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Effect of optimized nitrogen management through conventional and nano-fertilizers on nutrient dynamics and finger millet yield

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Nitrogen and zinc nutrition significantly influence crop productivity. Foliar application, especially using nano-nitrogen and nano-zinc, enhances nutrient use efficiency and rapidly corrects deficiencies, offering a promising approach to improve crop growth and performance alongside conventional fertilization practices. The present study was undertaken to assess the nutrient dynamics in finger millet (GPU-28). A field experiment was taken up at AICRPDA centre, Bengaluru for two seasons during rainy season (kharif) *Kharif* 2021 and 2022 in a factorial randomized complete block design replicated thrice. Treatments included four levels of nitrogen - N_1: No nitrogen, N_2: 50% of the recommended dose of nitrogen (RDN: 25 kg N ha^{-1}), N_3: 75% RDN (37.5 kg N ha^{-1}) and N_4: 100% RDN (50 kg N ha^{-1}); and four modes of fertilizers application - F_1: Soil application of zinc, F_2: Foliar spray of nano-nitrogen, F_3: Foliar spray of nano-zinc and F_4: Foliar spray of nano-nitrogen and nano-zinc along with two control treatments (Control-1: Recommended PK, Control-2: Recommended NPK). Nano-fertilizers were applied twice at 35 and 55 days after sowing (DAS) @ 2 mL L^{-1} and all treatments received recommended doses of phosphorus (40 kg P_2O_5 ha^{-1}) and potassium (37.5 kg K_2O ha^{-1}). Additionally, a complementary pot culture study was conducted to evaluate physiological responses of finger millet to nano-fertilizers under controlled conditions, which corroborated the field results. Application of 100% RDN combined with foliar sprays of nano-nitrogen and nano-zinc resulted in significantly higher grain yield (3453 kg ha^{-1}), uptake of nitrogen, phosphorus, potassium and zinc at all growth stages, which was comparable to the application of 75% RDN along with the same foliar applications of nano nutrients. Furthermore, higher nitrogen use efficiency was noticed with application of 75% RDN along with the foliar application of nano-N and nano-Zn. The nutrient balance study further confirmed that 75% RDN combined with nano fertilizers led to lower nitrogen losses compared to 100% RDN, indicating better nutrient use efficiency (NUE) and reduced environmental risks. In conclusion, applying 75% RDN combined with the recommended PK along with foliar application of nano-nutrients, demonstrates significant potential for efficient nutrient management.

KEYWORDS

finger millet, foliar spray, nano nutrients, nitrogen use efficiency, soil, properties

1 Introduction

Finger millet (*Eleusine coracana*), a climate-resilient cereal predominantly grown in the rainfed regions of southern Karnataka and other semi-arid areas, plays a vital role in dryland agriculture. It is a nutrient-dense crop, rich in calcium, dietary fiber and essential amino acids, making it particularly important for nutritional security in marginal farming systems (Shukla and Behera, 2020). The crop's adaptability to poor soils, limited rainfall, and minimal inputs makes it an ideal candidate for sustainable intensification in rainfed agriculture.

Despite its potential, finger millet productivity remains low due to declining soil fertility, especially under rainfed conditions where fertilizer use is minimal and often imbalanced. At the national level, food grain production faces challenges due to widespread soil nutrient mining and negative nutrient balances, which are estimated at 8–10 million tonnes annually (NAAS, 2018). However, unlike high-input cereals such as rice and wheat, finger millet is grown under low external input systems, and blanket recommendations or concerns of over-fertilization are not applicable to this crop. Instead, site-specific nutrient management and efficient delivery methods are required to address the nutrient limitations of rainfed finger millet systems.

Among essential nutrients, nitrogen plays a key role in plant development; its deficiency can significantly hinder the growth of roots, stems, foliage, flowers and fruits. Similarly, in the Indian context, zinc (Zn) has been recognized as the most deficient micronutrient, presenting additional challenges to achieving optimal crop productivity (Shukla and Behera, 2020). The lack of micronutrients in soil not only reduces crop yield but also diminishes the nutritional quality of grains (Fageria et al., 2002; Phattarakul et al., 2012; Dapkekar et al., 2018; Shukla et al., 2021). Micronutrient insufficiency occurs when animals and humans consume food derived from crops with low micronutrient concentrations (Shukla et al., 2021). Zinc deficiency, in particular, presents a critical health challenge, as it adversely affects human nutrition while simultaneously limiting crop production (Manzeke et al., 2019). Conventional soil application of Zn fertilizers such as $ZnSO_4$ often leads to fixation and reduced bioavailability. Foliar delivery of nano-Zn offers a promising alternative, potentially improving grain Zn content while enhancing overall crop performance (Raliya and Singh, 2016).

In this context, nano-fertilizers have emerged as a promising alternative due to their unique properties such as high surface area, enhanced foliar absorption, controlled nutrient release and targeted delivery, which collectively improve nutrient uptake and minimize losses (Naderi and Danesh-Shahraki, 2013; Moaveni and Kheiri, 2011; Huq et al., 2025) through site-targeted mechanisms, significantly enhancing nutrient use efficiency. Nano-fertilizers consist of nanoscale particles that exhibit a high surface area-to-volume ratio, improved nutrient retention and enhanced mobility within the soil-plant system. These characteristics contribute to better plant responses such as more efficient nutrient uptake, higher biomass production, improved photosynthetic activity and increased leaf expansion. A 2023 study in Prayagraj evaluated nano-ZnO (300–900 ppm) alone and in combination with foliar boron (0.1%–0.5%) on finger millet, where the 900 ppm nano-Zn plus 0.5% boron treatment significantly enhanced plant height, tiller count, biomass and yields (Kruthika et al., 2023). Beyond finger millet, pearl millet studies further validate the benefits of nano-nutrient applications. Foliar nano-urea at 4 mL L^{-1} (at 30 and 45 DAS) under 100% recommended NPK improved plant height, dry matter accumulation, chlorophyll content and grain Zn, N, P, and K concentrations in both grain and straw (Sharma et al., 2022). However, these studies are isolated and lack integration with nitrogen management or evaluation under rainfed systems.

Despite the growing interest in nano-fertilizer technology, limited research has explored their efficacy in millets, particularly under rainfed conditions where nutrient stress is prevalent. Most studies to date have focused on major cereals like wheat and rice (Kah et al., 2018; Mullen, 2019; Hu and Xianyu, 2021), with minimal attention given to small millets. Moreover, there is a lack of integrated assessments combining both field and physiological studies in pot culture to comprehensively evaluate the effects of nano-nutrient applications on plant metabolism and stress mitigation. Combining both perspectives offers valuable insights into how nano-fertilizers enhance nutrient use efficiency and strengthen crop resilience, particularly under rainfed conditions.

2 Materials and methods

2.1 Experimental site

The study was carried out during the *kharif* seasons of 2021 and 2022 at the All India Coordinated Research Project for Dryland Agriculture, University of Agricultural Sciences, GKVK, Bengaluru. The station's average annual rainfall over the past 38 years (1976–2020) was 921.0 mm. In 2021 and 2022, the recorded rainfall was 1190 mm and 1557 mm, respectively with the majority of rainfall occurring between May and October. The experimental site is characterized by soils from the Vijayapura soil series, classified as *Kandic paleustalfs*, and falls under the FAO classification of ferric *luvisols.* The soils, derived from laterite formation in a subtropical semi-arid climate, are reddish-brown in color and exhibit a sandy loam texture. The soil has a acidic pH of 5.05, low electrical conductivity (0.08 dS m^{-1}), and organic carbon content of 3.3 g kg^{-1}. The site's soils were low in available nitrogen (256 kg ha^{-1}) but medium in potassium (146 kg ha^{-1}) and phosphorus (51 kg ha^{-1}).

Soil texture was determined using the International Pipette Method, as described by Piper (1966). The soil pH was determined by the potentiometric method (Piper, 1966), and electrical conductivity using a conductivity bridge (Jackson, 1973). Organic carbon content was estimated using the Walkley and Black wet-oxidation method, (Jackson, 1973). Available nitrogen was determined following Alkaline permanganate method (Subbaiah and Asija, 1956). The available phosphorus and potassium content of the soil was quantified following Bray's and Flame photometer (Jackson, 1973).

2.2 Experimental design and treatments

The experiment was laid out in a factorial randomized complete block design (RCBD) with 18 treatment combinations, replicated three times. Each plot measured 4.2 m × 3.0 m, separated by 0.5 m between plots and 1.0 m between replications. The design involved two factors: four nitrogen levels and four fertilizer application methods, along with two control treatments.

Factor A: Nitrogen levels	Factor B: Methods of fertilizer application
A_1: No nitrogen (N_0)	B_1: Soil application of zinc @ 12.5 kg ha^{-1}
A_2: 50 per cent of recommended nitrogen (N_{50})	B_2: Foliar spray of nano-nitrogen @ 2 mL L^{-1} of water at 35 and 55 DAS
A_3: 75 per cent of recommended nitrogen (N_{75})	B_3: Foliar spray of nano-zinc @ 2 mL L^{-1} of water at 35 and 55 DAS
A_4: 100 per cent of recommended nitrogen (N_{100})	B_4: Foliar spray of nano-nitrogen and nano-zinc @ 2 mL L^{-1} of water at 35 and 55 DAS

Control treatments: Control-1: Recommended PK.
Control-2: Recommended NPK.
Recommended NPKZn dose was 50:40:37.5:12.5 kg ha^{-1}.

2.2.1 Nano-fertilizer details

Nano-nitrogen: Commercially procured (IFFCO Nano Urea), liquid formulation, average particle size 20–50 nm, characterized by dynamic light scattering (DLS).

Nano-zinc: Commercially procured (IFFCO Nano Zn), liquid formulation, average particle size 30–50 nm, characterized by scanning electron microscopy (SEM) and confirmed via X-ray diffraction (XRD).

Foliar application of nano-N and nano-Zn (@ 2 mL/L each was carried out twice at 35 and 55 DAS using 500 L ha^{-1} using a knapsack sprayer with a fine nozzle, ensuring uniform spray coverage until leaf surfaces were wet without runoff.

2.3 Crop details and management

The experimental land was prepared by ploughing using bullock drawn country plough. The land was levelled within the plots for sowing, Fertilizers nitrogen, phosphorus and potassium were applied through urea, di-ammonium phosphate and muriate of potash respectively, as per the treatment. Half quantity of N and full quantities of P and K were applied as basal by broadcasting followed by mixing. Remaining half of N was applied as top dressing 30 DAS followed by earthing up operation. The crop variety used was GPU-28, a widely cultivated finger millet variety in southern India. Seeds were sown at a spacing of 30 cm × 10 cm in the field. Standard crop management practices were followed during the experiment. Weed control was carried out through two manual weedings at 20 and 40 DAS. As the crop was grown under rainfed conditions, supplemental irrigation was provided only during prolonged dry spells. Pests and diseases were monitored regularly, and need-based plant protection measures were implemented to ensure healthy crop growth.

2.4 Plant analysis

The plant material was dried in an electric oven at 70 °C for 24 h and finely ground. Nutrient analyses were conducted using standard AOAC procedures (Helrich, 1990). Total nitrogen in plant samples was estimated using the Kjeldahl digestion and distillation method following the procedure outlined by Piper (1966). Total phosphorus was determined colorimetrically by using the vanado-molybdo-phosphoric yellow color method (Jackson, 1973). Potassium content was measured with the help of a calibrated flame photometer. Zinc concentration was determined using atomic absorption spectrophotometer, calibrated using certified zinc standards.

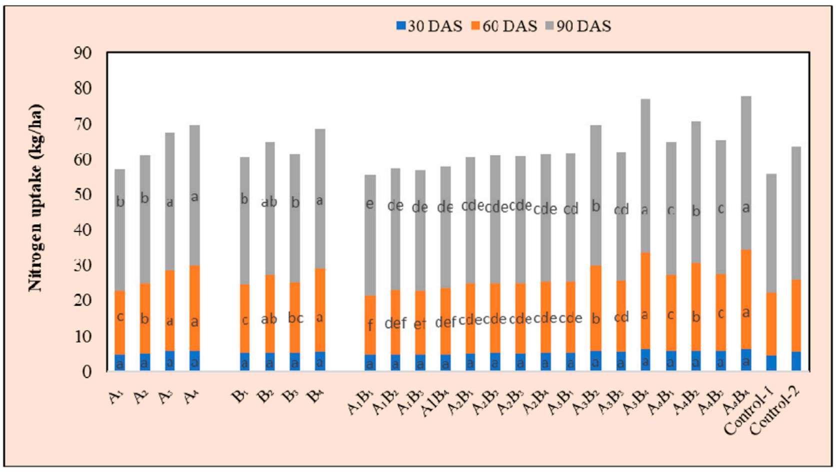

FIGURE 1
Nitrogen uptake (kg ha^{-1}) at different crop growth stages as influenced by nitrogen levels and methods of fertilizer application in finger millet (pooled data of 2 years). Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \le 0.05$.

