pm 0.19$	$19.13^{i} \pm 0.15$	$9.2^{g} \pm 1.49$	$490.67^{i} \pm 1.53$	$8.4^{h} \pm 0.10$	$1081.37^{i} \pm 2.83$	$1686.87^{i} \pm 1.40$
T_1 - HA0 + VC (2 t ha^{-1})	$2.14^{fg} \pm 0.25$	$21.1^{h} \pm 0.10$	$9.83^{g} \pm 0.85$	$494.33^{h} \pm 1.53$	$9.5^{g} \pm 0.40$	$1112.40^{h} \pm 2.83$	$1779.90^{h} \pm 1.40$
T_2 - HA0 + VC (4 t ha^{-1})	$2.93^{ef} \pm 0.12$	$22.2^{g} \pm 0.10$	$11.03^{f} \pm 0.25$	$525^{g} \pm 2.00$	$9.83^{f} \pm 0.25$	$1299.83^{g} \pm 2.83$	$1923.77^{g} \pm 1.40$
T_3 - HA (5 L ha^{-1}) + VC (0 t ha^{-1})	$3.38^{de} \pm 0.65$	$22.8^{f} \pm 0.10$	$13.3^{e} \pm 0.30$	$594.33^{f} \pm 1.53$	$10.46^{e} \pm 0.35$	$1433.50^{f} \pm 2.83$	$2107.27^{f} \pm 1.40$
T_4 - HA (5 L ha^{-1}) + VC (2t ha^{-1})	$4.33^{c} \pm 0.58$	$24^{d} \pm 0.10$	$15.5^{d} \pm 0.30$	$647^{d} \pm 1.00$	$10.83^{d} \pm 0.15$	$1685.50^{d} \pm 2.83$	$2292.27^{d} \pm 1.40$
T_5 - HA (5L ha^{-1}) + VC (4t ha^{-1})	$4.67^{bc} \pm 0.58$	$24.37^{c} \pm 0.15$	$17.27^{c} \pm 0.25$	$697^{c} \pm 1.00$	$11.63^{c} \pm 0.15$	$1787.83^{c} \pm 2.83$	$2395.70^{c} \pm 1.40$
T_6 - HA (10 L ha^{-1}) + VC (0 t ha^{-1})	$3.83^{cd} \pm 0.76$	$23.5^{e} \pm 0.10$	$14.87^{d} \pm 0.15$	$641^{e} \pm 1.00$	$10.13^{f} \pm 0.15$	$1540.47^{e} \pm 2.83$	$2249.10^{e} \pm 1.40$
T_7 - HA (10 L ha^{-1}) + VC (2 t ha^{-1})	$5.33^{ab} \pm 0.58$	$25.3^{b} \pm 0.10$	$19.8^{b} \pm 0.30$	$825.33^{b} \pm 1.53$	$12.73^{b} \pm 0.31$	$1935.50^{b} \pm 2.83$	$2612.93^{b} \pm 1.40$
T_8 - HA (10 L ha^{-1}) + VC (4 t ha^{-1})	$5.96^{a} \pm 0.06$	$25.9^{a} \pm 0.10$	$21.3^{a} \pm 0.30$	$841.33^{a} \pm 1.53$	$13.43^{a} \pm 0.35$	$2065.87^{a} \pm 2.83$	$2706.23^{a} \pm 1.40$
CD ($p < 0.05$)	0.85	0.15	1.09	2.61	0.31	34.5	41.59
SE(m)	0.28	0.051	0.36	0.87	0.10	17.8	15.17

HA- humic acid, VC- vermicompost. Values within a column followed by the same superscript letters are not significantly different and different letters are significantly different according to Duncan's multiple range test (DMRT) at $p < 0.05$.

Seed yield demonstrated significant enhancement across the various treatments. HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} resulted in the highest seed yield of 2065.87 kg ha^{-1}. The control exhibited the lowest yield at 1081.37 kg ha^{-1}. The rise in yield can be attributed to the combined impact of greater ear number, ear weight, seed number and test weight, all of which were positively affected by HA and VC (22).

The stover yield shows a similar pattern to that of the seed yield. HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} resulted in the highest stover yield, measuring 2706.23 kg ha^{-1}. The control exhibited the lowest stover yield at 1686.87 kg ha^{-1}. Increased stover yield signifies improved overall plant biomass and demonstrates the growth-promoting effect of humic substances and VC on vegetative characteristics.

