



RESEARCH ARTICLE

Productivity of pearl millet (*Pennisetum glaucum* L.) cultivars as influenced by zinc and iron fertilisation under rainfed conditions

Ranjana Mankotia^{1*}, Jai Kumar^{2*}, Arvind Parkash Singh¹, Anil Kumar¹, Brinder Singh², Vivak Manohar Arya³, Rohit Sharma², Rakesh Kumar¹, Gurleen Kaur⁴, Vikalp Ranjan⁴ & Vishal Dubey¹

¹Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu 180 009, Jammu and Kashmir, India

²Advanced Centre for Rainfed Agriculture, Rakh Dhiansar, Bari Brahmana 181 133, Jammu and Kashmir, India

³Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu 180 009, Jammu and Kashmir, India

⁴Department of Agronomy, Punjab Agricultural University, Ludhiana 141 004, Punjab, India

*Correspondence email - ranjanamankotia1407@gmail.com; drjaikumar006@gmail.com

Received: 02 January 2026; Accepted: 22 March 2026; Available online: Version 1.0: 29 May 2026

Cite this article: Ranjana M, Jai K, Arvind PS, Anil K, Brinder S, Vivak MA, Rohit S, Rakesh K, Gurleen K, Vikalp R, Vishal D. Productivity of pearl millet (*Pennisetum glaucum* L.) cultivars as influenced by zinc and iron fertilisation under rainfed conditions. Plant Science Today. 2026;13(sp2):01–09. <https://doi.org/10.14719/pst.13503>

Abstract

A field experiment was conducted during the kharif 2024 at the Research Farm of Advanced Centre for Rainfed Agriculture (ACRA), Rakh Dhiansar of Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu to study the influence of zinc (Zn) and iron (Fe) application on the productivity of pearl millet (*Pennisetum glaucum* L.) cultivars under rainfed agro-ecosystem. The experiment was laid out in a Factorial randomised block design (FRBD) and replicated thrice, comprising 14 treatment combinations of two pearl millet cultivars and 7 nutrient doses. The experimental results revealed that among the pearl millet cultivars, HHB 299 was significantly superior to Pusa 1201, in terms of growth, nutrient uptake, yield and yield attributes except for plant height (PH) and length of ear head. However, among the nutrient doses, significantly the highest growth, nutrient uptake, yield and yield attributes were obtained in treatment T₇. Moreover, the interaction between pearl millet cultivars and nutrient doses was significant, with HHB 299 showing the highest values when combined with T₇, while Pusa 1201 showed the lowest values when combined with T₁. Hence, treatment T₇, which is the soil application of 25 kg ha⁻¹ zinc sulfate (ZnSO₄) + soil application of 20 kg ha⁻¹ ferrous sulfate (FeSO₄) along with foliar application of 0.5 % ZnSO₄ + foliar application of 0.5 % FeSO₄ at 45 DAS in HHB 299 cultivar, proved to be an effective strategy in enhancing growth and yield of pearl millet under rainfed conditions.

Keywords: agronomic biofortification; growth; iron; nutrient uptake; pearl millet; rainfed agriculture; yield; zinc

Introduction

Pearl millet (*Pennisetum glaucum* L.) is regarded as one of the most resilient warm-season cereals, distinguished by its exceptional capacity to thrive under drought, poor soil fertility and high-temperature regimes (1). Commonly referred to as bajra, bajri, sajja, combo, or kambam (2), it is often labelled the Poor man's crop due to its prominence among resource-limited farming communities across Asia and Africa. It outperforms cereals such as wheat, rice, maize, sorghum and barley due to its C₄-based metabolism, high photosynthetic efficiency, greater biomass production and strong tolerance to abiotic stress, thereby enabling superior performance in low-input, marginal environments (3). Nutritionally, its grains contain 11–19 % protein, 60–78 % carbohydrates and 3.0–4.6 % fat and they are particularly rich in phosphorus and iron (4). Among major millets, it is one of the most concentrated sources of essential micronutrients, especially Iron (Fe), calcium (Ca) and zinc (Zn), making it a cost-effective alternative to staple grains such as wheat, rice and maize. Owing to its robustness and superior drought tolerance, pearl millet plays a

critical role in enhancing food and nutritional security and reducing poverty in regions facing recurrent climatic anomalies. In India, pearl millet occupies approximately 7.36 million hectares, yielding a total production of 11.20 million tonnes and an average productivity of 1523 kg ha⁻¹ (5). In the Union Territory of Jammu and Kashmir, pearl millet covered 19090 hectares, achieving a productivity of 529 kg ha⁻¹ and a total output of 10107 tonnes, representing approximately 0.09 % of national production (6).

Traditional pearl millet cultivars generally exhibit reduced productivity due to inherent genetic constraints, limiting further intensification of their cultivation in nutrient-deficient soils. Owing to its naturally high Fe and Zn content, pearl millet serves as an effective crop for mitigating micronutrient malnutrition. Advances in breeding have led to the development of both conventional and biofortified varieties with enhanced micronutrient density, thereby strengthening food and nutritional security in dryland farming systems (7). Balanced fertilisation further improves physiological performance and biomass accumulation compared to the application of single or limited nutrient combinations, particularly

with respect to micronutrient supply.

Micronutrients are integral to numerous metabolic and biochemical pathways and deficiencies can markedly impair growth and development, with severe deficits potentially halting growth entirely. Among these elements, Zn and Fe are especially crucial because of their roles in key enzymatic and physiological processes. Zinc is a key micronutrient and the fourth major yield-limiting element after nitrogen, phosphorous and potassium (8). It supports core physiological functions, including photosynthesis, protein and carbohydrate synthesis, hormonal regulation and reproductive development and is required for tryptophan biosynthesis and, subsequently, for indole acetic acid (IAA) biosynthesis (9, 10). By improving assimilate translocation, Zn enhances source-sink efficiency and yield formation. Deficiency of Zn reduces growth hormone production, causing short stems and tiny, malformed leaves that create rosette forms in dicots and fan-shaped growth in young monocots and is among the most widespread mineral deficiencies globally. Iron is likewise essential due to its central involvement in DNA synthesis, respiration, chlorophyll formation and photosynthesis (11). As a critical redox-active cofactor in metalloproteins, Fe drives numerous oxidation–reduction reactions fundamental to cellular metabolism (12). Its deficiency commonly establishes as Fe chlorosis, driven by inadequate bioavailable Fe relative to plant demand.