TABLE 1 Nitrogen uptake at harvest as influenced by nitrogen levels and methods of fertilizer application in finger millet (pooled data of 2 years).

Treatment	Grain uptake (kg ha^{-1})	Straw uptake (kg ha^{-1})	Total uptake (kg ha^{-1})
Factor A (nitrogen levels)			
A_1 - N_0	20.17^{d}	16.17^{b}	36.33^{d}
A_2 - N_{50}	21.66^{c}	16.57^{b}	38.23^{c}
A_3 - N_{75}	28.05^{b}	18.16^{a}	46.20^{b}
A_4- N_{100}	30.30^{a}	18.78^{a}	49.08^{a}
S.Em±	0.14	0.31	0.35
CD at 5%	0.41	0.88	1.02
Factor B (Method of fertilizer application)			
B_1 - Soil application of Zn	22.26^{d}	17.21^{a}	39.47^{c}
B_2 – Nano-N	26.18^{b}	17.57^{a}	43.75^{b}
B_3 – Nano-Zn	23.76^{c}	16.98^{a}	40.74^{c}
B_4 – Nano-N + Nano-Zn	27.98^{a}	17.90^{a}	45.88^{a}
S.Em±	0.14	0.31	0.35
CD at 5%	0.41	0.88	1.02
Interaction (A × B)			
A_1B_1	19.47^{i}	16.67^{de}	36.14^{i}
A_1B_2	20.70^{gh}	15.92^{e}	36.62^{hi}
A_1B_3	19.92^{hi}	16.02^{e}	35.94^{i}
A_1B_4	20.58^{gh}	16.06^{e}	36.64^{hi}
A_2B_1	20.71^{gh}	16.88^{cde}	37.59^{ghi}
A_2B_2	21.62^{fg}	16.57^{de}	38.20^{fgh}
A_2B_3	22.22^{f}	16.21^{e}	38.43^{fg}
A_2B_4	22.10^{f}	16.61d^{e}	38.71^{fg}
A_3B_1	22.35^{f}	17.20^{cde}	39.56^{f}
A_3B_2	31.13^{b}	18.78^{ab}	49.91^{b}
A_3B_3	24.19^{e}	17.28b^{cde}	41.47^{e}
A_3B_4	34.51^{a}	19.37^{a}	53.88^{a}
A_4B_1	26.50^{d}	18.10^{abcd}	44.60^{d}
A_4B_2	31.26^{b}	19.02^{a}	50.29^{b}
A_4B_3	28.72^{c}	18.42^{abc}	47.14^{c}
A_4B_4	34.72^{a}	19.58^{a}	54.30^{a}
S.Em±	0.28	0.61	0.71
CD at 5%	0.82	1.65	2.05
PK (Control-1)	18.53	12.52	31.05
NPK (Control-2)	24.53	17.74	42.27
S.Em±	0.28	0.58	0.67
CD at 5%	0.79	1.65	1.93
CV	2.94	5.80	3.77

RDF-50:40:37.5:12.5 kg NPKZn, ha^{-1};Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.
Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \leq 0.05$.

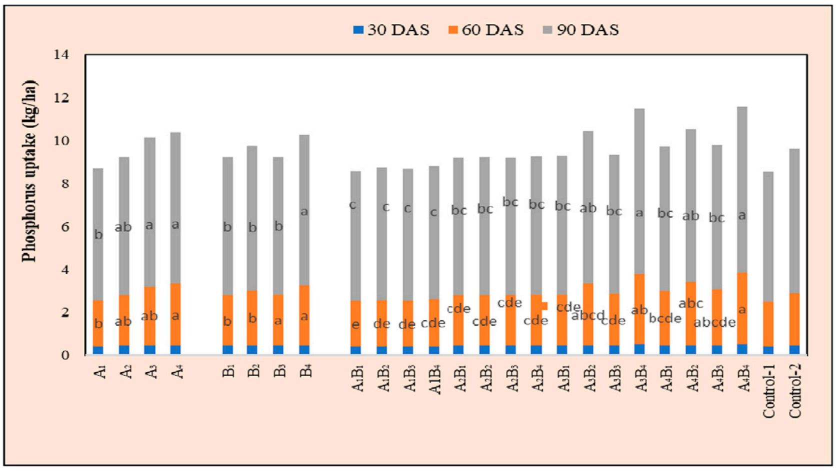

FIGURE 2
Phosphorus uptake (kg ha⁻¹) at different crop growth stages as influenced by nitrogen levels and methods of fertilizer application in finger millet. Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \le 0.05$.

Uptake of N, P, K, and Zn (kg/ha) was calculated individually using the following formula:

$$\text{Uptake of N/P/K (kg/ha)} = \frac{\text{N, P, or K \%} \times \text{dry weight (kg/ha)}}{100}$$

$$\text{Uptake of Zn (g/ha)} = \frac{\text{Zn (ppm)} \times \text{dry weight (kg/ha)}}{1000}$$

2.5 Soil analysis

Prior to chemical analysis, soil samples were collected, air-dried, ground using a wiley mill and sieved through a 2 mm mesh. Available nitrogen was assessed by following Alkaline permanganate method as outlined by Subbaiah and Asija (1956), available phosphorus and potassium content of the soil was quantified following Bray's colorimetry and Flame photometer method respectively outlined by Jackson (1973). All instruments were calibrated prior to analysis using appropriate standards.

2.6 Nutrient use efficiency (NUE)

Nutrient use efficiency (NUE) serves as a key indicator for assessing the performance of crop production systems. The different nutrient use efficiency of nitrogen, phosphorus and potassium (Paul et al., 2015) was calculated using established formulae as below

$$\text{PFP (kg/kg)} = \frac{\text{Yield obtained (kg)}}{\text{Quantity of nutrient applied (kg)}}$$

$$\text{AE (kg/kg)} = \frac{\text{Grain yield of fertilized plot (kg)} - \text{Grain yield of control plot (kg)}}{\text{Quantity of nutrient applied (kg)}}$$

$$\text{ARE (\%)} = \frac{\text{Nutrient uptake of fertilized plot} - \text{Nutrient uptake of control plot (kg)}}{\text{Quantity of nutrient applied (kg)}} \times 100$$

$$\text{IUE (kg /ha)} = \frac{\text{Yield (kg/ha)}}{\text{Uptake (kg/ha)}}$$

Note: PFP- Partial factor productivity; AE- Agronomic efficiency; ARE- Apparent recovery efficiency and IUE- Internal utilization efficiency.

2.7 Pot culture experiment

A complementary pot culture experiment was conducted to assess the physiological and biochemical responses of finger millet to nano-fertilizer application. Pots were filled with 10 kg of air-dried soil. Each treatment was replicated thrice in a completely randomized design (CRD). Nano fertilizers were applied using hand-held sprayers at the same concentrations and timings as in the field study (35 and 55 DAS). Crop management in pots included uniform irrigation every 3–4 days and manual weeding.

Treatment Details.

T_1: N_{50}PKZn
T_2: N_{75}PKZn
T_3: N_{100}PKZn
T_4: N_{50}PK + nano-N (35 and 55 DAS @ 2 mL L^{-1})
T_5: N_{75}PK + nano-N (35 and 55 DAS @ 2 mL L^{-1})
T_6: N_{100}PK + nano-N (35 and 55 DAS @ 2 mL L^{-1})
T_7: N_{50}PK + nano-N + nano-Zn (35 and 55 DAS @ 2 mL L^{-1})
T_8: N_{75}PK + nano-N + nano-Zn (35 and 55 DAS @ 2 mL L^{-1})
T_9: N_{100}PK + nano-N + nano-Zn (35 and 55 DAS @ 2 mL L^{-1})
T_{10}: Absolute control

The recommended NPKZn dose was 50:40:37.5:12.5 kg ha^{-1}.

2.7.1 Physiological and biochemical analysis

2.7.1.1 Chlorophyll content (mg g^{-1} FW)

Chlorophyll content was measured using the Dimethyl Sulfoxide (DMSO) method. Leaf samples were immersed in DMSO and

TABLE 2 Phosphorus uptake at harvest as influenced by nitrogen levels and methods of fertilizer application in finger millet.

Treatment	Grain uptake (kg ha^{-1})	Straw uptake (kg ha^{-1})	Total uptake (kg ha^{-1})
Factor A (Nitrogen levels)			
A_1 - N_0	2.74^{b}	4.04^{b}	6.78^{d}
A_2 - N_{50}	3.07^{b}	4.54^{b}	7.61^{c}
A_3 - N_{75}	4.20^{a}	6.20^{a}	10.39^{b}
A_4- N_{100}	4.49^{a}	6.63^{a}	11.11^{a}
S.Em±	0.04	0.06	0.02
CD at 5%	0.12	0.17	0.04
Factor B (Method of fertilizer application)			
B_1 - Soil application of Zn	3.27^{c}	4.82^{b}	8.09^{c}
B_2 – Nano-N	3.82^{ab}	5.64^{a}	9.45^{b}
B_3 – Nano-Zn	3.35^{bc}	4.94^{b}	8.29^{c}
B_4 – Nano-N + Nano-Zn	4.06^{a}	6.00^{a}	10.06^{a}
S.Em±	0.04	0.06	0.02
CD at 5%	0.12	0.17	0.04
Interaction (A × B)			
A_1B_1	2.70^{g}	3.99^{f}	6.69^{j}
A_1B_2	2.75^{fg}	4.06^{f}	6.80^{ij}
A_1B_3	2.72^{g}	4.02^{f}	6.75^{ij}
A_1B_4	2.77^{fg}	4.10^{f}	6.87^{ij}
A_2B_1	2.85^{fg}	4.22^{f}	7.07^{i}
A_2B_2	3.13^{efg}	4.62^{ef}	7.75^{g}
A_2B_3	2.99^{fg}	4.42^{ef}	7.42^{h}
A_2B_4	3.31^{ef}	4.89^{de}	8.21^{f}
A_3B_1	3.60^{de}	5.32^{cd}	8.93^{e}
A_3B_2	4.48^{bc}	6.62^{b}	11.11^{c}
A_3B_3	3.64^{de}	5.38^{cd}	9.02^{e}
A_3B_4	5.05^{a}	7.46^{a}	12.52^{a}
A_4B_1	3.91^{d}	5.77^{c}	9.68^{d}
A_4B_2	4.91^{ab}	7.25^{a}	12.15^{b}
A_4B_3	4.03^{cd}	5.95^{c}	9.97^{d}
A_4B_4	5.10^{a}	7.54^{a}	12.64^{a}
S.Em±	0.08	0.11	0.03
CD at 5%	0.24	0.33	0.09
PK (Control-1)	2.69	3.97	6.66
NPK (Control-2)	3.76	5.55	9.31
S.Em±	0.08	0.11	0.03
CD at 5%	0.24	0.32	0.09
CV	4.97	4.67	2.19

RDF-50:40:37.5:12.5 kg NPKZn, ha^{-1};Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.
Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \leq 0.05$.