The findings demonstrate that the integration of HA at 10 L ha^{-1} and VC at 4 t ha^{-1} was the most effective approach for improving yield components, including ear number, ear length, ear weight, seed number and seed weight, which resulted in significant increased seed and stover yields. The observed outcomes can be linked to the combined effects of HA and VC, which enhance nutrient availability, boost photosynthetic activity, support improved root development and optimize hormonal balance. The results aligned with previous studies, which demonstrated that the synergistic application of humic substances and organic manures resulted in notable yield improvements in cereals and various field crops (21).

Effect of vermicompost and humic acid on soil physico-chemical properties

Available N showed significant variation ($p < 0.05$) across the different treatments as shown in Table 3. The maximum (258.67 Kg ha^{-1}) N was observed in HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, which showed statistical superiority over all other treatments. The control carried the lowest N availability (226.3 Kg ha^{-1}). The periodic increase in available nitrogen through the combined application of HA and VC can be related to enhanced microbial activity, improved mineralization of organic matter and superior nitrogen retention promoted by humic substances (16).

Phosphorus (P) content in soil showed notable variation. The highest value recorded was 18.28 kg ha^{-1} in the treatment of HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, which was significantly greater than the other treatments. The minimum value was observed in the control (10.88 kg ha^{-1}). The enhanced availability of phosphorus could be attributed to the chelation effects of HA, which decreases P fixation in the soil and enhance its solubility (17). VC contributes organic acids and phosphatase enzymes, which facilitate P mineralization (16).

Significant variations have been observed in the levels of available K, with the highest measurement recorded at 221.43 kg ha^{-1} in the treatment of HA at 10 L ha^{-1} + VC at 4 t ha^{-1}, whereas the control recorded the lowest K (185.57 kg ha^{-1}). The combination of HA and VC played a significant role in increasing K levels through mineralization and enhancing cation exchange capacity (CEC), thereby improving nutrient retention and release.

The treatments did not significantly influence bulk density (g cm^{-3}), although a minor decreasing trend was observed in those that receive VC and HA. The minimum bulk density recorded was 1.79 g cm^{-3} in the treatment of HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, while the maximum was 1.86 g cm^{-1} in the control. The decreased bulk density observed in treated plots could indicate improved soil aggregation and a higher organic matter content, leading to a more porous and friable soil structure (23).

The porosity percentage was statistically non-significant; however, there was a slight increase in values observed in the treated plots. HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} demonstrated the highest porosity at 32.45 %, whereas the control showed the lowest porosity at 29.95 %. This enhancement could be associated with increased organic carbon levels, improved root penetration and microbial activity that contribute to the formation of soil pores.

The increase in soil organic carbon (OC) was significant ($p < 0.05$) with higher levels of HA and VC. The highest OC was observed in HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} (0.61 %), which was significantly greater than all other treatments. The control exhibited the lowest OC (0.33 %). The enhancement of OC is linked to the direct contributions from VC and HA, alongside the stimulation of microbial biomass, which promotes carbon cycling within the soil (14).

The synergistic use of HA and VC, specifically HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, markedly enhanced the soil fertility status by raising the levels of available nitrogen, phosphorus, potassium and organic carbon content. Furthermore, this treatment led to an improvement in soil physical condition, evidenced by a slight reduction in bulk density and an increase in porosity. The observed changes reflect enhanced soil health and the sustainability of crop production when utilizing organic amendments. The findings align with those of, who indicated that the use of integrated organic inputs improves nutrient cycling, microbial activity and soil structure (14, 15).

Effect of vermicompost and humic acid on nutrient content and nutrient uptake

The application of HA and VC resulted in a notable increase in N content in plant tissue. The maximum N content of 2.45 % was observed with HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, whereas the minimum value of 1.56 % was noted in the control group as shown in Table 4. The combination of HA and VC enhances N assimilation, likely through improved root proliferation, microbial activity and nitrogen-use efficiency (24). The P content showed significant variation across the treatments. The highest P content (0.18 %) was observed in HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, while the lowest content (0.154 %) was recorded in the control. The higher P content results from the chelating capacity of HA, enhancing phosphorus bioavailability, alongside the enzymatic activity stimulated by VC, which promotes P mineralization (25). The K content in plant tissue varied from 2.9 % in control to 4.08 % in HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, indicating a significant response to the treatment combinations ($p < 0.05$). Higher doses of HA and VC led to increased K uptake, likely attributable to enhanced CEC, which promotes the retention and availability of K ions in the soil (26).