High temperature, low organic matter and imbalanced fertilisation reduce soil fertility and nutrient availability in pearl millet, worsening issues such as drought, high pH and heat stress (13). These factors limit root nutrient uptake and contribute to micronutrient deficiencies in crop. Agronomic biofortification through seed treatment, along with sole or combined application of Zn and Fe, especially foliar feeding, is more effective under rainfed, moisture-limited conditions. While soil application is still necessary, foliar sprays provide a timely nutrient boost when root uptake is restricted. Therefore, selecting suitable cultivars and optimising Zn and Fe application methods is essential. The objectives of this study were to evaluate how soil and foliar applications of Zn and Fe affected the growth, yield and nutrient uptake of different pearl millet cultivars while also assessing the relative economics of the various treatment combinations.

Materials and Methods

Location and soil of the experimental field plot

The field experiment was carried out during kharif 2024 at the Advanced Centre for Rainfed Agriculture (ACRA), Rakh Dhiansar, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu. The site lies in the subtropical Shivalik foothills of Jammu and Kashmir at 332 m above mean sea level, positioned at 32°39' N and 74°53' E. Before the experiment, soil samples were collected from 5 randomly selected spots at a depth of 0–15 cm using a core sampler. The soil of the experimental field was sandy loam in texture, slightly acidic (pH-6.67) in reaction, low in organic carbon (2.64 g kg⁻¹), available N (168.4 kg ha⁻¹), K (101.02 kg ha⁻¹) and Zn (0.56 mg kg⁻¹), while medium in available P (13.95 kg ha⁻¹) and Fe (10.1 mg kg⁻¹).

Climatic condition

The average annual rainfall of the experimental site is 1072.8 mm. The crop received a total of 705.3 mm of uniformly distributed rain

during its cycle. The maximum and minimum temperatures ranged from 32 to 35 °C and 21.7 to 25.2 °C, respectively. In the morning and afternoon, the relative humidity varied between 77 % and 90 % and 56 % and 70 % respectively.

Experimental design

The experiment was laid out in Factorial randomised block design (FRDB) having 2 factors (A and B). Factor A comprised of two pearl millet cultivars viz. HHB-299 and Pusa-1201 while factor B had 7 nutrient doses of Zn and Fe viz. T₁: Control, T₂: Soil application of 25 kg ha⁻¹ zinc sulfate (ZnSO₄), T₃: Soil application of 20 kg ha⁻¹ ferrous sulfate (FeSO₄), T₄: Soil application of 25 kg ha⁻¹ ZnSO₄ + foliar application of 0.5 % FeSO₄ [25 and 45 days after sowing (DAS)], T₅: Soil application of 20 kg ha⁻¹ FeSO₄ + foliar application of 0.5 % ZnSO₄ (25 and 45 DAS), T₆: Soil application of 25 kg ha⁻¹ ZnSO₄ + soil application of 20 kg ha⁻¹ FeSO₄ and T₇: T₆ + foliar application of 0.5 % ZnSO₄ + foliar application of 0.5 % FeSO₄ (45 DAS), all supplemented with a uniform application of recommended dose of fertilisers (RDF).

Agronomic practices and fertiliser application

Each treatment combination was replicated thrice in a gross plot size of 4.5 m × 3.0 m. Both the pearl millet cultivars were sown on the 11th of July 2024, at a spacing of 45 cm × 15 cm with a seed rate of 5 kg ha⁻¹ at about 3 cm depth by the kera method. The RDF for the pearl millet crop [(N: P₂O₅: K₂O) at 100:60:25 kg ha⁻¹] was applied to all of the treatments. Two-thirds of the N dose and the full doses of P and K were applied as basal and one-third of N was top-dressed at 30 DAS as urea, diammonium phosphate (DAP) and muriate of potash (MOP). Soil application of Zn and Fe as their sulphates (ZnSO₄ and FeSO₄ respectively) was carried out as per the technical programme. Likewise, foliar applications of Zn and Fe as ZnSO₄ and FeSO₄, respectively, were applied at 25 and 45 DAS using a manually operated knapsack sprayer.

Observations recorded

For recording growth parameters viz., plant height (PH) (cm) and number of tillers (NT) m⁻² during the crop growth period, 5 randomly selected plants from net plots of each treatment were tagged, while dry matter accumulation (DMA) (g m⁻²) was assessed separately by collecting samples from a one-meter row length taken from the second row of each plot, avoiding border effects. These samples were initially shade-dried and subsequently oven-dried at 65 ± 5 °C until a constant weight was achieved. The same 5 tagged plants used for growth observations were later utilised to record the yield attributes viz., number of ear head (NEH) m⁻², length of ear head (LEH) (cm), girth of ear head (GEH) (cm), weight of grains ear head⁻¹ (WGEH) (g), 1000-grain weight (TGW) (g), grain (kg ha⁻¹) and stover yield (kg ha⁻¹) ensuring consistency and accurate correlation between growth behaviour and yield performance.

At the time of harvest, samples of pearl millet stover and grains were taken from each plot according to treatment. After 48 hr of oven drying at 65 ± 5 °C, the samples of both grain and stover were ground using an electric grinder and prepared for the determination of N, P, K, Zn and Fe concentrations using the standard procedure listed in Table 1.

By multiplying the percentage nutrient content by its yield, the amount of nutrients absorbed by pearl millet grain and stover was determined.

Table 1. Methods employed for nutrient content studies of grain and stover samples of pearl millet

Sl. No.	Nutrient assessed	Method adopted
1.	Nitrogen	Modified Kjeldhal's method (14)
2.	Phosphorus	Ammonium vanadomolybdo phosphoric acid yellow colour method (14)
3.	Potassium	Ammonium acetate method (14)
4.	Zinc	Atomic absorption spectrophotometer method (15)
5.	Iron	Atomic absorption spectrophotometer method (15)

Statistical analysis

Experimental data were analyzed using Fisher's analysis of variance technique (ANOVA) through the OPSTAT software and treatment effects were tested under the null hypothesis using the F-test of significance (16). Treatment differences were further interpreted by calculating standard errors and critical differences at the 5 % significance level (17).