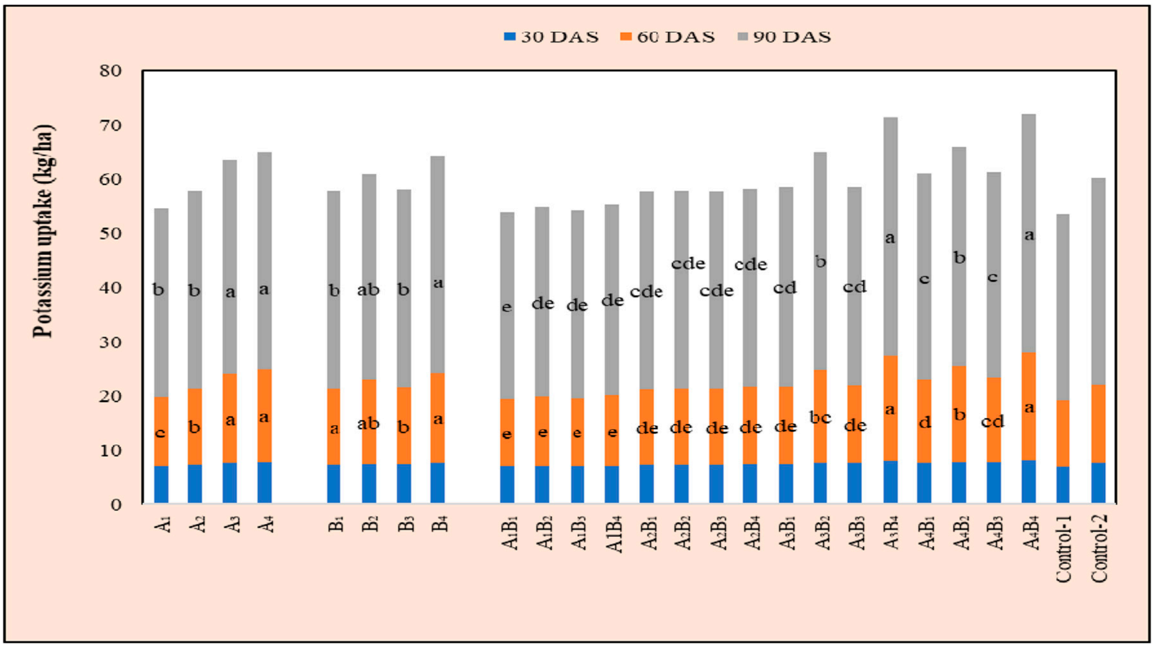

FIGURE 3
Potassium uptake (kg ha^{-1}) at different crop growth stages as influenced by nitrogen levels and methods of fertilizer application in finger millet. Note- Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at p ≤ 0.05.

incubated at 60–65 ˚C. After incubation, absorbance was recorded at 663 nm and 645 nm using a spectrophotometer.

2.7.2 Assay of antioxidant enzyme

2.7.2.1 Enzyme extraction

For the enzyme assay, leaf samples were collected before and 10 days after foliar spraying of nano nutrients at 25, 45 and 65 DAS and stored in ice box. A 0.5-g fresh leaf sample was homogenized in 3 mL of 0.1 M phosphate buffer (pH 7.8) containing 0.5 mM EDTA, using a pre-chilled mortar and pestle. The homogenized tissue was then centrifuged at 10,000 rpm for 10 min at 4 ˚C, and the supernatant was collected for enzyme analysis.

2.7.2.2 Catalase activity assay

Catalase (CAT) activity was assessed using the method given by Barber (1980). To the reaction mixture, 1.5 mL of phosphate buffer, 1 mL of H_2O_2 (0.005 M) and 0.5 mL of enzyme extract were added, and the mixture was incubated at 20 ˚C for 1 min. The reaction was stopped by adding 5 mL of 0.7 N H_2SO_4. The reaction mixture was then titrated with 0.01 N $KMnO_4$ until a faint purple color persisted for at least 15 s. A blank was prepared by mixing the extract with the reaction mixture without incubation. Catalase (CAT) activity was calculated and expressed as mmol H_2O_2 consumed per minute per gram of tissue (mmol $H_2O_2^{-1}$ min^{-1} g^{-1}).

2.7.2.3 Peroxidase activity assay

Peroxidase (POX) activity was determined by following the method of Summer and Gjessing (1943). To the reaction mixture, 1 mL of O-dianisidine (0.01 M in methanol), 0.5 mL of H_2O_2 (0.02 M), 1 mL of phosphate buffer, 2.4 mL of distilled water and 0.2 mL of enzyme extract were added. The mixture was incubated at 30 ˚C for 5 min, after which the reaction was stopped by adding 1 mL of 2 N H_2SO_4. A blank tube, which excluded H_2O_2, was prepared by adding 0.5 mL of distilled water. The color intensity was measured using a spectrophotometer at 430 nm. The peroxidase (POX) activity was expressed as mmol H_2O_2 consumed per minute per gram of tissue (mmol $H_2O_2^{-1}$ min^{-1}g^{-1}).

2.7.2.4 Superoxide dismutase (SOD) activity assay

SOD activity was assayed by following the method of Dhindsa et al. (1981). To the reaction mixture, 0.3 mL of supernatant was added, along with 1.3 µM riboflavin, 63 µM nitroblue tetrazolium (NBT), and 200 mM methionine. The tubes were covered with aluminum foil to shield them from light. A blank was prepared by excluding the enzyme supernatant as a control. The tubes were then exposed to light in a light box for 3 min. The color intensity was measured using a spectrophotometer at a wavelength of 560 nm. SOD activity was expressed as a fold increase over the activity in normal salt-treated plants, in units per gram.

2.8 Statistical analysis

The experimental data were analyzed using Fisher's Analysis of Variance (ANOVA). Data from both seasons were analyzed separately for each year, as well as pooled across the two seasons for a combined statistical evaluation. Analyses of year wise and pooled data were performed as per Gomez and Gomez (1984).

When the F-test indicated a significant difference among treatment means, the corresponding critical difference (CD) was calculated. If no significant difference was found, the results were

TABLE 3 Potassium uptake at harvest as influenced by nitrogen levels and methods of fertilizer application in finger millet.

Treatment	Grain uptake (kg ha^{-1})	Straw uptake (kg ha^{-1})	Total uptake (kg ha^{-1})
Factor A (Nitrogen levels)			
A_1 - N_0	15.48^{c}	24.46^{d}	38.89^{d}
A_2 - N_{50}	16.67^{b}	26.34^{c}	41.88^{c}
A_3 - N_{75}	18.44^{a}	29.14^{b}	46.32^{b}
A_4- N_{100}	19.12^{a}	30.22^{a}	48.04^{a}
S.Em±	0.11	0.05	0.10
CD at 5%	0.33	0.16	0.28
Factor B (Method for fertilizer application)			
B_1 - Soil application of Zn	16.74^{d}	26.46^{d}	42.07^{d}
B_2 – Nano-N	17.69^{b}	27.96^{b}	44.46^{b}
B_3 – Nano-Zn	17.10^{c}	27.03^{c}	42.97^{c}
B_4 – Nano-N + Nano-Zn	18.17^{a}	28.71^{a}	45.65^{a}
S.Em±	0.11	0.05	0.10
CD at 5%	0.33	0.16	0.28
Interaction (A × B)			
A_1B_1	14.99^{j}	23.69^{j}	37.67^{j}
A_1B_2	15.66h^{ij}	24.75^{i}	39.35^{i}
A_1B_3	15.52^{ij}	24.53^{i}	39.00^{i}
A_1B_4	15.74^{hij}	24.87^{i}	39.53^{i}
A_2B_1	16.37^{ghi}	25.87^{h}	41.13^{h}
A_2B_2	16.84^{fg}	26.61^{fg}	42.31^{g}
A_2B_3	16.51^{gh}	26.08^{gh}	41.47^{h}
A_2B_4	16.96^{fg}	26.81^{f}	42.62^{g}
A_3B_1	17.50^{ef}	27.66^{e}	43.97^{f}
A_3B_2	18.89^{bcd}	29.85^{c}	47.46^{d}
A_3B_3	17.64^{ef}	27.88^{e}	44.32^{f}
A_3B_4	19.71^{ab}	31.15^{b}	49.53^{b}
A_4B_1	18.11^{de}	28.62^{d}	45.50^{e}
A_4B_2	19.38^{abc}	30.63^{b}	48.70^{c}
A_4B_3	18.73^{cd}	29.61^{c}	47.07^{d}
A_4B_4	20.26^{a}	32.02^{a}	50.91^{a}
S.Em±	0.23	0.11	0.20
CD at 5%	0.66	0.31	0.56
PK (Control-1)	14.15	22.36	35.55
NPK (Control-2)	17.79	28.11	44.70
S.Em±	0.24	0.94	0.21
CD at 5%	0.70	2.69	0.59
CV	3.43	1.72	1.82

RDF-50:40:37.5:12.5 kg NPKZn, ha^{-1}; Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.
Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \le 0.05$.

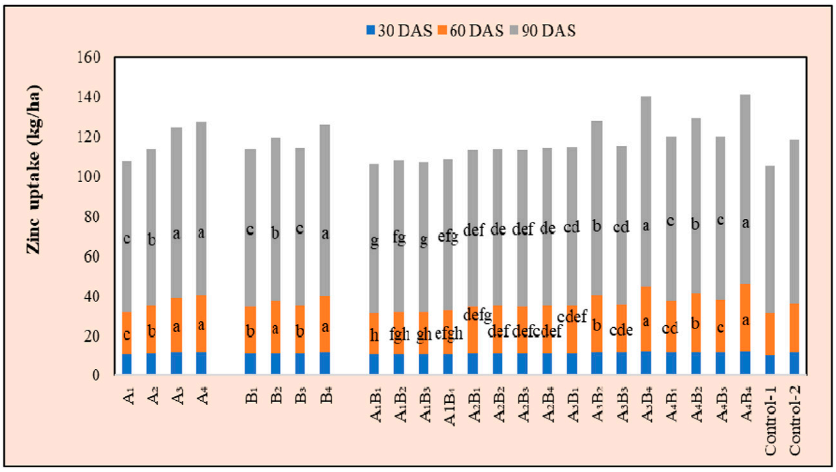

FIGURE 4
Zinc uptake (g ha^{-1}) at different crop growth stages as influenced by nitrogen levels and methods of fertilizer application in finger millet. Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \leq 0.05$.

marked as NS (Non-Significant) in relation to the CD values. All the data were analyzed and the results are presented and discussed at a probability level of 0.05 per cent and correlation study was done as given by Gomez and Gomez (1984). The Pearson correlation coefficient, used to assess the relationship between two variables, was computed based on the experimental data.

3 Results

3.1 Nitrogen uptake

Increasing nitrogen levels enhanced nitrogen uptake by finger millet at all growth stages (Figure 1). Significantly higher uptake was recorded with 100% RDN (24.18 and 39.56 kg ha^{-1}), which was statistically on par with 75% RDN at 60 and 90 DAS respectively. Among the different fertilizer application methods, foliar spray of nano-N + nano-Zn further enhanced uptake (23.58 and 39.32 kg ha^{-1}), surpassing nano-N alone. Significant interaction effects were observed. The combination of 100% RDN + nano-N + nano-Zn resulted in significantly higher uptake (28.26 and 43.31 kg ha^{-1}), which was comparable to 75% RDN + nano-N + nano-Zn. The lowest uptake was recorded in the PK-only control at 60 and 90 DAS, respectively.

Nitrogen uptake in grain and straw was significantly higher under 100% RDN (30.30 and 18.78 kg ha^{-1}), followed by 75% RDN (Table 1). Among the different fertilizer application methods, nano-N + nano-Zn yielded greater uptake in grain (27.98 kg ha^{-1}) and straw (17.90 kg ha^{-1}). The interaction of 100% RDN + nano-N + nano-Zn recorded the highest total uptake (34.72 and 19.58 kg ha^{-1} in grain and straw), comparable to 75% RDN + nano-N + nano-Zn.

3.2 Phosphorus uptake

Phosphorus uptake by finger millet was significantly influenced by nitrogen levels, fertilizer application methods, and their interaction (Figure 2; Table 2). Uptake increased with higher nitrogen application, with the maximum observed under 100% RDN (2.85 and 7.06 kg ha^{-1}), which was statistically similar to 75% RDN, both significantly superior to the control at 60 and 90 DAS, respectively (Figure 2). Among the methods of fertilizer application, foliar spray of nano-N and nano-Zn resulted in significantly higher phosphorus uptake (2.78 and 7.01 kg ha^{-1}) followed by nano-N alone. The interaction of 100% RDN with foliar spray of nano-N and nano-Zn recorded significantly higher uptake (3.34 and 7.73 kg ha^{-1}), statistically on par with 75% RDN + nano-N + nano-Zn at 60 and 90 DAS, respectively.

At harvest, phosphorus uptake in grain and straw was also significantly higher with 100% RDN (4.49 and 6.63 kg ha^{-1}, respectively). Foliar spray of nano-N and nano-Zn enhanced phosphorus uptake in grain (4.06 kg ha^{-1}) and straw (6.00 kg ha^{-1}), outperforming nano-N alone. The combination of 100% RDN with nano-N and nano-Zn resulted in significantly higher uptake in grain (5.10 kg ha^{-1}) and straw (7.54 kg ha^{-1}), statistically on par with 75% RDN + nano-N + nano-Zn (5.05 and 7.46 kg ha^{-1}).