The N uptake in kg ha^{-1} by plants showed a significant increase with the treatments applied. The highest total N uptake was observed in the treatment of HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, amounting to 97.43 kg ha^{-1}. The control treatment exhibited the lowest N uptake, recorded at 85.24 kg ha^{-1}. The enhancement results from the combined influence of elevated N content and increased biomass production associated with HA and VC treatments (18). Total P uptake varied from 2.15 kg ha^{-1} in the control

Table 3. Effect of different levels of humic acid and vermicompost on the soil physicochemical properties

Treatments	Available N kg ha^{-1}	Available P kg ha^{-1}	Available K kg ha^{-1}	Bulk density (g cm^{-3})	Porosity (%)	Organic carbon (%)
T$_0$ - HA0 +VC (control)	$226.3^{i} \pm 0.29$	$10.88^{i} \pm 0.08$	$185.57^{f} \pm 1.87$	$1.86^{a} \pm 0.01$	$29.95^{a} \pm 0.21$	$0.33^{i} \pm 0.25$
T$_1$ - HA0 + VC (2 t ha^{-1})	$229.7^{h} \pm 0.37$	$11.22^{h} \pm 0.09$	$191.3^{ef} \pm 1.12$	$1.83^{a} \pm 0.06$	$30.94^{a} \pm 2.37$	$0.54^{e} \pm 0.25$
T$_2$ - HA0 + VC (4 t ha^{-1})	$232.27^{g} \pm 0.45$	$11.48^{g} \pm 0.08$	$193.23^{e} \pm 2.33$	$1.82^{a} \pm 0.01$	$31.32^{a} \pm 0.56$	$0.56^{d} \pm 0.25$
T$_3$ - HA (5 L ha^{-1}) + VC (0 t ha^{-1})	$236.53^{f} \pm 0.37$	$12.58^{f} \pm 0.08$	$196.73^{de} \pm 2.04$	$1.85^{a} \pm 0.05$	$30.19^{a} \pm 1.76$	$0.55^{e} \pm 0.25$
T$_4$ - HA (5 L ha^{-1}) + VC (2t ha^{-1})	$241.8^{d} \pm 0.24$	$13.73^{d} \pm 0.15$	$204.97^{bc} \pm 4.39$	$1.83^{a} \pm 0.02$	$30.94^{a} \pm 0.81$	$0.58^{c} \pm 0.25$
T$_5$ - HA (5L ha^{-1}) + VC (4t ha^{-1})	$247.67^{c} \pm 0.29$	$15.47^{c} \pm 0.15$	$209.4^{ab} \pm 1.61$	$1.80^{a} \pm 0.06$	$32.08^{a} \pm 2.33$	$0.59^{b} \pm 0.25$
T$_6$ - HA (10 L ha^{-1}) + VC (0 t ha^{-1})	$238.9^{e} \pm 0.24$	$13.27^{e} \pm 0.15$	$200.77^{cd} \pm 2.09$	$1.85^{a} \pm 0.05$	$30.19^{a} \pm 1.95$	$0.56^{d} \pm 0.25$
T$_7$ - HA (10 L ha^{-1}) + VC (2 t ha^{-1})	$253.7^{b} \pm 0.37$	$16.38^{b} \pm 0.08$	$216.67^{b} \pm 1.82$	$1.84^{a} \pm 0.07$	$30.57^{a} \pm 2.75$	$0.60^{ab} \pm 0.25$
T$_8$ - HA (10 L ha^{-1}) + VC (4 t ha^{-1})	$258.67^{a} \pm 0.29$	$18.28^{a} \pm 0.08$	$221.43^{a} \pm 6.45$	$1.79^{a} \pm 0.03$	$32.45^{a} \pm 1.22$	$0.61^{a} \pm 0.25$
CD ($p < 0.05$)	0.630	0.146	5.592	NS	NS	0.003
SE(m)	0.210	0.049	1.865	0.028	1.038	0.001

HA- humic acid, VC- vermicompost. Values within a column followed by the same superscript letters are not significantly different and different letters are significantly different according to Duncan's multiple range test (DMRT) at $p < 0.05$.

