Journal of Soil Science and Plant Nutrition (2023) 23:540–555
https://doi.org/10.1007/s42729-022-01064-8

ORIGINAL PAPER

Effect of Integrated Nutrient Management and Foliar Spray of Zinc in Nanoform on Rice Crop Nutrition, Productivity and Soil Chemical and Biological Properties in Inceptisols

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Received: 22 April 2022 / Accepted: 15 November 2022 / Published online: 5 December 2022

Abstract
The impact of combined use of inorganic and organic nutrients in supplementation with foliar spray of zinc in nanoform on rice has never been studied to date. It was postulated that such combination could ensure better growth and yield in Inceptisols through better availability of nutrients and also enhanced soil biological activities. Eight treatment combinations (variable levels of recommended dose of nitrogen (RD_N), from farmyard manure (FYM) and/or nano zinc) were tested on rice (var. Shatabdi (IET 4786)). Standard growth and yield parameters, pigment analysis, available soil nutrients status, their concentration and uptake by plant, soil microbial status and dehydrogenase enzyme activity were analysed. The maximum grain yield (5.06 t ha^{-1}) was obtained from 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + foliar nano zinc spray treatment exhibiting the maximum number of panicles m^{-2} and a higher number of grains $panicle^{-1}$ that increased the grain yield by 8.82% compared with that of the 100% RD_N from chemical fertilizer treatment (4.65 t ha^{-1}). Sole application of nano zinc resulted in 4.01 t ha^{-1} grain yield that was 17.6% improved over control. Better microbial population in soil was ensured by enhancement in dehydrogenase enzyme activity in FYM-treated plots than 100% recommended dose of fertilizer at all growth stages of rice. Application of zinc in nanoform under INM system not only enhanced the productivity of rice and zinc use efficiency but also ameliorated soil health by improving soil chemical as well as biological properties.

Keywords Foliar spray · Integrated nutrient management · Microbial population · Nano zinc · Nutrient uptake · Rice yield

Abbreviations

AAS	Atomic absorption spectrophotometer
AH	At harvest
AMSL	Above mean sea level
ANOVA	The analysis of variance
CFU	Colony forming unit
CGR	Crop growth rate
DAT	Date after transplanting
DMRT	Duncan multiple range test
EDX	Electron dispersive X-ray
FTIR	Fourier transform infrared
FYM	Farm yard manure
H_3BO_3	Boric acid
HNO_3	Nitric acid
HCl	Hydrochloric acid
H_3PO_4	Orthophosphoric acid
H_2SO_4	Sulphuric acid
INM	Integrated nutrient management
K_2Cr2O_7	Potassium dichromate
LAI	Leaf area index
MOP	Muriate of potash
$NaHCO_3$	Sodium bicarbonate
NaOH	Sodium hydroxide
NAR	Net assimilation rate
$(NH_4)_2Fe(SO_4)_2(H_2O)_6$	Ferrous ammonium sulphate
$(NH_4)_6Mo_7O_{24}$	Ammonium molybdate
RD_N	Recommended dose of nitrogen
SEM	Scanning electron microscopy

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SL	Soluble liquid
$SnCl_2$	Stannous chloride
SSP	Single super phosphate
TPF	Triphenyl formazan
XRD	X-ray diffraction
ZnO NPs	Zinc oxide nanoparticles
2,4-D	2,4-Dichlorophenoxyacetic acid

1 Introduction

Rice (*Oryza sativa* L.) is the backbone of the rural population and the food security of the maximum residents worldwide which is considered as one of the most important food grains of the world's population. In rice production, India ranks first in area (45 million ha) and also secures the second-highest position in production by producing about 118 Mt of milled rice with a productivity of 3.96 t ha^{-1} (FAOSTAT 2020). Application of chemical nitrogenous fertilizer maintains a vital function in improvement of rice yield. Fertilizer N use efficiency generally varies from 30 to 40% in rice soils, because maximum nitrogen losses are found due to volatilization of ammonia, denitrification, leaching, runoff etc. which result in negative effect on yield and moreover pollute the environment simultaneously. Intensive cropping with inorganic fertilizers results in continuous soil fertility exhaustion which leads to a net negative balance of soil nutrients, which will suppose major restraints in the future for sustainable crop production. A part of applied organic manure is left in the soil after harvesting of preceding crop which is advantageous to succeeding crops in a good proportion. Thus, partial substitution of chemical fertilizers with organic manure is a reliable way not only to obtain fairly high productivity of rice but also to nourish soil health and fertility.

Application of fertilizers releasing N, P and K nutrients is a routine practice by Indian farmers, but use of micronutrients is unusual. The occurrence of micronutrient deficiency is because of continuous cultivation, destruction of productive topsoil and leaching loss of nutrients. Among the micronutrients, zinc plays an important role for the growth of plant, particularly for rice cultivated in submerged conditions (Fageria et al. 2002; Quijano-Guerta et al. 2002). It is also an integral component of many enzyme structures like oxidoreductases, isomerases, hydrolases, ligases, transferases and lyases (Auld 2001). The important role of zinc for plant growth can be adjudicated as it controls synthesis of indole acetic acid which regulates the plant growth (Tarafdar et al. 2014), synthesis of chlorophyll and formation of carbohydrate (Vitosh et al. 1994). The nutrient use efficiency of zinc as fertilizer generally varies between 2 and 5%. So, to mitigate zinc-deficient disorder, an efficient technique should be adopted for proper application of zinc fertilizer without hampering the plant growth and yield. To enhance the use efficiency as well as to reduce the rate of application, the nanosized zinc particle as fertilizer was proposed due to its penetrating capacity and large surface area. Foliar application of zinc in rice was found beneficial to improve concentration of zinc in grain rather than soil application due to avoidance of chemical interactions that obstruct uptake of zinc through plant's root (Mabesa et al. 2013).