3.3 Potassium uptake

Potassium uptake by finger millet increased significantly with higher nitrogen levels (Figure 3). Significantly higher uptake was recorded under 100% RDN (17.06 and 40.10 kg ha^{-1} at 60 and 90 DAS, respectively), while the lowest occurred with no nitrogen application. Among the different methods of fertilizer application, foliar spray of nano-N and nano-Zn resulted in significantly higher uptake (16.64 and 39.86 kg ha^{-1} at 60 and 90 DAS), followed by nano-N alone (15.39 and 38.00 kg ha^{-1}, respectively). The interaction between nitrogen level and application method was significant. The combination of 100% RDN with foliar spray of nano-N and nano-Zn recorded significantly higher potassium uptake (19.93 and 43.90 kg ha^{-1} at 60 and 90 DAS) and was statistically comparable to 75% RDN with the same foliar spray (19.42 and 43.87 kg ha^{-1}).

TABLE 4 Zinc uptake at harvest as influenced by nitrogen levels and methods of fertilizer application in finger millet.

Treatment	Grain uptake (g ha^{-1})	Straw uptake (g ha^{-1})	Total uptake (g ha^{-1})
Factor A (Nitrogen levels)			
A_1 - N_0	38.22^{d}	46.31^{d}	84.53^{d}
A_2 - N_{50}	42.27^{c}	51.22^{c}	93.49^{c}
A_3 - N_{75}	47.13^{b}	57.12^{b}	104.25^{b}
A_4- N_{100}	48.59^{a}	58.88^{a}	107.47^{a}
S.Em±	0.14	0.10	0.07
CD at 5%	0.41	0.28	0.21
Factor B (Method of fertilizer application)			
B_1 - Soil application of Zn	42.29^{c}	51.24^{d}	93.53^{d}
B_2 – Nano-N	44.56^{b}	53.99^{b}	98.55^{b}
B_3 – Nano-Zn	43.08^{c}	52.20^{c}	95.28^{c}
B_4 – Nano-N + Nano-Zn	46.28^{a}	56.09^{a}	102.37^{a}
S.Em±	0.14	0.10	0.07
CD at 5%	0.41	0.28	0.21
Interaction (A × B)			
A_1B_1	37.25^{h}	45.14^{m}	82.38^{o}
A_1B_2	38.27^{h}	46.37^{l}	84.64^{m}
A_1B_3	37.80^{h}	45.81^{lm}	83.61^{n}
A_1B_4	39.55^{g}	47.93^{k}	87.48^{L}
A_2B_1	40.58^{f}	49.17^{j}	89.76^{k}
A_2B_2	42.85^{e}	51.92^{h}	94.76^{i}
A_2B_3	41.50^{f}	50.29^{i}	91.79^{j}
A_2B_4	44.14^{d}	53.49^{g}	97.63^{h}
A_3B_1	44.81^{d}	54.30^{f}	99.11^{g}
A_3B_2	48.31^{b}	58.54^{cd}	106.85^{d}
A_3B_3	45.12^{d}	54.67^{f}	99.79^{g}
A_3B_4	50.30^{a}	60.96^{b}	111.26^{b}
A_4B_1	46.51^{c}	56.36^{e}	102.86^{f}
A_4B_2	48.81^{b}	59.15^{c}	107.96^{c}
A_4B_3	47.90^{b}	58.04^{d}	105.94^{e}
A_4B_4	51.14^{a}	61.97^{a}	113.10^{a}
S.Em±	0.29	0.19	0.14
CD at 5%	0.82	0.55	0.42
PK (Control-1)	36.42	44.14	80.56
NPK (Control-2)	45.40	55.01	100.41
S.Em±	0.29	0.20	0.15
CD at 5%	0.84	0.56	0.43

RDF-50:40:37.5:12.5 kg NPKZn, ha^{-1};Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.
Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \leq 0.05$.

TABLE 5 Available major nutrient status of soil as influenced by nitrogen levels and methods of fertilizer application in finger millet.

Treatment	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
Factor A (Nitrogen levels)			
A_1 - N_0	244.51^c	97.11^a	167.61^a
A_2 - N_{50}	265.06^b	95.25^a	156.75^b
A_3 - N_{75}	270.84^a	89.58^b	138.48^c
A_4- N_{100}	259.94^b	87.45^b	132.54^d
S.Em±	1.88	0.71	3.36
CD at 5%	5.43	2.04	9.70
Factor B (Method of fertilizer application)			
B_1 - Soil application of Zn	262.51^a	93.87^a	155.79^a
B_2 – Nano-N	259.71^{ab}	91.81^{ab}	146.21^b
B_3 – Nano-Zn	260.88^a	93.00^a	153.58^a
B_4 – Nano-N + Nano-Zn	257.25^b	90.70^b	139.80^c
S.Em±	1.88	0.71	3.36
CD at 5%	5.43	2.04	9.70
Interaction (A × B)			
A_1B_1	243.41^g	95.99	170.10
A_1B_2	244.53^g	97.86	164.32
A_1B_3	244.02^g	98.53	172.29
A_1B_4	246.09^g	96.04	163.71
A_2B_1	263.10^e	96.66	155.36
A_2B_2	269.38^{bc}	94.89	159.83
A_2B_3	262.90^e	95.34	160.07
A_2B_4	264.85^{de}	94.09	151.73
A_3B_1	276.04^a	92.92	151.78
A_3B_2	269.31^{bc}	88.07	130.75
A_3B_3	272.64^{ab}	90.48	149.58
A_3B_4	265.37^{de}	86.86	121.80
A_4B_1	267.49^{cd}	89.93	145.92
A_4B_2	255.63^f	86.44	129.94
A_4B_3	263.98^{de}	87.64	132.36
A_4B_4	252.69^f	85.80	121.44
S.Em±	3.76	1.41	6.72
CD at 5%	10.52	NS	NS
PK (Control-1)	246.41	94.68	161.74
NPK (Control-2)	282.76	89.09	152.88
S.Em±	3.70	1.42	6.54
CD at 5%	10.62	4.08	18.81
CV	3.12	4.83	5.60

RDF-50:40:37.5:12.5 kg NPKZn, ha^{-1};Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.
Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \leq 0.05$.

TABLE 6 Grain yield, straw yield and harvest index as influenced by nitrogen levels and method of fertilizer application in finger millet.

Treatment	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})			Harvest index		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
Factor A (Nitrogen levels)									
A_1 - N_0	1523	1879	1701^{d}	2128	2844	2486^{d}	0.42	0.40	0.41
A_2 - N_{50}	2041	2334	2188^{c}	2834	3620	3227^{c}	0.42	0.40	0.41
A_3 - N_{75}	2822	3152	2987^{b}	4222	4464	4343^{b}	0.40	0.41	0.41
A_4- N_{100}	2925	3213	3069^{a}	4428	4548	4488^{a}	0.40	0.41	0.40
S.Em±	54	31	32	83	54	51	0.01	0.005	0.004
CD at 5%	157	89	93	241	156	146	NS	NS	NS
Factor B (Method of fertilizer application)									
B_1 - Soil application of Zn	2025	2428	2226^{d}	2999	3530	3265^{d}	0.41	0.41	0.41
B_2 – Nano-N	2439	2707	2573^{b}	3509	3919	3714^{b}	0.41	0.41	0.41
B_3 – Nano-Zn	2185	2525	2355^{c}	3266	3735	3500^{c}	0.40	0.40	0.40
B_4 – Nano-N + Nano-Zn	2662	2919	2791^{a}	3838	4292	4065^{a}	0.41	0.40	0.41
S.Em±	54	31	32	83	54	51	0.01	0.005	0.004
CD at 5%	157	89	93	241	156	146	NS	NS	NS
Interactions (A × B)									
A_1B_1	1362	1652	1507^{n}	1977	2673	2325^{m}	0.41	0.38	0.40
A_1B_2	1535	1906	1720^{l}	2143	2812	2478^{l}	0.42	0.41	0.41
A_1B_3	1512	1851	1681^{m}	2133	2809	2471^{l}	0.41	0.40	0.41
A_1B_4	1684	2109	1897^{k}	2257	3081	2669^{k}	0.43	0.41	0.42
A_2B_1	1728	2230	1979^{j}	2378	3107	2743^{j}	0.42	0.42	0.42
A_2B_2	2151	2329	2240^{h}	2995	3834	3414^{h}	0.42	0.38	0.40
A_2B_3	2061	2273	2167^{i}	2890	3594	3242^{i}	0.42	0.39	0.40
A_2B_4	2226	2504	2365^{g}	3072	3943	3508^{g}	0.42	0.39	0.41
A_3B_1	2415	2876	2645^{f}	3651	4051	3851^{f}	0.40	0.41	0.41
A_3B_2	3033	3295	3164^{b}	4448	4513	4480^{b}	0.41	0.42	0.41
A_3B_3	2471	2908	2689^{e}	3784	4230	4007^{e}	0.39	0.41	0.40
A_3B_4	3368	3531	3449^{a}	5007	5063	5035^{a}	0.40	0.41	0.41
A_4B_1	2595	2954	2775^{d}	3991	4288	4139^{d}	0.39	0.41	0.40
A_4B_2	3036	3296	3166^{b}	4450	4514	4482^{b}	0.41	0.42	0.41
A_4B_3	2699	3069	2884^{c}	4256	4308	4282^{c}	0.39	0.41	0.40
A_4B_4	3371	3535	3453^{a}	5015	5081	5048^{a}	0.40	0.41	0.41
S.Em±	109	62	64	167	108	101	0.02	0.01	0.01
CD at 5%	314	178	186	481	312	293	NS	NS	NS
Control 1	1223	1632	1427	1901	2438	2169	0.39	0.40	0.39
Control 2	2499	2932	2715	3957	4246	4101	0.39	0.41	0.40
S.Em±	109	65	63	159	107	100	0.02	0.01	0.01

(Continued on following page)

TABLE 6 (*Continued*) Grain yield, straw yield and harvest index as influenced by nitrogen levels and method of fertilizer application in finger millet.

Treatment	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})			Harvest index		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
CD at 5%	313	186	182	458	309	287	NS	NS	NS

RDF-50:40:37.5:12.5 kg NPKZn, ha^{-1};Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.
Note- Values of means followed by different letter(s) (based on Duncan's multiple range tests) within each column are significantly different at $p \leq 0.05$.

TABLE 7 Nitrogen use efficiency of finger millet as influenced by nitrogen levels and method of fertilizer application.

Treatment	Partial factor productivity (kg kg^{-1})			Agronomic efficiency (kg kg^{-1})			Apparent recovery efficiency (%)			Internal use efficiency (kg kg^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
A_1B_1	-	-	-	-	-	-	-	-	-	39.29	44.01	41.65
A_1B_2	-	-	-	-	-	-	-	-	-	43.65	50.13	46.89
A_1B_3	-	-	-	-	-	-	-	-	-	44.09	49.74	46.92
A_1B_4	-	-	-	-	-	-	-	-	-	47.98	55.44	51.71
A_2B_1	69.12	89.19	79.16	20.22	23.93	22.07	25.10	27.24	26.17	47.86	57.17	52.52
A_2B_2	85.75	91.67	88.71	37.00	27.82	32.41	27.39	29.60	28.50	58.60	58.14	58.37
A_2B_3	82.42	90.90	86.66	33.51	25.64	29.58	28.27	30.75	29.51	56.16	57.45	56.81
A_2B_4	88.74	93.16	90.95	39.99	34.77	37.38	29.35	31.78	30.57	59.87	58.39	59.13
A_3B_1	64.39	76.68	70.54	31.79	33.17	32.48	21.79	23.58	22.68	63.48	63.11	64.10
A_3B_2	80.72	87.68	84.20	48.18	44.26	46.22	48.23	52.16	50.19	63.28	63.62	63.45
A_3B_3	65.88	77.55	71.72	33.28	34.04	33.66	26.69	28.87	27.78	61.93	67.71	64.82
A_3B_4	89.61	93.95	91.78	57.08	50.53	53.80	58.38	63.14	60.76	65.09	70.04	66.76
A_4B_1	51.90	59.08	55.49	27.45	26.45	26.95	26.05	28.18	27.11	60.63	63.91	62.27
A_4B_2	60.63	65.81	63.22	36.21	33.23	34.72	36.91	39.92	38.41	62.92	63.22	63.07
A_4B_3	53.98	61.39	57.68	29.53	28.75	29.14	30.92	33.44	32.18	59.68	62.82	61.25
A_4B_4	67.31	70.58	68.94	42.89	38.00	40.45	44.61	48.24	46.43	64.72	62.73	63.73
C-1	-	-	-	-	-	-	-	-	-	40.86	50.71	45.79
C-2	49.97	58.63	54.30	25.52	26.00	25.76	21.56	23.33	22.44	61.56	66.98	64.27

"–" indicates values not applicable due to absence of nitrogen application in the corresponding treatments.
Treatment details.
A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano-N.
A_3 – N_{75}; B_3 – Nano-Zn.
A_4 – N_{100}; B_4 – Nano-N + Nano-Zn.
C-1 – PK; C-2 – NPK.