Results and Discussion

Growth parameters

Growth was determined in terms of plant height (cm), number of tillers m^{-2} , dry matter accumulation ($g\ m^{-2}$) and the data so obtained are presented in Table 2. Among both the cultivars of pearl millet, the significantly highest Plant height (198.13 cm) was recorded in Pusa 1201 compared to HHB 299. Plant height variations among cultivars could stem from differences in internode length and genetic characteristics, thereby affecting shoot vigour. Among the nutrient doses, treatment T_7 had the highest plant height (218.05 cm), significantly higher than all other treatments. The increase in plant height might be due to the synergistic effect of combined Zn and Fe application, which enhanced meristematic activity, cell division and cell elongation. Given the Zn-deficient soil of the experimental site, balanced and timely micronutrient application improved auxin synthesis, enzyme activation, chlorophyll formation and nutrient uptake, thereby promoting greater internodal elongation and overall vegetative growth (18). Similarly, increase in PH was found by combined foliar application of $ZnSO_4$ (0.5 %) and $FeSO_4$ (0.2 %) in finger millet (19) while similar results were found through foliar spray

of $ZnSO_4$ (0.5 %) + $FeSO_4$ (1 %) + citric acid (0.1 %) twice at vegetative and flowering stages in finger millet grown in red sandy loam soil having available Zn and Fe content lower than the critical limit (20).

However, compared to Pusa 1201, the cultivar HHB 299 had the noticeably highest number of tillers m^{-2} at harvest (23.26). This might be due to distinct genetic attributes that favoured profuse tillering. Treatment T_7 recorded the highest number of tillers m^{-2} (25.62) and did not differ statistically from treatment T_6 (25.33). The higher number of tillers m^{-2} may be attributed to the combined application of RDF, along with soil and foliar doses of Zn and Fe, which likely enhanced nutrient availability and metabolic activity, thereby improving nutrient uptake and tiller formation. Similar results were reported in another study, which showed that the highest NT m^{-2} was recorded with the soil application of $50\ kg\ ha^{-1}$ $ZnSO_4$ and $25\ kg\ ha^{-1}$ $FeSO_4$ in pearl millet grown in clayey textured soil with low available Zn and Fe content (21).

Similarly, cultivar HHB 299 of pearl millet expressed significantly higher dry matter accumulation ($610.18\ g\ m^{-2}$) compared to Pusa 1201, which might be due to a higher number of tillers m^{-2} . Among the nutrient doses, treatment T_7 showed the highest dry matter accumulation ($662.18\ g\ m^{-2}$), significantly higher than that of all other treatments. The enhanced dry matter accumulation might be attributed to the combined application of Zn and Fe, which are vital for N metabolism, chlorophyll synthesis and the activity of enzymes involved in N assimilation, thereby promoting overall plant growth. By supporting chlorophyll formation, these micronutrients helped in maintaining a physiological balance between photosynthesis and respiration and directly influenced biomass production. The findings resonate with

Table 2. Effect of cultivars and nutrient doses on growth parameters of pearl millet at harvest

Treatments	Plant height (cm)	Number of tillers m^{-2}	Dry matter accumulation ($g\ m^{-2}$)
Cultivars			
V ₁ : HHB 299	176.83	23.26	610.18
V ₂ : Pusa 1201	198.13	19.87	517.32
SEm ($\pm$)	2.28	0.22	4.46
CD (5 %)	6.63	0.63	12.96
Nutrient doses			
T ₁ : Control	156.68	16.30	449.33
T ₂ : Soil application of $25\ kg\ ha^{-1}$ $ZnSO_4$	173.75	19.77	528.05
T ₃ : Soil application of $20\ kg\ ha^{-1}$ $FeSO_4$	170.42	19.42	518.65
T ₄ : Soil application of $25\ kg\ ha^{-1}$ $ZnSO_4$ + foliar application of 0.5 % $FeSO_4$ (25 and 45 DAS)	202.27	21.95	609.05
T ₅ : Soil application of $20\ kg\ ha^{-1}$ $FeSO_4$ + foliar application of 0.5 % $ZnSO_4$ (25 and 45 DAS)	204.13	22.59	612.52
T ₆ : Soil application of $25\ kg\ ha^{-1}$ $ZnSO_4$ + soil application of $20\ kg\ ha^{-1}$ $FeSO_4$	187.08	25.33	566.46
T ₇ : T ₆ + Foliar application of 0.5 % $ZnSO_4$ + foliar application of 0.5 % $FeSO_4$ (45 DAS)	218.05	25.62	662.18
SEm ($\pm$)	4.27	0.40	8.34
CD (5 %)	12.40	1.18	24.24
Interaction (V×T)	NS	S	S

Recommended dose of N: P_2O_5 : K_2O at 100:60:25 $kg\ ha^{-1}$ respectively was applied uniformly to all the treatments.

results from previous studies, which indicated that in pearl millet, the application of the 100 % recommended dose of nitrogen (RDN) + foliar sprays of $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ and $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ at 0.5 % each at 30 and 45 DAS increased total dry matter production (22). Another study inferred the highest total dry matter production with soil application of ZnSO_4 at 15 kg ha^{-1} , along with foliar application of nano-Zn at 4 mL L^{-1} in pearl millet (23).

Yield and yield attributes

The cultivar HHB 299 recorded significantly higher number of ear head m^{-2} (21.22), girth of ear head (9.63 cm), weight of grains per ear head (40.71 g) and 1000-grain weight (11.26 g) than Pusa 1201, as presented in Table 3 and Fig. 1. However, Pusa 1201 noted significantly higher length of ear head (25.15 cm) compared to HHB 299 cultivar of pearl millet. A higher number of ear head m^{-2} in HHB 299 might be due to better tillering ability and more effective tiller retention. However, the higher length of ear head of Pusa 1201 and the greater girth of ear head of HHB 299 might be due to the genetic makeup of the cultivars. Similar results were reported in another study (24). The highest weight of grain head⁻¹ and 1000-grain weight of HHB 299 might be attributed to efficient nutrient uptake in the presence of Zn and Fe, which led to an increase in transformation of assimilates in the grain, i.e., better partitioning of photosynthates from source to sink and subsequent development of heavier seeds (25). However, the treatment T_7 recorded the significantly highest number of ear head m^{-2} (24.08), length of ear head (28.10 cm), girth of ear head (10.76 cm), weight of grain ear head⁻¹ (46.79 g) and 1000-grain weight (12.92 g) in pearl millet. Such a response, as recorded, was probably due to the continuous supply of Zn and Fe, which supported the assimilation, absorption and translocation of photosynthates from leaves to the developing ear

head, thereby enhancing key yield-attributing traits. Similar increases in yield attributes were corroborated by results from other investigations using foliar spraying with 0.5 % ZnSO_4 and FeSO_4 , each at 35 and 55 DAS, in pearl millet (26, 27).

