ANSF
APPLIED AND NATURAL SCIENCE FOUNDATION

Journal of Applied and Natural Science
17(3), 981 - 991 (2025)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Research Article

Impact of zinc fortification on yield and quality of Pearl millet (*Pennisetum glaucum* L.) in the Western ghat region of Coimbatore District under irrigated conditions

T. Dhivyalakshmi
Division of Agronomy, School of Agricultural Sciences, Karunya University, Coimbatore – 641114 (Tamil Nadu) India
R. Augustine*
Division of Agronomy, School of Agricultural Sciences, Karunya University, Coimbatore – 641114 (Tamil Nadu) India
R. Santhosh Anto Kumar
Division of Agronomy, School of Agricultural Sciences, Karunya University, Coimbatore – 641114 (Tamil Nadu) India
A. Visuvasa Anto Shiny
Division of Agronomy, School of Agricultural Sciences, Karunya University, Coimbatore – 641114 (Tamil Nadu) India

*Corresponding author. E-mail: augustiner@karunya.edu

Article Info
https://doi.org/10.31018/jans.v17i3.6345
Received: November 01, 2024
Revised: July 22, 2025
Accepted: August 02, 2025

How to Cite
Dhivyalakshmi, T. *et al.* (2025). Impact of zinc fortification on yield and quality of Pearl millet (*Pennisetum glaucum* L.) in the Western ghat region of Coimbatore District under irrigated conditions. *Journal of Applied and Natural Science*, 17(3), 981 - 991. https://doi.org/10.31018/jans.v17i3.6345

Abstract
Pearl millet is recognized for its resilience to harsh climates and high nutritional value, making it a key crop for climate-resilient and low-input agricultural systems. This study aimed to assess the effectiveness of zinc fertilization in Pearl millet (Pennisetum glaucum L.) hybrids in conjunction with nitrogen fertilizer. During the *Kharif* seasons of 2022 and 2023, the study was conducted in the field at South Farm, Karunya Institute of Technology & Sciences (KITS) campus, Karunya University, Coimbatore, Tamil Nadu. Six sub-plot treatments were examined in the main plots for two hybrids, M_1 (non-biofortified) and M_2 (biofortified), as well as their corresponding foliar applications supplemented with ZnO (S_4, S_5, and S_6) and soil nitrogen applications at 40 kg ha^{-1} (S_1), 60 kg ha^{-1} (S_2), and 80 kg ha^{-1} (S_3). Zinc fortification using 80 kg ha^{-1} N and ZnO foliar spray (S_6) significantly improved pearl millet growth, yield, and quality in the western ghat zone of Tamil Nadu, India. Application of Zinc oxide @ 0.5% foliar spray at 25 and 50 days after sowing with 80 kg ha^{-1} of N fertilizer (S_6) had shown significant higher plant height (194.01 cm), grain yield (3.62 t ha^{-1}), crude protein (10.85%), iron (79.33 mg kg^{-1}) and zinc (42.32 mg kg^{-1}).
This study offers novel insights into optimizing nutrient management for pearl millet, a crucial crop for food and nutritional security within climate-resilient farming systems. These findings not only contribute to the development of low-input, nutrient-rich crop production models but also support the broader goals of sustainable agriculture and biofortification to combat hidden hunger in marginal environments.

Keywords: Foliar, Fortification, Nitrogen, Nutrition, Zinc

INTRODUCTION

Pearl millet, a crucial cereal crop, ranks sixth after rice, wheat, maize, barley, and sorghum. Millet, a staple food, is cultivated on approximately 30 million hectares in Asia and Africa, encompassing over 10 million hectares in Asia and 18 million hectares in Africa (Raheem et al., 2021). Pearl millet has a higher nutritional value than sorghum, maize, rice, and wheat. Pearl millet is a highly nutritious grain, containing 17-65 mg/g of protein, as well as Fe, Zn, and lysine, making it a valuable source of iron and zinc. Uppal et al. (2015) found that it contains a higher protein content, improved fat digestion, and antioxidants such as coumaric and ferulic acids. The source of energy is also abundant.

Out of all the environmental challenges, heat and drought are the two most essential productivity restrictions. Pearl millet, a resilient crop species, can meet the increasing global food demands due to its ability to withstand high temperatures and low rainfall. Due to its innate resistance to biotic and abiotic stresses, pearl millet, a native plant, thrives in marginal soils with erratic rainfall and environmental challenges (Serba and Yadav, 2016). Singhal *et al*. (2018) highlight that it can significantly address micronutrient deficiency in developing countries by providing 30-40% inorganic nutrients, affordable staple food, and sufficient iron and zinc.

Nitrogen (macronutrient) and zinc (micronutrient) are known to work in concert to promote the growth, yield, and nutrient content of pearl millet (Prasad *et al.,* 2014a and Chappali *et al*., 2024). Furthermore, excessive application of nitrogen results in low nitrogen usage efficiency, even if the highest amount of nitrogen is needed for growth and development. Simultaneously, insufficient application and low soil zinc levels result in low grain zinc levels. Therefore, the most appropriate and economical method for increasing the zinc content of grain is through agronomic zinc biofortification (Singh and Prasad, 2014; Somanath *et al*., 2023).

The crop responds to fertilizer delivery immediately as foliar application rates are lower than those for soil application, making it easy to supply the same amount of nutrients. It is also advantageous when soil characteristics, such as heavy textures, high pH calcareous soils, or lime, prevent the roots from supplying essential nutrients, like zinc. When applied topically, zinc enhances grain quality and production in pearl millet (Zong et al., 2011; Gurusiddappan *et al*., 2023). Higher nitrogen application has been shown to positively correlate with increased uptake and concentration of micronutrients (Fe and Zn) in the grains of edible crops (Faisal and Muhammad, 2019; Qingyue *et al*., 2022).

The present study compared different combinations of N-fertiliser doses to evaluate the effectiveness of zinc fertilizers in promoting successful pearl millet **(***Pennisetum glaucum* L.**)** seed crops. This research investigates the effect of Zinc fortification on Pearl millet growth metrics, yield components, and quality by combining nitrogen doses with zinc foliar spray.

MATERIALS AND METHODS

Experimental site

A field study conducted in July 2022 and 2023 at South Farm, KITS campus, Karunya University, Coimbatore, Tamil Nadu (Fig.1), examined the effect of zinc fortification on the yield and quality of pearl millet (*Pennisetum glaucum* L.).

The experiment site was situated at an elevation of 467 meters above mean sea level, with geographical coordinates of 10.934°N, 76.75°E. The average annual rainfall in Coimbatore is 875.50 mm, with a peak of 925 mm during the southwest monsoon (Fig. 2). The average temperature is 36.4°C, with a minimum of 24.2°C (Fig. 3). The relative humidity fluctuates between 65% and 85% (www.weatherandclimate.com/india/tamilnadu/coimbatore).

