Nano Fertilizer Application Under Different Establishment Techniques for Sustainable Paddy (*Oryza sativa* L.) Production

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Rice production in Asia is a cornerstone of global food security. Implementing innovative crop establishment practices and utilizing nano fertilizers can enhance rice yields and mitigate environmental concerns, thereby contributing to a resilient and sustainable food system. Therefore, a field experiment was conducted over 2020 and 2021 that included various methods of application (seed treatment, root dipping, soil and foliar application) of nano fertilizers (nano nitrogen and nano zinc) under different rice establishment methods (conventional paddy and SRI). Statistical analysis was performed using Fisher's analysis of variance and Duncan's multiple range test ($p \leq 0.05$). The findings showed that the application of 75% N and two foliar sprays of nano-nitrogen and nano-zinc at 25 to 30 and 45 to 50 days after transplanting under System of Rice Intensification method (Treatment T_{14}) was statistically superior in improving growth and yield parameters, grain and straw yield, and in enhancing the quality of rice over other treatments. Studies revealed strong positive correlations between all the measures, with the exception of the proportion of chaffiness and unfilled grains. The results of the stepwise regression analysis revealed the percentage dependence of grain and straw yield on growth, yield, and quality factors.

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Keywords: Sustainable agriculture; Paddy; SRI; Nano fertilizers; Quality; Yield; Correlation; Regression

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INTRODUCTION

The world's population is predicted to surpass 9.7 billion by 2050, necessitating a 60% increase in food production (United Nations Department for Economic and Social Affairs 2019). The most contributing cereal crops, namely maize, rice, wheat, and their products in world, account for 140.43, 516.25 and 535.49 kcal/capita/day, respectively (FAO 2022). With 197 g/day and 71.9 kg/year, rice has the highest net availability per person of all the cereals in 2020 to 2021 (Directorate of Economics and Statistics 2021).

Rice provides about 700 calories day^{-1} person^{-1} for about 3000 million people living mostly in developing countries (Sangeetha and Baskar 2015).

The success of rice production in Asia will determine the future stability of the world's food supply. In addition to using between 24% and 30% of the global freshwater, rice consumes between 34% and 43% of the irrigation water on the global scale (Surendran *et al*. 2021). According to predictions, Asia's 17 to 22 million hectares of irrigated rice land will experience water scarcity by 2025 (Tuong and Bouman 2002), prompting widespread use of water-saving techniques. While the total employment in agriculture dropped in India from 63.32% in 1991 to 42.6% in 2019 as a result of rapid economic growth in non-agricultural sectors and rising labor wages, manual rice transplanting requires 25 to 50 man-days ha^{-1} (Zhang *et al*. 2011; Singh and Sharma 2012).

Crop establishment procedures can be changed to provide solutions to all of the aforementioned issues. However, transplanting machines are expensive, so poor farmers cannot afford them. Non-availability of herbicides, compulsory land leveling, and more quantity of seeds (8 to 10 kg acre^{-1}) makes direct seeded rice disadvantageous. Aerobic rice is not appropriate for higher rainfall areas where water cannot be controlled and also requires relatively extra weed management (Alam *et al*. 2014; Alam *et al*. 2016; Chakraborty *et al*. 2017). System of Rice Intensification (SRI) is a renowned methodology that greatly enhances rice yield without requiring additional seeds, chemical fertilizer, or other external inputs (Devi and Ponnarasi 2009).

The efficiency of nitrogen fertilizers in Asia is only 20% to 30%, compared to 45% globally. A proper and effective nutrient management could achieve 75% to 80% of potential yield (Sapkota *et al.* 2021). Management of nutrients helps to lower fertilizer losses and increase production (Ye *et al*. 2019). Most rice growing areas are nitrogen-poor, necessitating a strong concentration on nitrogen nutrition (Fageria and Baligar 2003). Consumption of nitrogenous fertilizers in India during 2019 to 2020 was 19,100 thousand tons while it was only 16,735 thousand tons during 2016 to 2017 (Department of Fertilizers, Ministry of Chemicals and Fertilizers 2020).

Zinc deficiency is prevalent in many rice-growing regions (Impa and Johnson-Beebout 2012), with *ca.* 50% of soils in these areas exhibiting low zinc levels (Singh 2008). Submergence of the soil, which is prevalent in rice production, causes a Zn shortage. Zinc deficiency is also common in alkaline or calcareous soils (Prasad *et al*. 2014). Field studies have shown that seed treatment, foliar application, or a combination can effectively enhance zinc uptake and accumulation in grains (Nair *et al*. 2010).

Nanotechnology is a strategy to enhance nutrient use efficiency. Nano fertilizers can be alternatives to conventional fertilizers for gradual and controlled supply of nutrients in the soil (Kottegoda *et al*. 2011; Shang *et al*. 2019). They could be a crucial development in the protection of the environment because they can be applied in smaller quantities compared to traditional fertilizers (Adisa *et al*. 2019), hence reducing leaching, runoff, and gas emissions to the atmosphere (Manjunatha *et al*. 2016). Given the recognized significance of these nano nitrogen and nano zinc in plant development and their common deficiencies in agricultural soils, this investigation was undertaken to explore their potential benefits on growth, yield, and quality parameters of rice.

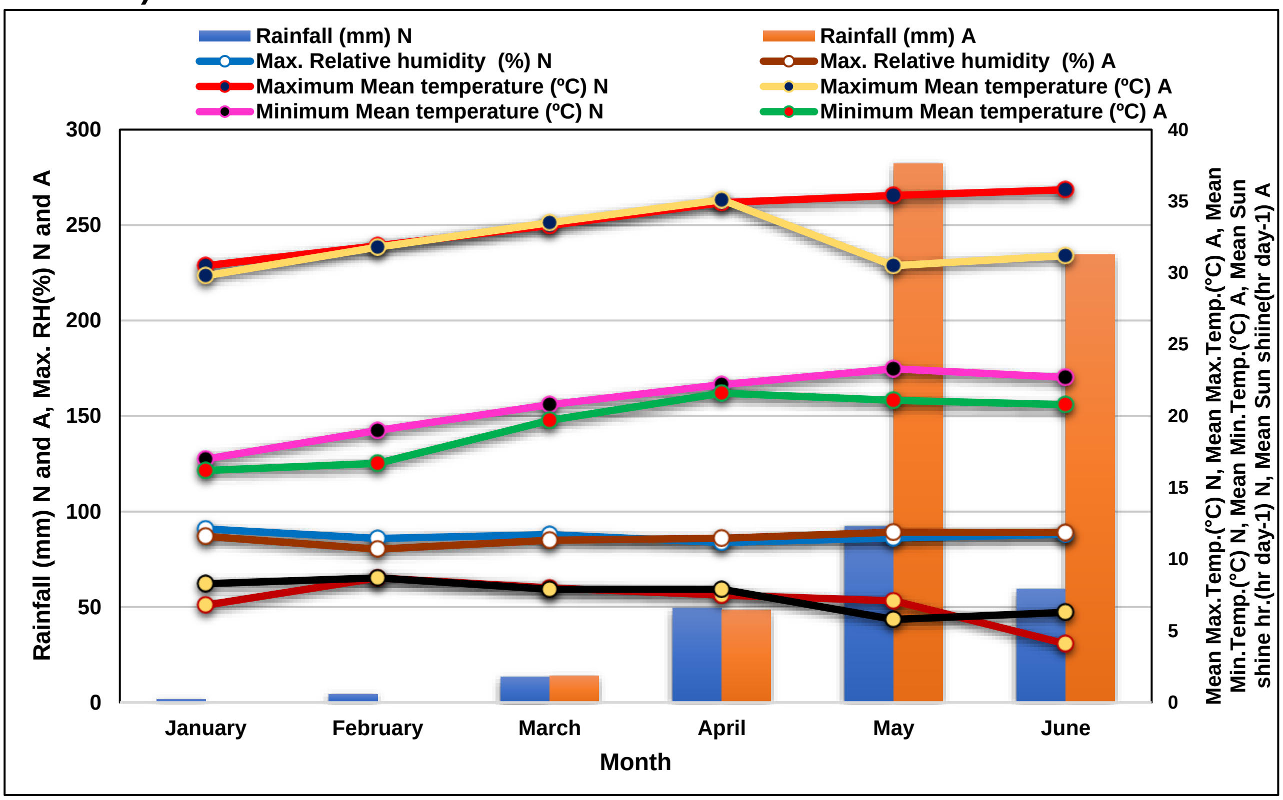
EXPERIMENTAL

Experimental Site

The field experimentation was conducted at the A-block, College of Agriculture, Vishweshwaraiah Canal Farm, Mandya, situated in the Agro-Climatic Zone VI (Southern Dry Zone) of Karnataka at 12º 57' N latitude and 76º 83' E longitude at an altitude of 678 m above mean sea level.