Likewise, the pearl millet cultivar HHB 299 showed significant results with respect to grain ($3090.42 \text{ kg ha}^{-1}$) and stover yield ($7420.68 \text{ kg ha}^{-1}$) as compared to Pusa 1201. The highest grain yield of HHB 299 might be attributed to its greater number of ear head m^{-2} and girth of ear head, which contributed to increased photosynthate accumulation and more effective transfer to the developing grains, while the highest stover yield might be due to higher dry matter content, leading to more interception of light for photosynthesis. These results corroborate the findings of another study, which reported similar results in pearl millet (28). Among the nutrient doses, treatment T_7 produced the highest grain yield ($3452.04 \text{ kg ha}^{-1}$) and stover yield ($8375.73 \text{ kg ha}^{-1}$), likely due to the combined effects of Zn and Fe in enhancing key physiological functions, improving growth attributes and promoting the efficient translocation of photosynthates to reproductive structures. However, another study reported similar results in pearl millet, where treatment with graded fertiliser doses, along with soil application of $25 \text{ kg ha}^{-1} \text{ FeSO}_4$ and $20 \text{ kg ha}^{-1} \text{ ZnSO}_4$, produced higher grain and stover yields (29). Furthermore, the results are congruent with the reports of another investigation (30).

The interaction between pearl millet cultivars and nutrient doses was significant for growth, yield and yield attributes, except for plant height, ear head length and ear head girth, as presented in Table 4. HHB 299 recorded the highest values for growth, yield and yield attributes in combination with T_7 [T_6 + Foliar application of 0.5 % ZnSO_4 + Foliar application of 0.5 % FeSO_4 (45 DAS)], while Pusa

Table 3. Effect of cultivars and nutrient doses on yield and yield attributes of pearl millet

Treatments	Ear head m^{-2}	Length of ear head (cm)	Girth of ear head (cm)	Weight of grains ear head ⁻¹ (g)	1000-grain weight (g)	Grain yield (kg ha^{-1})	Stover yield (kg ha^{-1})
Cultivars							
V ₁ : HHB 299	21.22	23.18	9.63	40.71	11.26	3090.42	7420.68
V ₂ : Pusa 1201	18.08	25.12	8.41	36.49	9.89	2547.04	6516.01
SEm ($\pm$)	0.22	0.30	0.12	0.26	0.09	34.53	76.42
CD (5 %)	0.64	0.87	0.35	0.76	0.26	100.36	222.14
Nutrient doses							
T ₁ : Control	15.09	20.19	7.23	29.11	8.12	2176.09	5565.16
T ₂ : Soil application of $25 \text{ kg ha}^{-1} \text{ ZnSO}_4$	17.41	22.49	8.37	33.81	9.17	2517.71	6346.08
T ₃ : Soil application of $20 \text{ kg ha}^{-1} \text{ FeSO}_4$	16.82	21.83	7.91	33.56	9.04	2475.49	6253.44
T ₄ : Soil application of $25 \text{ kg ha}^{-1} \text{ ZnSO}_4$ + foliar application of 0.5 % FeSO_4 (25 and 45 DAS)	21.84	25.82	9.76	43.31	11.84	3123.31	7590.70
T ₅ : Soil application of $20 \text{ kg ha}^{-1} \text{ FeSO}_4$ + foliar application of 0.5 % ZnSO_4 (25 and 45 DAS)	22.21	26.45	10.04	43.74	12.06	3166.58	7695.00
T ₆ : Soil application of $25 \text{ kg ha}^{-1} \text{ ZnSO}_4$ + soil application of $20 \text{ kg ha}^{-1} \text{ FeSO}_4$	20.11	24.17	9.07	39.87	10.87	2819.88	6952.31
T ₇ : T ₆ + Foliar application of 0.5 % ZnSO_4 + foliar application of 0.5 % FeSO_4 (45 DAS)	24.08	28.10	10.76	46.79	12.92	3452.04	8375.73
SEm ($\pm$)	0.41	0.56	0.23	0.49	0.16	64.59	142.96
CD (5 %)	1.20	1.62	0.66	1.42	0.48	187.77	415.58
Interaction (V×T)	S	NS	NS	S	S	S	S

Recommended dose of N: P₂O₅: K₂O at 100:60:25 kg ha^{-1} respectively was applied uniformly to all the treatments.