Prior to seeding, three replicates of soil samples were taken from each treatment plot to examine the initial physicochemical characteristics. The experimental field was a sandy clay loam soil, part of the Peelamedu series, classified as Typic Ustropepts. The trials of pearl millet hybrids NBH 5767 (non-biofortified) and HHB 299 (biofortified) were conducted during the *Kharif* 2022 and 2023 seasons, respectively.

Field experiment details

The field experiment utilized a split-plot design, with three replicates across 36 plots, each measuring 12 m² (4 m × 3 m). M_1 (non-biofortified) and M_2 (biofortified) pearl millet hybrids were studied in the *2022 and 2023 Kharif seasons, with the primary plots consisting of both* non-biofortified and biofortified treatments. The

Fig. 1. *Map showing the South Farm, Karunya Institute of Technology & Sciences (KITS) study area*

sub-plots were subjected to six distinct nutrient-level treatments. These included foliar applications: S_4 (S_1 + ZnO), S_5 (S_2 + ZnO), and S_6 (S_3 + ZnO), and soil applications: S_1 (40 kg ha^{-1}), S_2 (60 kg ha^{-1}), and S_3 (80 kg ha^{-1}).

The sub-plots were subjected to six distinct nutrient-level treatments. Using a mouldboard plough mounted on a tractor, each plot in the experimental field was ploughed once before being levelled and harrowed to create a fine tilth without altering the design for the subsequent growing season. Each plot's irrigation channels and bunds were altered following ploughing. All suggested cultural practices and plant protection measures for pearl millet have been implemented in accordance with the Crop Production Guide for Tamil Nadu's agricultural crops (https://tnau.ac.in/site/research/crop-production-guide/).

Soil application (Manure and fertilizer)

The soil was enriched with the necessary quantities of well-decomposed FYM 10 days prior to puddling. An NPK dose of 80:40:40 kg ha^{-1} was supplied by muriate of potash (60% K_2O), urea (46% N), and single super phosphate (16% P_2O_5), following the treatment plan (Giri *et al.*, 2024). Half of the base doses of potassium (K), phosphorus (P), and nitrogen (N) were given, with the remaining 50% applied 25 days post-transplant.

Foliar application (Zinc)

Following the prescribed treatment schedule, a 0.5% ZnO solution was applied twice as a foliar spray at 25 and 50 days after sowing.

Seeds and sowing

The study utilized biofortified (NBH 5767) and non-biofortified (HHB 299) hybrid seeds of pearl millet. Before planting along the ridges, the seeds were treated with Azospirillum and Pseudomonas. One seed per hill was used to transplant the seedlings, with a 45 x 25 cm spacing between each transplant. Plant protection measures and suggested agronomic techniques were implemented.

Gap filling and thinning were performed 7 days after transplanting, while hand weeding was done 20 and 40 days after sowing for weed management.

Sampling methods and measurements

The pearl millet crops in the experiment were planted at a density of 15 plants per m^2. For plant growth analysis, data were measured from ten plants per plot per sampling until the plants reached physiological maturity. Plant heights and harvests were executed for each replicate. The plant samples were separated into leaves, stems, panicles, and grains. Leaf area at the plant level was calculated as the sum of the areas of each green leaf on a plant, and leaf area index (LAI) was calculated (Williams, 1946). An electronic balance was used to weigh the grains after they had been separated, ears manually threshed, and the biological yield recorded. At maturity, grain yield was harvested from 1 m^2 per plot. The harvest index, expressed as a percentage, was calculated by dividing the grain yield by the biological yield. The concentrations of crude protein (%) and Fe, Zn were measured in milligrams per kg of grain of pearl millet (Parkinson and Allen, 1975).

Growth related parameters

Plant height was determined by measuring from the ground level to the apex. To determine this indicator, 10 plants were taken from each plot. Each plant was measured from ground level to the apex at the time of physiological maturity within the net plot area, and the means were recorded as plant height.

The LAI was worked out by using the following formula suggested by Williams (1946).

$$\text{Leaf Area Index (LAI)} = \frac{\text{Leaf area plant}^{-1}(\text{cm}^2)}{\text{Ground area occupied plant}^{-1}(\text{cm}^2)}$$

To determine the DMP, the selected samples were oven-dried for 24 hours at 80°C ± 5°C to a constant weight.

The number of tillers was counted in all the plants present in 1 Sq.m quadrate for each treatment and finally averaged.

Yield related parameters

Ten different samples were used to compute no. of tillers $plant^{-1}$, total no. of effective tillers $plant^{-1}$, ear head length (cm) and ear head girth (cm). During harvesting, samples were taken to adjust the seed moisture to 14% for yield and weight of 1,000 seeds by weighing on an electronic balance. The plants were sun-dried in the field for 4 days after harvesting to record the biological yield (tons ha^{-1}). After recording the biological yield, the ears were manually threshed, and the grains were separated and weighed using a digital balance to record the grain yield. The harvest index was calculated as the ratio of grain yield to biological yield, expressed as a percentage of the biological yield.

Grain nutrient analysis

Grain protein was determined by the formula: Protein (%) = N content (%) x 6.25. The N content was measured according to Kreig & Holt (Parkinson and Allen, 1975). The samples were ashed in a muffle furnace at 550 °C for 10 h. The ash was dissolved in concentrated HCl, and the iron-zinc content was determined by atomic absorption spectrometry (Shimadzu AAF-6701, Japan), as suggested in the AOAC method No. 965.09 (AOAC, 2000).

Statistical analysis

The data was analyzed using the split-plot design method and ANOVA techniques recommended by Gomez and Gomez (1984), with the 'F' test used to determine the significance of differences between means. The significant differences between treatments were determined by exceeding the tabulated value of the calculated 'F-value.

RESULTS AND DISCUSSION

Growth parameters

The effects of zinc fortification and nitrogen fertilizer levels on pearl millet plant height, leaf area index, dry matter output, and days to flowering are presented in Table 1. The ideal combination of foliar micronutrient spray and nitrogen fertilizer ensures a balanced and timely nutrient supply, significantly enhancing crop performance. Consequently, pearl millet grown under adequate and well-balanced nutrition exhibited superior growth parameters.