The details of the weather parameters recorded during the crop growth period are depicted in Fig. 1. The soil at the experiment site was sandy clay loam in texture with 57.3%, 14.0%, and 28.6% sand, silt, and clay, respectively. The soil was alkaline in reaction (pH 8.1) and low in soluble salts (0.45 dS m^{-1}).

a)



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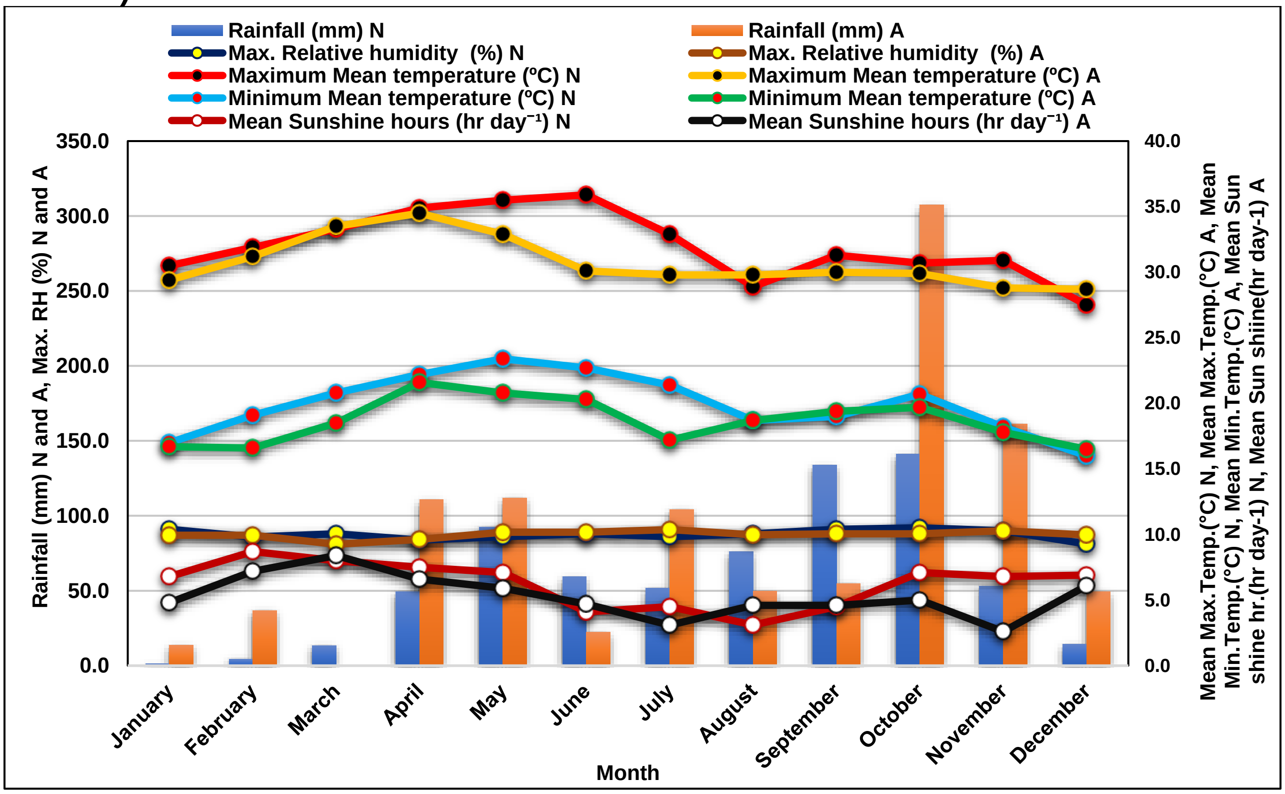


Fig. 1. Meteorological data of the experimental area at College of Agriculture, V. C. Farm, Mandya during a) 2020 and b) 2021

The soil was in the medium range in organic carbon (0.52%), available nitrogen (318 kg ha^{-1}), P_2O_5 (33.5 kg ha^{-1}), K_2O (226 kg ha^{-1}), and S (15.3 mg kg^{-1}). The exchangeable calcium and magnesium content of soil was 8.86 and 2.91 cmol (p+) kg^{-1}, respectively. The DTPA extractable iron, zinc, manganese, copper, and hot water-soluble boron content was 34.9, 1.53, 11.2, and 3.11 mg kg^{-1}, respectively. Bacterial, fungal, and actinomycetes population was 14.2 cfu × 10^5 g^{-1} of soil, 12.2 cfu × 10^4 g^{-1} of soil, and 5.28 cfu × 10^3 g^{-1} of soil, respectively. The dehydrogenase activity was 129 µg TPF g^{-1} soil hr^{-1}, urease activity was 10.7 µg NH_4^+-N g^{-1} hr^{-1}, acid and alkaline phosphatase activity was 17.9 and 13.0 µmol g^{-1} hr^{-1}, respectively.

Treatments and Layout

The experiments were conducted during *kharif* 2020 and 2021. Considering the nature of factors under study and the convenience of agricultural operation, the experiment was laid out in randomized complete block design. The whole field was divided into three blocks each representing a replication. The experiment consisted of 14 treatments and was randomly allocated within the replications. A distance of 0.3 m between treatments and 0.50 m between replications was provided. Bunds with the height of 30 cm were raised in the space available between replications and treatments.

The treatments included were as follows: T_1: TP with recommended practice; T_2: SRI with recommended practice; T_3: TP with 50% RDN + ST; TP_4 with 50% RDN + RD; T_5: TP with 50% RDN + FS; T_6: SRI with 50% RDN + ST; T_7: SRI with 50% RDN + RD; T_8: SRI with 50% RDN + FS; T_9: TP with 75% RDN + ST; T_{10}: TP with 75% RDN + RD;

T_{11}: TP with 75% RDN + FS; T_{12}: SRI with 75% RDN + ST; T_{13}: SRI with 75% RDN + RD; T_{14}: SRI with 75% RDN + FS (Note: TP: Transplanted paddy; SRI: System of Rice Intensification; RP: Recommended practice; ST: Seed treatment; RD: Root dipping; FS: Foliar sprays of both N_{nano} and Zn_{nano}; Recommended FYM, 100% P and K is common to all the treatments; Recommendations are as per package of practice of University of Agricultural Sciences, GKVK, Bangalore).

ST: Seed treatment involved immersing the seeds in a nano-nutrient solution at a concentration of 1000 milliliters per hectare of seed material. This treatment involved soaking the seeds in a solution containing the nano-nutrients prior to sowing. This treatment aimed to enhance seed germination, early seedling vigor, and overall plant growth by delivering essential micronutrients directly to the germinating seeds.

RD: Seedlings were dipped in a 1000 mL/ha nano nutrient solution to facilitate root uptake of nutrients. This technique is commonly used to enhance early plant growth and nutrient acquisition, particularly for micronutrients like zinc.

FS: Two foliar applications of both N_{nano} and Zn_{nano} solutions were administered at two critical growth stages: 25-30 and 45-50 days after transplanting *i.e.* with 20 days interval. Each application utilized a 0.4% concentration solution, ensuring optimal nutrient delivery to the plants.

A commercial nano-nitrogen and a nano-zinc product were sourced from IFFCO, a public sector company.

Seeds were sown in the nursery beds and trays for manual transplanted paddy and SRI method, respectively. Fifteen days prior to transplanting, 10 t ha^{-1} FYM was applied to the experimental plots. The recommended doses of 100 kg N ha^{-1}, 50 kg P_2O_5 ha^{-1}, 50 kg K_2O ha^{-1}, and 20 kg $ZnSO_4$ ha^{-1} fertilizers were applied for specific treatments through urea, single super phosphate (SSP), muriate of potash (MOP), and zinc sulphate ($ZnSO_4$), respectively. A full dose of recommended phosphorus and potassium were applied at the time of transplanting to all the treatments along with 50% N as a basal dose. The remaining 50% N was applied in two splits at 30 and 60 DAT as top dressing according to the treatments.