At harvest, potassium uptake in grain and straw showed a similar pattern (Table 3). Significantly higher grain and straw uptake was recorded under 100% RDN (19.12 and 30.22 kg ha^{-1}, respectively), which was comparable to 75% RDN (18.44 and 29.14 kg ha^{-1}, respectively). Foliar application of nano-N and nano-Zn enhanced uptake in grain (18.17 kg ha^{-1}) and straw (28.71 kg ha^{-1}), outperforming nano-N alone. Interaction effects revealed significantly higher uptake under 100% RDN + nano-N + nano-Zn (20.26 and 32.02 kg ha^{-1} in grain and straw), statistically on par with 75% RDN + nano-N + nano-Zn. A similar trend was observed in total potassium uptake.

3.4 Zinc uptake

The uptake of zinc was significantly influenced by different nitrogen levels across all crop growth stages, except at 30 DAS (Figure 4; Table 4). As fertilizer application increased, zinc uptake also showed a significant rise. The highest zinc uptake was observed with 100% RDN application (28.88 and 86.86 g ha^{-1} at 60 and 90 DAS, respectively), followed by 50% RDN (23.80 and 78.74 g ha^{-1}), which was comparable to 75% RDN. Foliar spray of nano-N and nano-Zn resulted in significantly higher zinc uptake at 35 and 55 DAS (28.17 and 86.34 g ha^{-1}, respectively), followed by

TABLE 8 Phosphorus use efficiency of finger millet as influenced by nitrogen levels and method of fertilizer application.

Treatment	Partial factor productivity (kg kg^{-1})			Agronomic efficiency (kg kg^{-1})			Apparent recovery efficiency (%)			Internal use efficiency (kg kg^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
A_1B_1	34.04	41.29	37.67	3.48	0.50	1.99	0.04	0.05	0.05	212.10	237.85	224.98
A_1B_2	38.37	47.66	43.01	7.80	6.87	7.33	0.31	0.35	0.34	234.49	270.11	252.30
A_1B_3	37.79	46.26	42.03	7.23	5.47	6.35	0.19	0.21	0.21	233.15	264.27	248.71
A_1B_4	42.11	52.72	47.42	11.54	11.93	11.74	0.49	0.54	0.52	255.16	295.72	275.44
A_2B_1	43.20	55.75	49.47	12.64	14.95	13.79	0.96	1.06	1.02	254.08	303.71	278.90
A_2B_2	53.76	57.47	55.62	23.20	17.44	20.32	2.56	2.82	2.71	288.95	285.68	287.31
A_2B_3	51.51	56.82	54.16	20.95	16.02	18.48	1.77	1.95	1.88	289.60	294.59	292.09
A_2B_4	55.64	58.41	57.03	25.07	21.80	23.44	3.65	4.01	3.86	282.33	273.64	277.98
A_3B_1	60.37	71.89	66.13	29.80	31.10	30.45	5.36	5.88	5.66	281.34	310.30	295.82
A_3B_2	75.83	82.37	79.10	45.27	41.58	43.42	10.53	11.55	11.11	284.45	285.66	285.05
A_3B_3	61.76	72.71	67.24	31.20	31.92	31.56	5.58	6.12	5.89	284.73	310.09	297.41
A_3B_4	84.19	88.26	86.23	53.62	47.47	50.55	13.88	15.21	14.63	280.31	271.50	275.90
A_4B_1	64.88	73.85	69.37	34.31	33.06	33.69	7.14	7.83	7.54	279.48	293.88	286.68
A_4B_2	75.91	82.40	79.15	45.34	41.61	43.47	13.01	14.26	13.72	260.47	261.41	260.94
A_4B_3	67.48	76.73	72.10	36.91	35.94	36.43	7.84	8.59	8.27	282.23	296.13	289.18
A_4B_4	84.27	88.36	86.32	53.70	47.57	50.64	14.17	15.53	14.94	278.11	269.08	273.60
C-1	30.570	40.79	35.68	-	-	-	-	-	-	190.43	235.83	213.13
C-2	62.47	73.29	67.88	31.90	32.50	32.20	6.28	6.88	6.62	279.48	302.56	291.02

"–" indicates not applicable. Agronomic Efficiency (AE) and Apparent Recovery Efficiency (ARE) are calculated as differences between fertilized and control treatments. For control plot (C-1), these values are undefined.
Treatment details.
A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano-N.
A_3 – N_{75}; B_3 – Nano-Zn.
A_4 – N_{100}; B_4 – Nano-N + Nano-Zn.
C-1 - PK; C-2 – NPK.

foliar spray of only nano-N. Significant interaction effects were observed between nitrogen levels and fertilizer application methods for zinc uptake at all stages of crop growth. At 60 and 90 DAS, the combined application of 100% RDN with foliar spray of nano fertilizers resulted in significantly higher zinc uptake (33.75 and 95.11 g ha^{-1}), which was comparable to the application of 75% RDN with foliar spray of nano fertilizers. A similar trend was observed for zinc uptake in the grain, straw and total crop.

3.5 Soil available nutrient status

Soil available nitrogen (259.9 kg ha^{-1}), phosphorus (87.5 kg ha^{-1}), and potassium (132.5 kg ha^{-1}) were found to be the lowest under the treatment involving 100% RDN, in contrast to the slightly higher values recorded with 75% RDN application (Table 5). Among the different fertilizer application methods, foliar spraying of nano-N and nano-Zn at 35 and 55 DAS resulted in lower residual soil NPK values (257.2, 90.7, and 139.8 kg ha^{-1}, respectively) (Table 5). However, the combination of 75% RDN with foliar spray of nano-N and nano-Zn at the same intervals (35 and 55 DAS) significantly improved soil available nitrogen, phosphorus, and potassium (265.4, 86.9, and 121.8 kg ha^{-1}, respectively) compared to the 100% RDN treatment coupled with nano fertilizer spraying. The soil available zinc content did not show any significant variation across nitrogen levels or fertilizer application methods.

3.6 Grain and straw yield (kg ha^{-1})

A substantial difference between treatments was seen regarding grain and straw yield of finger millet (Table 6). The results of the present study indicated that among various nitrogen levels, the application of 100% recommended nitrogen (N) along with recommended phosphorus and potassium (PK) produced significantly higher grain (3069 kg ha^{-1}) and straw yield (4488 kg ha^{-1}) of finger millet, which was statistically at par with the yield obtained with 75% recommended N + PK (2987 and 4343 kg ha^{-1}, respectively). Regarding fertilizer application methods, foliar spray of nano-nitrogen and nano-zinc at 35 and 55 DAS

TABLE 9 Potassium use efficiency of finger millet as influenced by nitrogen levels and method of fertilizer application.

Treatment	Partial factor productivity (kg kg^{-1})			Agronomic efficiency (kg kg^{-1})			Apparent recovery efficiency (%)			Internal use efficiency (kg kg^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
A_1B_1	36.31	44.04	40.18	3.71	0.53	2.12	5.31	5.98	5.64	38.41	41.66	40.04
A_1B_2	40.92	50.83	45.88	8.32	7.32	7.82	9.53	10.72	10.13	41.34	46.15	43.75
A_1B_3	40.31	49.35	44.83	7.71	5.84	6.77	8.65	9.73	9.19	41.16	45.28	43.22
A_1B_4	44.92	56.23	50.58	12.31	12.72	12.52	9.99	11.23	10.61	45.26	50.69	47.98
A_2B_1	46.08	59.46	52.77	13.48	15.95	14.71	13.99	15.74	14.87	44.57	51.93	48.25
A_2B_2	57.35	61.31	59.33	24.74	18.60	21.67	16.96	19.08	18.02	54.00	52.15	53.07
A_2B_3	54.95	60.60	57.77	22.34	17.09	19.72	14.85	16.70	15.78	52.84	52.50	52.67
A_2B_4	59.35	62.31	60.83	26.75	23.25	25.00	17.73	19.95	18.84	55.48	52.64	54.06
A_3B_1	64.39	76.68	70.54	31.79	33.17	32.48	21.13	23.76	22.44	58.28	62.27	60.28
A_3B_2	80.89	87.86	84.38	48.28	44.35	46.32	29.89	33.62	31.75	67.92	66.24	67.08
A_3B_3	65.88	77.55	71.72	33.28	34.04	33.66	22.01	24.75	23.38	59.13	62.87	61.00
A_3B_4	89.80	94.15	91.97	57.20	50.64	53.92	35.07	39.45	37.26	72.28	67.92	70.10
A_4B_1	69.21	78.78	73.99	36.60	35.26	35.93	24.97	28.09	26.53	60.65	62.14	61.40
A_4B_2	80.97	87.89	84.43	48.36	44.38	46.37	32.99	37.10	35.04	66.31	64.68	65.49
A_4B_3	71.98	81.85	76.91	39.37	38.34	38.85	28.90	32.51	30.70	61.00	62.38	61.69
A_4B_4	89.89	94.26	92.07	57.28	50.74	54.01	38.54	43.35	40.95	70.46	66.24	68.35
C-1	32.61	43.51	38.06	-	-	-	-	-	-	36.42	43.92	40.17
C-2	66.63	78.18	72.40	34.03	34.66	34.35	22.94	25.81	24.37	59.42	62.93	61.17

"–" indicates not applicable. Agronomic Efficiency (AE) and Apparent Recovery Efficiency (ARE) are calculated as differences between fertilized and control treatments. For control plot (C-1), these values are undefined.
Treatment details.
A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano-N.
A_3 – N_{75}; B_3 – Nano-Zn.
A_4 – N_{100}; B_4 – Nano-N + Nano-Zn.
C-1 - PK; C-2 – NPK.

recorded significantly higher grain (2791 kg ha^{-1}) and straw yield (4065 kg ha^{-1}) compared to the individual foliar application of nano-nitrogen or nano-zinc. The interaction effect between nitrogen levels and fertilizer application methods was also significant; the combined application of 100% N + PK with foliar spray of nano-N and nano-Zn resulted in the highest grain (3453 kg ha^{-1}) and straw yield (5048 kg ha^{-1}), closely followed by 75% N + PK along with nano-N and nano-Zn foliar spray (3449 and 5035 kg ha^{-1}, respectively). These findings suggest that the integrated use of conventional and nano fertilizers leads to enhanced yield performance over the use of conventional fertilizers alone. The lowest grain and straw yields (1427 and 2169 kg ha^{-1}, respectively) were recorded under the control treatment receiving only PK.

3.7 Nitrogen use efficiency

Across all fertilizer application methods, application of 75% recommended dose of nitrogen (RDN) consistently resulted in higher nitrogen use efficiency compared to the 100% RDN treatment (Table 7). The combination of 75% RDN with recommended phosphorus and potassium (PK), along with foliar spray of nano-nitrogen and nano-zinc, recorded the highest pooled values of partial factor productivity of nitrogen (PFP_n) at 91.78 kg grain per kg N applied and agronomic efficiency of nitrogen (AE_n) at 53.80 kg grain per kg N applied, indicating superior productivity per unit of nitrogen input. The apparent recovery efficiency of nitrogen (ARE_n) was also maximized (60.76%) under this combined treatment, demonstrating improved nitrogen uptake efficiency by the crop. This suggests that using a combination of N75 and Nano-N + Nano-Zn optimizes nitrogen recovery, leading to minimal nitrogen losses. Treatments with Nano-Zn (B3) generally show higher ARE values, supporting the role of zinc in enhancing nitrogen absorption and utilization by crops. Control treatments show relatively lower IUEn, confirming the advantage of advanced nitrogen management techniques.