Plant height

The study revealed a significant difference (P = 0.05) in plant height resulting from the application of different nitrogen fertilizer levels. The highest plant height at harvest was achieved in S_6 - N @ 80 kg ha^{-1} with ZnO foliar application, followed by S_5 (185.77) - N @ 60 kg ha^{-1} and S_4 (176.17 cm) - N @ 40 kg ha^{-1}. The even and steady delivery of nutrients may have contributed to enhanced crop growth as it approached the reproductive stage, as indicated by the increase in plant height. Increased nitrogen intake, an essential protein and protoplasmic component that supports vegetative growth, causes plants to grow taller (194.01 cm). Grain yield per plant and plant height were significantly positively correlated. Rahman *et al*. (2013) reported comparable findings. Zinc oxide (ZnO) foliar spray with high nitrogen levels demonstrated significant superiority in growth parameter values in both growing seasons due to its effective crop utilization and ability to overcome soil deficiency problems. Zinc foliar application may contribute to plant height growth by producing IAA, enhancing auxin metabolism, stimulating enzyme activity, and increasing photosynthetic pigments, thereby supporting vegetative development in treated corn plants (Hamid *et al*., 2013). Zinc actively participates in auxin production, which increases cell size and number, thereby enhancing plant height in pearl millet (Dashadi *et al*., 2013; Gurusiddappan *et al*., 2023). It showed that the administration of NPK at 400 kg ha^{-1} resulted in higher plants that differed from those in other treatments. This was presumably because the administration of NPK400 kg ha^{-1} has fulfilled the nitrogen requirement of plants (Usman *et al*., 2022).

Leaf area index

The leaf Area Index (LAI) significantly influences trans-

Table 1. Impact of zinc fortification on growth components of pearl millet (data from the pooled *Kharif* season)

Treatment		PH (cm)	LAI	DMP (kg ha^{-1})	Days to 50% flowering	No. of tillers plant^{-1}	Total no. of effective tillers plant^{-1}
Hybrids							
M_1 – Non-biofortified		176.00	2.07	3120.69	45.17	23.58	4.46
M_2 – Biofortified		167.04	1.41	2773.66	40.83	17.21	3.56
SE(d)		0.99	0.02	18.61	0.33	0.63	0.09
CD (P=0.05)		4.61	0.08	86.22	1.54	2.94	0.40
Nutrient levels							
S_1- N @ 40 kg ha^{-1}		152.48	1.26	2376.32	49.00	12.95	1.39
S_2 - N @ 60 kg ha^{-1}		156.70	1.39	2527.16	46.50	14.98	2.50
S_3 - N @ 80 kg ha^{-1}		163.97	1.48	2803.68	45.00	17.58	3.43
S_4 - S_1 + ZnO @ 0.5% foliar spray		176.17	1.76	3040.57	42.50	20.99	4.55
S_5 - S_2 + ZnO @ 0.5% foliar spray		185.77	2.08	3246.96	39.00	25.02	5.48
S_6 - S_3 + ZnO @ 0.5% foliar spray		194.01	2.46	3688.34	36.00	30.85	6.67
SE(d)		1.28	0.04	37.46	0.59	0.44	0.23
CD (P=0.05)		2.69	0.08	78.69	1.25	0.94	0.48
M at S	SE(d)	1.93	0.05	52.98	0.84	0.86	0.31
	CD (P=0.05)	5.35	0.13	128.59	NS	2.99	0.71
S at M	SE(d)	1.81	0.06	51.82	0.84	0.63	0.32
	CD (P=0.05)	5.02	0.13	125.78	NS	2.19	0.75

ZnO: Zinc Oxide; NS: Non-significant; PH: Plant height; LAI: Leaf area index; DMP: Dry matter production location and photosynthesis. The study found a significant increase in LAI at harvest (2.46, 2.08, and 1.76) in S_6, S_5, and S_4, respectively, under different nutrient-level treatments. The study reported by Boetang *et al*. (2006) found that enhanced nitrogen utilization led to a larger leaf surface area, resulting in higher leaf area in the maize crop. Sassenrath (1995) indicated that the rapid attenuation of PAR mainly occurred in the upper canopy of cotton genotypes that had larger and fairly flat leaves, compared with genotypes that had more erect leaves. Larger leaf area allows for greater light interception, leading to increased photosynthetic activity and higher biomass production was recorded in T-0 than in the CRI60 and Ji958 cotton cultivars (Zhigang *et al*., 2016).

Dry matter production

The nutrient level treatment S_6 (3688.34 kg ha^{-1}) showed significantly higher dry matter production (DMP) compared to S_5 (3246.96 kg ha^{-1}). The second group, S_4, weighed 3040.57 kg ha^{-1}, followed by S_3 (2803.68 kg ha^{-1}). Kolawole and Samson's (2009) investigation revealed a strong relationship between dry matter production and leaf area index (LAI), indicating that higher LAI causes more substantial dry matter accumulation in the maize crop. The rationale for enhanced dry matter accumulation in pearl millet could be attributed to a combined increase in plant height and photosynthetically active leaf area caused by ZnO. The study by Prasad and Naik (2013) found that improved N (100 kg ha^{-1}) with Zn (0.5%) spraying extended leaf area duration, increased photosynthetic rate, and increased dry matter accumulation in sweet corn.

Zn enhanced the activity of meristematic cells, which was reflected in better vegetative growth, including increased photosynthetic area and the number of tillers, and ultimately contributed to increased dry matter production in pearl millet (Shekhawat and Kumawat, 2017). A coupled increase in plant height and photosynthetically active leaf area due to 0.5% ZnO foliar spray might be the reason for increased dry matter accumulation in pearl millet. Additionally, they may be due to the complementary effect of other inherent nutrients, such as magnesium, iron, and sulfur, with zinc (Koti et al., 2009; Gurusiddappan et al., 2023).

Days to 50% flowering

The increase in days to 50% flowering was found to be higher under S_1 (49.00) and S_2 (46.50) nutrient treatments. The treatment was comparable to S_3 (45.00), followed by S_4 (42.50), S_5 (39.00), and S_6 (36.00). The lower days taken to flowering were influenced significantly by fertility management practices. Kumar *et al.* (2018) also reported similar results. Although N @ 40 kg ha^{-1} (S_1) produced the most significant number of days required to reach 50% flowering, this indicates that there are not enough nutrients available to accomplish growth improvement. Kumar *et al*. (2018) also reported similar results, finding that the higher number of days taken in silking was observed in the case of

Table 2. Impact of Zinc fortification on yield and its components of Pearl millet (Pooled *Kharif* season data)