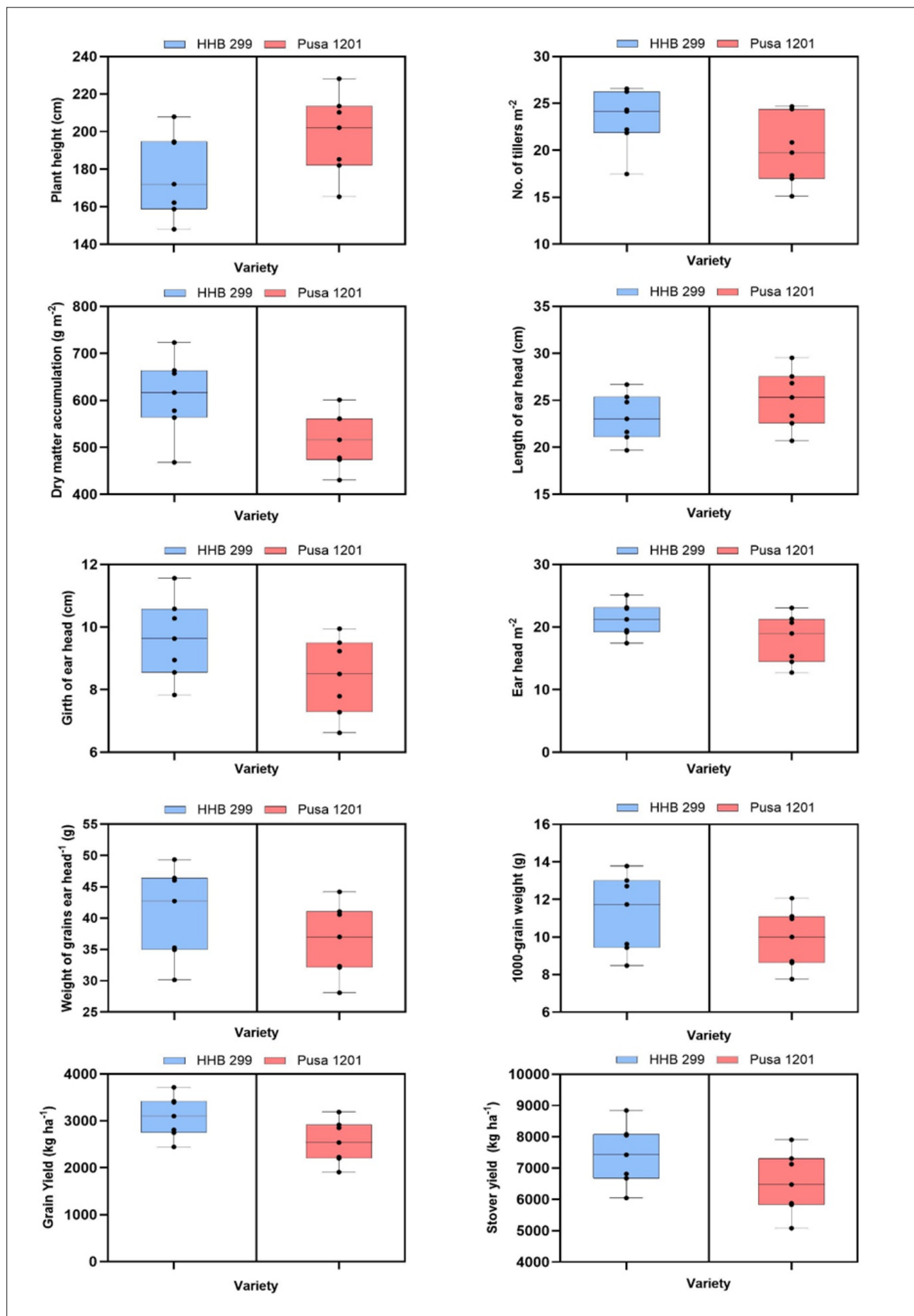


Fig. 1. Box-and-whisker plots illustrating differences between HHB 299 and Pusa 1201 across growth, yield and yield attributing parameters of pearl millet.

Table 4. Interaction effect of cultivars and nutrient doses on growth, yield and yield attributes of pearl millet

Treatment combination	Number of tillers m ⁻²	Dry matter accumulation (g m ⁻²)	Ear head m ⁻²	Weight of grains ear head ⁻¹ (g)	1000-grain weight (g)	Grain yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)
V ₁ T ₁	17.48	468.07	17.44	30.15	8.48	2443.63	6046.12
V ₁ T ₂	22.20	578.26	19.49	35.28	9.63	2807.95	6816.81
V ₁ T ₃	21.86	563.49	19.18	34.97	9.44	2748.71	6676.37
V ₁ T ₄	24.14	657.40	22.97	46.04	12.71	3395.20	8052.64
V ₁ T ₅	24.33	663.88	23.13	46.41	13.01	3419.23	8083.35
V ₁ T ₆	26.26	616.88	21.23	42.74	11.74	3102.72	7427.07
V ₁ T ₇	26.56	723.26	25.10	49.37	13.78	3715.47	8842.43
V ₂ T ₁	15.11	430.59	12.73	28.08	7.76	1908.55	5084.20
V ₂ T ₂	17.33	477.84	15.33	32.34	8.71	2227.47	5875.35
V ₂ T ₃	16.99	473.82	14.46	32.15	8.63	2202.28	5830.51
V ₂ T ₄	19.76	560.69	20.72	40.58	10.97	2851.43	7128.76
V ₂ T ₅	20.84	561.15	21.28	41.07	11.10	2913.93	7306.66
V ₂ T ₆	24.40	516.03	18.98	37.00	10.00	2537.03	6477.54
V ₂ T ₇	24.67	601.10	23.06	44.21	12.07	3188.61	7909.03
SEm (±)	0.57	11.79	0.58	0.69	0.23	91.35	202.18
CD (5 %)	1.66	34.28	1.70	2.00	0.68	265.54	587.72

Table 5. Effect of cultivars and nutrient doses on total nutrient uptake of pearl millet

Treatments	Nitrogen uptake (kg ha ⁻¹)	Phosphorus uptake (kg ha ⁻¹)	Potassium uptake (kg ha ⁻¹)	Zinc uptake (g ha ⁻¹)	Iron uptake (g ha ⁻¹)
Cultivars					
V ₁ : HHB 299	76.28	22.53	95.14	323.20	503.28
V ₂ : Pusa 1201	63.59	17.36	77.20	254.02	387.82
SEm (±)	0.78	0.27	0.76	3.35	4.92
CD (5 %)	2.27	0.78	2.22	9.75	14.30
Nutrient doses					
T ₁ : Control	54.34	13.68	64.77	191.92	325.30
T ₂ : Soil application of 25 kg ha ⁻¹ ZnSO ₄	63.27	17.30	77.10	249.38	380.51
T ₃ : Soil application of 20 kg ha ⁻¹ FeSO ₄	60.32	16.20	74.78	234.69	391.04
T ₄ : Soil application of 25 kg ha ⁻¹ ZnSO ₄ + foliar application of 0.5 % FeSO ₄ (25 and 45 DAS)	75.81	22.48	95.02	327.44	508.29
T ₅ : Soil application of 20 kg ha ⁻¹ FeSO ₄ + foliar application of 0.5 % ZnSO ₄ (25 and 45 DAS)	79.21	23.40	97.62	342.90	499.21
T ₆ : Soil application of 25 kg ha ⁻¹ ZnSO ₄ + soil application of 20 kg ha ⁻¹ FeSO ₄	70.38	19.94	85.85	291.38	445.59
T ₇ : T ₆ + Foliar application of 0.5 % ZnSO ₄ + foliar application of 0.5 % FeSO ₄ (45 DAS)	86.20	26.63	108.05	382.56	568.89
SEm (±)	1.46	0.50	1.43	6.27	9.21
CD (5 %)	4.25	1.46	4.16	18.23	26.76

Recommended dose of N:P₂O₅: K₂O at 100:60:25 kg ha⁻¹ respectively was applied uniformly to all the treatments.

1201 in combination with T₁ (control) recorded the lowest values significantly. It might be due to greater Zn and Fe uptake by the HHB 299 cultivar compared to Pusa 1201, resulting in increased meristematic activity and an improved source-to-sink relationship (31).