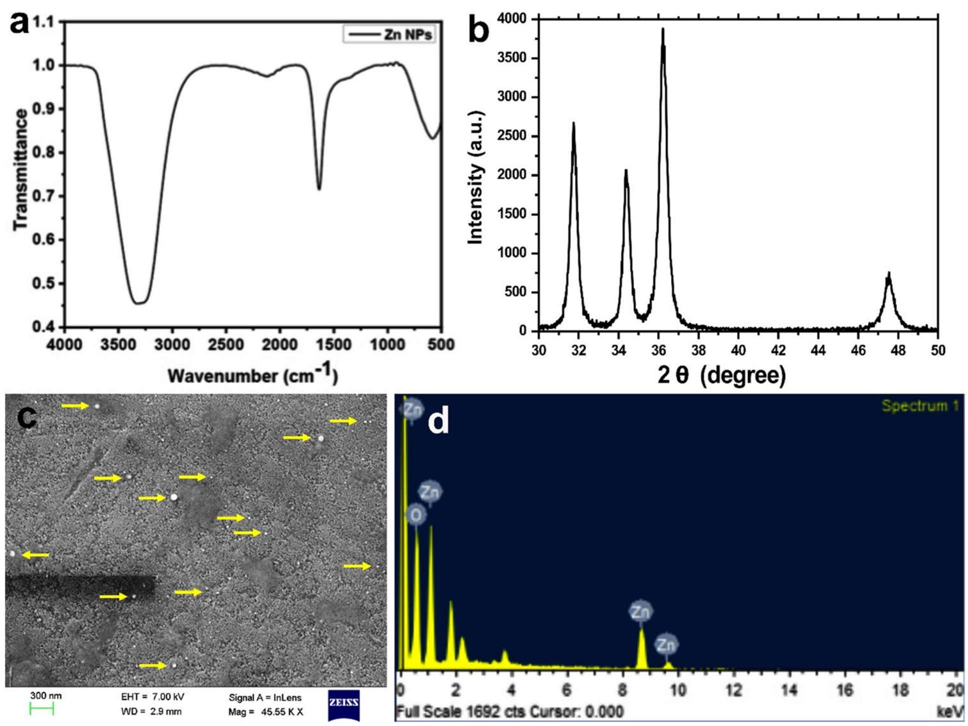


Fig. 1 Characterization of zinc nanoparticles using **a** Fourier transform infrared (FTIR) spectroscope image, **b** X-ray diffraction (XRD) analysis image, **c** scanning electron microscopy (SEM) image, **d** electron-dispersive X-ray (EDX) spectroscopy image

Table 1 Effect of integrated nutrient management along with foliar spray of nano zinc on vegetative growth parameters of rice

Treatments	Plant height (cm)			No. of productive tillers per m^2			Dry matter accumulation (g m^{-2})		
	30 DAT	60 DAT	AH	30 DAT	60 DAT	AH	30 DAT	60 DAT	AH
T_1	52.46 ± 1.79c	75.28 ± 2.98c	89.35 ± 1.84b	234.67 ± 3.66c	262.83 ± 9.39d	253.83 ± 1.34e	118.46 ± 2.97d	288.13 ± 6.83e	438.21 ± 16.80e
T_2	59.15 ± 0.65b	94.93 ± 1.64a	103.11 ± 2.06a	288.08 ± 6.66a	310.67 ± 0.36ab	300.17 ± 7.79ab	221.15 ± 3.32b	509.96 ± 10.28ab	755.75 ± 11.40b
T_3	62.38 ± 1.17ab	94.15 ± 0.28a	100.96 ± 2.30a	287.77 ± 5.50a	305.50 ± 10.89ab	290.00 ± 5.36bc	224.06 ± 4.48b	511.74 ± 1.44ab	757.79 ± 3.25b
T_4	63.05 ± 2.03ab	93.28 ± 1.21a	100.98 ± 0.09a	278.17 ± 8.05a	297.25 ± 6.31bc	277.92 ± 5.85 cd	231.71 ± 3.12ab	474.38 ± 11.80c	699.71 ± 12.04c
T_5	53.78 ± 1.42c	81.83 ± 1.33b	93.97 ± 2.43b	253.25 ± 8.00b	277.92 ± 10.02 cd	266.58 ± 8.05de	134.35 ± 6.50c	319.14 ± 10.92d	480.71 ± 18.14d
T_6	63.50 ± 1.48a	96.57 ± 2.17a	101.02 ± 1.72a	295.92 ± 3.83a	318.33 ± 5.23ab	307.25 ± 1.84ab	234.17 ± 4.37ab	529.13 ± 7.61a	795.17 ± 8.39a
T_7	64.52 ± 0.82a	95.75 ± 2.17a	104.26 ± 2.86a	296.33 ± 6.09a	322.75 ± 6.39a	310.67 ± 4.14a	234.18 ± 4.15ab	533.71 ± 6.24a	805.08 ± 5.98a
T_8	64.30 ± 0.90a	96.27 ± 3.53a	101.33 ± 0.40a	282.92 ± 4.88 a	300.83 ± 6.50abc	280.25 ± 7.15 cd	247.75 ± 9.80a	499.28 ± 12.92bc	732.75 ± 8.21bc

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), *T_2* 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, *T_3* 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, *T_4* 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, *T_5* $N_0P_0K_0$ + nano zinc spray, *T_6* 100% RD_N from commercial chemical fertilizer + nano zinc spray, *T_7* 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, *T_8* 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

Nanotechnology has been found as an innovative technique to meet the challenges related with agriculture in a much better way than regular conventional methods (Verma et al. 2018). It is associated with the transformation of materials into nanoscale (1 to 100 nm) for creating functional materials, sensors and devices (Verma et al. 2019, 2022). Nanofertilizers are synthesized or modified forms of traditional fertilizers. Less particle size causes expansion of specific surface area and more numbers of particles per unit area of a fertilizer which results in maximum chance of contact of nanofertilizers with the applied surface material. Fertilizers enclosed in nanoparticles increase the nutrient availability and uptake by the crops (Tarafdar et al. 2012a). Application of nanoparticles as foliar spray of fertilizer remarkably boosts the crop yield (Tarafdar et al. 2012b). Effective supply of zinc to plants from zinc oxide nanoparticle (ZnO NP) application is expected due to their tiny size, easy dissolvability and diffusible qualities that make quick absorption by the plant serving the nutritional requirements and insufficiencies in the crop plant (Raliya and Tarafdar 2013). Thus, it was found to improve the vegetative as well as physiological characteristics of rice crop (Bala et al. 2019; Wu et al. 2020; Yan et al. 2021).

Considering the above facts, this experiment was initiated with integrated nutrient management and foliar spray of zinc in nanoform with a target to observe better nutrient use efficiency without hampering soil health and for profitable performance of *Kharif* rice in Inceptisols.

Table 2 Effect of integrated nutrient management along with foliar spray of nano zinc on leaf area index and total chlorophyll content of rice

Treatments	Leaf area index			Total chlorophyll content (mg g^{-1})	
	30 DAT	60 DAT	AH	30 DAT	60 DAT
T_1	1.41 ± 0.04d	3.03 ± 0.11d	2.24 ± 0.07e	0.86 ± 0.04d	1.59 ± 0.01e
T_2	1.92 ± 0.04b	4.34 ± 0.08b	3.19 ± 0.04c	1.11 ± 0.03c	1.80 ± 0.05d
T_3	1.88 ± 0.02b	4.35 ± 0.06b	3.28 ± 0.07bc	1.14 ± 0.03c	1.80 ± 0.04d
T_4	1.96 ± 0.07b	4.47 ± 0.15ab	3.28 ± 0.08bc	1.07 ± 0.01c	1.73 ± 0.02d
T_5	1.70 ± 0.07c	3.53 ± 0.09c	2.66 ± 0.08d	1.27 ± 0.03b	1.92 ± 0.02c
T_6	2.13 ± 0.02a	4.55 ± 0.01ab	3.46 ± 0.03ab	1.55 ± 0.01a	2.30 ± 0.01a
T_7	2.14 ± 0.02a	4.71 ± 0.08a	3.56 ± 0.09a	1.49 ± 0.03a	2.31 ± 0.03a
T_8	2.14 ± 0.04a	4.70 ± 0.09a	3.54 ± 0.06a	1.49 ± 0.02a	2.21 ± 0.01b