Table 4. Effect of different levels of humic acid and vermicompost on the nutrient content and nutrient uptake of pearl millet

Treatments	Nitrogen content %	Phosphorous content %	Potassium content %	Total nitrogen uptake kgha^{-1}	Total phosphorous uptake kg ha^{-1}	Total potassium uptake kgha^{-1}
T$_0$ - HA0 +VC (control)	$1.56^{c} \pm 0.009$	$0.154^{b} \pm 0.0034$	$2.9^{d} \pm 0.16$	$85.24^{f} \pm 0.52$	$2.15^{de} \pm 0.02$	$102.24^{h} \pm 0.94$
T$_1$ - HA0 + VC (2 t ha^{-1})	$1.70^{c} \pm 0.007$	$0.156^{b} \pm 0.0031$	$3.04^{cd} \pm 0.06$	$86.52^{e} \pm 0.72$	$2.22^{d} \pm 0.02$	$105.41^{g} \pm 1.31$
T$_2$ - HA0 + VC (4 t ha^{-1})	$1.83^{bc} \pm 0.001$	$0.158^{b} \pm 0.0027$	$3.21^{c} \pm 0.10$	$87.49^{e} \pm 0.49$	$2.27^{d} \pm 0.02$	$106.48^{g} \pm 2.26$
T$_3$ - HA (5 L ha^{-1}) + VC (0 t ha^{-1})	$1.83^{bc} \pm 0.023$	$0.155^{b} \pm 0.0020$	$3.32^{b} \pm 0.19$	$89.09^{d} \pm 0.55$	$2.49^{cd} \pm 0.03$	$108.39^{f} \pm 0.86$
T$_4$ - HA (5 L ha^{-1}) + VC (2t ha^{-1})	$1.84^{bc} \pm 0.014$	$0.158^{b} \pm 0.0035$	$3.43^{b} \pm 0.10$	$91.08^{c} \pm 0.80$	$2.71^{c} \pm 0.07$	$112.94^{d} \pm 3.07$
T$_5$ - HA (5L ha^{-1}) + VC (4t ha^{-1})	$2.01^{b} \pm 0.027$	$0.164^{ab} \pm 0.0040$	$3.71^{ab} \pm 0.11$	$93.29^{c} \pm 0.74$	$3.06^{b} \pm 0.04$	$115.38^{c} \pm 0.95$
T$_6$ - HA (10 L ha^{-1}) + VC (0 t ha^{-1})	$2.07^{b} \pm 0.042$	$0.158^{b} \pm 0.0034$	$3.26^{c} \pm 0.11$	$89.99^{d} \pm 0.79$	$2.62^{c} \pm 0.03$	$110.63^{e} \pm 1.92$
T$_7$ - HA (10 L ha^{-1}) + VC (2 t ha^{-1})	$2.25^{ab} \pm 0.030$	$0.176^{a} \pm 0.0017$	$3.99^{a} \pm 0.12$	$95.56^{b} \pm 0.78$	$3.24^{ab} \pm 0.03$	$119.38^{b} \pm 0.24$
T$_8$ - HA (10 L ha^{-1}) + VC (4 t ha^{-1})	$2.45^{a} \pm 0.023$	$0.180^{a} \pm 0.0015$	$4.08^{a} \pm 0.10$	$97.43^{a} \pm 0.77$	$3.61^{a} \pm 0.04$	$122.00^{a} \pm 3.13$
CD ($p < 0.05$)	0.039	0.005	0.206	1.2	0.031	3.072
SE(m)	0.013	0.002	0.068	0.089	0.010	1.016

HA- humic acid, VC- vermicompost. Values within a column followed by the same superscript letters are not significantly different and different letters are significantly different according to Duncan's multiple range test (DMRT) at $p < 0.05$.

group to 3.61 kg ha^{-1} in the treatment with HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1}, indicating a significant increase associated with the application of HA and VC. The increased uptake is associated with enhanced root activity, greater P availability in the soil and improved translocation within the plant (18). A comparable pattern was noted for K absorption. HA at 10 L ha^{-1} combined with VC at 4 t ha^{-1} resulted in the highest uptake of 122.00 kg ha^{-1}, significantly more than all other treatments. This results from enhanced plant metabolism and improved root absorption due to HA and VC. The findings demonstrate that the combined application of HA and VC, specifically HA at 10 L ha^{-1} and VC at 4 t ha^{-1}, significantly improved the nutrient content (N, P, K) and their overall uptake. The increase results from enhanced soil fertility, organic carbon enrichment, improved root development and greater nutrient availability and mobility. The findings are consistent with earlier studies, which observed that organic amendments, especially HA and BV, enhance nutrient absorption and utilization efficiency (25, 27).