TABLE 10 Influence of combined application of conventional and foliar spray of nano-N and nano-Zn fertilizers on total chlorophyll (mg g^{-1} FW) and catalase activity (mmol $H_2O_2^{-1}$ $min^{-1}g^{-1}$ FW) (Pooled data of 2 years).

Treatments	Total chlorophyll			Catalase activity		
	25 DAS	45 DAS	65 DAS	25 DAS	45 DAS	65 DAS
T_1: N_{50}PKZn	4.39	5.31	5.72	0.36	0.38	0.44
T_2: N_{75}PKZn	5.18	5.85	6.65	0.40	0.42	0.55
T_3: N_{100}PKZn	5.29	5.91	6.80	0.40	0.43	0.60
T_4: N_{50}PK + nano-N	4.68	5.49	6.31	0.37	0.39	0.47
T_5: N_{75}PK + nano-N	5.37	6.16	6.94	0.42	0.46	0.62
T_6: N_{100}PK + nano-N	5.61	6.41	7.11	0.43	0.48	0.64
T_7: N_{50}PK + nano-N + nano-Zn	4.93	5.78	6.43	0.39	0.42	0.49
T_8: N_{75}PK + nano-N + nano-Zn	5.87	6.72	7.62	0.43	0.50	0.66
T_9: N_{100}PK + nano N + nano-Zn	5.95	6.91	7.77	0.44	0.51	0.67
T_{10}: Absolute control	4.05	4.46	4.61	0.35	0.35	0.43
S.Em±	0.49	0.30	0.25	0.01	0.01	0.01
CD at 5%	NS	0.89	0.74	NS	0.02	0.04

RDF- 50:40:37.5:12.5 kg NPKZn, ha^{-1}; Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.

TABLE 11 Influence of combined application of conventional and foliar spray of nano-N and nano-Zn fertilizers on peroxidase activity (mmol $H_2O_2^{-1}$ $min^{-1}g^{-1}$ FW) and super oxidase dismutase activity (U. g^{-1} FW) (Pooled data of 2 years).

Treatments	Peroxidase activity				Super oxidase dismutase activity	
	25 DAS	45 DAS	65 DAS	25 DAS	45 DAS	65 DAS
T_1: N_{50}PKZn	1.46	1.38	1.49	0.054	0.070	0.076
T_2: N_{75}PKZn	1.58	1.58	1.60	0.061	0.073	0.082
T_3: N_{100}PKZn	1.61	1.61	1.64	0.062	0.074	0.084
T_4: N_{50}PK + nano-N	1.54	1.48	1.53	0.056	0.071	0.079
T_5: N_{75}PK + nano-N	1.63	1.66	1.69	0.064	0.076	0.084
T_6: N_{100}PK + nano-N	1.65	1.67	1.71	0.065	0.081	0.087
T_7: N_{50}PK + nano-N + nano-Zn	1.55	1.52	1.55	0.060	0.073	0.082
T_8: N_{75}PK + nano-N + nano-Zn	1.65	1.69	1.76	0.067	0.084	0.092
T_9: N_{100}PK + nano N + nano-Zn	1.67	1.72	1.79	0.068	0.087	0.094
T_{10}: Absolute control	1.39	1.27	1.43	0.053	0.068	0.073
S.Em±	0.09	0.05	0.05	0.004	0.001	0.001
CD at 5%	NS	0.15	0.14	NS	0.002	0.004

RDF- 50:40:37.5:12.5 kg NPKZn, ha^{-1}; Nano-N, and nano-Zn spray at 35 and 55 DAS @ 2 mL L^{-1}.

3.8 Phosphorus and potassium use efficiency

The pooled data over 2 years on phosphorus and potassium use efficiencies including partial factor productivity (PFP), agronomic efficiency (AE), apparent recovery efficiency (ARE), and internal use efficiency (IUE) demonstrated significant influence of nitrogen levels and fertilizer application methods (Tables 8, 9). Among all fertilizer application strategies, application of 100% recommended dose of nitrogen (RDN) consistently resulted in higher phosphorus and potassium use efficiencies, followed by 75% RDN. Across all nitrogen levels, the soil application of zinc showed comparatively

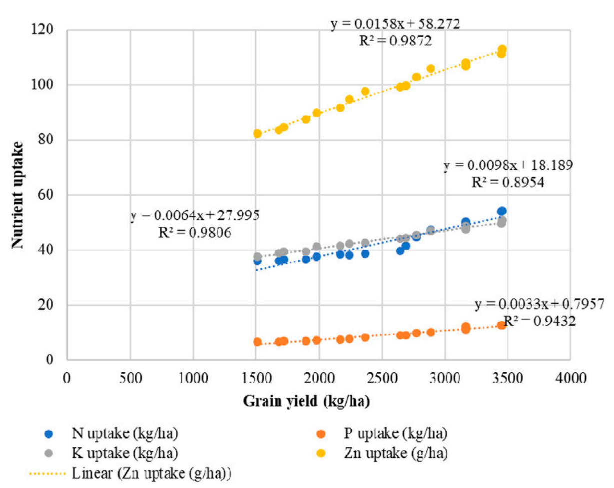

FIGURE 5
Simple linear regression relationship between yield and nutrient uptake.

lower P and K use efficiencies. Notably, the combined application of 100% RDN and recommended PK, along with foliar spray of nano-nitrogen and nano-zinc, recorded the higher PFPp (86.32 kg kg^{-1}), AEp (50.64 kg kg^{-1}), AREp (14.94%) PFPk (92.07 kg kg^{-1}), AEk (54.01 kg kg^{-1}), AREk (40.95%) indicating improved nutrient utilization under integrated nutrient management.

3.9 Pot culture studies

3.9.1 Effect of conventional and nano fertilizers on physiology of finger millet

3.9.1.1 Chlorophyll content (mg g^{-1} FW)

The influence of combined application of conventional and foliar application of nano-nitrogen and nano-Zinc fertilizers on total chlorophyll content 10 days before and after foliar spraying pooled over 2 years is given in Table 10. Before spray (25 DAS), there was no significant difference in chlorophyll content. Application of 100% NPK along with foliar sprays of nano-N and nano- Zn twice resulted in significantly higher chlorophyll a (4.40 and 4.78 mg g^{-1}

TABLE 12 Nitrogen balance (kg ha^{-1}) of finger millet during 2021 as influenced by nitrogen levels and method of fertilizer application.

Nitrogen balance								
Treatments	Initial N (1)	Fertilizers (2)	FYM (3)	Total 4=(1+2+3)	Plant uptake (5)	Expected balance 6 = (4-5)	Actual balance (7)	Net gain/ loss 8=(7-6)
A_1B_1	256.1	0.0	37.5	293.6	34.7	258.9	249.7	-9.2
A_1B_2	256.1	0.0	37.5	293.6	35.2	258.4	250.0	-8.4
A_1B_3	256.1	0.0	37.5	293.6	34.6	259.0	250.0	-9.0
A_1B_4	256.1	0.0	37.5	293.6	35.2	258.4	250.1	-8.3
A_2B_1	256.1	25.0	37.5	318.6	36.1	282.5	261.8	-20.7
A_2B_2	256.1	25.0	37.5	318.6	36.7	281.9	265.4	-16.5
A_2B_3	256.1	25.0	37.5	318.6	36.9	281.7	259.7	-22.0
A_2B_4	256.1	25.0	37.5	318.6	37.2	281.4	260.6	-20.8
A_3B_1	256.1	37.5	37.5	331.1	38.0	293.1	270.0	-23.1
A_3B_2	256.1	37.5	37.5	331.1	48.0	283.1	266.6	-16.5
A_3B_3	256.1	37.5	37.5	331.1	39.8	291.2	268.1	-23.1
A_3B_4	256.1	37.5	37.5	331.1	51.8	279.3	263.1	-16.2
A_4B_1	256.1	50.0	37.5	343.6	42.9	300.7	266.1	-34.7
A_4B_2	256.1	50.0	37.5	343.6	48.3	295.3	256.8	-38.5
A_4B_3	256.1	50.0	37.5	343.6	45.3	298.3	263.6	-34.7
A_4B_4	256.1	50.0	37.5	343.6	52.2	291.4	254.2	-37.2
C-1	256.1	50.0	37.5	293.6	29.8	263.8	249.2	-14.6
C-2	256.1	50.0	37.5	343.6	40.6	303.0	270.0	-33.0

A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano N.
A_3 – N_{75}; B_3 – Nano Zn.
A_4 – N_{100}; B_4 – Nano N + Nano Zn.
C-1 – PK; C-2 – NPK.

TABLE 13 Nitrogen balance (kg ha^{-1}) of finger millet during 2022 as influenced by nitrogen levels and method of fertilizer application.

Nitrogen balance								
Treatments	Initial N (1)	Fertilizers (2)	FYM (3)	Total 4=(1+2+3)	Plant uptake (5)	Expected balance 6=(4-5)	Actual balance (7)	Net gain/ loss 8 = (7-6)
A_1B_1	249.7	0.0	37.5	287.2	37.6	249.6	237.1	-12.5
A_1B_2	250.0	0.0	37.5	287.5	38.1	249.4	239.1	-10.4
A_1B_3	250.0	0.0	37.5	287.5	37.3	250.2	238.1	-12.1
A_1B_4	250.1	0.0	37.5	287.6	38.1	249.5	242.1	-7.5
A_2B_1	261.8	25.0	37.5	324.3	39.1	285.2	264.5	-20.7
A_2B_2	265.4	25.0	37.5	327.9	39.7	288.2	273.4	-14.9
A_2B_3	259.7	25.0	37.5	322.2	40.0	282.2	266.2	-16.0
A_2B_4	260.6	25.0	37.5	323.1	40.2	282.9	269.1	-13.9
A_3B_1	270.0	37.5	37.5	345.0	41.1	303.9	282.1	-21.8
A_3B_2	266.6	37.5	37.5	341.6	51.9	289.8	272.0	-17.8
A_3B_3	268.1	37.5	37.5	343.1	43.1	300.1	277.1	-22.9
A_3B_4	263.1	37.5	37.5	338.1	56.0	282.1	267.6	-14.5
A_4B_1	266.1	50.0	37.5	353.6	46.4	307.2	268.9	-38.3
A_4B_2	256.8	50.0	37.5	344.3	52.3	292.1	254.4	-37.6
A_4B_3	263.6	50.0	37.5	351.1	49.0	302.2	264.3	-37.9
A_4B_4	254.2	50.0	37.5	341.7	56.4	285.3	251.2	-34.1
C-1	249.2	0.0	37.5	286.7	32.3	254.4	243.7	-10.7
C-2	270.0	50.0	37.5	357.5	43.9	313.5	295.5	-18.0

A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano N.
A_3 – N_{75}; B_3 – Nano Zn.
A_4 – N_{100}; B_4 – Nano N + Nano Zn.
C-1 – PK; C-2 – NPK.

F.W), chlorophyll b (4.08 and 4.15 mg g^{-1} FW) and total chlorophyll (6.91 and 7.77 mg g^{-1} FW) at 45 (10 days after first spray) and 65 DAS (10 days after second spray), respectively and were statistically similar with the application of 75% nitrogen and recommended PK + two sprays of nano-N and nano- Zn. Increased nitrogen levels have increased the total chlorophyll content from the range of 5.31–6.91 mg g^{-1} FW at 45 DAS and 5.72–7.77 mg g^{-1} FW at 65 DAS.

3.9.1.2 Anti-oxidant enzyme activity

The antioxidant enzyme activity in finger millet was significantly influenced by the integrated application of conventional fertilizers and foliar spray of nano-nitrogen (nano-N) and nano-zinc (nano-Zn). The relevant data are presented in Tables 10, 11. In the present study, the activity of catalase, peroxidase and superoxide dismutase enzymes showed a marked increase following foliar application of nano-fertilizers at 35 and 55 days after sowing (DAS). The treatment involving 100% recommended dose of nitrogen (RDN) along with recommended phosphorus and potassium, in combination with foliar spray of nano-N and nano-Zn, resulted in significantly higher activities of catalase (0.51 and 0.67 mmol H_2O_2 min^{-1} g^{-1} FW), peroxidase (1.72 and 1.79 mmol H_2O_2 min^{-1} g^{-1} FW), and superoxide dismutase (0.087 and 0.094 U g^{-1} FW) at 45 and 65 DAS, respectively. This was statistically on par with the treatment comprising 75% RDN and recommended PK with nano-fertilizer foliar spray, which recorded catalase (0.50 and 0.66 mmol H_2O_2 min^{-1} g^{-1} FW), peroxidase (1.69 and 1.76 mmol H_2O_2 min^{-1} g^{-1} FW), and superoxide dismutase (0.084 and 0.092 U g^{-1} FW) activities at the respective time intervals (10 days after each foliar spray).