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), *T_2* 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, *T_3* 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, *T_4* 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, *T_5* $N_0P_0K_0$ + nano zinc spray, *T_6* 100% RD_N from commercial chemical fertilizer + nano zinc spray, *T_7* 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, *T_8* 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

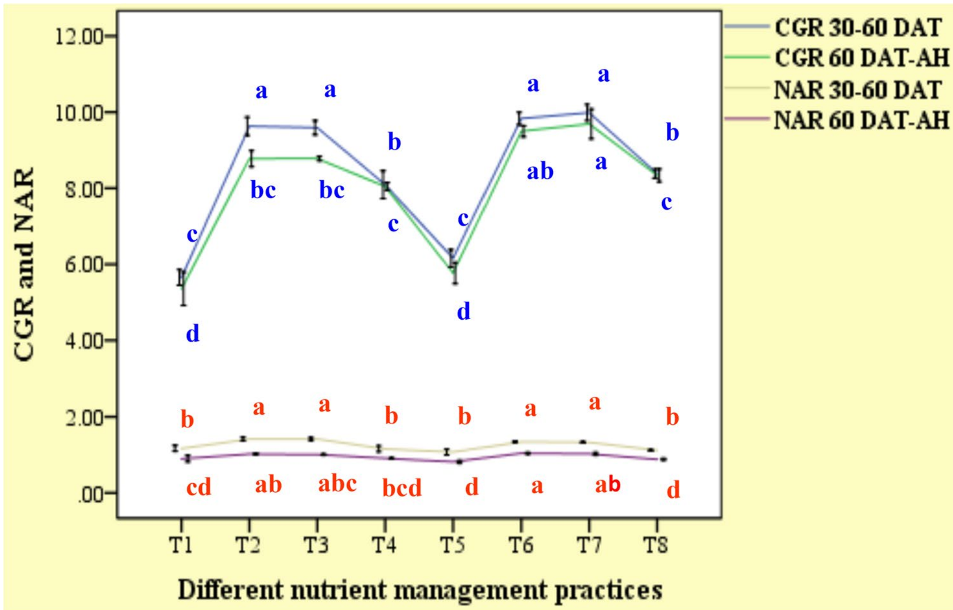


Fig. 2 Effect of integrated nutrient management along with foliar spray of nano zinc on crop growth rate (CGR) and net assimilation rate (NAR) of rice. RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray. Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

2 Materials and Methods

2.1 Experimental Site and Material

The field trial was carried on for 2 consecutive years at the 'D' Block Farm of Bidhan Chandra Krishi Viswavidyalaya, Kalyani, Nadia, West Bengal (India), situated at 22° 58′ 8″ N latitude and 88° 25′ 5″ E longitude with an altitude of 9.75 m above mean sea level (AMSL) during *Kharif* season of 2018 and 2019. The experiment was conducted on a low-land, well-drained alluvial soil (order — Inceptisol) that belonged to the textural class of sandy loam and alkaline in reaction (pH 7.4) containing 0.55% organic carbon content, 208.70 kg available N ha^{-1}, 26.5 kg available P_2O_5 ha^{-1}, 232.6 kg available K_2O ha^{-1} and 1.2 mg available Zn kg^{-1}.

Table 3 Effect of integrated nutrient management along with foliar spray of nano zinc on root growth of rice

Treatments	Root length (cm)			Root dry weight (g) per hill			Root length density (cm cm^{-3})		
	30 DAT	60 DAT	AH	30 DAT	60 DAT	AH	30 DAT	60 DAT	AH
T_1	17.52 ± 0.25c	20.42 ± 0.51e	20.50 ± 0.69d	3.34 ± 0.07f	6.56 ± 0.11f	7.50 ± 0.51c	0.76 ± 0.04d	0.97 ± 0.03d	1.21 ± 0.04c
T_2	19.13 ± 0.68ab	22.19 ± 0.89 cd	23.27 ± 0.33bc	4.21 ± 0.02 cd	8.38 ± 0.07c	9.39 ± 0.16b	0.95 ± 0.04c	1.70 ± 0.02c	1.84 ± 0.07b
T_3	19.27 ± 0.13ab	23.48 ± 0.85bc	23.08 ± 0.27c	4.36 ± 0.01bc	9.06 ± 0.13b	9.54 ± 0.17b	1.06 ± 0.03b	2.00 ± 0.04b	2.21 ± 0.06a
T_4	19.53 ± 0.64a	25.00 ± 0.48ab	24.93 ± 0.52ab	4.64 ± 0.01a	9.22 ± 0.21b	10.14 ± 0.09b	1.19 ± 0.01a	2.15 ± 0.02a	2.27 ± 0.03a
T_5	17.96 ± 0.60bc	20.25 ± 0.21e	21.10 ± 0.94d	3.39 ± 0.09f	7.00 ± 0.13e	7.74 ± 0.19c	0.81 ± 0.01d	1.06 ± 0.01d	1.23 ± 0.03c
T_6	18.98 ± 0.22ab	21.16 ± 0.20de	22.91 ± 0.71c	3.80 ± 0.01e	7.82 ± 0.08d	9.45 ± 0.09b	0.96 ± 0.02c	1.69 ± 0.03c	1.83 ± 0.05b
T_7	19.21 ± 0.31ab	24.82 ± 0.28ab	25.45 ± 0.38a	4.43 ± 0.10b	9.33 ± 0.16b	11.34 ± 0.26a	1.13 ± 0.02ab	1.99 ± 0.03b	2.25 ± 0.04a
T_8	19.13 ± 0.36ab	26.37 ± 0.49a	26.23 ± 0.52a	4.10 ± 0.11d	10.30 ± 0.21a	11.27 ± 0.26a	1.20 ± 0.01a	2.06 ± 0.03b	2.29 ± 0.04a

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

Table 4 Effect of integrated nutrient management along with foliar spray of nano zinc on yield attributes and yield of rice

Treatments	No. of panicles per m^2	Panicle length (cm)	No. of filled grains per panicle	Test weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index
T_1	239.44 ± 9.38d	20.80 ± 1.52a	93.43 ± 2.09d	17.19 ± 0.63c	3.41 ± 0.14e	4.13 ± 0.10e	0.45 ± 0.01bc
T_2	284.22 ± 8.15ab	22.58 ± 0.02a	109.02 ± 4.76b	19.35 ± 0.19ab	4.65 ± 0.09bc	5.23 ± 0.11c	0.47 ± 0.01a
T_3	281.39 ± 12.84ab	22.46 ± 0.24a	110.63 ± 1.97b	19.47 ± 0.95ab	4.61 ± 0.18bc	5.41 ± 0.02bc	0.46 ± 0.01ab
T_4	268.06 ± 5.85bc	22.35 ± 0.24a	103.53 ± 5.17bc	18.85 ± 0.51abc	4.40 ± 0.08c	5.21 ± 0.15c	0.46 ± 0.01ab
T_5	253.89 ± 7.50 cd	21.08 ± 0.25a	96.50 ± 2.15 cd	18.17 ± 0.42bc	4.01 ± 0.05d	4.51 ± 0.10d	0.47 ± 0.00a
T_6	298.61 ± 6.50a	23.73 ± 1.47a	121.11 ± 1.12a	19.96 ± 0.08a	4.91 ± 0.09ab	5.72 ± 0.14a	0.46 ± 0.00ab
T_7	300.28 ± 2.82a	23.67 ± 1.78a	119.73 ± 1.88a	19.19 ± 0.01ab	5.06 ± 0.16a	5.85 ± 0.06a	0.46 ± 0.01ab
T_8	269.44 ± 3.09bc	22.20 ± 1.16	106.22 ± 2.22b	19.32 ± 0.68ab	4.50 ± 0.12c	5.63 ± 0.08ab	0.44 ± 0.00c