Nutrient uptake

Among the pearl millet cultivars, HHB 299 showed highest total uptake of N (76.28 kg ha⁻¹), P (22.53 kg ha⁻¹), K (95.14 kg ha⁻¹), Zn (323.20 g ha⁻¹) and Fe (503.28 g ha⁻¹) as compared to Pusa 1201 having corresponding values of 63.59 kg ha⁻¹, 17.36 kg ha⁻¹, 77.20 kg ha⁻¹, 254.02 g ha⁻¹ and 387.82 g ha⁻¹, respectively (Table 5). Moreover, treatment T₇ recorded a significantly higher total N (86.20 kg ha⁻¹), P (26.63 kg ha⁻¹), K (108.05 kg ha⁻¹), Zn (382.56 g ha⁻¹) and Fe (568.89 g ha⁻¹) uptake of pearl millet. In contrast, treatment T₁ (control) recorded the least nutrient uptake of N (54.34 kg ha⁻¹), P (13.68 kg ha⁻¹), K (64.77 kg ha⁻¹), Zn (191.92 g ha⁻¹) and Fe (325.30 g ha⁻¹). It might be due to the synergistic effects of Zn and N, which increased enzymatic activity, leading to greater vegetative growth and root development. Similar reports were also obtained from another study on pearl millet (22). Enhanced root proliferation improves the uptake of P, K, Zn and Fe, while Zn- and Fe-dependent enzymes

support carbohydrate metabolism. Zinc also boosts N content by facilitating DNA, RNA and protein synthesis. Potassium aids stomatal regulation, assimilate transport and water balance, strengthening plant resilience. Additionally, Zn and Fe promote auxin and chlorophyll synthesis, thereby improving overall physiological activity and micronutrient absorption, with foliar application ensuring direct uptake and efficient translocation from the source to the sink. The outcomes are consistent with a pooled 3-year study, which found that soil application of FeSO₄ at 10 kg ha⁻¹ and ZnSO₄ at 10 kg ha⁻¹ increased the uptake of macronutrients (N, P and K) and micronutrients (Zn and Fe) (32). It was also reported that the highest Zn and Fe uptake was obtained with the soil application of ZnSO₄ at 15 kg ha⁻¹ and FeSO₄ at 10 kg ha⁻¹, along with foliar application of 0.5 % ZnSO₄ and FeSO₄ in pearl millet (33). Additionally, similar results have been reported in other studies (34–36).

Correlation analysis

The correlation matrix revealed uniformly strong and positive associations among all measured traits, indicating a highly integrated response among yield components and nutrient uptake parameters. Yield and yield attributing characteristics viz., grain yield (kg ha⁻¹), stover yield (kg ha⁻¹), ear head m², length of ear head (cm),

Table 6. Pearson correlation matrix showing relationships among yield, yield attributes and nutrient uptake parameters in HHB 299

	Ear head m ⁻²	Length of ear head (cm)	Girth of ear head (cm)	Weight of grains ear head ⁻¹ (g)	1000- grain weight (g)	Grain yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	Nitrogen uptake (kg ha ⁻¹)	Phosphorus uptake (kg ha ⁻¹)	Potassium uptake (kg ha ⁻¹)	Zinc uptake (g ha ⁻¹)	Iron uptake (g ha ⁻¹)
Ear head m ⁻²	1.00											
Length of ear head (cm)	0.99	1.00										
Girth of ear head (cm)	0.99	0.99	1.00									
Weight of grains ear head ⁻¹ (g)	0.99	1.00	0.99	1.00								
1000-grain weight (g)	1.00	1.00	0.99	1.00	1.00							
Grain yield (kg ha ⁻¹)	0.99	1.00	0.99	1.00	1.00	1.00						
Stover yield (kg ha ⁻¹)	0.99	1.00	0.99	1.00	1.00	1.00	1.00					
Nitrogen Uptake (kg ha ⁻¹)	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00				
Phosphorus Uptake (kg ha ⁻¹)	0.99	1.00	0.99	0.99	0.99	1.00	1.00	0.99	1.00			
Potassium Uptake (kg ha ⁻¹)	0.99	1.00	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00		
Zinc Uptake (g ha ⁻¹)	0.99	1.00	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	
Iron Uptake (g ha ⁻¹)	0.98	0.99	0.98	1.00	1.00	1.00	1.00	0.98	0.99	0.99	0.99	1.00

Correlation is significant at $p \leq 0.05$ level.

Table 7. Pearson correlation matrix showing relationships among yield, yield attributes and nutrient uptake parameters in Pusa 1201

	Ear head m ⁻²	Length of ear head (cm)	Girth of ear head (cm)	Weight of grains ear head ⁻¹ (g)	1000- grain weight (g)	Grain yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	Nitrogen uptake (kg ha ⁻¹)	Phosphorus uptake (kg ha ⁻¹)	Potassium uptake (kg ha ⁻¹)	Zinc uptake (g ha ⁻¹)	Iron uptake (g ha ⁻¹)
Ear head m ⁻²	1.00											
Length of ear head (cm)	1.00	1.00										
Girth of ear head (cm)	1.00	1.00	1.00									
Weight of grains ear head ⁻¹ (g)	0.99	0.98	0.98	1.00								
1000-grain weight (g)	0.99	0.99	0.98	1.00	1.00							
Grain yield (kg ha ⁻¹)	1.00	1.00	0.99	0.99	0.99	1.00						
Stover yield (kg ha ⁻¹)	1.00	1.00	1.00	0.98	0.98	1.00	1.00					
Nitrogen uptake (kg ha ⁻¹)	0.99	0.98	1.00	0.97	0.96	0.99	0.99	1.00				
Phosphorus uptake (kg ha ⁻¹)	1.00	1.00	1.00	0.98	0.98	1.00	1.00	0.99	1.00			
Potassium uptake (kg ha ⁻¹)	1.00	1.00	1.00	0.98	0.98	1.00	1.00	0.99	1.00	1.00		
Zinc uptake (g ha ⁻¹)	1.00	1.00	1.00	0.99	0.99	1.00	1.00	0.99	1.00	1.00	1.00	
Iron uptake (g ha ⁻¹)	1.00	0.99	0.98	0.98	0.98	0.99	1.00	0.98	0.99	0.99	0.98	1.00

Correlation is significant at $p \leq 0.05$ level.

girth of ear head (cm), weight of grains per ear head (g) and 1000-grain weight (g) showed strong mutual correlations, reflecting their collective contribution to final yield formation. Similarly, nutrient uptake parameters (N, P, K, Zn and Fe) were closely interrelated, demonstrating synchronised nutrient absorption and translocation within the crop. The strong positive correlations between nutrient uptake and yield parameters further suggest that efficient nutrient acquisition directly supports DMA, grain development and overall physiological vigour. The Pearson correlation matrix presented in Table 6 and 7 clearly illustrates this pattern, showing near-perfect associations ($r = 1$).