4 Discussion

4.1 Nutrient uptake

Nutrient uptake is critical for increasing production and nutrient content. In the present study, significantly higher nitrogen uptake (Figure 1; Table 1) observed under foliar application of nano-nitrogen and nano-zinc, particularly in the

TABLE 14 Phosphorus balance (kg ha^{-1}) of finger millet during 2021 as influenced by nitrogen levels and method of fertilizer application.

Phosphorus balance								
Treatments	Initial P (1)	Fertilizers (2)	FYM (3)	Total 4 = (1+2+3)	Plant uptake (5)	Expected balance 6 = (4-5)	Actual balance (7)	Net gain/ loss 8 = (7-6)
A_1B_1	51.3	40.0	18.8	110.1	6.4	103.6	83.4	-20.2
A_1B_2	51.3	40.0	18.8	110.1	6.5	103.5	82.3	-21.2
A_1B_3	51.3	40.0	18.8	110.1	6.5	103.6	83.3	-20.2
A_1B_4	51.3	40.0	18.8	110.1	6.6	103.5	82.2	-21.2
A_2B_1	51.3	40.0	18.8	110.1	6.8	103.3	81.1	-22.1
A_2B_2	51.3	40.0	18.8	110.1	7.4	102.6	80.9	-21.7
A_2B_3	51.3	40.0	18.8	110.1	7.1	102.9	81.2	-21.7
A_2B_4	51.3	40.0	18.8	110.1	7.9	102.2	80.2	-22.0
A_3B_1	51.3	40.0	18.8	110.1	8.6	101.5	79.0	-22.5
A_3B_2	51.3	40.0	18.8	110.1	10.7	99.4	76.7	-22.7
A_3B_3	51.3	40.0	18.8	110.1	8.7	101.4	78.8	-22.6
A_3B_4	51.3	40.0	18.8	110.1	12.0	98.0	75.3	-22.8
A_4B_1	51.3	40.0	18.8	110.1	9.3	100.8	76.9	-23.8
A_4B_2	51.3	40.0	18.8	110.1	11.7	98.4	74.5	-23.9
A_4B_3	51.3	40.0	18.8	110.1	9.6	100.5	75.7	-24.8
A_4B_4	51.3	40.0	18.8	110.1	12.1	97.9	75.1	-22.8
C-1	51.3	40.0	18.8	110.1	6.4	103.7	80.4	-23.3
C-2	51.3	40.0	18.8	110.1	8.9	101.1	76.9	-24.3

A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano N.
A_3 – N_{75}; B_3 – Nano Zn.
A_4 – N_{100}; B_4 – Nano N + Nano Zn.
C-1 – PK; C-2 – NPK.

treatment receiving 100% RDN with foliar nano spray is attributed to rapid absorption and efficient penetration through the stomata, enhancing nutrient uptake by the plant. In addition, the smaller particle size of nano fertilizers allows for easier penetration through leaf pores and cell walls, facilitating rapid absorption and efficient translocation via phloem to various plant parts. Nano urea comprises nitrogen particles at the nanoscale (18–30 nm), which possess an exceptionally high surface area up to 10,000 times greater than that of conventional 1 mm urea prills and contain approximately 55,000 nano particles per unit mass-volume compared to a single 1 mm urea particle. These nano nitrogen particles, with pore sizes around 20 nm, can readily penetrate plant cell walls and reach the plasma membrane. Particles within the range of 20–50 nm are capable of entering through stomatal openings. Once inside, they are transported to various parts of the plant via the phloem through plasmodesmata (approximately 40 nm in diameter). Furthermore, these nano particles can interact with carrier proteins via aquaporins, ion channels, or endocytic pathways and are subsequently metabolized within plant cells. The foliar application of nano nitrogen and nano zinc enhances nutrient absorption due to their high surface area and particle size being smaller than the natural pore size (5–50 nm) of the leaf cuticle. This allows for efficient penetration and translocation within plant tissues, ultimately improving nutrient uptake and utilization. These results are in accordance with the findings of Rathnayaka et al. (2018) in rice. In the present study, the enhanced nitrogen uptake resulting from the foliar application of nano-nitrogen and nano-zinc can be attributed to the synergistic interaction between nitrogen and zinc, which likely promoted increased enzymatic activity within the plant system. These findings are consistent with earlier reports by Ashoka et al. (2008) and Apoorva et al. (2016) in rice.

The increase in phosphorus uptake (Figure 2; Table 2) with nano-fertilizer application, particularly at 100% RDN with foliar nano nutrients, may be due to improved root exudation and rhizosphere acidification, promoting phosphate desorption and availability, as reported by Lahari et al. (2021) and Sahu et al. (2022) in rice. Mala et al. (2017) also observed improved P uptake under nano-fertilizer treatment in field bean, corroborating current results. In the present study, the combination of 100 per cent RDN with foliar spray of nano-N and nano-Zn at 2 mL L^{-1} resulted in greater phosphorus uptake. These results are consistent with those of Apoorva et al. (2016) in rice. Potassium uptake (Figure 3; Table 3)

TABLE 15 Phosphorus balance (kg ha^{-1}) of finger millet during 2022 as influenced by nitrogen levels and method of fertilizer application.

Phosphorus balance								
Treatments	Initial P (1)	Fertilizers (2)	FYM (3)	Total 4 = (1+2+3)	Plant uptake (5)	Expected balance 6 = (4-5)	Actual balance (7)	Net gain/ loss 8 = (7-6)
A_1B_1	83.4	40.0	18.8	142.2	7.0	135.2	102.6	-32.6
A_1B_2	82.3	40.0	18.8	141.0	7.1	134.0	109.3	-24.7
A_1B_3	83.3	40.0	18.8	142.1	7.0	135.1	109.2	-25.9
A_1B_4	82.2	40.0	18.8	141.0	7.2	133.8	106.4	-27.5
A_2B_1	81.1	40.0	18.8	139.9	7.4	132.5	110.1	-22.5
A_2B_2	80.9	40.0	18.8	139.7	8.1	131.6	110.5	-21.1
A_2B_3	81.2	40.0	18.8	140.0	7.7	132.3	110.2	-22.0
A_2B_4	80.2	40.0	18.8	138.9	8.5	130.4	108.8	-21.6
A_3B_1	79.0	40.0	18.8	137.7	9.3	128.5	109.0	-19.4
A_3B_2	76.7	40.0	18.8	135.4	11.6	123.9	106.4	-17.5
A_3B_3	78.8	40.0	18.8	137.6	9.4	128.2	106.2	-22.0
A_3B_4	75.3	40.0	18.8	134.0	13.0	121.0	104.6	-16.4
A_4B_1	76.9	40.0	18.8	135.7	10.1	125.6	107.8	-17.8
A_4B_2	74.5	40.0	18.8	133.3	12.6	120.7	102.5	-18.1
A_4B_3	75.7	40.0	18.8	134.4	10.4	124.1	105.7	-18.4
A_4B_4	75.1	40.0	18.8	133.8	13.1	120.7	102.9	-17.8
C-1	80.4	40.0	18.8	139.2	6.9	132.2	101.4	-30.9
C-2	76.9	40.0	18.8	135.6	9.7	125.9	106.3	-19.6

A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano N.
A_3 – N_{75}; B_3 – Nano Zn.
A_4 – N_{100}; B_4 – Nano N + Nano Zn.
C-1 – PK; C-2 – NPK.

was also enhanced under foliar nano-N and nano-Zn application, potentially due to improved nutrient retention and slow-release behavior of nano-N, as well as the synergistic effect between N and K. Similar patterns have been observed in rice (Apoorva et al., 2016).

Higher dry matter production in 100% RDN and 75% RDN resulted in significantly higher zinc uptake. The higher zinc uptake observed with foliar application of nano nutrients (Figure 4; Table 4) could be attributed to the enhanced uptake and translocation efficiency of nano zinc oxide compared to bulk zinc forms. The increase in zinc content in both grain and straw, when combined with 100% RDN and foliar application of nano-N and nano-Zn, may be due to the efficient absorption of zinc through the leaf epidermis. This process facilitates its remobilization into the grain via the phloem and various zinc-regulated transporters, which likely play a pivotal role in regulating this uptake and translocation. Zhou et al. (2011) also reported ZnO nanoparticles with high specific surface and surface can be easily adsorbed on physical surface. Moreover, it can react with biological proteins and even absorbed into the cell faster. Lin and Xing (2007) also investigated and found that ZnO nanoparticles were primarily adsorbed onto the cell surface and then their uptake is followed further quickly and efficiently translocated to the sink. Ashpakbeg and Jamadar (2016) reported the positive effect of foliar applied nanoparticles which enhanced the zinc uptake in upland paddy by 48 per cent over control and enzyme activity by 53 per cent.

However, despite these benefits, the potential risks and limitations associated with nano fertilizers warrant cautious consideration. The long-term impacts of repeated nano-fertilizer application on soil health, potential nanoparticle accumulation, soil microbial diversity, and unintended ecological consequences remain insufficiently studied. Nanoparticles might alter soil enzyme activities, microbial community structures, or interact with non-target organisms, leading to unknown environmental effects. Additionally, the performance of nano fertilizers could vary significantly across different soil textures, pH levels and climatic conditions, which could limit their universal applicability.

4.2 Available nutrient status of soil

The nutrient retention in the soil after crop harvest primarily depends on both the nutrient supply from various sources and the crop's nutrient uptake. Generally, a higher nutrient uptake by the

TABLE 16 Potassium balance (kg ha^{-1}) of finger millet during 2021 as influenced by nitrogen levels and method of fertilizer application.

Potassium balance								
Treatments	Initial P (1)	Fertilizers (2)	FYM (3)	Total 4 = (1+2+3)	Plant uptake (5)	Expected balance 6 = (4-5)	Actual balance (7)	Net gain/ loss 8 = (7-6)
A_1B_1	146.3	37.5	37.5	221.3	35.5	185.9	167.3	-18.6
A_1B_2	146.3	37.5	37.5	221.3	37.0	184.3	165.5	-18.8
A_1B_3	146.3	37.5	37.5	221.3	36.7	184.6	168.2	-16.4
A_1B_4	146.3	37.5	37.5	221.3	37.2	184.1	166.5	-17.6
A_2B_1	146.3	37.5	37.5	221.3	38.7	182.6	160.8	-21.8
A_2B_2	146.3	37.5	37.5	221.3	39.8	181.5	161.5	-20.0
A_2B_3	146.3	37.5	37.5	221.3	39.0	182.3	161.8	-20.5
A_2B_4	146.3	37.5	37.5	221.3	40.1	181.2	159.2	-22.0
A_3B_1	146.3	37.5	37.5	221.3	41.4	180.0	158.4	-21.5
A_3B_2	146.3	37.5	37.5	221.3	44.7	176.7	147.3	-29.3
A_3B_3	146.3	37.5	37.5	221.3	41.7	179.6	159.3	-20.4
A_3B_4	146.3	37.5	37.5	221.3	46.6	174.7	143.0	-31.7
A_4B_1	146.3	37.5	37.5	221.3	42.8	178.5	155.6	-22.9
A_4B_2	146.3	37.5	37.5	221.3	45.8	175.5	146.6	-28.9
A_4B_3	146.3	37.5	37.5	221.3	44.3	177.0	148.6	-28.5
A_4B_4	146.3	37.5	37.5	221.3	47.9	173.4	142.3	-31.1
C-1	146.3	37.5	37.5	221.3	33.5	187.9	163.7	-24.2
C-2	146.3	37.5	37.5	221.3	42.1	179.3	162.2	-17.1

A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano N.
A_3 – N_{75}; B_3 – Nano Zn.
A_4 – N_{100}; B_4 – Nano N + Nano Zn.
C-1 – PK; C-2 – NPK.

crop results in lower residual nutrient availability in the soil. However, several factors, including soil type, nutrient application methods, crop variety and environmental conditions, influence both nutrient uptake by the crop and the residual nutrients remaining in the soil. This lower available soil nutrients is due to the higher uptake of these nutrients by the plant resulting in lower soil nutrient status which is obvious. The soil available nitrogen was slightly higher in 75 per cent RDN than 100 per cent RDN (Table 5) was due to fact that loss of nitrogen from denitrification, volatilization, leaching and fixation in the soil especially NO_3-N and NH_4-N was higher with application of 100 per cent RDN (Zhao et al., 2019). Similar was the observation with respect to phosphorus and potassium because of synergistic interaction of N, P and K and higher seed yield which led to higher uptake of N, P and K (Tarafdar et al., 2014; Meena and Kumar, 2017) thereby resulting in lower available P and K. It is essential to note that excessive nitrogen application may exacerbate nutrient losses and reduce soil sustainability over time. Nano fertilizers may offer a partial solution by improving nutrient retention and uptake efficiency, but their role in reducing leaching and environmental losses must be confirmed through long-term studies under varying field conditions.