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

2.2 Procurement and Characterization of Zinc Nanoparticles

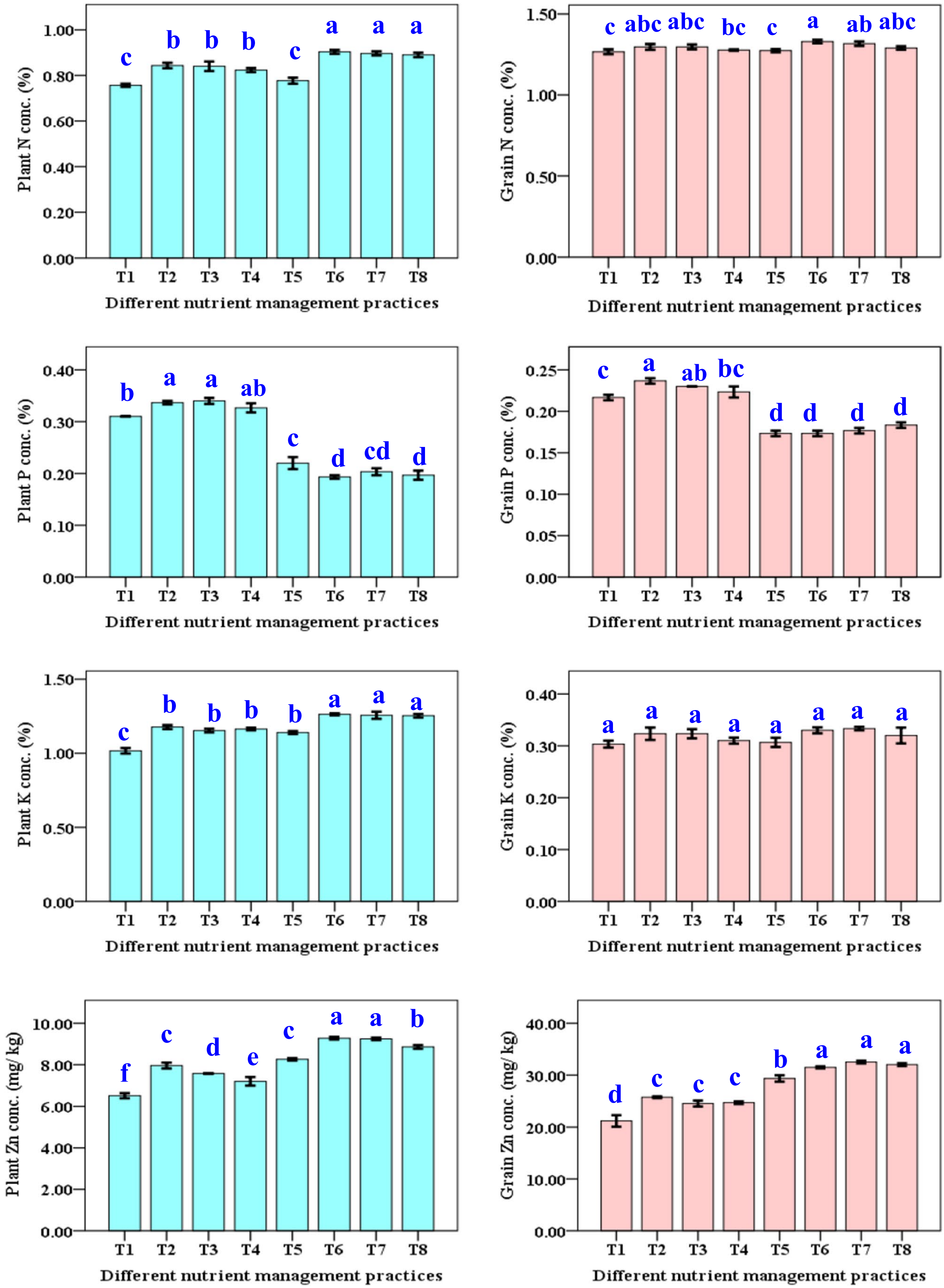
The nanosized particles of zinc were obtained from ICAR-Central Arid Zone Research Institute, Jodhpur, India. The particles were characterized using Fourier transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM) and electron-dispersive X-ray (EDX) spectroscopy measurements (Fig. 1) to determine the nature and size of the particle. Scanning electron micrograph (Fig. 1c) shows zinc nanoparticles range from 5 to 70 nm and possess an average size 20 nm at least in one dimension. EDX (Fig. 1d) shows the purity of the particle used for the study.

2.3 Experimental Design and Nutrient Application

The experiment was laid out in a randomized block design with three replications possessing eight treatments viz. T_1 — control ($N_0P_0K_0$), T_2 — 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 — 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 — 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 — $N_0P_0K_0$ + nano zinc spray, T_6 — 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 — 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray and T_8 — 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray, wherein the dimensions of every experimental plot were 9 m × 3 m. The rice variety taken was Shatabdi (IET 4786) and sown at the rate of 50 kg ha^{-1}. Rice seedlings of 22 days and 21 days of age were transplanted in the main field on 26 July and 30 July during 2018 and 2019 respectively by maintaining a proper distance of 20 cm × 10 cm. The recommended dose of fertilizers was 60:30:30 kg ($N/P_2O_5/K_2O$) ha^{-1}. Urea, single super phosphate (SSP) and muriate of potash (MOP) were used as inorganic source of nitrogen, phosphorus and potassium respectively, and for organic purpose, farmyard manure was applied. Half of the needed quantity of inorganic nitrogen and a complete dose of phosphorus and potassium were applied by broadcasting method before transplanting of rice, and the remaining amount of the required nitrogen was applied at 21 DAT and 42 DAT by dividing into 2 equal splits. Application of total amount of FYM was done during the course of land preparation. Applied FYM contained 0.53% N, 0.17% P, 0.56% K and 1.81 μg g^{-1} Zn. Two sprays of nano zinc with a dose of 10 mg L^{-1} each were given at all respective treatments 2 weeks after transplanting and 5 weeks after transplanting of rice seedlings (Tarafdar et al. 2014).