Methods of Application of Nano Fertilizers

Nano fertilizers were applied as seed treatment (before sowing), root dipping (before transplanting), soil application (mixing nano fertilizers with sand and applied as top dressing), and foliar application (sprayed directly onto the leaves). These are shown in the Fig. 2.

a) Seed treatment

b) Root dipping

c) Soil application

d) Foliar application

Fig. 2. Methods of nano fertilizers application: a) Seed treatment; b) Root dipping; c) Soil application; d) Foliar application

Characterization of Nano Particles

Dynamic light scattering (Zeta Sizer) for particle size analysis

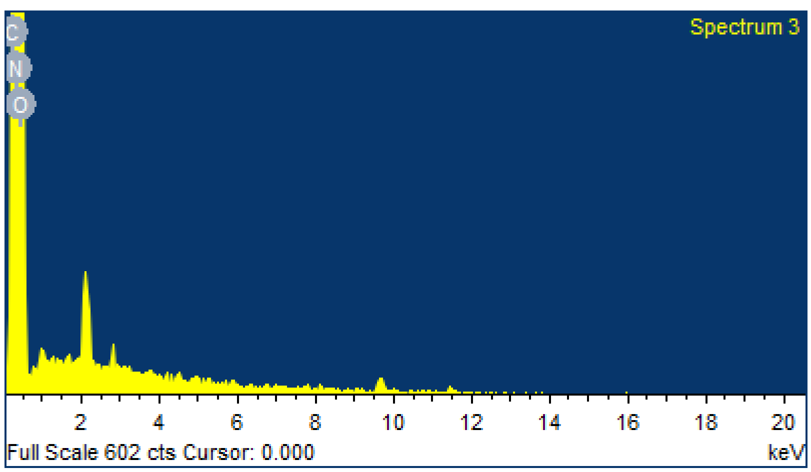
The average particle diameters of nano nitrogen and nano zinc particles were characterized from the intensity distribution analysis by using Zeta Sizer. The average particle diameters of nano nitrogen and nano zinc particles were found to be 57.45 nm and 65.2 nm, respectively. Similar results were confirmed with Gazulla *et al.* (2013) and Wazid *et al.* (2018).

Scanning electron microscopy for surface morphology analysis

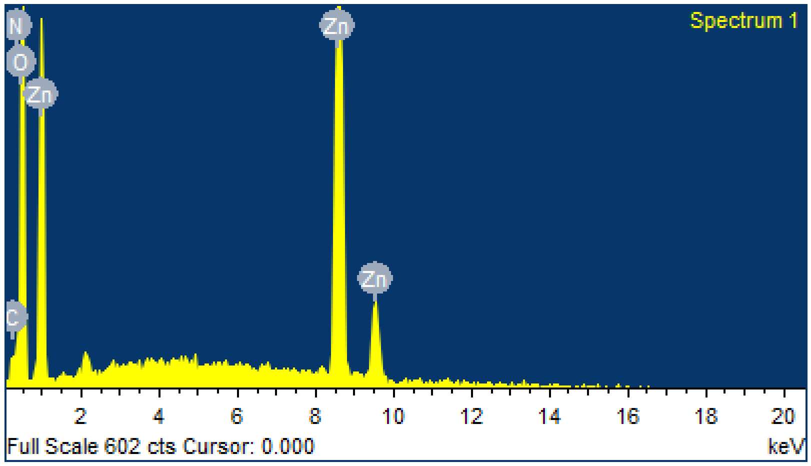
The morphological features of nano nitrogen and nano zinc particles were characterized by scanning electron microscopy (SEM; EVO 18; Carle Zeiss India Pvt Ltd., Germany) and are shown in Fig. 3. The nano nitrogen particles formed were spherical shaped and zinc showed a spherical shape as well. The results are in agreement with the findings of Gazulla *et al.* (2013) and Alamdari *et al.* (2020). The SEM images of nano nitrogen and nano zinc particles on the nano fertilizer sprayed paddy leaves are shown in Fig. 4.

Energy dispersive X-ray spectroscopy for elemental content

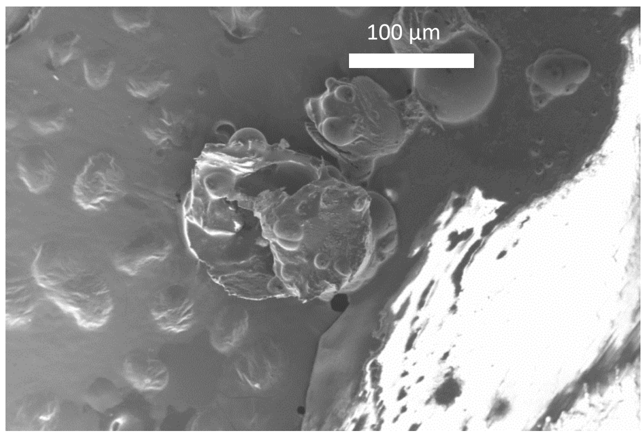
Energy dispersive X-ray spectroscopy (EDX) (Oxford 80; Carle Zeiss India Pvt Ltd., Germany) is an elemental analysis technique, which is used in combination with SEM to determine the chemical composition in the sample and is shown in Fig. 3. The nano nitrogen particles formed were 45.4% weight basis N content in the sample whereas, nano zinc particles formed were 67.2% weight basis Zn content in the sample. Similar results were confirmed with (Gazulla *et al.* 2013).



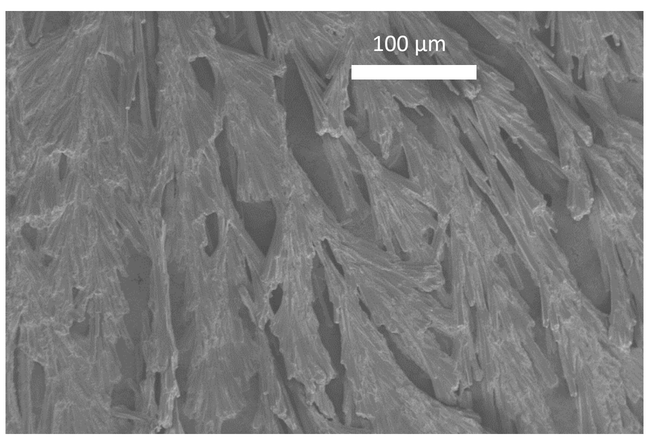
a) Energy-dispersive X-ray spectroscopy of nano nitrogen