Treatment		EHL (cm)	EHG (cm)	TW (g)	GY (t ha^{-1})	SY (t ha^{-1})	HI
Hybrids							
M_1 – Non-biofortified		19.07	2.69	12.07	3.09	6.94	28.71
M_2 – Biofortified		16.01	2.28	10.91	2.42	4.62	26.60
SE(d)		0.07	0.03	0.14	0.02	0.43	0.25
CD (P=0.05)		0.31	0.13	0.63	0.13	2.03	1.16
Nutrient levels							
S_1- N @ 40 kg ha^{-1}		11.36	1.13	9.18	1.82	4.92	21.43
S_2 - N @ 60 kg ha^{-1}		12.81	1.27	10.11	2.04	5.30	23.34
S_3 - N @ 80 kg ha^{-1}		15.08	1.93	11.26	2.64	5.62	25.59
S_4 - S_1 + ZnO @ 0.5% foliar spray		17.79	2.69	11.31	3.03	6.06	29.76
S_5 - S_2 + ZnO @ 0.5% foliar spray		22.56	3.67	12.63	3.36	6.25	32.01
S_6 - S_3 + ZnO @ 0.5% foliar spray		25.65	4.27	14.42	3.62	6.50	33.81
SE(d)		0.34	0.09	0.24	0.05	0.44	0.24
CD (P=0.05)		0.72	0.21	0.51	0.11	0.92	0.49
M at S	SE(d)	0.45	0.13	73.67	0.72	0.71	0.39
	CD (P=0.05)	0.97	0.28	NS	1.84	2.18	1.23
S at M	SE(d)	0.48	0.14	0.34	0.74	0.62	0.33
	CD (P=0.05)	1.05	0.31	NS	1.85	1.89	1.04

EHL: Ear head length; EHG: Ear head girth; TW: Test weight; GY: Grain yield; SY: Straw yield; HI: Harvest index; N – Nitrogen; ZnO – Zinc Oxide; NS: Non-significant

Table 3. Impact of Zinc fortification on grain quality of Pearl millet (Pooled *Kharif* season data)

Treatment		Crude Protein (%)	Fe (mg kg^{-1})	Zn (mg kg^{-1})
Hybrids				
M_1 – Non-biofortified		8.46	73.48	36.44
M_2 – Biofortified		10.06	76.27	41.64
SE(d)		0.06	3.44	0.91
CD (P=0.05)		0.26	14.82	3.93
Nutrient levels				
S_1 - N @ 40 kg ha^{-1}		7.37	69.91	35.05
S_2 - N @ 60 kg ha^{-1}		8.25	72.19	37.13
S_3 - N @ 80 kg ha^{-1}		8.90	74.53	38.68
S_4 - S_1 + ZnO @ 0.5% foliar spray		9.73	75.53	39.78
S_5 - S_2 + ZnO @ 0.5% foliar spray		10.45	77.76	41.29
S_6 - S_3 + ZnO @ 0.5% foliar spray		10.85	79.33	42.32
SE(d)		0.24	1.89	1.05
CD (P=0.05)		0.50	3.94	2.18
M at S	SE(d)	0.16	1.29	0.68
	CD (P=0.05)	0.33	3.20	1.50
S at M	SE(d)	0.17	1.34	0.74
	CD (P=0.05)	0.36	2.79	1.54

Fe – Iron; Zn – Zinc; N – Nitrogen; ZnO – Zinc Oxide

fertility management practices, which were recorded under F1 (100% RDF) and O3 (25 t FYM/ha), among the rest of the treatments in pearl millet hybrids. However, N @ 40 kg ha^{-1} (S_1) yielded a considerably more prominent number of days necessary to reach 50% flowering, which shows that insufficient nutrients are available to support the growth increase. The results align with the research of Afe et al. (2015) and Bekele et al. (2018), which showed that plots treated with the combined application of pressmud at 2.5 t ha-1 mixed with NPK 30 kg N ha-1 and foliar fertilizer commenced tasselling earlier at 38 days after planting in the pearl millet crop.

Tillers per plant

The amount of nitrogen fertilizer administered through foliar applications had a significant (P ≤ 0.05) impact on the number of tillers and effective tillers per plant. The highest no. of tillers (30.85) was recorded in S_6 – N @ 80 kg ha^{-1} with ZnO foliar application, followed by S_5 (25.02) – N @ 60 kg ha^{-1} with ZnO foliar applications and S_4 (20.99) – N @ 40 kg ha^{-1} with ZnO foliar applications through various nitrogen level treatments. The lowest number of tillers (12.95) were recorded at S_1 - N @ 40 kg ha^{-1}.

Increased nitrogen availability from inorganic and zinc fertilizers may (100 % RDF +15 t FYM ha-1 + Bio NP Consortia (T5)) increase in both total and effective tillers at harvest, leading to stiffer straws, which have resulted in profuse tillering in pearl millet (Manish *et al*., 2021)

Yield and yield components

Table 2 presents the effects of nitrogen management practices on ear head length, ear head girth, thousand-grain weight, and grain and straw yield in pearl millet fortification.

The yield components showed significant differences (P ≤ 0.05) across different sub-plot nutrient level combinations. Among the treatments, the highest ear head length (25.65 cm), ear head girth (4.27 cm), and thousand-grain weight (14.42 g) were recorded in S_6 (N @ 80 kg ha^{-1} with ZnO foliar application. The ear head length, girth, and test weight of ear heads treated with nitrogen fertilizer integrated with zinc source were comparable but significantly higher than those treated with nitrogen alone. An up-and-down trend with a significant difference was shown by 1000 grain weight in response to zinc application along with full NPK (Khattak et al., 2015). The increase in grain yield (3.62 t ha^{-1}) may be attributed to the slow release of nutrients, as well as the timely availability and release of nutrients. Non-biofortified maize (Commercial Hybrids) achieves high yields primarily due to their genetic potential, which enables them to tolerate higher densities, increased nitrogen availability, and micronutrient fertilizers for optimal plant development (Ahmad *et al*. 2017).