Correlation matrix and correlation between different variables

The Pearson correlation matrix indicated strong and significant positive relationships ($p < 0.01$) among all measured growth and yield parameters of the crop (Table 5). Plant height demonstrated a significant correlation with leaf area (r=0.990), number of leaves (r=0.988), ear weight (r=0.979), seed yield (r=0.989) and stover yield (r=0.988), highlighting its significant influence on overall biomass and productivity. Leaf area exhibited a strong correlation with stover yield (r = 0.993), seed yield (r = 0.992) and specific growth (r = 0.990), underscoring the significance of photosynthetic surface area in influencing both vegetative and reproductive output. The quantity of leaves showed significant correlations with seed yield (r = 0.972) and stover yield (r = 0.983), thereby enhancing the function of canopy development in yield performance. The chlorophyll index showed a significant correlation with CGR (r=0.994) and seed yield (r=0.977), indicating that photosynthetic efficiency is essential for biomass accumulation. Dry weight showed a strong correlation with ear weight (r = 0.988), seeds per ear (r = 0.992) and stover yield (r = 0.985), suggesting that increased biomass enhances both grain and stover productivity. Seed yield displayed very strong positive correlations with the number of ears (r = 0.999), ear weight (r = 0.994) and stover yield (r = 0.994), suggesting a close relationship between reproductive traits and grain production.

The correlation matrix indicated highly significant ($p < 0.01$) positive relationships between nutrient uptake (N, P, K), nutrient content in plants and their respective available forms in soil (Table 6). Nitrogen uptake showed a near-perfect positive correlation with available N (r = 1.000**), K uptake (r = 0.997**) and P uptake (r = 0.993**), demonstrating a strong synchrony between soil nutrient availability and plant absorption efficiency. The uptakes of K and P exhibited a strong correlation with their respective available forms (r = 1.000** for K; r = 1.000** for P), indicating effective nutrient acquisition under the applied treatments. The nutrient content in plant tissues, including N content (r = 0.939**) and K content (r = 0.987**), displayed strong correlations with soil nutrient availability and uptake.

OC exhibited moderate but significant positive correlations with nutrient uptake (ranging from r = 0.640 to 0.731*), indicating its contribution to nutrient retention and availability. Bulk density displayed negative correlations with all nutrient variables (r = -0.615 with N uptake), whereas porosity demonstrated positive associations, indicating the inverse relationship between soil compaction and nutrient dynamics. Pairwise correlation matrices, were analyze the relation between growth, yield and soil nutrient parameters (Fig. 3, 4). In the initial matrix, there were positive linear relationships identified among growth and yield characteristics, including plant height, dry weight, seeds per ear and seed yield. This suggests that enhanced vegetative growth has a beneficial impact on yield components.

The significant connections between plant height, dry weight and stover yield indicate their possible efficiency as predictive measures for biomass accumulation and grain productivity. The second matrix evaluated the relationships between soil properties, nutrient contents and nutrient uptake. Strong positive correlations were observed between soil available N and both N content and uptake, along with a relationship between OC and available nutrients. This suggests that enhanced soil fertility directly improves nutrient availability and the efficiency of plant uptake. The negative correlations with bulk density and porosity underscores their different effects on nutrient dynamics. Due to decrease in bulk density by addition of manures, porosity of soil increased. So, increase in bulk density reduced the porosity that's why correlation is negative. The collective findings highlight the essential role of soil health for promoting absorbing nutrients and enhancing crop performance.