b) Energy-dispersive X-ray spectroscopy of nano zinc

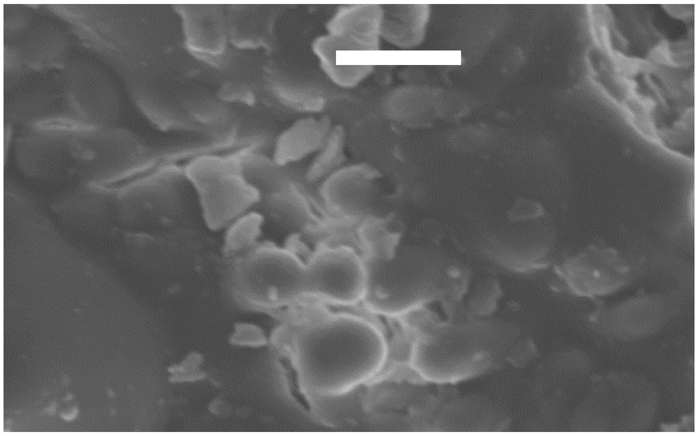


c) Scanning electron microscope image of nano nitrogen

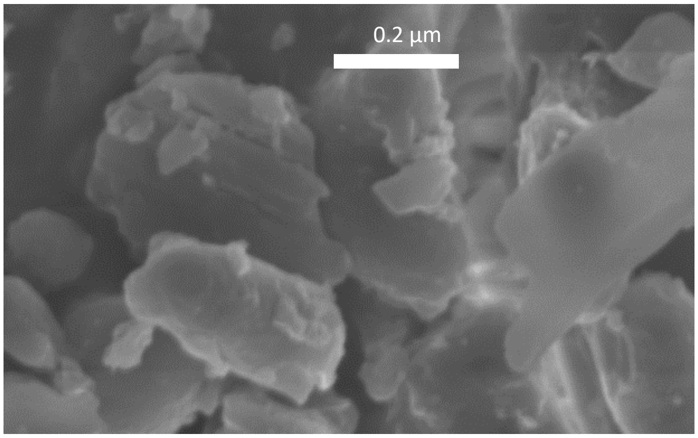


d) Scanning electron microscope image of nano zinc

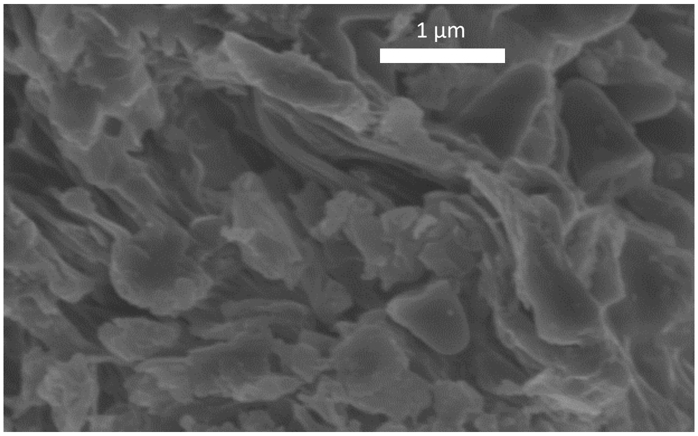
Fig. 3. Characteristics of nano nitrogen and nano zinc particles: a) EDX of nano-N; b) EDX of nano-Zn; c) SEM of nano-N; d) SEM of nano-Zn



a) SEM image of paddy leaves with foliar spray of nano nitrogen



b) SEM image of paddy leaves with foliar spray nano zinc



c) SEM image of paddy leaves with foliar spray nano nitrogen and nano zinc

Fig. 4. SEM images of nano fertilizers on paddy leaves (nano N and nano Zn sprayed): a) SEM image of paddy leaves with nano-N; b) SEM image of paddy leaves with nano-Zn; c) SEM image of paddy leaves with nano-N and nano-Zn

Biochemical Analysis

Carbohydrates

The total carbohydrate content was estimated by the method of Hedge and Hofreiter (1962). Carbohydrate was first hydrolyzed into simple sugars using dilute hydrochloric acid. In hot acidic medium, glucose was dehydrated to hydroxmethyl furfural. This compound formed with anthrone a green-colored product with absorption maximum at 630 nm.

Protein

Total protein was estimated by modified Lowry's method given by Hartree (1972). Determination of protein concentration by ultraviolet absorption depends on the presence of aromatic amino acids in the proteins. To the extracted samples, alkaline $CuSO_4$ reagent was added and incubated at room temperature for 10 min followed by 0.5 mL of Folin's phenol reagent. The contents were mixed well, and the absorbance was measured at 650 nm after 15 min in a spectrophotometer (Cary 60 UV-Vis; Agilent Technologies, India). From the standard graph, the amount of protein in the given unknown solution was calculated.

Tryptophan content

The tryptophan content in grain sample was estimated by colorimetric method (Sadasivam and Manickam 1992). The protein in the grain sample was hydrolyzed with a proteolytic enzyme, papain. Then, the hydrolyzed sample was incubated at 65 °C overnight. A total of 1.0 mL supernatant was taken after centrifugation. To this, 4 mL of ferric chloride was added and kept for incubation at 65 °C for 15 min. The indole ring of tryptophan gives an orange red color with ferric chloride under strongly acidic condition. The intensity was measured at 545 nm. The tryptophan content in sample was estimated by comparing with standard curve:

$$Trptophan\ content = \frac{Tryptophan\ value\ from\ the\ graph\ in\ \mu g\ \times\ 0.096}{Percent\ of\ N\ in\ the\ sample} \times 100$$

Statistical Analysis

Observations recorded during different phenological phases of rice crop were analyzed statistically to find out the result and to draw a conclusion of the experiment conducted. Fisher's method of analysis of variance (ANOVA) was used in the analysis, as given by Gomez and Gomez (1984). Significance between the treatments was tested by Duncan's multiple range test at a significance level of $p \leq 0.05$. The analysis was performed using IBM SPSS, version 22. Correlation and regression analysis were conducted using R4.2.0 software package.

RESULTS AND DISCUSSION

Plant Vegetative Growth Parameters

Different growth parameters, such as plant height, number of tillers per hill, dry matter accumulation in leaves, stem, and panicles, were statistically influenced by the application of 75% N and two foliar sprays of nano nitrogen and nano zinc at 25 to 30 and

45 to 50 DAT under SRI method over rest of the treatments. Data pertaining to growth parameters are presented in Table 1.

Benzon *et al*. (2015) revealed that plant height was more enhanced when nano fertilizer was combined with conventional fertilizers because nano fertilizer can either provide nutrients for the plant or aid in the transport or absorption of available nutrients, thereby resulting in better crop growth. The transplanting of younger seedlings with wider spacing helped for both direction weeding and the application of nano nitrogen and nano zinc as foliar spray improved the availability of nutrients throughout the crop growth period influencing the number of tillers per hill under the SRI method (Geethalakshmi *et al.* 2011; Ghafari and Jamshid 2013).

The increase in dry matter accumulation may be due to the high reactivity of nano fertilizers, especially when they are applied as foliar spray because of more specific surface area in plant leaves (Dhoke *et al*. 2013). Large root volume, profuse tillering, and wider spacing of 25 cm × 25 cm sustained minimum injury while transplanting and established quickly due to the availability of nutrients (Hossain *et al*. 2003; Sathyanarayana and Babu 2004). Further, optimum utilization of resources leads to early tillering in SRI, which made the plants have more time for accumulation of photosynthates in panicles. Nano nitrogen and nano zinc fertilizers applied to the rice crop were readily available to the crop and that made the crop physiologically more active. As a result of better uptake and efficient utilization of nutrients, increased mobilization and accumulation of photosynthates in the reproductive parts of rice were observed. These results are in line with the findings of Armin *et al*. (2014) and Kumar *et al.* (2015a). The positive effect on plant growth of nano fertilizers was reported by Hassan *et al.* (2011), Morteza *et al.* (2013), Kannan *et al.* (2012), Prasad *et al.* (2012), Hedait and Salama (2012), and Tapan *et al.* (2013).

Table 1. Influence of Different Methods of Nano Nitrogen and Nano Zinc Applications on Growth Parameters of Paddy at Harvest During *Kharif* 2020 and 2021

Treatments	Plant Height (cm)			No. of Tillers Hill^{-1}			Dry Matter Accumulation in Leaves (g hill^{-1})			Dry Matter Accumulation in Stem (g hill^{-1})			Dry Matter Accumulation in Panicles (g hill^{-1})		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T$_1$: TP+ Recommended practice	110.57c	125.20e	117.88d	11.03h	13.04h	12.03i	39.54d	47.83d	43.68d	61.18cd	69.43cd	65.31cd	61.01d	60.46d	60.74d
T$_2$: SRI+ Recommended practice	118.56bc	130.11de	124.33cd	18.21f	21.54e	19.88f	93.79b	113.47b	103.63b	97.19b	110.29b	103.74b	105.49b	104.55b	105.02b
T$_3$: TP+ 50% RDN + ST	121.74b	133.83cde	127.79cd	15.60fg	18.46efg	17.03gh	34.93d	42.26d	38.59d	47.98e	54.44e	51.21e	56.30d	55.79d	56.05d
T$_4$: TP**+**50% RDN + RD	124.98b	137.47bcde	131.23bc	13.23gh	15.65gh	14.44hi	35.98d	43.54d	39.76d	50.83de	57.69de	54.26de	58.15d	57.63d	57.89d
T$_5$: TP**+**50% RDN + FS	138.87a	150.77abc	144.82a	18.36f	21.71e	20.03f	37.18d	44.98d	41.08d	58.86cde	66.79cde	62.83cde	59.34d	58.81d	59.08d
T$_6$: SRI+ 50% RDN + ST	124.13b	136.63bcde	130.38bc	24.08de	28.48d	26.28e	40.03d	48.43d	44.23d	62.88cd	71.36cd	67.12c	61.25d	60.70d	60.97d
T$_7$: SRI**+**50% RDN + RD	123.18b	138.74bcde	130.96bc	27.71c	32.77c	30.24cd	55.56c	67.21c	61.38c	63.93c	72.54c	68.23c	74.93c	74.25c	74.59c
T$_8$: SRI**+**50% RDN + FS	138.07a	143.06abcd	140.57ab	30.86ab	38.51ab	34.68ab	93.57b	113.21b	103.39b	96.24b	109.22b	102.73b	103.26b	102.34b	102.80b
T$_9$: TP+ 75% RDN + ST	120.81b	136.63bcde	128.72bcd	16.82f	19.90ef	18.36fg	55.60c	67.27c	61.44c	65.24c	74.04c	69.64c	76.68c	75.99c	76.34c
T$_{10}$: TP**+**75% RDN + RD	124.21b	136.26bcde	130.23bc	15.45fg	18.27fg	16.86gh	92.23b	111.58b	101.90b	93.69b	106.32b	100.00b	100.50b	99.60b	100.05b
T$_{11}$: TP**+**75% RDN + FS	140.88a	152.55ab	146.72a	21.64e	25.59d	23.62e	94.44b	114.26b	104.35b	100.92b	114.53b	107.73b	112.67b	111.66b	112.16b
T$_{12}$: SRI+ 75% RDN + ST	127.40b	136.88bcde	132.14bc	26.66cd	31.53c	29.09d	94.99b	114.93b	104.96b	97.85b	111.04b	104.44b	110.99b	109.99b	110.49b
T$_{13}$: SRI**+**75% RDN + RD	128.16b	136.93bcde	132.55bc	29.02bc	35.90b	32.46bc	95.96b	116.09b	106.02b	98.07b	111.30b	104.69b	111.96b	110.96b	111.46b
T$_{14}$: SRI**+**75% RDN + FS	142.36a	154.92a	148.64a	32.39a	39.64a	36.01a	107.62a	130.20a	118.91a	113.12a	128.37a	120.75a	127.66a	126.51a	127.09a