The treatment that received 1.0 % $ZnSO_4$ as a foliar spray recorded 55 % higher grain yield, while that with 15 kg ha^{-1} $ZnSO_4$ as soil treatment + 1.0 % $ZnSO_4$ as foliar spray recorded 48 % higher grain yield over the control in wheat crop (Khattak *et al*., 2015). Increase in

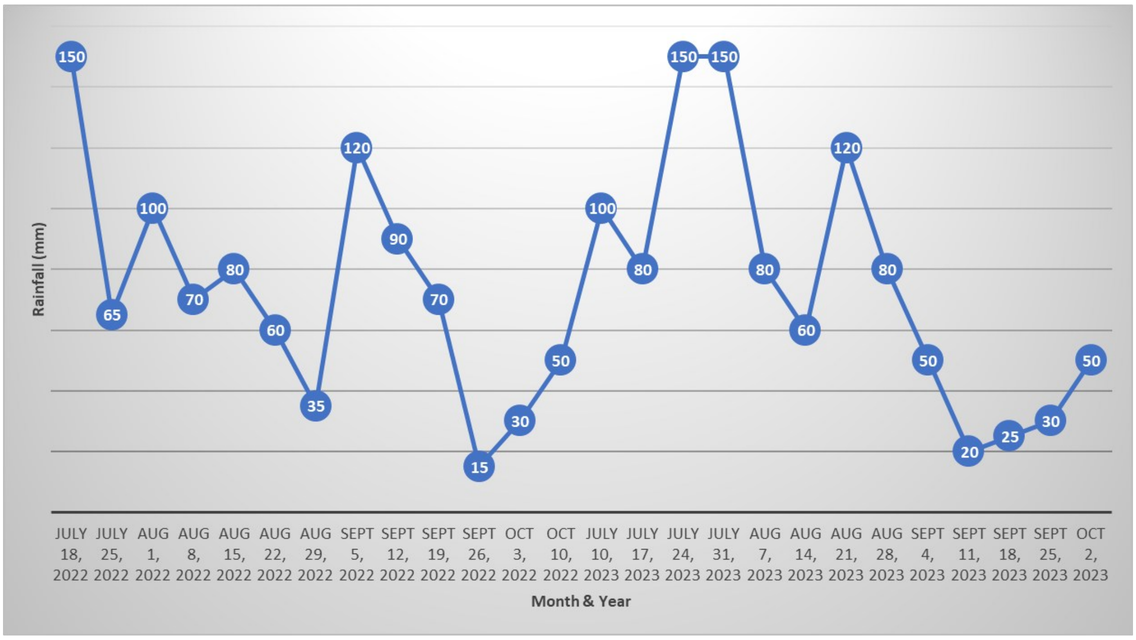

Fig. 2. *Weekly total rainfall (mm) for 2022–2023 cropping season (July–October)*

the grain yield of maize and wheat with Zn addition at the rate of 5 kg ha^{-1} or 2 times as a foliar spray of 0.5 % $ZnSO_4$, and this treatment showed an economical value greater than all the other concentrations added to pearl millet (Khattak *et al*., 2006).

Ved et al. (2002) stated that foliar-applied zinc enhances photosynthesis, stimulates early plant growth, and improves nitrogen fixation, grain protein, and yield. The study found that S_6 (N @ 80 kg ha^{-1} + ZnO foliar application) yielded significantly higher grain and stover yields, followed by S_5 (N @ 60 kg ha^{-1} + ZnO @ 0.5% foliar spray). Increased nutrient availability and the presence of vital micronutrients like iron and zinc resulted in greater yields from foliar treatments.

A balanced nutrient supply that permits adequate photosynthetic absorption is responsible for the rise in dry matter production. In addition to improving grain and straw productivity, the effective conversion of the source to the sink lengthened the ear head. Foliar spray nutrient supplementation enhanced nutrient availability throughout the crop season, resulting in improved crop growth and development, as well as higher agricultural productivity (Zerihun *et al.,* 2013). Grain and straw yields were higher in N @ 80 kg ha^{-1} + ZnO @ 5% foliar spray (S_6) by 98.90 and 32.11%, respectively, than in N @ 40 kg ha^{-1} (soil treatment only). Nutrient uptake enhances nutrient accumulation and translocation to developing earheads, thereby improving filling and grain weight, and ultimately leading to higher yields in maize (Chakraborti *et al*., 2009). Micronutrient fertilization in pearl millet has resulted in a significant increase in straw yield, likely due to enhanced plant growth and biomass production, as well as increased nutrient uptake. The study found that the grain yield of pearl millet (*Pennisetum glaucum* L.) var. Kaveri super boss, Nandi-75) indicated the cumulative positive influence of yield-attributing traits (Mehta *et al*. 2008). Prasad *et al*. (2014b) and Giri *et al*. (2024) also observed a linear increase in grain yield and biological yield of pearl millet with increased nitrogen levels.

Quality parameters

Table 3 displays the effects of zinc fortification on the crude protein, iron (Fe), and zinc (Zn) of pearl millet at varying nitrogen levels. According to the study, the most effective method for increasing the amount of crude protein, iron, and zinc in grains after harvest was S_6 (N @ 80 kg ha^{-1} with ZnO foliar treatment). The application of S_1-N at 80 kg ha^{-1} yielded the lowest values when compared to S_6 (N @ 60 kg ha^{-1} with ZnO foliar spray). The difference in the increase level in concentrations of these ions, viz., Fe, Mn, Cu, and Zn, between the two genotypes (IR64 and IR68144-3B) suggested that N fertilizer application only influences the accumulation of elements in different parts of rice but does not affect the characteristic expression of the genotypes.

A significantly higher protein content (12.48%) was recorded with 120 kg N ha^{-1} than with no fertilizer N application in pearl millet (Sunita *et al*., 2024). The results suggested that the increased application of nitrogen led to a subsequent increase in total rice grain protein content, indicating that any increase in N absorption by roots eventually enhances its assimilation in leaves and reassimilation in developing grains (Chandel *et al*., 2010).

Zinc, which is essential for the metabolism of nitrogen and carbohydrates and the biosynthesis of plant growth regulators (IAA), may be the cause of the increase in the maximum crude protein percentage observed in the

Table 4. Interaction effect of hybrids and nutrient management on grain quality of Pearl millet (Pooled *Kharif* season data)

Hybrid	Nutrient levels	Crude Protein (%)	Fe (mg kg^{-1})	Zn (mg kg^{-1})
H_1	F_1 - N @ 40 kg ha^{-1}	6.88	69.25	32.63
	F_2 - N @ 60 kg ha^{-1}	7.68	70.85	34.70
	F_3 - N @ 80 kg ha^{-1}	8.13	73.03	35.85
	F_4 - F_1 + ZnO @ 0.5% foliar spray	8.77	74.08	37.07
	F_5 - F_2 + ZnO @ 0.5% foliar spray	9.43	76.10	38.48
	F_6 – F_3 + ZnO @ 0.5% foliar spray	9.86	77.57	39.90
H_2	F_1 - N @ 40 kg ha^{-1}	7.85	70.57	37.47
	F_2 - N @ 60 kg ha^{-1}	8.82	73.53	39.57
	F_3 - N @ 80 kg ha^{-1}	9.67	76.02	41.52
	F_4 - F_1 + ZnO @ 0.5% foliar spray	10.70	76.98	42.48
	F_5 - F_2 + ZnO @ 0.5% foliar spray	11.47	79.42	44.10
	F_6 – F_3 + ZnO @ 0.5% foliar spray	11.83	81.08	44.73
M at S	SE (d)	0.16	1.29	0.68
	CD (P=0.05)	0.33	3.20	1.50
S at M	SE (d)	0.17	1.34	0.74
	CD (P=0.05)	0.36	2.79	1.54