2.4 Intercultural Operation and Recording of Data

Hand weeding was made twice at 20 and 40 days after sowing. Irrigations were given as and when required. One spray of imidacloprid 200 SL (17.8%, w/w) was applied to control the sucking insect pest during the tillering stage of the crop. Growth parameters, yield attributes and yield of rice were measured, and chemical analyses of plant and soil samples were conducted, and economic analysis was done. Five plants from each experimental plot were selected indiscriminately and tagged for measuring vegetative parameters during the crop growth period. The growth parameters were started recording 30 days after sowing, and successive


Plant N conc. (%)
c b b b c a a a
Grain N conc. (%)
c abc abc bc c a ab abc
Plant P conc. (%)
b a a ab c d cd d
Grain P conc. (%)
c a ab bc d d d d
Plant K conc. (%)
c b b b b a a a
Grain K conc. (%)
a a a a a a a a
Plant Zn conc. (mg/ kg)
f c d e c a a b
Grain Zn conc. (mg/ kg)
d c c c b a a a
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices

◂**Fig. 3** Effect of different nutrient management practices along with foliar spray of nano zinc on rice. T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

observations were taken at a discontinuity of 30 days till harvest of the crop. Standard procedures were used to ascertain yield-contributing characters and yield. Ultimately, the yield was calculated in t ha^{-1}.

2.5 Estimation of Total Chlorophyll Content

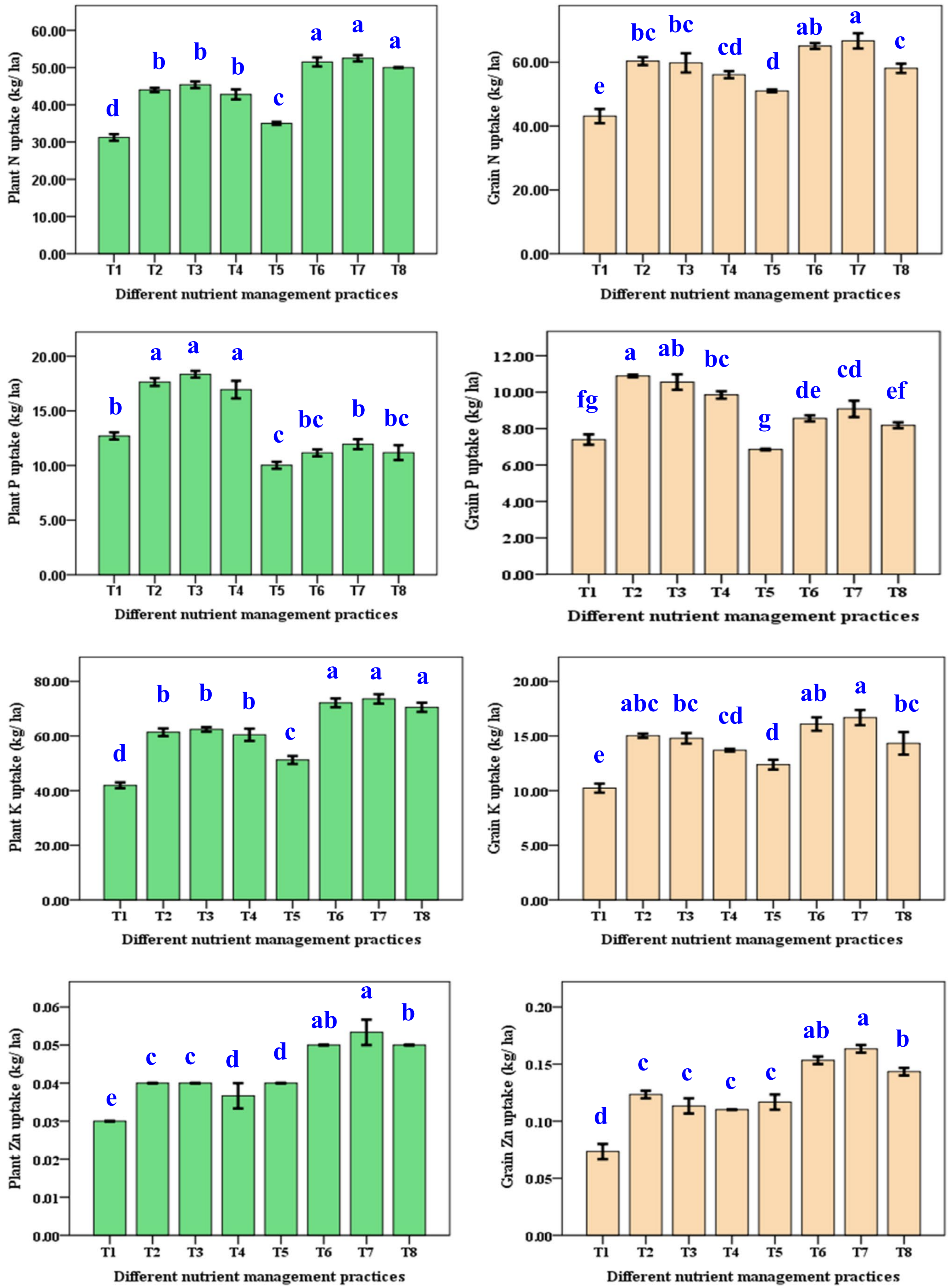
The chlorophyll content in the rice leaf samples collected from each of the treatment plot was estimated as per Arnon (1949). One hundred milligrams of fresh leaf sample was finely chopped and taken in a stoppered test tube. Then, 10 ml of 80% acetone was added to the tube, and it was allowed to stand at room temperature for 7 days under dark. Then, the green liquid was collected in a separate test tube, and the colourless leaf particles were discarded. Absorbance was read at 645- and 663-nm wavelengths in Systronics-105 spectrophotometer against a blank containing only 80% acetone.

$$\text{mg of total chlorophyll g}^{-1}\text{of fresh tissue} = [(20.2 \times \text{A645}) + (8.02 \times \text{A663})] \times \frac{V}{1000 \times W}$$

where V = volume of the extract (ml), W = fresh weight of leaf tissue (g), A = absorbance