Values marked by a different letter differ significantly according to Duncan's multiple range test ($p \leq 0.05$)

Table 2. Influence of Different Methods of Nano Nitrogen and Nano Zinc Applications on Yield Parameters of Paddy at Harvest During *Kharif* 2020 and 2021

Treatments	Panicle Length			Panicle Weight			Total Number of Unfilled Grains Panicle^{-1}			Percent Chaffiness			Test Weight		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1: TP+ Recommended practice	16.49c	18.60c	17.54cd	3.07d	3.35d	3.21d	61.44ef	63.96de	62.70ef	36.58g	30.14f	33.36g	17.58c	19.18bc	18.38cd
T_2: SRI+ Recommended practice	18.71bc	21.10bc	19.90bcd	3.34cd	3.64cd	3.49cd	54.15bcde	56.67bcd	55.41bcde	32.47d	26.62cd	29.55cd	19.41bc	21.18bc	20.29bcd
T_3: TP+ 50% RDN + ST	16.05c	18.10c	17.07d	2.80d	3.05d	2.93d	77.25h	79.77g	78.51h	43.36j	36.25i	39.80j	17.03c	18.58c	17.81d
T_4: TP+50% RDN + RD	16.22c	18.30c	17.26cd	2.90d	3.16d	3.03d	72.83gh	75.35fg	74.09gh	40.77i	33.85h	37.31i	17.43c	19.02bc	18.22cd
T_5: TP+50% RDN + FS	16.40c	18.50c	17.45cd	3.06d	3.34d	3.20d	66.43fg	68.95ef	67.69fg	38.47h	31.80g	35.13h	17.56c	19.16bc	18.36cd
T_6: SRI+ 50% RDN + ST	16.67c	18.80c	17.73cd	3.12cd	3.40cd	3.26d	61.22ef	63.74de	62.48ef	36.45g	30.03f	33.24g	18.09bc	19.74bc	18.91bcd
T_7: SRI+50% RDN + RD	17.11bc	19.30bc	18.21cd	3.14cd	3.42cd	3.28d	61.01def	63.53de	62.27def	36.30g	29.89f	33.10g	18.09bc	19.74bc	18.91bcd
T_8: SRI+50% RDN + FS	18.09bc	20.40bc	19.24bcd	3.20cd	3.49cd	3.34cd	54.96cde	57.48cd	56.22cde	32.85d	26.88cd	29.87de	18.35bc	20.02bc	19.19bcd
T_9: TP+ 75% RDN + ST	17.11bc	19.30bc	18.21cd	3.16cd	3.45cd	3.30cd	57.64de	60.16d	58.90de	34.97f	28.74ef	31.85f	18.11bc	19.76bc	18.94bcd
T_{10}: TP+75% RDN + RD	17.64bc	19.90bc	18.77bcd	3.19cd	3.48cd	3.34cd	57.34de	59.86d	58.60de	33.97e	27.84de	30.91ef	18.28bc	19.94bc	19.11bcd
T_{11}: TP+75% RDN + FS	19.68b	22.20b	20.94b	4.63b	5.05b	4.84b	46.13ab	48.65ab	47.39ab	28.32b	23.04b	25.68b	20.74ab	21.90b	21.32ab
T_{12}: SRI+ 75% RDN + ST	18.71bc	21.10bc	19.90bc	3.67c	4.00c	3.84c	52.65bcd	55.17bcd	53.91bcd	31.53c	25.75c	28.64c	19.56bc	21.34bc	20.45bcd
T_{13}: SRI+75% RDN + RD	18.71bc	21.10bc	19.90bc	4.59b	5.00b	4.80b	47.01abc	49.53abc	48.27abc	28.91b	23.50b	26.21b	19.70bc	21.49bc	20.59bc
T_{14}: SRI+75% RDN + FS	22.13a	24.97a	23.55a	5.35a	5.83a	5.59a	41.01a	43.53a	42.27a	23.94a	19.30a	21.62a	22.56a	24.62a	23.59a

Values marked by a different letter differ significantly according to Duncan's multiple range test (p ≤ 0.05)

Table 3. Influence of Different Methods of Nano Nitrogen and Nano Zinc Applications on Grain and Straw Yields of Paddy at Harvest During *Kharif* 2020 And 2021

Treatments	Grain Yield			Straw Yield		
	2020	2021	Pooled	2020	2021	Pooled
T_1: TP+ Recommended practice	5455cde	6118def	5787de	6501cd	7291cde	6896de
T_2: SRI+ Recommended practice	6155bcde	6903bcde	6529bcd	7335bcd	8226bcde	7780bcd
T_3: TP+ 50% RDN + ST	5245e	5882f	5563e	6250d	7009e	6629e
T_4: TP+50% RDN + RD	5373de	6026ef	5700de	6403cd	7181de	6792de
T_5: TP+50% RDN + FS	5395de	6050def	5723de	6429cd	7210de	6819de
T_6: SRI+ 50% RDN + ST	5474cde	6139def	5807de	6523cd	7316cde	6919cde
T_7: SRI+50% RDN + RD	5539cde	6212 cdef	5875cde	6600bcd	7402cde	7001cde
T_8: SRI+50% RDN + FS	5862bcde	6574bcdef	6218bcde	6985bcd	7834bcde	7410bcde
T_9: TP+ 75% RDN + ST	5811bcde	6517bcdef	6164bcde	6924bcd	7766bcde	7345bcde
T_{10}: TP+75% RDN + RD	5835bcde	6544bcdef	6189bcde	6953bcd	7798bcde	7375bcde
T_{11}: TP+75% RDN + FS	6478b	7265b	6871b	7719b	8657b	8188b
T_{12}: SRI+ 75% RDN + ST	6209bcd	6964bcd	6587bcd	7399bcd	8299bcd	7849bcd
T_{13}: SRI+75% RDN + RD	6347bc	7119bc	6733bc	7564bc	8483bc	8023bc
T_{14}: SRI+75% RDN + FS	7434a	8338a	7886a	8859a	9936a	9397a
Values marked by a different letter differ significantly according to Duncan's multiple range test ($p \leq 0.05$)						

Yield Parameters

Different yield parameters represented in Tables 2 and 3, such as panicle length, panicle weight, total number of unfilled grains per panicle, percent chaffiness, test weight, grain yield, and straw yield, were statistically influenced by the application of 75% N and two foliar sprays of nano nitrogen and nano zinc at 25 to 30 and 45 to 50 DAT under SRI method.

Statistically higher panicle length and weight may be due to the enhanced availability of micronutrient by nano zinc application, which increased the photosynthesis and translocation of photosynthates to sink, synthesis of amino acid, chlorophyll, and better carbohydrates transformation along with the positive attributes of SRI. Stomata and base of the trichomes are the major ways for the nano particles to enter into the plant by foliar application, and then the nano particles are translocated to various tissues of the plants (Uzu *et al.* 2010). Similar results were reported by Safarined *et al.* (2013), Sirisena *et al.* (2013), Ruiqiang and Rattan (2014), and Eleyan *et al.* (2018).