H_1 – Non-biofortified; H_2 – Biofortified; Fe – Iron; Zn – Zinc; N – Nitrogen; ZnO – Zinc Oxide

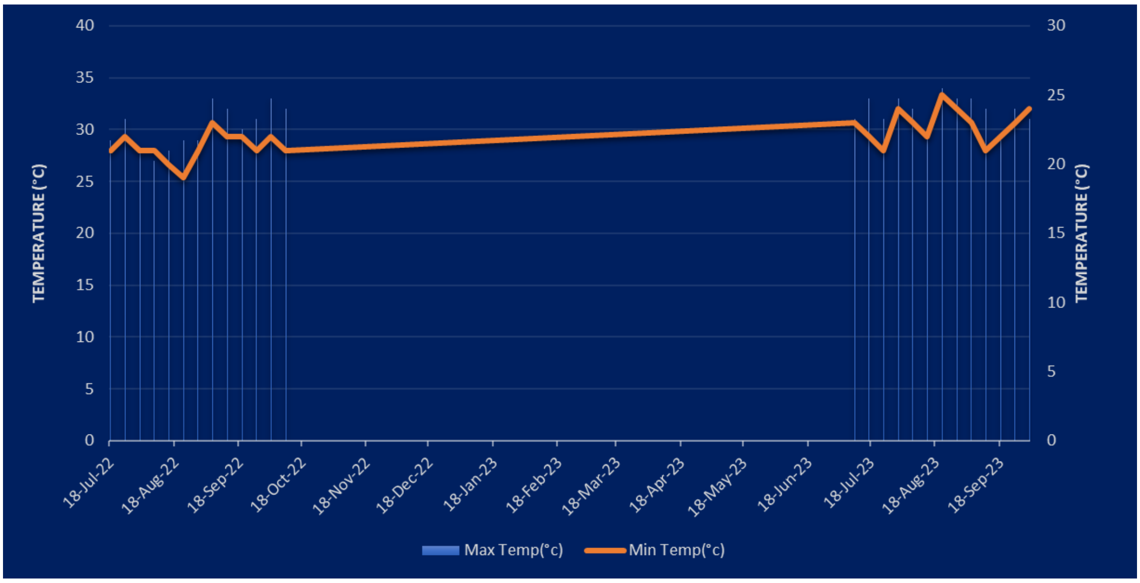

Fig.3. *Weekly max and min temperatures in 2022–2023 during the cropping season (July–October)*

combined treatments (N fertilizer (120:65:110) with $ZnSO_4$ 1% foliar). This might be the reason for the increase in protein content. Without affecting biological yield, foliar zinc spraying in alkaline soils significantly increased test weight and grain protein content in the wheat variety "Siran 2008" (Khattak *et al*., 2015). Such an increase in bioavailability of Fe and Zn in grain might be due to the foliar application at an active (vegetative and reproductive) crop stage. For foliar Zn application frequency, two- and three-times application led to a greater increase of grain Zn mass concentration (10.2 ± 2.07 and 8.71 ± 1.26 mg kg^{-1}) than a one-time application, which led to an increase by 5.98 ± 1.28 mg kg^{-1} in rice (Lu Liu *et al*., 2023).
Hidoto et al. (2017) confirmed that foliar Zn treatment increased grain Zn content by 22% over Zn seed priming in the chickpea crop. Zn foliar fertilization also provided additional benefits, including vigorous early-stage growth, improved yield, and tolerance to biotic and abiotic stresses. The results agreed with Mohsin *et al.* (2014) and Augustine and Kalyanasundaram (2020) in two stages of zinc foliar applications in the maize crop.

Interaction of hybrid and nutrient levels

"Genotype plays a crucial role in determining the accumulation of iron (Fe), zinc (Zn), and protein in rice grains. It can be concluded that while grain nutritional traits were significantly influenced by location, genotype × location interaction, nitrogen fertilizer levels, and genotype × nitrogen application interaction, the genotypic differences emerged as the most significant factor influencing grain protein, iron, and zinc contents in rice." Therefore, selecting genotypes with higher grain micronutrient content across various soil types is a sound strategy (Chandel *et al*., 2010).

Comparative analysis of grain protein, iron, and zinc values of the 2 pearl millet hybrids grown under different treatments indicated that the ranking of hybrids for crude protein, grain iron, and zinc content at different nitrogen and zinc foliar applications in two seasons remained more or less the same. It can thus be concluded that although grain nutritive traits showed a significant effect of seasons, the interaction between hybrids x nutrient levels, as well as hybrid differences, was found to be the most significant factor determining the grain protein, iron, and zinc contents in pearl millet grains. The study found that a biofortified hybrid with N @ 80 kg ha^{-1} + ZnO @ 5% foliar spray showed higher crude protein, Fe, and Zn levels compared to a non-biofortified hybrid (Table 4). The lowest quality was recorded under the N @ 40 kg ha^{-1} (S_1) with biofortified hybrid and non-biofortified in both *Kharif* seasons. Significant quality changes might occur due to genetic potential, agronomic, and environmental changes.

Conclusion

This study's findings demonstrated that HHB 299 (biofortified) hybrids in pearl millet cultivated during the *Kharif* season under irrigated conditions was highly responsive to zinc fortification. The study recommends a combination of ZnO foliar application and nitrogen application at 80 kg ha^{-1} in the soil (S_6) for optimal growth, productivity, and quality of pearl millet. This long-term, integrated strategy has the potential to provide a valuable nutritional source for both human and animal populations. The Fe and Zn content of pearl millet grains was significantly increased by applying ZnO foliar spray (S_6) during the active vegetative stage, thereby improving the grains' overall quality. ZnO foliar treatments combined with inorganic fertilizers have been shown to be a successful way to improve grain quality. Experimental results show that zinc fortification, particularly through ZnO foliar applications, can significantly increase pearl millet yield and quality, making it a viable cultivation strategy in Tamil Nadu's Western Ghats region.

Conflict of interest

The authors declare that they have no conflict of interest.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the management and staff members of the School of Agricultural Sciences, Karunya University, Coimbatore, Tamil Nadu, India for their coordination during the research studies.