The correlation matrix for HHB 299 and Pusa 1201 revealed consistently strong positive associations among yield, yield attributes and nutrient uptake parameters. In HHB 299, correlation values were nearly perfect (0.98–1.00), reflecting a highly synchronised physiological response where an increase in nutrient uptake (N, P, K, Zn and Fe) was closely accompanied by proportional increases in length of ear head, girth of ear head, weight of grain ear head¹, 1000-grain weight and hence, overall yield. This indicates efficient nutrient translocation and superior nutrient-use efficiency within the cultivar.

Moreover, Pusa 1201 also showed strong positive correlations; however, the values displayed slightly greater variability (0.96–1.00) than HHB 299. These observations indicate that Pusa 1201 exhibits markedly lower nutrient uptake, leading to discernible differences in its growth and yield performance. Overall, the strong correlations across both cultivars emphasize the central role of nutrient uptake in enhancing biomass accumulation, ear head development and final grain yield in pearl millet. These results suggest that HHB 299 possesses a more stable internal mechanism regulating nutrient absorption, biomass partitioning and grain filling.

Conclusion

Based on the results, it can be concluded that higher growth and yield in pearl millet can be achieved with soil application of 25 kg ha⁻¹ ZnSO₄ and 20 kg ha⁻¹ FeSO₄ along with foliar application of 0.5 % ZnSO₄ and 0.5 % FeSO₄ at 45 DAS (T₇) in HHB 299 cultivar. Moreover, the pearl millet cultivar HHB 299, with soil application of 25 kg ha⁻¹ ZnSO₄ and 20 kg ha⁻¹ FeSO₄, along with foliar application of 0.5 % ZnSO₄ and 0.5 % FeSO₄ at 45 DAS (T₇), also ensured better nutrient uptake through improved availability and greater absorption by the crop. Future research may focus on evaluating the long-term effects of combined Zn and Fe application on soil health and nutrient dynamics under different agro-climatic conditions. Additionally, studies could explore optimising micronutrient doses and application timings for other pearl millet cultivars to further enhance productivity and nutrient use efficiency.

Acknowledgements

We gratefully acknowledge the Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, for providing the resources and institutional support that enabled the successful completion of this study. We also extend our sincere thanks to the Advanced Centre for Rainfed Agriculture, Rakh Dhiansar, for providing the necessary facilities to conduct the experiment. Our appreciation further goes to the staff and field

workers of the institute for their valuable assistance throughout crop production and management.

Authors' contributions

RM carried out the field experiment, collection and analysis of data. JK, APS, AK, BS and VMA were involved in the conceptualisation and design of the study, provided overall supervision of the research work and contributed to the preparation and compilation of the manuscript. RS and RK participated in critical review and sequence alignment. GK, VR and VD participated in the finalisation of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used QUILLBOT, GRAMMARLY and BYPASSGPT in order to contribute to linguistic refinement, reorganisation of sentence structure and improvement of clarity and coherence in the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

1. Rinku, Shekhawat PS, Kumawat N, Rathore PS, Yadav PK, Om H. Effect of nitrogen levels and biofertilizers on growth and yield of pearl millet (*Pennisetum glaucum* L.) under northwestern Rajasthan. *Ann Agric Res.* 2016;35(3):311–4.
2. Kaur M, Goyal ME. Influence of different nitrogen levels on growth, yield and quality of forage pearl millet (*Pennisetum glaucum* L.) genotypes. *Forage Res.* 2019;45(1):43–6.
3. Nambiar VS, Dhaduk JJ, Sareen N, Shahu T, Desai R. Potential functional implications of pearl millet (*Pennisetum glaucum*) in health and disease. *J Appl Pharm Sci.* 2011;1(10):62–7.
4. Bhanuchandar B, Prasanthi M, Dawson J. Effect of levels of nitrogen and potassium on growth and yield of rainfed pearl millet (*Pennisetum glaucum* L.). *Int J Curr Microbiol Appl Sci.* 2020;9(11):2194–7. <https://doi.org/10.20546/jicmas.2020.911.261>
5. Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. *Agricultural Statistics at a Glance 2024 (कृषि सांख्यिकी एक झलक 2024)*. New Delhi: Department of Agriculture & Farmers Welfare; 2024.
6. Directorate of Economics and Statistics, UT Administration of Jammu & Kashmir. *Digest of Statistics 2025*. Jammu & Kashmir: Directorate of Economics and Statistics. https://ecostatjk.nic.in/showdata.aspx?q=Digest_Stat
7. Govindaraj M, Rai KN, Cherian B, Pfeiffer WH, Kanatti A, Shivade H. Breeding biofortified pearl millet varieties and hybrids to enhance millet markets for human nutrition. *Agriculture.* 2019;9(5):106. <https://doi.org/10.3390/agriculture9050106>
8. Shukla AK, Behera SK, Prakash C, Tripathi A, Patra AK, Dwivedi BS, et al. Deficiency of phyto-available sulphur, zinc, boron, iron, copper and manganese in soils of India. *Sci Rep.* 2021;11:19760. <https://doi.org/10.1038/s41598-021-99040-2>