Because nano fertilizers are considered as the biological pump for the plants to absorb nutrients and water (Ma *et al.* 2009), more photosynthate accumulation was found in those treatments that received nano nitrogen and nano zinc as foliar spray. Hence, a lower number of unfilled grains and lesser percent chaffiness was recorded in those treatments. Similar results were reported by Harsini *et al.* (2014) and Kumar *et al.* (2015a).

Table 4. Influence of Different Methods of Nano Nitrogen and Nano Zinc Applications on Quality Parameters of Paddy at Harvest During *Kharif* 2020 and 2021

Treatments	Carbohydrates			Protein			Tryptophan			Lysine		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1: TP+ Recommended practice	73.20bc	75.55b	74.38bc	6.61cde	6.91cd	6.76cde	0.68cd	0.71c	0.69c	4.01def	4.19de	4.10de
T_2: SRI+ Recommended practice	79.99bc	82.56b	81.28bc	7.30bc	7.64abc	7.47bc	0.71cd	0.74bc	0.72bc	3.47abcd	3.63abc	3.55abc
T_3: TP+ 50% RDN + ST	69.95c	72.21b	71.08c	5.87e	6.14d	6.01e	0.64d	0.67c	0.66c	4.16f	4.36e	4.26e
T_4: TP+50% RDN + RD	71.69bc	74.00b	72.84bc	6.24de	6.53cd	6.38de	0.67cd	0.70c	0.69c	4.13f	4.32e	4.22e
T_5: TP+50% RDN + FS	71.69bc	74.00b	72.84bc	6.61cde	6.91cd	6.76cde	0.68cd	0.71c	0.69c	4.09ef	4.28e	4.18e
T_6: SRI+ 50% RDN + ST	74.71bc	77.11b	75.91bc	6.61cde	6.91cd	6.76cde	0.69cd	0.72c	0.71c	3.93cdef	4.11cde	4.02cde
T_7: SRI+50% RDN + RD	76.21bc	78.67b	77.44bc	6.87cd	7.18cd	7.03cd	0.69cd	0.73c	0.71c	3.78bcdef	3.95bcde	3.87bcde
T_8: SRI+50% RDN + FS	77.72bc	80.23b	78.98bc	7.03bcd	7.35bc	7.19cd	0.71cd	0.74bc	0.72c	3.47abcd	3.63abc	3.55abc
T_9: TP+ 75% RDN + ST	77.27bc	79.76b	78.52bc	6.99cd	7.31bc	7.15cd	0.71cd	0.74bc	0.72bc	3.54abcde	3.71abcd	3.63abcd
T_{10}: TP+75% RDN + RD	77.60bc	80.10b	78.85bc	7.03bcd	7.35bc	7.19cd	0.71cd	0.74bc	0.72bc	3.47abcd	3.63abc	3.55abc
T_{11}: TP+75% RDN + FS	82.80b	85.47ab	84.14b	7.97ab	8.33ab	8.15ab	0.81ab	0.85ab	0.83ab	3.28ab	3.43ab	3.35ab
T_{12}: SRI+ 75% RDN + ST	80.74bc	83.34b	82.04bc	7.36bc	7.63abc	7.49bc	0.72cd	0.75bc	0.73bc	3.46abcd	3.61abc	3.54abc
T_{13}: SRI+75% RDN + RD	81.50bc	84.12b	82.81bc	7.28bc	7.62abc	7.45bc	0.75bc	0.77abc	0.76bc	3.36abc	3.52ab	3.44ab
T_{14}: SRI+75% RDN + FS	94.57a	96.91a	95.74a	8.26a	8.64a	8.45a	0.84a	0.88a	0.86a	3.20a	3.35a	3.27a

Values marked by a different letter differ significantly according to Duncan's multiple range test ($p \leq 0.05$)

The increased seed weight upon nano nitrogen and nano zinc fertilization was attributed to efficient action of zinc in metabolic processes, like enhanced uptake, translocation of sugars, and higher carbohydrate accumulation in seeds. These results were in line with the findings of Abdoli *et al*. (2014).

The lower yield in normal transplanted paddy with lesser nitrogen was due to lesser production of yield attributing characters because of competition by closer spacing. The results were in line with the findings of Hossain *et al*. (2003), Barison and Uphoff (2010), and Elamathi *et al*. (2012).

Quality Parameters of Paddy

Data pertaining to quality parameters of paddy grains *viz*., carbohydrates, protein, lysine, and tryptophan were recorded and represented based on pooled data of two successive *kharif* seasons in Table 4. Treatment with application of 75% N and two foliar sprays of nano nitrogen and nano zinc at 25 to 30 and 45 to 50 DAT under SRI method recorded statistically higher carbohydrates, protein, and tryptophan contents during *kharif* season. Whereas, statistically higher lysine content was recorded in the treatments in which tryptophan has been found lower, *i.e*., with seed treatment with nano nitrogen and nano zinc before sowing and application of 50% N under transplanted paddy.

Carbohydrates (%)

The availability of essential major and micro nutrients increased due to the nano fertilizers that influenced the amino acid accumulation, improvement in carbohydrate and crude fiber content in straw and grain during the various phenological stages of the crop (Nadi *et al.* 2013).

Protein (%)

Nano zinc enhances the cation-exchange capacity of the roots, which in turn enhances absorption of essential nutrients and foliar application of nano nitrogen, improved dry matter accumulation, and higher nitrogen uptake, which is responsible for higher protein content. Nano nitrogen and nano zinc plays a vital role in carbohydrate and proteins metabolism as well as it controls plant growth hormone, *i.e*., IAA. The results are in accordance with the findings of Satdev *et al.* (2021).

Tryptophan and Lysine (%)

Nano nitrogen and nano zinc enhance the quality by increasing absorption and allocation of other vital nutrients to the plant, thus enhancing the metabolic processes of the plant and playing an important role in many biochemical reactions within the plants. They also improve the protein content through amino acid accumulation due to increased nitrogen metabolism. They act as a stimulant factor that increases the production of indole acetic acid, thereby leading to an increase in amino acids such as tryptophan and decreased lysine content. It is mainly due to the antagonistic activity of tryptophan and lysine (Kisan *et al.* 2015).

Correlation Matrix

The degree of linear association of the grain yield with growth and yield variables (plant height, number of tillers, dry matter accumulation in leaves, stem and panicles, panicle length, panicle weight, chaffiness, and unfilled grains per panicle) is presented in a correlation matrix in Fig. 5.

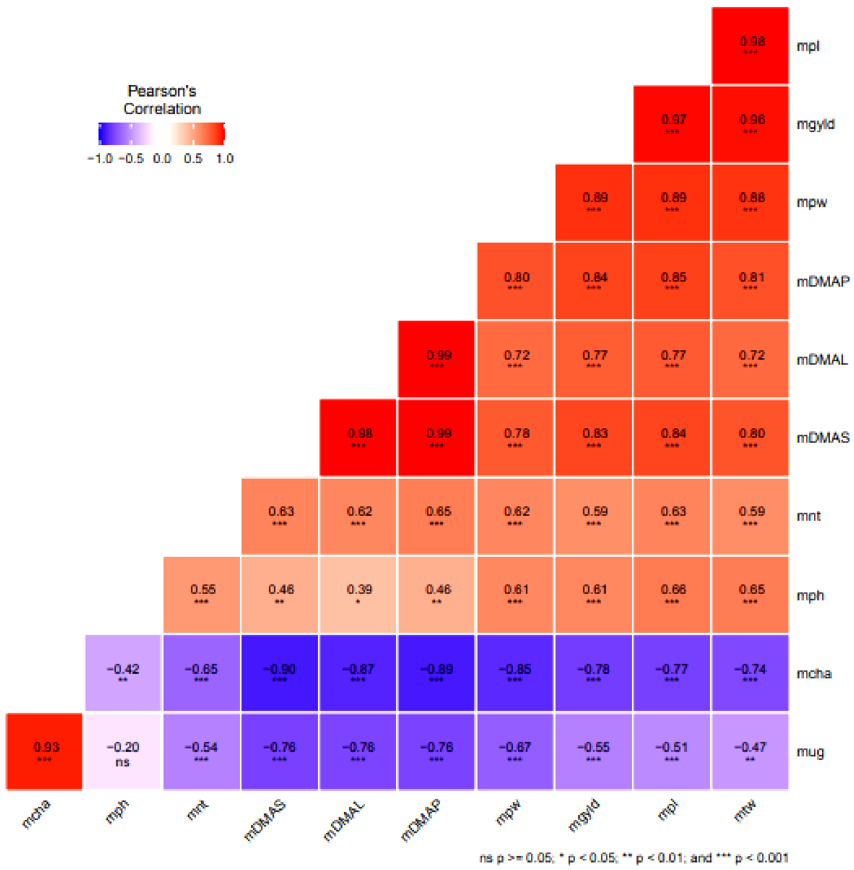


Fig. 5. Pearson's correlation matrix for growth and yield variables in paddy as influenced by different methods of nano nitrogen and nano zinc applications