REFERENCES

1. Afe, A. I., Atanda, S., Aduloju, M. O., Ogundare, S. K. & Talabi, A. A. (2015). Response of maize (Zea mays L.) to combined application of organic and inorganic (soil and foliar applied) fertilizers. *African Journal of Biotechnology*, 14, 3006-010. https://doi.org/10.5897/AJB2015.14808
2. Boateng, S.A., J.Zickermann & M. Kornoohrens (2006). Poultry manure effect on growth and yield of maize. *West Africa Journal of Applied Ecology*, 9, 1-11. https://doi.org/10.4314/wajae.v9i1.45682
3. Ahmad, W., Jan, M. T., Ilyas, M., Shah, T., Moinullah, K. A., Ahmad, A. & Khan, S. (2017). Phenology and yield components of maize as influenced by different forms of dairy manure with supplemental nitrogen management. *International Journal of Agriculture and Environmental Research*, 3, 137- 46.
4. AOAC (2000). Official Methods of Analysis of AOAC International. 17. Gaithersburg, USA: Association of Official Analytical Chemists.
5. Augustine, R. and Kalyanasundaram, D. (2020). Agronomic biofortification through micronutrient management in maize: A review. *Journal of Applied and Natural Science*, 12(3), 430-437. https://doi.org/10.31018/jans.v12i3.2356
6. Bekele, A., Kibret, K., Bedadi, B., Balemi, T. & Yli-Halla, M. (2018). Effects of lime, vermicompost and chemical P fertilizer on yield of maize in Ebantu district. Western highlands of Ethiopia. *African Journal of Agriculture Research*, 13, 477-89. https://doi/org/10.5897/AJAR2017.12949
7. Chakraborti, M., Prasanna, B. M., Hossain, F., Singh, A. M. & Guleria, S. K. (2009). Genetic evaluation of kernel Fe and Zn concentrations and yield performance of selected maize (Zea mays L.) genotypes. *Range Management and Agroforestry*, 30, 109-14.
8. Chandel, G., Banrjee, S., See, S., Meena, R., Sharma, D. J. & Verulkar, S.B. (2010). Effect of Different Nitrogen Fertilizer Levels and Native Soil Properties on Rice Grain Fe, Zn and Protein Contents. *Rice Science*, 17,3. https://doi.org/10.1016/S1672-6308(09)60020-2
9. Chappali Bharathi, Karishma Singh and Joy Dawson. 2024. Effect of Nitrogen and Zinc on Yield and Economics of Pearl Millet. *Journal of Experimental Agriculture International*. 46(8), 174-178. https://doi.org/10.9734/jeai/2024/v46i82692
10. Faisal Nadeem and Muhammad Farooq. (2019). Application of Micronutrients in Rice-Wheat Cropping System of South Asia. *Rice Science*, 26(6), 356-371. https://doi.org/10.1016/j.rsci.2019.02.002
11. Giri U., P. Lodh, B. Thangjam, N. Paul, D. P. Awasthi, Sangappa, S. Das, D. Sen,Th. Irenaeus K.S., D. Debbarma & A. Sarkar. (2024). Effect of different fertilizer doses and spacing on performance of Pearl Millet (Pennisetum glaucum L.) under Tripura Agro-Climatic Condition. 9, 5, Sep-Oct. https://dx.doi.org/10.22161/ijeab.95.40
12. Gurusiddappan. S., S. B. Patil, R. A. Nandagavi & Vidyavathi G. Yadahalli. (2023). Soil and foliar application of zinc increased pearl millet productivity in calcareous vertisols of Karnataka. *Journal of Farm Sciences*, 36(1), (26-