2.6 Analysis of Plant Samples for Nutrient Concentration in Plant

The analysis of N in plant samples was performed by micro-Kjeldahl method (AOAC 1995). For this analysis, 1 g of plant sample (mix of stem and leaf sample) was taken in 800 ml Kjeldahl flask in which 20 ml of conc. H_2SO_4 and 2–3 g of Hibbard's mixture were added. After shaking it properly, the Kjeldahl flask was placed on the heater of the digestion operator and allowed to heat for 40–45 min until white flume appeared throughout the inside portion of the Kjeldahl flask. After cooling of the Kjeldahl flask, 150 ml distilled water and 100 ml 40% NaOH solution were added, and it was properly placed on the heater of the distillation operator. Twenty-five millilitres of 4% H_3BO_3 was taken to a 50-ml conical flask, and it was set with the corresponding tube of the Kjeldahl. One hundred millilitre of distillate was collected in the conical flask. After cooling of the distillate, titration was done by 0.1 (N) H_2SO_4 solution. During titration, the colour of the solution changed from greenish to deep orange. The analysis of P and K in plant samples was performed by the vanadate-molybdate acid yellow colour method (Piper 1966) and flame photometer method (Jackson 1973) respectively. For this analysis, 1 g of plant sample was taken in a 100-ml conical flask, and 5 ml of conc. HNO_3 was added in it and placed in digestion box. It was allowed 3 h 30 min to 4 h for digestion maintaining 180–200 heat unit. Change of colour of the solution to white indicated completion of digestion. The next day, taking the digested sample from the digestion box, 5 ml of the triacid mixture was added to it and was shaken properly and placed into the digestion box for the second digestion. When the solution turned into a white colour, the conical flask was taken from the digestion box and was allowed to cool. Ten millilitres of conc. HCl was added into the conical flask; it was washed properly and poured in to a 100-ml volumetric flask. Ten millilitres of 6 (N) of HCl was added into the conical flask, washed properly and again poured into the previous 100-ml volumetric flask. Then, distilled water was taken into that conical flask, washed properly and again poured into that 100-ml conical flask and was made the volume up to 100 ml. After that, the solution was allowed to filtrate with the help of funnel and filtrate paper. For analysis of P, 1 ml of filtrate solution was taken into a 50-ml volumetric flask with the measuring cylinder. Then, 15 ml of distilled water, 4–5 drops of 2,4-D solution and 4 (N) HCl were added in sequence to the filtrate solution until HCl neutralized the solution showing a colour less sample. Then, 5 ml of $(NH_4)_6Mo_7O_{24}$ solution and 6–7 drops of 5% $SnCl_2$ were added to the solution. The volume of the solution was made up to 50 ml with the distilled water. Reading of sample was taken with the help of a spectrophotometer. For analysis of K, 1 ml of filtrate solution was taken into the 50-ml volumetric flask with the measuring cylinder and was made up the 50-ml volume with the help of distilled water. Reading of the sample was taken with the help of a flame photometer. Analysis of Zn content in plant samples was done after dry ashing in a muffle furnace, by an atomic absorption spectrophotometer (PerkinElmer made Pinaacle 900H) where 0.5 g of plant sample was taken in crucible, and the crucible was kept in the muffle furnace at 550 °C for 5 h. Next day, 10 ml of 6 (N) HCl was added in the crucible. The solution was filtrated in a 50-ml volumetric flask by using filter paper 1. The volume of the volumetric flask was made up with double-distilled water and kept in a container, and reading was taken by AAS.


Plant N uptake (kg/ ha)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
d b b b c a a a
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Grain N uptake (kg/ ha)
60.00
40.00
20.00
0.00
e bc bc cd d ab a c
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Plant P uptake (kg/ ha)
20.00
15.00
10.00
5.00
0.00
b a a a c bc b bc
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Grain P uptake (kg/ ha)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
fg a ab bc g de cd ef
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Plant K uptake (kg/ ha)
80.00
60.00
40.00
20.00
0.00
d b b b c a a a
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Grain K uptake (kg/ ha)
20.00
15.00
10.00
5.00
0.00
e abc bc cd d ab a bc
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Plant Zn uptake (kg/ ha)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
e c c d d ab a b
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices
Grain Zn uptake (kg/ ha)
0.20
0.15
0.10
0.05
0.00
d c c c c ab a b
T1 T2 T3 T4 T5 T6 T7 T8
Different nutrient management practices

◂**Fig. 4** Effect of integrated nutrient management along with foliar spray of nano zinc on nutrients concentration of rice. T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

2.7 Soil Sample Analysis for Organic Carbon Content and Available Nutrients in Soil

The organic carbon content of soil was determined by Walkley and Black (1934)'s method. In this method, 1.0 g of soil was wet oxidized by 10 ml of 1(N) K_2Cr2O_7 and 20 ml conc. H_2SO_4. The digested material was kept in a dark place for 30 min followed by titration with 0.5 (N) $(NH_4)_2Fe(SO_4)_2(H_2O)_6$ after the addition of 200 ml of water and 10 ml of H_3PO_4 and expressed as percentage (%). The available soil nitrogen was estimated by a Kjeldahl flask using the alkaline permanganate method (Subbiah and Asija 1956) following titration with H_2SO_4. Available phosphorus of soil was determined following Olsen's (Olsen et al. 1954) method using 0.5 (M) $NaHCO_3$ (pH 8.5) extractant as the reaction of the soil samples was in the range of neutral to slightly alkaline (pH 6.7–8.1). Neutral normal ammonium acetate was used to estimate available potassium of soil by using flame photometer (Jackson 1973). Available zinc content of the soil was determined by extracting the soils with 0.005 (M) DTPA

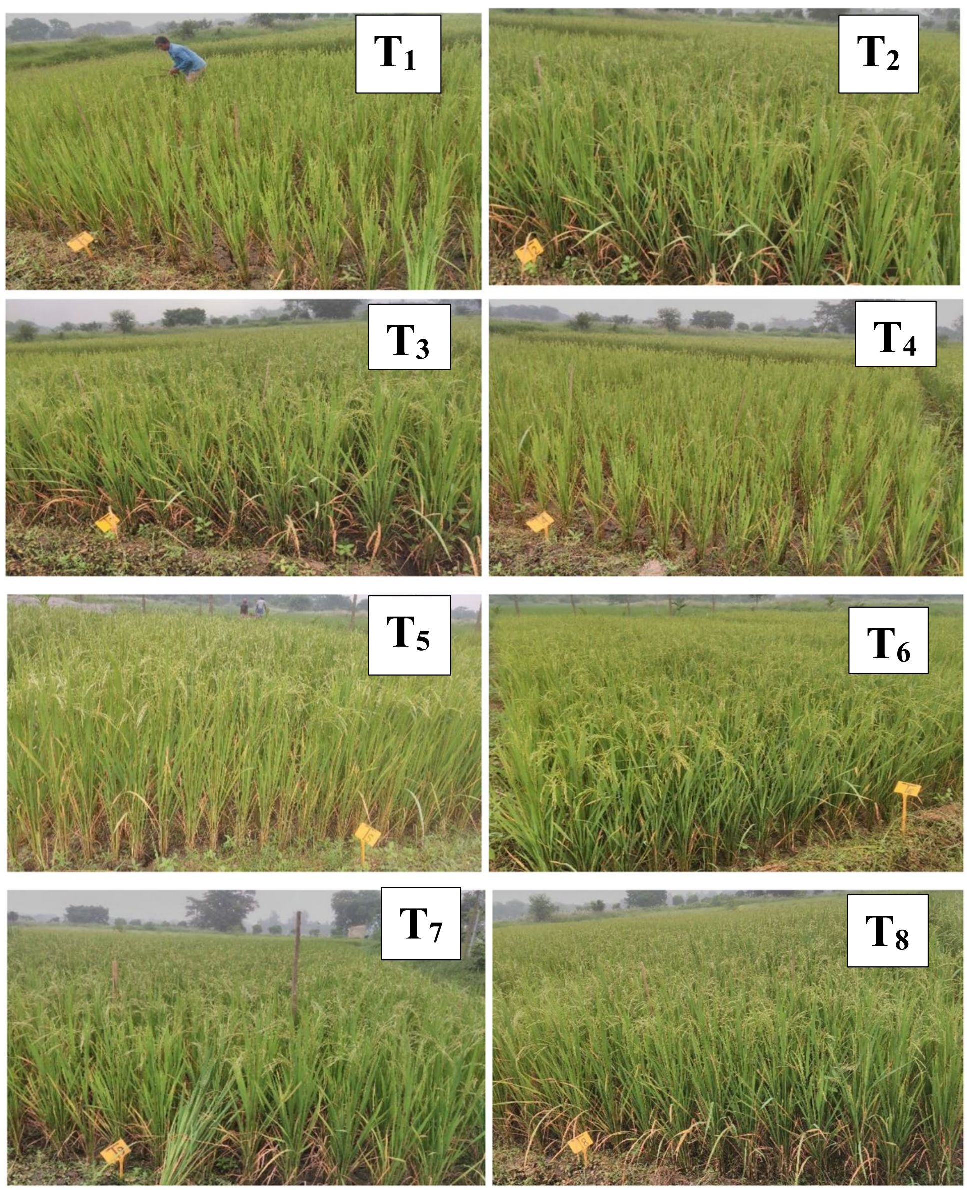


Fig. 5 Effect of integrated nutrient management along with foliar spray of nano zinc on nutrients uptake by rice. T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray. Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