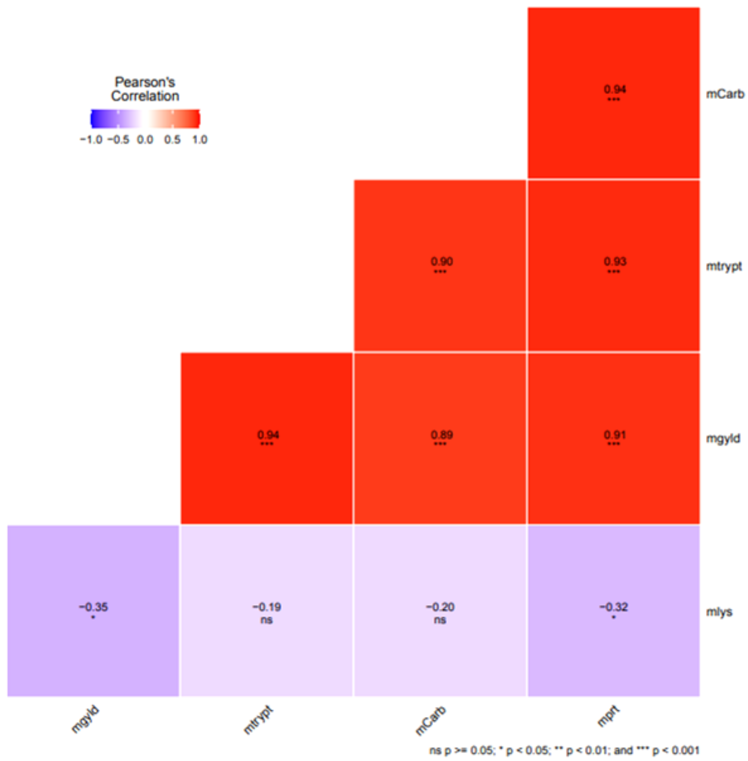


Fig. 6. Pearson's correlation matrix for quality variables in paddy as influenced by different methods of nano nitrogen and nano zinc applications

The yield demonstrated a positive correlation with key vegetative growth parameters, including plant height, tiller number, and dry matter accumulation in leaves, stems, and panicles. Additionally, panicle length and weight were positively associated with yield. Conversely, a statistically significant negative correlation was observed between yield and grain quality parameters, such as chaffiness and the number of unfilled grains per panicle. These findings highlight the importance of these traits in determining the overall yield potential of the crop.

The degree of linear association of the grain yield with quality parameter variables (carbohydrates, protein, tryptophan, and lysine) is presented in a correlation matrix in Fig. 6. The yield positively correlated with the carbohydrates, protein, and tryptophan, while statistically negative correlations were observed with the lysine.

Table 5. Regression Coefficient Estimates of Pooled Data for Different Variables in Stepwise Regression Analysis

Sl. No.	Y (Dependent Variable) = a+b_1x_1+b_2x_2+………………..+e (Independent Variable)	Multiple R^2 Value
1	**Grain yield =** -3390.866 + 0.200 X_1 - 5.114 X_2 - 21.867 X_3 + 8.559 X_4 + 28.080 X_5 + 195.670 X_6 + 15.638 X_7 + 156.951 X_8 - 40.877 X_9 + 123.380 X_{10}	0.9601
2	**Grain yield =** 375.457 + 19.240 A_1 + 0.677 A_2 + 7532.109 A_3 – 304.756 A_4	0.9149
3	**Straw yield =** 6983.041 - 2.236 X_1 - 6.618 X_2 + 18.357 X_3 – 23.273 X_4 – 5.899 X_5 + 96.351 X_6 + 41.889 X_7 + 169.483 X_8 + 67.627 X_9 – 234.228 X_{10}	0.9850
4	**Straw yield =** 25.472 + 97.269 A_1 – 236.992 A_2 + 3526.563 A_3 – 302.590 A_4	0.9806

where X_1 = Plant height, X_2 = No. of tillers, X_3 = Dry matter accumulation in leaves, X_4 = Dry matter accumulation in stem, X_5 = Dry matter accumulation in panicles, X_6 = Panicle length, X_7 = Panicle weight, X_8 = Test weight, X_9 = Unfilled grains, X_{10} = Chaffiness;
A_1 = Carbohydrates, A_2 = Protein, A_3 = Tryptophan, A_4 = Lysine

Stepwise Regression Analysis

Stepwise regression analysis was performed using the grain yield (kg/ha) as a dependent variable and the remaining variables as independent variables. The correlation matrix (Figs. 5 and 6) showed a significant correlation among independent variables, which generates a multicollinearity problem. Stepwise regression analysis overcomes the problem of multicollinearity. The results of stepwise regression coefficients of pooled data for grain yield with growth/yield parameters revealed that out of the many independent variables, ten (Plant height, No. of tillers, Dry matter accumulation in leaves, Dry matter accumulation in stem, Dry matter accumulation in panicles, Panicle length, Panicle weight, test weight, unfilled grains, and chaffiness) were considered to explain the variable grain yield. The regression model was found to be highly significant, with F calculated to be 74.51 (p-value = < $2.2e^{-16}$). This statistical analysis revealed a highly significant regression model, indicating a strong association between the independent and dependent variables. This suggests that the model effectively captures the underlying relationship between the variables and provides a reliable prediction of the dependent variable based on the values of the independent variables. The regression coefficients for all variables are shown in Table 5. The ten variables were found to be significant, and can be used to predict the grain yield. The regression model is as follows:

Grain Yield = -3390.8656 + 0.1998 Plant height - 5.1140 No. of tillers - 21.8672 Dry matter accumulation in leaves + 8.5588 Dry matter accumulation in stem + 28.0795 Dry matter accumulation in panicles + 195.6700 Panicle length + 15.6383 Panicle weight + 156.9508 Test weight - 40.8765 Unfilled grains + 123.3795 Chaffiness

The coefficient of determination (R^2) of 0.9601 indicates that 96.01% of the variability in grain yield can be explained by the variations in the independent variables (growth and yield parameters) included in the model. This high R^2 value suggests that the model is a good fit for the data and that the growth and yield parameters are strong predictors of grain yield. The adjusted R^2 value was 0.9472 (Fig. 7).

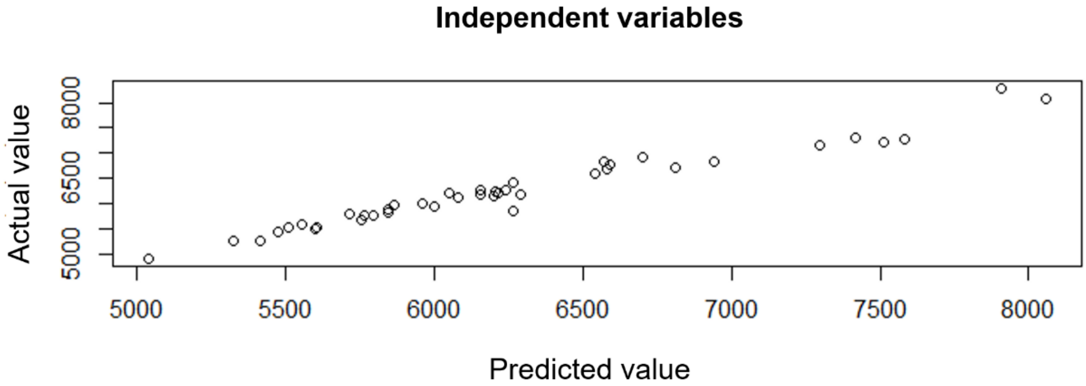


Fig. 7. Stepwise regression coefficients of pooled data for grain yield with growth/yield parameters

The results of stepwise regression coefficients of pooled data for grain yield with quality parameters revealed that four independent variables *viz*., carbohydrates, protein, tryptophan, and lysine were considered to explain the variable grain yield. The regression model was found to be highly significant, with F calculated to be 99.39 (p-value = < $2.2e^{-16}$). The highly significant F-statistic of 99.39 indicates that the regression model as a whole is a strong fit for the data. This suggests that at least one of the independent variables in the model is significantly associated with the dependent variable. The regression coefficients for all variables are shown in Table 5. The four variables were found to be significant, and can be used to predict the grain yield. The regression model is as follows:

Grain Yield = 375.4571 + 19.2400 Carbohydrates + 0.6768 Protein + 7532.1086 Tryptophan – 304.7564 Lysine

The coefficient of determination (R^2) value was 0.9149, which means that 91.49% of the variation in the dependent variable (grain yield) is explained by the model. The adjusted R^2 value was 0.9057 (Fig. 8).