32). https://doi.org.10.61475/jfm.v36i01.337

13. Hamid R Tohidi Moghadam, Hossein Zahedi & Ashkan Ashkiani. (2013). Effect of zinc foliar application on auxin and gibberellin hormones and catalase and superoxide dismutase enzyme activity of corn (*Zea mays* L.) under water stress. *Maydica*, 58, 218-223.
14. Hidoto, L., Worku, W., Mohammed, H. & Bunyamin, T. (2017). Effects of Zinc application strategy on Zinc content and productivity of chickpea grown under Zinc deficient soils. *Journal of Soil Science and Plant Nutrition*, 17(1), 112-126. http://dx.doi.org/10.4067/S0718-95162017005000009
15. Khattak, S. G., Dominy, P. J. & Ahmad, W. (2015). Effect of Zn as soil addition and foliar application on yield and protein content of wheat in alkaline soil. *Journal of National Science Foundation*, 43 (4), 303–312. https://doi.org/10.4038/jnsfsr.v43i4.7965
16. Khattak S.G., Peter J. Dominy & Wiqar Ahmad. (2015). Assessment of Zn Interaction with Nutrient Cations in Alkaline Soil and its effect on Plant Growth. *Journal of Plant Nutrition,* 38,1110–1120. https://doi.org/10.1080/01904167.2015.1009093.
17. Khattak S.G., Rohullah A., Malik A., Perveen Q. & Ibrar M. (2006). Assessing maize yield and quality as affected by Zn as soil or foliar applications. *Sarhad Journal of Agriculture* **22**: 465 – 472.
18. Kolawole Edomwonyi & Samson Uduzei Remison (2009). Growth and Yield of Maize as Influenced by sowing date and Poultry Manure Application. *Notulae Botanicae Horti Agrobotanici. Cluj-Napoca,* 37(1), 199-203. https://doi.org/10.15835/nbha3713140
19. Kumar, D., Kumar, M. & Kumar, R. (2018). Evaluate the integrated nutrient use on growth and yield of hybrid Maize under central plain zone of Uttar Pradesh, India. *International Journal of Current Microbiology and Applied Science*, 7, 518-30. https://doi.org/10.20546/ijcmas.2018.703.062
20. Lindsay, W.L. & W.A. Norvell. (1978). Development of DTPA soil test for zinc, Iron,Manganese and Copper. *Soil Science Society of America Journal*, 42,421-428.
21. Lu Liu, Wen-Feng Cong, Bruno Suter, Fusuo Zhang, Wopke van der Werf & Tjeerd Jan Stomph. (2023). How much can Zn or Fe fertilization contribute to Zn and Fe mass concentration in rice grain? A global meta-analysis. *Field Crops Research*, 301,109033.https://doi.org/10.1016/j.fcr.2023.109033
22. Manish Yadav, N.J., Jadav, Dileep Kumar, C.H., Raval, Drashti Chaudhari, & Nisha Chaudhary. 2021. Effect of Different Nutrient Management Practices on Growth, Yield Attributes and Yield of Transplanted Pearl Millet (*Pennisetum glaucum* L.). *International Journal of Plant & Soil Science, 33(22), 260-266.* https://doi.org/10.9734/IJPSS/2021/v33i2230704
23. Mehta, A.C., Khafi, H.R., Bunsa, B.D., Dangaria, C.J. & Davada B K (2008). Effect of soil application and foliar spray of zinc sulphate on yield, uptake and net return of pearl millet. *Research Crops*, 9(1), 31-32.
24. Mohsin, A. U., Ahmad, A. U. H., Farooq, M. & Ullah, S. (2014). Influence of zinc application through seed treatment and foliar spray on growth, productivity and grain quality of hybrid pearl millet. *Journal of Animal and Plant Sciences*, 24, 1494-503.
25. Parkinson, J.A., & Allen, S.E. (1975). A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. *Communications in Soil Science and Plant Analysis*, 6, 1-11.
26. Prasad, S.K., M. K. Singh. & Renu Singh. (2014a). Effect of Nitrogen and Zinc Fertilizer on Pearl Millet (*Pennisetum Glaucum* L.) under Agri-Horti System of Eastern Uttar Pradesh. *The Bioscan*, 9(1), 163-166, 2014.
27. Prasad, S. K., Singh, M. K., & Renu Singh, (2014b). Effect of nitrogen and zinc fertilizer on pearl millet (*Pennisetum glaucum*) under agri-horti system of eastern Uttar Pradesh. *Significance*, *400*, 1-5.
28. Prasad, P.H. & Naik, A. (2013). Effect of varying NPK levels and bio-fertilizers on growth and yield of sweet corn. *Journal of Indian Society of Soil Science*, 34, 271-274. https://dx.doi.org/10.18782/2320-7051.6379
29. Qingyue Zhao, Wenqing Cao, Xinping Chen, Tjeerd Jan Stomph & Chunqin Zou. (2022). Global analysis of nitrogen fertilization effects on grain zinc and iron of major cereal crops. *Global Food Security*, 33, 100631. https://doi.org/10.1016/j.gfs.2022.100631
30. Raheem, D., Dayoub, M., Birech, R. & Nakiyemba, A. (2021). The contribution of cereal grains to food security and sustainability in Africa: potential application of UAV in Ghana, Nigeria, Uganda, and Namibia. *Urban Science*, 5,8. https://doi.org/10.3390/urbansci5010008
31. Rahman, M.H., Islam, M.R., Jahiruddin, M., Puteh, A.B. & Mondal, M.M.A. (2013). Influence of Organic Matter on Nitrogen Mineralization Pattern in Soils under Different Moisture Regimes*. International Journal of Agriculture and Biology,* 15, 55-61.
32. Sassenrath-Cole GF (1995). “Dependence of canopy light distribution on leaf and canopy structure for two cotton (Gossypium) species”. Agricultural and Forest Meteorology 77: 55–72. https://doi.org/10.1016/0168-1923(95)02238-S
33. Serba, D. D. & Yadav, R. S. (2016). Genomic tools in pearl millet breeding for drought tolerance: status and prospects. *Frontiers in Plant Science*, 7,1724. https://doi.org/10.3389/fpls.2016.01724
34. Shekhawat, P. S. & Kumawat, N. (2017). Response of zinc fertilization on production and profitability of Pearl millet (*Pennisetum glaucum*. L) under rainfed condition of Rajasthan. *Journal of Agriculture Search*, 4(4), 251-254. https://doi.org/10.21921/jas.v4i04.10203
35. Singh, M.K. & Prasad, S.K. (2014). Agronomic aspects of Zinc biofortification in rice (*Oryza sativa* L.). *The Proceedings of the National Academy of Sciences*, 84, 613-623. https://doi.org/10.1007/s40011-014-0329-4
36. Singhal, T., Satyavathi, C.T., Kumar, A., Sankar, S. M., Singh, S. P. & Bharadwaj, C. (2018). Genotype x environment interaction and genetic association of grain iron and zinc content with other agronomic traits in RIL population of pearl millet. *Crop Pasture Science*, 69, 1092–1102. https://doi.org/10.1071/CP18306
37. Somanath Nayak, Yashbir Singh Shivay, Radha Prasanna, Sunil Mandi, Shamima Parveen, Kirttiranjan Baral, Kadapa Sreenivasa Reddy. (2023). Soil and foliar application of Zn enhances its biofortification, bioavailability and productivity in both biofortified and non-biofortified wheat varieties. *Journal of Food Composition and Analysis*, 124,105691. https://doi.org/10.1016/

j.jfca.2023.105691

38. Sunita Sheoran, Dhram Prakash, Dev Raj, Virender Singh Mor, Parmod Kumar Yadav, Rajeev Kumar Gupta, Saud Alamri & Manzer H. Siddiqui. Long-term organic and N fertilization influence the quality and productivity of pearl millet under pearl millet-wheat sequence in north India. (2024). *Scientific Reports,* 14,19503. https://doi.org/10.1038/s41598-024-70009-1
39. Tai, U. P. & Young, C. T. (1974). Variation in protein percentage in different portions of peanut cotyledons. *Crop Science.* 14, 22–29.
40. Uppal, R. K., Wani, S.P., Garg, K.K. & Alagarswamy, G. (2015). Balanced nutrition increases yield of Pearl millet under drought. *Field Crop Research*, 177, 86-97. https://doi.org/10.1016/j.fcr.2015.03.006
41. Usman Made, Adrianton, Silvy Setia Sari and Amirudin. (2022). Growth and Yield of Sweet Corn (*Zea Mays Saccharata*) at Various NPK Fertilizer Doses and Liquid Organic Fertilizer Concentrations. International Journals of Advanced Research, 10(11), 1026-1031. https://dx.doi.org/10.21474/IJAR01/15760
42. Ved, R., Misra, S.K. & Upadhyay, R.M. (2002). Effects of sulphur, zinc and biofertilizers on the quality characteristics of mungbean. Indian Journal of Pulses Research, 2, 139-141.

Zerihun, A., Sharma, J.J., Nigussie, D. & Fred, K. (2013). The effect of integrated organic and inorganic fertilizer rates on performances of soybean and maize component crops of a soyabean/pearl millet mixture at Bako, Western Ethiopia. *African Journal of Agriculture Research*, 8,3921-9. https://doi.org/10.5897/AJAR12.1044

43. Zhigang Bai, Shuchun Mao, Yingchun Han, Lu Feng, Guoping Wang, Beifang Yang,Xiaoyu Zhi, Zhengyi Fan, Yaping Lei, Wenli Du, Yabing Li. (2016). Study on Light Interception and Biomass Production of Different Cotton Cultivars. *PLOS ONE, 5: 1-17,* https://doi.org/10.1371/journal.pone.0156335
44. Zong, X., Wang, H., Song, Z., Liu, D. & Zhang, A. (2011). Foliar Zn fertilization impacts on yield and quality in Pearl millet (*Pennisetum glaucum* L.). *Frontiers of Agriculture in China,* 5(4), 552-555. https://doi.org/10.1007/s11703-011-1132-9