Table 5 Effect of integrated nutrient management along with foliar spray nano zinc on chemical properties of post-harvest soil of rice and total nutrients uptake by rice

Treatments	Soil chemical properties					Plant nutrients uptake			
	Soil organic carbon (%)	Soil available nitrogen (kg ha^{-1})	Soil available phosphorus (kg ha^{-1})	Soil available potassium (kg ha^{-1})	Soil available zinc (mg kg^{-1})	Total nitrogen uptake (kg ha^{-1})	Total phosphorus uptake (kg ha^{-1})	Total potassium uptake (kg ha^{-1})	Brown rice zinc conc. (mg kg^{-1})
T_1	0.56 ± 0.01b	140.17 ± 1.85c	21.08 ± 0.31 cd	172.58 ± 1.35b	0.86 ± 0.01d	74.34 ± 3.07e	20.10 ± 0.61c	52.15 ± 1.20d	21.19. ± 1.12d
T_2	0.60 ± 0.02b	151.32 ± 1.44b	21.69 ± 0.46c	173.23 ± 1.96ab	0.91 ± 0.02c	104.32 ± 1.78bc	28.52 ± 0.40ab	76.37 ± 1.50b	25.77 ± 0.16c
T_3	0.74 ± 0.01a	160.92 ± 2.20a	25.27 ± 0.28a	175.99 ± 0.90ab	0.94 ± 0.01bc	105.17 ± 2.58bc	28.90 ± 0.73a	77.18 ± 0.97b	24.55 ± 0.57c
T_4	0.71 ± 0.02a	163.80 ± 1.13a	25.51 ± 0.40a	177.70 ± 1.68a	0.93 ± 0.02bc	98.88 ± 2.30c	26.79 ± 0.61b	74.15 ± 2.14b	24.72 ± 0.25c
T_5	0.56 ± 0.03b	141.32 ± 1.68c	20.47 ± 0.51d	173.89 ± 2.36ab	0.92 ± 0.01c	86.03 ± 0.47d	16.88 ± 0.36d	63.59 ± 1.71c	29.36 ± 0.60 b
T_6	0.60 ± 0.02b	152.34 ± 2.50b	21.10 ± 0.35 cd	175.86 ± 1.08ab	0.97 ± 0.01ab	116.58 ± 1.65a	19.72 ± 0.22c	88.22 ± 1.94a	31.48 ± 0.19a
T_7	0.74 ± 0.02a	160.72 ± 1.41a	24.00 ± 0.14b	177.89 ± 1.37a	0.99 ± 0.01a	119.18 ± 3.24a	21.03 ± 0.59c	90.26 ± 2.43a	32.51 ± 0.26a
T_8	0.74 ± 0.00a	165.68 ± 1.72a	24.66 ± 0.27ab	177.92 ± 0.46a	1.00 ± 0.00a	108.11 ± 1.51b	19.35 ± 0.83c	84.84 ± 2.63a	32.02 ± 0.27a

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

Table 6 Effect of integrated nutrient management along with foliar spray of nano zinc on microbial population count of soil

Treatments	Microbial population count (CFU (1×10^6) g^{-1} of dry soil)								
	Bacteria			Fungi			Actinomycetes		
	30 DAT	60 DAT	AH	30 DAT	60 DAT	AH	30 DAT	60 DAT	AH
T_1	34.33 ± 0.17e	40.00 ± 0.87d	32.17 ± 0.17c	8.83 ± 0.93c	11.00 ± 0.29b	7.5 ± 0.76d	24.50 ± 0.50c	30.00 ± 2.18b	22.83 ± 0.73b
T_2	36.17 ± 0.73e	43.00 ± 0.76c	34.67 ± 0.73b	9.67 ± 0.60c	11.67 ± 0.93b	7.83 ± 0.33d	26.00 ± 1.04c	31.83 ± 0.60b	24.17 ± 0.44b
T_3	40.83 ± 0.93c	53.50 ± 0.58b	38.17 ± 0.17a	13.33 ± 0.67a	17.00 ± 0.29a	9.67 ± 0.44bc	33.67 ± 1.09b	45.00 ± 1.80a	31.67 ± 1.01a
T_4	44.50 ± 0.29ab	55.83 ± 0.88a	37.50 ± 1.00a	14.17 ± 0.67a	16.67 ± 1.20a	11.33 ± 0.33ab	38.00 ± 0.76a	46.00 ± 2.36a	30.67 ± 0.33a
T_5	35.33 ± 0.44e	40.67 ± 0.93d	33.50 ± 0.76bc	9.17 ± 0.17c	11.50 ± 0.29b	7.5 ± 0.58d	25.33 ± 0.60c	29.50 ± 1.32b	24.17 ± 1.20b
T_6	38.33 ± 0.67d	43.50 ± 0.29c	35.17 ± 0.93b	9.67 ± 0.44c	11.33 ± 0.83b	8 ± 0.58 cd	26.50 ± 1.15c	32.50 ± 1.04b	24.83 ± 0.67b
T_7	43.00 ± 0.50b	56.50 ± 0.87a	37.83 ± 0.93a	11.50 ± 0.29b	16.50 ± 1.15a	11 ± 0.87ab	35.67 ± 1.17ab	45.17 ± 0.44a	30.50 ± 0.50a
T_8	45.17 ± 0.67a	56.83 ± 0.83a	38.67 ± 0.17a	13.83 ± 0.44a	17.17 ± 0.73a	11.83 ± 0.44a	37.83 ± 0.17a	46.50 ± 1.76a	32.17 ± 0.73a

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

solution adjusted to pH 7.3 (soil/extractant = 1:2) following the method of Lindsay and Norvell (1978).

2.8 Microbial Analysis in Soil Samples

The serial dilution and pour plate method (Zubere 1994) was used to estimate the total microbial population (bacteria, actinomycetes and fungi) of soil. Nutrient agar, rose Bengal agar and actinomycete isolation agar were used as growth media for culturing and counting bacteria, fungi and actinomycetes respectively.