4.3 Grain and straw yield

Increased nitrogen rates from 0 to 100 per cent RDN significantly enhanced the grain and straw yield (Table 6). This was mainly due to higher dry matter, leading to higher production and transportation of assimilates to fill the seeds thereby resulting in higher yield McDonald (2002). The increased grain yield observed in the study was primarily attributed to nitrogen application, which enhanced dry matter production, improved the growth rate, promoted internode elongation and stimulated the activity of growth hormones such as gibberellins. These findings align with the results reported by Singh et al. (2000) in rice. The lowest grain and straw yield were recorded with the application of only phosphorus and potassium (control-1), which can be attributed to the imbalanced fertilization that lacked adequate nitrogen.

Furthermore, significant increase in the grain yield observed with the foliar application of nano nutrients was attributed to the improvement in growth parameters and test weight, ultimately leading to an increase in grain yield (Du et al., 2011). This was attributed to improved nutrient uptake by the crop, which facilitated optimal growth of plant parts and supported essential metabolic processes such as photosynthesis. The result was an increased accumulation and translocation of photosynthates to the economic parts of the plant, ensuring higher yield. This can be linked to the enhanced strength of both the source (leaves) and sink (economic part), ultimately contributing to increased productivity. These findings agree with Liu and Lal (2014) and Benzon et al. (2015) in rice.

According to De Rosa et al. (2010), nano fertilizers have the capability to release nutrients in a controlled manner in response to the reaction to various signals like heat, moisture and other abiotic stress. This unique characteristic allows to regulate the release of nutrients, ensuring that crops receive correct quantity of nutrients in suitable proportion and promotes productivity of finger millet grain and straw yield. Millan et al. (2008) stated that NH_4^+ ions held within the internal channels of zeolite are released slowly and freely, which allows the crop to absorb the nutrients progressively, leading to enhanced dry matter production of the crop and ultimately yield. Nano fertilizers have higher surface area to volume ratio thereby increased finger millet productivity effectively (Khanm et al., 2018). Similar trend was observed by Khalil et al. (2019) in maize. Conventional fertilizer along with nano fertilizer application increased the yield and because nano fertilizers have a synergistic impact with conventional fertilizer to improve nutrient absorption by plant cells, resulting in optimal growth (Jyothi and Hebsur, 2017). Similar results were reported by Benzon et al. (2015) in rice and Rathnayaka et al. (2018) in rice.

4.4 Simple linear regression analysis

Although correlation gives information about the nature of relationship that exists between different variables, the significance of the relation and extent is not well defined (Sanam et al., 2021). To assess the relative influence of various nutrient uptake parameters on grain yield, linear regression analysis was performed between each explanatory variable (nutrient uptake) and the dependent variable (grain yield). The relationship between nitrogen uptake and grain yield is illustrated in Figure 5, highlighting that nitrogen uptake plays a critical role in determining yield outcomes under different nitrogen levels and fertilizer application methods. Based on the coefficient of determination (R^2), the predictive contribution of nitrogen, phosphorus, potassium and zinc uptake to grain yield was found to be 89.5%, 94.3%, 98.1%, and 98.7%, respectively.

4.5 Nutrient use efficiency

The data demonstrate that nano-fertilizers, especially the combination of Nano-N and Nano-Zn, significantly improve nitrogen use efficiency in finger millet (Table 7). This effect is most pronounced at N_{75} (A_3B_4), where agronomic efficiency, apparent recovery efficiency, and internal use efficiency are maximized. These findings suggest that 75% recommended dose of nitrogen coupled with nano-fertilizers can sustain high yields while optimizing nitrogen utilization, thereby reducing environmental impacts like nitrogen leaching. Nano-fertilizers having higher surface area due to very smaller size of the nanoparticles that provide more sites to facilitate the different metabolic process in the plant system (Jakhar et al., 2022). This enhances the production of photosynthates while minimizing the nutrient input required by the crop and thus direct contact of nanoparticles by foliar application improved the NUE. 100% N levels has recorded lower nitrogen use efficiency because of the loss of nitrogen from denitrification, volatilization, leaching and fixation in the soil especially NO_3-N and NH_4-N. Higher AE_N was mainly due to more capacity of the plant to increase yield per unit nutrient uptake leading to better accumulation and conversion of N from source to sink. These results are in conformity with the findings of Hulmani et al. (2021) in maize. Sharaf-Eldin et al. (2022) noticed that the application of nano fertilizers (NFs) enhanced fertilizer use efficiency even at reduced nitrogen levels. In the present study, the highest apparent recovery efficiency and nitrogen use efficiency were recorded with 75% of the recommended nitrogen dose along with foliar application of nano nutrients. Higher phosphorus and potassium use efficiencies were found with combined application of 100% N and recommended PK along with foliar spray of nano-N and nano-Zn (Tables 8, 9) was mainly due to efficient utilization of nutrients which is applied as foliar spray results in higher yield. These results were in conformity with the findings of Hulmani et al. (2021) in maize.

4.6 Pot culture studies

4.6.1 Physiological and biochemical analysis

Nano fertilizer application has resulted in higher chlorophyll content (Tables 10, 11) was due to better penetration, mobility and transport of nutrients to the chloroplasts where chlorophyll synthesis occurs. Also, nano zinc activate enzyme δ-aminolevulinic acid dehydratase (ALAD). ALAD plays a crucial role in chlorophyll biosynthesis, acting as a key enzyme in the tetrapyrrole synthesis pathway. Awasthi et al. (2020) stated that when compared to control, nitrogen nano particles were able to permeate plant biological membranes and boost chlorophyll pigments, notably chlorophyll-a, raise up to 38 per cent.

Catalase, peroxidase and superoxide dismutase are enzymes involved in the detoxification of reactive oxygen species (ROS) in plants. ROS are produced as byproducts of various metabolic processes, and their accumulation can lead to oxidative stress and damage to plant cells. Application of nano zinc and nano nitrogen plays a role in regulating the activity of these enzymes. An increase in the activity of these antioxidant enzymes suggests a mitigation of reactive oxygen species (ROS) stress in plants treated with nano fertilizers, which may be attributed to both enhanced ROS production and a corresponding upregulation of the plant's defense mechanisms to scavenge and neutralize ROS, thereby minimizing oxidative damage. Zinc is a cofactor for peroxidase, and its availability can influence the enzyme's Zinc plays a crucial role in plants by regulating free radicals and mitigating their detrimental effects through the enhancement of the plant's

TABLE 17 Potassium balance (kg ha^{-1}) of finger millet during 2022 as influenced by nitrogen levels and method of fertilizer application.

Potassium balance								
Treatments	Initial P (1)	Fertilizers (2)	FYM (3)	Total 4 = (1+2+3)	Plant uptake (5)	Expected balance 6 = (4-5)	Actual balance (7)	Net gain/loss 8 = (7-6)
A_1B_1	167.3	37.5	37.5	242.3	39.9	187.7	173.0	-14.7
A_1B_2	165.5	37.5	37.5	240.5	41.7	181.0	163.2	-17.8
A_1B_3	168.2	37.5	37.5	243.2	41.3	189.2	176.4	-12.8
A_1B_4	166.5	37.5	37.5	241.5	41.9	180.3	160.9	-19.4
A_2B_1	160.8	37.5	37.5	235.8	43.6	171.1	149.9	-21.2
A_2B_2	161.5	37.5	37.5	236.5	44.8	174.9	158.1	-16.8
A_2B_3	161.8	37.5	37.5	236.8	43.9	175.6	158.4	-17.3
A_2B_4	159.2	37.5	37.5	234.2	45.1	166.7	144.3	-22.4
A_3B_1	158.4	37.5	37.5	233.4	46.6	166.0	145.1	-20.9
A_3B_2	147.3	37.5	37.5	222.3	50.3	143.1	114.2	-29.0
A_3B_3	159.3	37.5	37.5	234.3	46.9	163.6	139.9	-23.7
A_3B_4	143.0	37.5	37.5	218.0	52.4	133.1	100.6	-32.5
A_4B_1	155.6	37.5	37.5	230.6	48.2	159.3	136.2	-23.1
A_4B_2	146.6	37.5	37.5	221.6	51.6	141.7	113.3	-28.4
A_4B_3	148.6	37.5	37.5	223.6	49.8	145.0	116.2	-28.8
A_4B_4	142.3	37.5	37.5	217.3	53.9	132.5	101.6	-30.9
C-1	163.7	37.5	37.5	238.7	37.6	180.4	159.8	-20.7
C-2	162.2	37.5	37.5	237.2	47.3	166.7	143.6	-23.2

A_1 – N_0; B_1 – Soil application of Zn.
A_2 – N_{50}; B_2 – Nano N.
A_3 – N_{75}; B_3 – Nano Zn.
A_4 – N_{100}; B_4 – Nano N + Nano Zn.
C-1 – PK; C-2 – NPK.

antioxidant systems, as highlighted in the study by Zago and Oteiza (2001).

4.7 Nutrient balance

The balance sheet of soil available nitrogen, phosphorus and potassium was notably influenced by varying nitrogen levels and different methods of fertilizer application was worked out for two seasons (Tables 12–17). During both the first and second seasons, the actual nutrient balance was generally lower than the expected balance across all treatments, suggesting a net loss of nutrients, likely due to leaching and deep percolation. However, higher net loss was recorded with higher nitrogen levels (N100) as compared to lower nitrogen levels (N_{75}, N_{50} and N_0) while, least nitrogen loss occurs with treatment which has no additional nitrogen (−8.27 kg ha^{-1} and 7.46 kg ha^{-1}) during both the seasons respectively. The higher nitrogen loss occurs with treatment 100% recommended nitrogen along with soil application of zinc during both the seasons respectively (34.65 kg ha^{-1} and 38.33 kg ha^{-1}). Generally, treatments using Nano N, Nano Zn, or their combination resulted in lower nitrogen losses compared to soil applications of Zn. Phosphorus and potassium losses were more consistent across treatments, but treatments with higher nitrogen levels (75% and 100% recommended nitrogen) exhibited slightly higher phosphorus and potassium losses.

5 Conclusion

The combined foliar application of nano-nitrogen and nano-zinc along with 75% RDN significantly improved nutrient uptake, nutrient use efficiency and soil available nutrient status in finger millet. This approach sustains high crop yields while minimizing nitrogen losses, making it a more sustainable alternative compared to conventional fertilizer practices. Long term field evaluations are essential to validate the consistency and durability of these findings across seasons and soil types. Future research should also focus on assessing the scalability of nano-fertilizer application across diverse agro-ecological zones and farming systems. Moreover, exploring the synergistic effects of nano-fertilizers in combination with nano-organic formulations or biofertilizers could further enhance nutrient efficiency, soil health and crop productivity under sustainable production systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MS: Data curation, Formal Analysis, Methodology, Writing – original draft. Mudalagiriyappa: Conceptualization, Methodology, Resources, Supervision, Validation, Visualization, Writing – review and editing. BV: Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing – review and editing. KG: Conceptualization, Resources, Supervision, Visualization, Writing – review and editing. HL: Writing – review and editing. KD: Resources, Supervision, Validation, Writing – review and editing. VV: Writing – review and editing. DR: Writing – review and editing. TS: Writing – review and editing. MK: Writing – review and editing. VS: Writing – review and editing.

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Conflict of interest

Authors TS and MK were employed by Indian Farmers Fertilizer Cooperative Limited, IFFCO Sadan

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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