Conclusion

The combined application of HA at 10 L ha^{-1} and VC at 4 t ha^{-1} markedly enhanced the growth, yield characteristics and nutrient dynamics of bajra. The combined effects of HA and VC resulted in significant improvements in plant height, leaf area, stem girth, chlorophyll index, dry matter accumulation and crop growth rate. Yield parameters such as ear number, ear length, ear weight, seed count, test weight, seed yield and stover yield exhibited significant increases under combined organic treatments. Additionally, the physicochemical properties of soil, including available N, P, K and OC content, showed significant increases, alongside minor enhancements in bulk density and porosity. The improved nutrient content and uptake of N, P and K in plant tissues further substantiates the beneficial effect of HA and VC on nutrient use efficiency. The findings highlight the potential benefits of combining humic substances with organic amendments to enhance soil fertility, plant physiological performance and sustainable bajra production. The findings support earlier research and promote the implementation of organic practices in nutrient management for arid and semi-arid agro-ecosystems.

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Table 5: Pearson correlation between growth and yield attributes of bajra

	Plant height	**Leaf area**	**Leaves**	**CI**	**DW**	**SG**	**CGR**	**ears**	**Ear length**	**Ear weight**	**Seeds ear^{-1}**	**Test weight**	**Seed yield**	**Stover yield**
Plant height	1	.990**	.988**	.961**	.953**	.973**	.947**	.991**	.987**	.979**	.944**	.953**	.989**	.988**
Leaf area	.990**	1	.987**	.958**	.964**	.990**	.952**	.989**	.970**	.985**	.963**	.939**	.992**	.993**
leaves	.988**	.987**	1	.919**	.942**	.965**	.902**	.973**	.980**	.967**	.935**	.918**	.972**	.983**
CI	.961**	.958**	.919**	1	.947**	.964**	.994**	.973**	.924**	.972**	.954**	.961**	.977**	.960**
DW	.953**	.964**	.942**	.947**	1	.950**	.954**	.978**	.942**	.988**	.992**	.975**	.975**	.985**
SG	.973**	.990**	.965**	.964**	.950**	1	.957**	.981**	.933**	.981**	.960**	.919**	.989**	.980**
CGR	.947**	.952**	.902**	.994**	.954**	.957**	1	.967**	.913**	.968**	.958**	.965**	.972**	.955**
ears	.991**	.989**	.973**	.973**	.978**	.981**	.967**	1	.971**	.993**	.970**	.968**	.999**	.995**
Ear length	.987**	.970**	.980**	.924**	.942**	.933**	.913**	.971**	1	.953**	.921**	.946**	.964**	.973**
Ear weight	.979**	.985**	.967**	.972**	.988**	.981**	.968**	.993**	.953**	1	.987**	.970**	.994**	.996**
Seeds ear^{-1}	.944**	.963**	.935**	.954**	.992**	.960**	.958**	.970**	.921**	.987**	1	.958**	.972**	.979**
Test weight	.953**	.939**	.918**	.961**	.975**	.919**	.965**	.968**	.946**	.970**	.958**	1	.963**	.963**
Seed yield	.989**	.992**	.972**	.977**	.975**	.989**	.972**	.999**	.964**	.994**	.972**	.963**	1	.994**
Stover yield	.988**	.993**	.983**	.960**	.985**	.980**	.955**	.995**	.973**	.996**	.979**	.963**	.994**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 6. Pearson's correlation between soil available nutrient status, nutrient content and nutrient uptake

	N uptake	**P uptake**	**K uptake**	**N content**	**K content**	**P content**	**Available N**	**Available P**	**Available K**	**OC**	**BD**	**Porosity**
N uptake	1	.993**	.997**	.939**	.987**	.923**	1.000**	.993**	.997**	.703*	-.615	.605
P uptake	.993**	1	.986**	.932**	.980**	.930**	.993**	1.000**	.986**	.640	-.635	.629
K uptake	.997**	.986**	1	.936**	.979**	.916**	.997**	.986**	1.000**	.731*	-.618	.606
N content	.939**	.932**	.936**	1	.911**	.905**	.939**	.933**	.936**	.707*	-.562	.548
K content	.987**	.980**	.979**	.911**	1	.947**	.987**	.979**	.979**	.657	-.613	.606
P content	.923**	.930**	.916**	.905**	.947**	1	.923**	.930**	.916**	.543	-.602	.601
Available N	1.000**	.993**	.997**	.939**	.987**	.923**	1	.993**	.997**	.703*	-.615	.605
Available P	.993**	1.000**	.986**	.933**	.979**	.930**	.993**	1	.986**	.639	-.635	.629
Available K	.997**	.986**	1.000**	.936**	.979**	.916**	.997**	.986**	1	.730*	-.618	.606
OC	.703*	.640	.731*	.707*	.657	.543	.703*	.639	.730*	1	-.605	.569
BD	-.615	-.635	-.618	-.562	-.613	-.602	-.615	-.635	-.618	-.605	1	-.999**
Porosity	.605	.629	.606	.548	.606	.601	.605	.629	.606	.569	-.999**	1

** Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

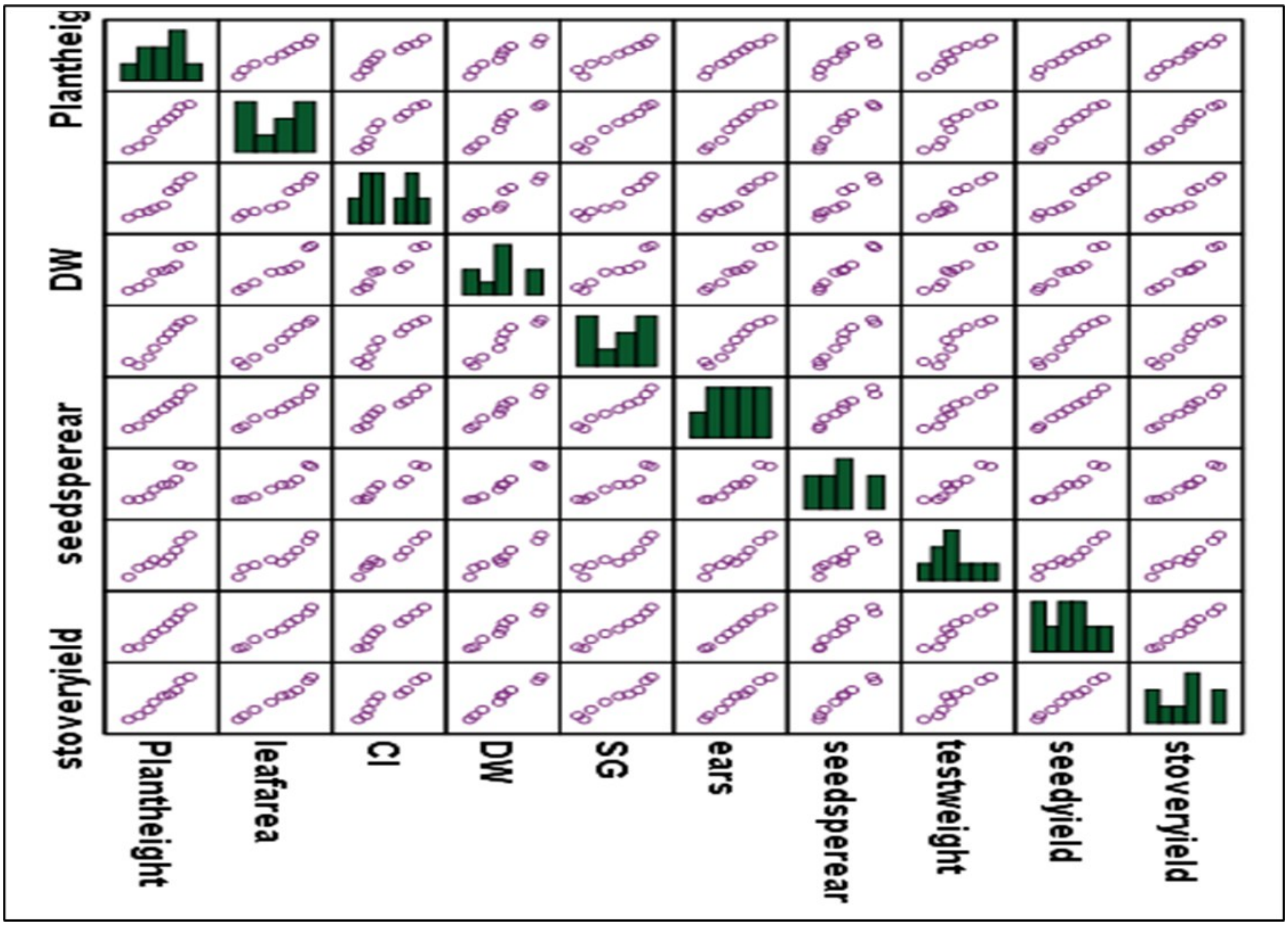

Fig. 3. Pairwise scatterplot matrix displaying the relationships among growth and yield attributes of maize under various treatments. Diagonal cells show histograms representing the distribution of individuals. The lower triangular matrix presents scatterplots illustrating pairwise correlation.