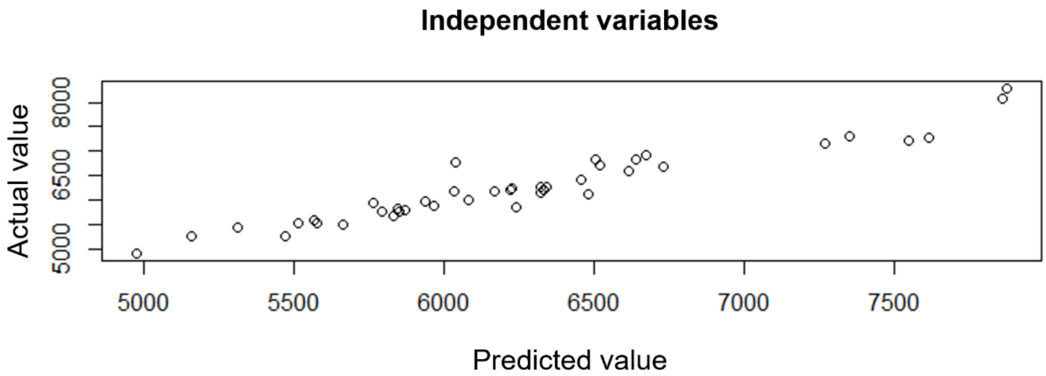


Fig. 8. Stepwise regression coefficients of pooled data for grain yield with quality parameters

The results of stepwise regression coefficients of pooled data for straw yield with growth/yield parameters revealed that out of the many independent variables, ten (Plant height, No. of tillers, Dry matter accumulation in leaves, Dry matter accumulation in stem, Dry matter accumulation in panicles, Panicle length, Panicle weight, test weight, unfilled grains. and chaffiness) were considered to explain the variable straw yield.

The regression model was found to be highly significant, with F calculated to be 203.5 (p-value = < $2.2e^{-16}$). The regression coefficients for all variables are shown in Table 5. The ten variables were found to be significant, and can be used to predict the grain yield. The regression model is as follows:

Straw Yield = 6983.041 - 2.236 Plant height - 6.618 No. of tillers + 18.357 Dry matter accumulation in leaves – 23.273 Dry matter accumulation in stem – 5.899 Dry matter accumulation in panicles + 96.351 Panicle length + 41.889 Panicle weight + 169.483 Test weight + 67.627 Unfilled grains – 234.228 Chaffiness

The coefficient of determination (R^2) value was 0.985, which means that 98.50% of the variation in the dependent variable (straw yield) is explained by the model and also indicates the extent of dependability on growth and yield variables. The adjusted R^2 value was 0.9802 (Fig. 9).

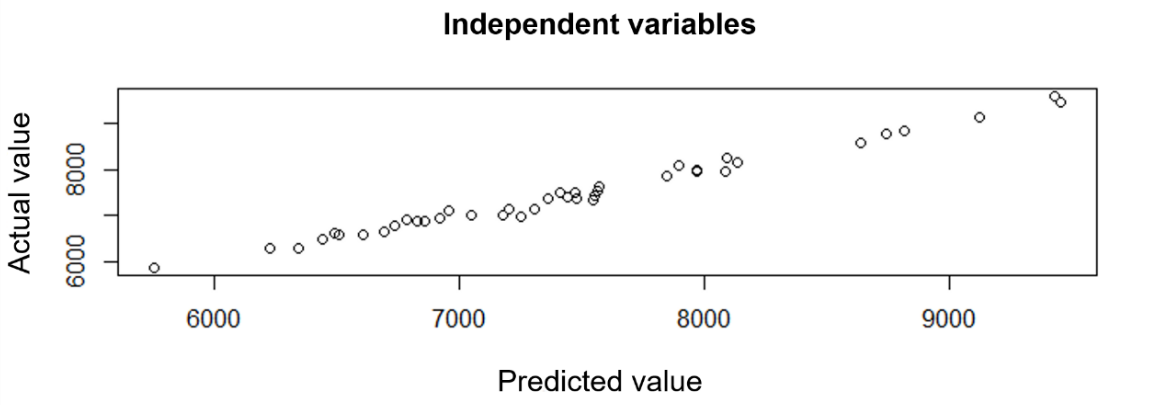


Fig. 9. Stepwise regression coefficients of pooled data for straw yield with growth/yield parameters

The results of stepwise regression coefficients of pooled data for straw yield with quality parameters revealed that four independent variables *viz*., Carbohydrates, protein, tryptophan, and lysine, were considered to explain the variable straw yield. The regression model was found to be highly significant, with F calculated to be 517.9 (p-value = < $2.2e^{-16}$). The regression coefficients for all variables are shown in Table 5. The four variables were found to be significant, and can be used to predict the grain yield. The regression model is as follows:

Straw Yield = 25.472 + 97.269 Carbohydrates – 236.992 Protein + 3526.563 Tryptophan – 302.590 Lysine

The coefficient of determination (R^2) value was 0.9825, which means that 98.25% of the variation in the dependent variable (straw yield) is explained by the model. The adjusted R^2 value was 0.9806 (Fig. 10).

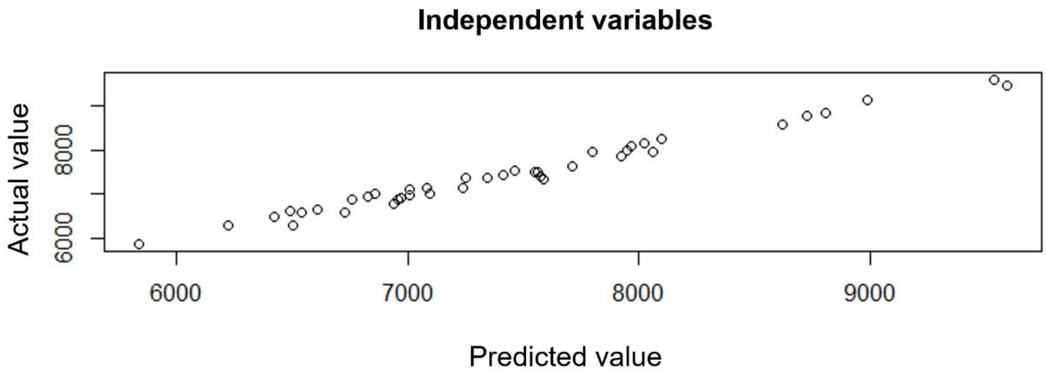


Fig. 10. Stepwise regression coefficients of pooled data for straw yield with quality parameters

CONCLUSIONS

1. The treatment receiving 75% N and two foliar sprays of nano nitrogen and nano zinc at 25 to 30 and 45 to 50 DAT under SRI method (T14) was statistically superior in improving growth and yield parameters, grain and straw yields, and it was also superior in enhancing the quality of rice over rest of the treatments.
2. The lower yield in normal transplanted paddy with lesser nitrogen can be attributed to lesser production of yield attributing characters because of competition by closer spacing.
3. Correlation studies showed high positive correlation among all the parameters except for unfilled grains and chaffiness percentage, which showed high negative correlation with the grain yield.
4. The stepwise regression analysis showed the percentage dependability of grain and straw yields on the growth, yield, and quality parameters. It infers that the improvement in such variables is the key to enhance the yield of paddy in regions with similar agro-climatic conditions.

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CONFLICT OF INTEREST

There are no relevant financial or non-financial competing interests to report.

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