9. Khinchi V, Kumawat SM, Dotaniya CK, Rakesh S. Effect of nitrogen and zinc levels on yield and economics of fodder pearl millet (*Pennisetum americanum* L.). *Int J Pure Appl Biosci.* 2017;5(3):426–30.
10. Welch RM. The impact of mineral nutrients in food crops on global human health. *Plant Soil.* 2002;247:83–90. <https://doi.org/10.1023/A:1021140122921>
11. Kim J, Rees DC. Structural models for the metal centers in the nitrogenase molybdenum-iron protein. *Science.* 1992;257(5077):1677–82. <https://doi.org/10.1126/science.1529354>
12. Rout GR, Sahoo S. Role of iron in plant growth and metabolism. *Rev Agric Sci.* 2015;3:1–24. <https://doi.org/10.7831/ras.3.1>
13. Djanaguiraman M, Prasad PV. Impact of drought and high-temperature stresses on growth and development stages, physiological, reproductive and yield traits of pearl millet. In: Prasad PV, editor. *Agronomy Monographs*. Hoboken (NJ): John Wiley & Sons, Inc.; 2024. p. 249–276. <https://doi.org/10.1002/9780891184034.ch9>
14. Jackson ML. Soil chemical analysis. New Delhi (India): Prentice Hall of India Pvt Ltd; 1973. p. 151–4.
15. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Sci Soc Am J.* 1978;42(3):421–8. <https://doi.org/10.2136/sssaj1978.03615995004200030009x>
16. Cochran WG, Cox GM. Experimental designs. *Soil Sci.* 1957;84(5):425. <https://doi.org/10.1097/00010694-195711000-00018>
17. Panse VG, Sukhatme PV. Statistical Methods for Agricultural Workers. 2nd ed. New Delhi: Indian Council of Agricultural Research; 1967.
18. Hafeez MB, Rehman A, Ramzan Y, Nadeem M, Batool S, Ahmad J, et al. Application of zinc and iron-based fertilizers improves the growth attributes, productivity and grain quality of two wheat (*Triticum aestivum*) cultivars. *Front Nutr.* 2021;8:779595. <https://doi.org/10.3389/fnut.2021.779595>
19. Sandhya Rani Y, Triveni U, Patro TSSK, Anuradha N. Effect of nutrient management on yield and quality of finger millet (*Eleusine coracana* (L.) Gaertn). *Int J Chem Stud.* 2017;5(6):1211–6.
20. Vijayakumar M, Sivakumar R, Tamilselvan N. Effect of zinc and iron application on yield attributes, available nutrients status and nutrient uptake of finger millet under rainfed condition. *Int J Curr Microbiol Appl Sci.* 2020;9(5):3237–46. <https://doi.org/10.20546/ijcmas.2020.905.384>
21. Lavanya YV, Mosha K, Rekha MS, Subbaiah PV. Response of pearl millet to soil and foliar nutrition of zinc and iron. *Andhra Agric J.* 2020;67(4):270–5.
22. Ravi S, Narayan Rao K, Jadhav RL, Bhat SN, Shankar KA. Effect of graded levels of nitrogen with iron and zinc nutrition on growth, yield and quality of pearl millet (*Pennisetum glaucum* L.). *Int J Environ Clim Change.* 2023;13(9):2425–33. <https://doi.org/10.9734/ijecc/2023/v13i92475>
23. Sasalatti GN, Patil SB, Nandagavi RA, Yadahalli VG. Soil and foliar application of zinc increased pearl millet productivity in calcareous vertisols of Karnataka. *J Farm Sci.* 2023;36(1):26–32. <https://doi.org/10.61475/jfm.v36i01.337>
24. Srikanya B, Revathi P, Reddy MM, Chandra Shaker K. Screening of foxtail millet (*Setaria italica* L.) genotypes at different sowing dates for higher returns in northern transition zone of Telangana. *Bioscan.* 2019;14(3):183–90.
25. Jitarwal J, Mehera B, Kumar P, Mahala G, Mund RK. Effect of zinc and panchagavya on growth and yield of pearl millet (*Pennisetum glaucum* L.). *Int J Plant Soil Sci.* 2024;36(6):444–9. <https://doi.org/10.9734/ijpss/2024/v36i64646>
26. Reddy RUK, Dawson J, Vidya Sagar DR. Effect of zinc, iron and their methods of application on growth and yield of pearl millet (*Pennisetum glaucum* L.). *Int J Curr Microbiol Appl Sci.* 2020;9(10):1639–44. <https://doi.org/10.20546/ijcmas.2020.910.197>
27. Kalaliya A, Sharma SK, Kamboj BR. Effect of nutrient management on growth, yield attributing characters, yield and economics of rainfed pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Pharma Innov J.* 2022;11(7):290–4.
28. Bharathi C, Singh K, Dawson J. Influence of nitrogen and zinc on plant growth and yield attributes of pearl millet. *Int J Res Agron.* 2024;7(5):193–5. <https://doi.org/10.33545/2618060X.2024.v7.i5c.673>
29. Fulpagare DD, Patil TD, Thakare RS. Effect of application of iron and zinc on nutrient availability and pearl millet yield in vertisols. *Int J Chem Stud.* 2018;6(6):2647–50.
30. Meena BL, Kumar P, Kumar A, Meena RL, Kaledhonkar MJ, Sharma PC. Zinc and iron nutrition to increase the productivity of pearl millet-mustard cropping system in salt affected soils. *Int J Curr Microbiol Appl Sci.* 2018;7(8):3201–11. <https://doi.org/10.20546/ijcmas.2018.708.343>
31. Satyavathi CT, Khandelwal V, Rajpurohit BS, Supriya A, Beniwal BR, Kamlesh K, et al. Pearl millet-hybrids and varieties. Jodhpur (India): ICAR-All India Coordinated Research Project on Pearl Millet; 2018. p. 142.
32. Durgude AG, Kadam SR, Pharande AL. Response of hybrid maize to soil and foliar application of iron and zinc on Entisols. *Asian J Soil Sci.* 2014;9(1):36–40.
33. Sharanappa, Latha HS, Ravi MV. Studies on agronomic biofortification with zinc and iron on nutrient availability, uptake and yield in pearl millet [*Pennisetum glaucum* (L.)] genotypes. *J Pharmacogn Phytochem.* 2020;9(4):721–5.
34. Eshwar M, Srilatha M, Bhanu Rekha K, Sharma SKH. Characterization of humic substances by functional groups and spectroscopic methods. *Int J Curr Microbiol Appl Sci.* 2017;6(10):1768-1774. <https://doi.org/10.20546/ijcmas.2017.610.213>
35. Karrimi AS, Reddy APK, Babazoi F, Kohistani T. Growth, yield and post-harvest soil available nutrients in sweet corn (*Zea mays* L.) as influenced by zinc and iron nutrition. *J Pharmacogn Phytochem.* 2018;7(4):2372–4.
36. Vaja RP, Bhuvra HM, Jani CP, Mokariya LK. Effect of iron and zinc fortification on chemical properties of soil and nutrient content and uptake by summer pearl millet (*Pennisetum glaucum* (L.) R. Br. Emend. Stuntz). *Int J Chem Stud.* 2020;8(5):2179–82. <https://doi.org/10.22271/chemi.2020.v8.i5ad.10627>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.