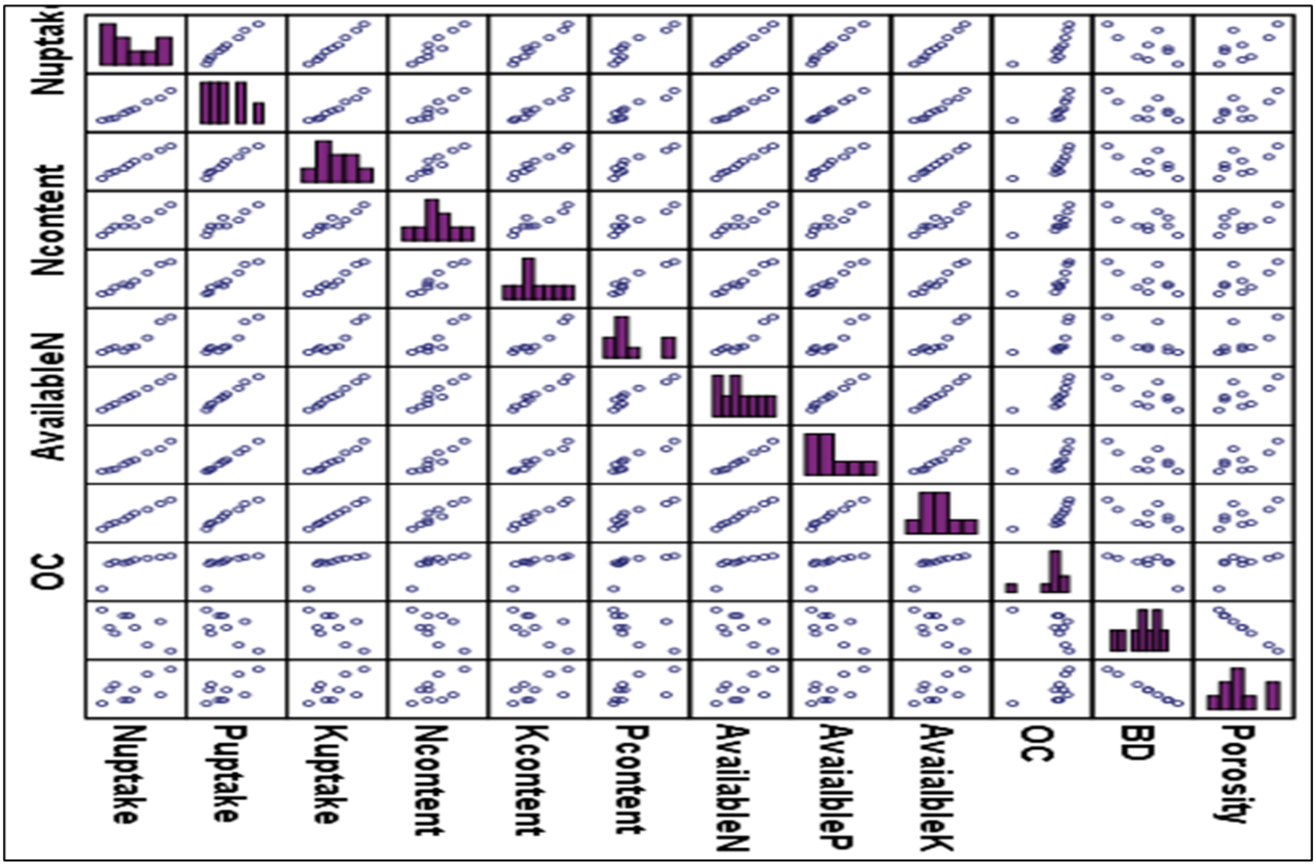

Fig. 4. Pairwise scatterplot matrix showing the interrelationships among soil properties, nutrient content and nutrient uptake in maize. The diagonal plots represent histograms showing the distribution of individual variables. The lower triangle shows scatterplots reflecting the pairwise correlations between variables.

Authors' contributions

BE prepared the research plan, conducted the analysis, contributed to manuscript writing and participated in proofreading. AJ provided guidance throughout the research, supported the development of the methodology and assisted in writing and proofreading the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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