2.9 Dehydrogenase Enzyme Activity in Soil Samples

The soil dehydrogenase enzyme activity was measured by following the methods described by Klein et al. (1971), where 1 g of air-dried soil was taken in an air-tight screw-capped test tube of 15-ml capacity, and 0.2 ml of 3% 2,3,5-triphenyl tetrazolium chloride solution and 0.5 ml of 1% glucose solution were added. After incubation of the tubes at 28 ± 0.5 °C for 24 h, 10 ml of methanol was added into the tubes and was allowed to stand for 6 h. Clear pink-coloured supernatant liquid was withdrawn, absorbance was

Table 7 Effect of integrated nutrient management along with foliar spray of nano zinc on dehydrogenase enzyme estimation of soil

Treatments	Dehydrogenase enzyme estimation (μg TPF g^{-1} h^{-1})		
	30 DAT	60 DAT	AH
T_1	2.23 ± 0.05e	2.77 ± 0.04e	2.13 ± 0.05d
T_2	2.55 ± 0.04d	3.67 ± 0.05c	2.60 ± 0.02b
T_3	2.78 ± 0.03bc	3.82 ± 0.03b	2.79 ± 0.05a
T_4	2.89 ± 0.04ab	3.86 ± 0.02ab	2.83 ± 0.01a
T_5	2.29 ± 0.06e	2.94 ± 0.02d	2.28 ± 0.02c
T_6	2.67 ± 0.03c	3.76 ± 0.08bc	2.67 ± 0.04b
T_7	2.85 ± 0.04b	3.86 ± 0.02ab	2.83 ± 0.03a
T_8	3.01 ± 0.03a	3.98 ± 0.02a	2.89 ± 0.01a

Data represent mean ± standard error. Data for each column with different lowercase letters are significantly different according to Duncan's multiple range test (DMRT) (Duncun 1955) at $P = 0.05$

T_1 control ($N_0P_0K_0$), T_2 100% RD_N (recommended dose of nitrogen) from commercial chemical fertilizer, T_3 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM, T_4 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM, T_5 $N_0P_0K_0$ + nano zinc spray, T_6 100% RD_N from commercial chemical fertilizer + nano zinc spray, T_7 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray, T_8 50% RD_N from commercial chemical fertilizer + 50% RD_N from FYM + nano zinc spray

read at a wavelength of 485 nm, and the outcomes were mentioned in μg TPF g^{-1} h^{-1}.

2.10 Experimental Design and Statistical Analysis

The analysis of variance (ANOVA) was accomplished to visualize the impacts of various nutrient management practices on rice in a randomized block design, by using SPSS (IBM® SPSS Statistics, Ver. 24, USA). Comparison among the treatments (mean ± SE) was performed by Duncan's multiple range test (DMRT) (Duncun 1955) ($p = 0.05$).

3 Results

3.1 Characterization of Zinc Nanoparticles

The nanoparticles obtained from the above-mentioned source were successfully characterized using FTIR, XRD, SEM and EDX methods. These experiments confirmed the nature, size, shape and quality of zinc nanoparticles.

3.2 Effect on Vegetative Growth Parameters of Rice

Results showed that application of 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray produced significantly tall plants (104.26 cm) which was at par with all other treatments except control and only nano zinc sprayed plot at harvest stage. The highest number of productive tillers per m^2 (322.75) was found at 60 DAT by using 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray. Accumulation of dry matter increased with the advancement of crop growth and was obtained maximum (805.08 g m^{-2}) at harvest stage by application of 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray and that was at par with 100% RD_N from commercial chemical fertilizer + nano zinc spray treated plot. Plant height, number of productive tillers per m^2 and accumulation of dry matter were increased by 1.12, 3.50 and 6.53%, respectively, compared to that of 100% RD_N from inorganic fertilizer application (Table 1).

3.3 Effect on Leaf Area Index and Total Chlorophyll Content of Rice

Leaves are important organs that have an active role in photosynthesis, and net photosynthesis is indicated by total chlorophyll content of leaves. The leaf area index of rice plants starts increasing from initial growth stage and reaches maximum at 60 DAT, then it slightly decreases at the harvesting stage due to the drying and withering of lower leaves. Seventy-five per cent RD_N from chemical fertilizer + 25% RD_N from FYM + nano zinc spray–treated plot recorded the highest LAI both at 60 DAT and harvest stage (4.71 and 3.56 respectively). LAI increased by 11.46, 8.53 and 11.60% in rice at 30 DAT, 60 DAT and at harvest respectively in 75% RD_N from commercial chemical fertilizer + 25% RD_N from FYM + nano zinc spray–treated plot compared with those in 100% RD_N from inorganic fertilizer application. Maximum total chlorophyll content was obtained from 100% RD_N from inorganic fertilizer + foliar spray of nano zinc and 75% RD_N from chemical fertilizer + 25% RD_N from FYM + nano zinc spray–treated plots at 30 DAT and 60 DAT respectively (Table 2).

3.4 Effect on CGR and NAR of Rice

Crop growth rate (CGR) is the dry matter production rate of a crop in per unit area, and net photosynthesis rate is specified by net assimilation rate (NAR). The highest crop growth rate was attained from 75% RD_N from inorganic fertilizer + 25% RD_N from FYM + nano zinc spray–treated plot both during 30–60 DAT and 60 DAT–AH stages (9.98 and 9.69 g m^{-2} day^{-1} respectively). Among the various nutrient management practices, the maximum NAR value between 30 and 60 DAT was obtained with the application of 75% RD_N from inorganic fertilizer + 25% RD_N from FYM (1.42 g m^{-2} day^{-1}) and during the period of 60 DAT–harvest of rice, it was observed in 100% RD_N from inorganic fertilizer + foliar spray of nano zinc (1.04 g m^{-2} day^{-1})–treated plot (Fig. 2).

3.5 Effect on Root Growth of Rice

A considerable effect of varying treatment combinations was noticed in root length, dry weight of root per hill and root length density of *Kharif* rice, and these were varied significantly at all of crop growth stages (Table 3). The highest root length of rice was observed in 50% RD_N from chemical fertilizer + 50% RD_N from FYM applied plot at 30 DAT (19.53 cm) and in 50% RD_N from inorganic fertilizer + 50% RD_N from FYM + nano zinc–treated plot at both 60 DAT and harvest stages (26.37 and 26.23 cm respectively). The highest root dry weight (g) per hill was obtained from 50% RD_N from chemical fertilizer + 50% RD_N from FYM, 50% RD_N from chemical fertilizer + 50% RD_N from FYM + nano zinc spray and 75% RD_N from inorganic fertilizer + 25% RD_N from FYM + nano zinc spray–treated plot respectively at 30 DAT, 60 DAT and harvest stage (4.64, 10.30 and 11.34 g respectively). Amidst the various nutrient combination applications, 50% RD_N from chemical fertilizer + 50% RD_N from FYM + nano zinc spray recorded maximum root length density both at 30 DAT and at harvest stage (1.20 and 2.29 cm cm^{-3} respectively). At 60 DAT, it was found highest in 50% RD_N from chemical fertilizer + 50% RD_N from FYM treated plot (2.15 cm cm^{-3}).

3.6 Effect on Yield Attributing Characters and Yield of Rice

The yield-attributing and associated characteristics of rice like the number of panicles per m^2, panicle length, no. of filled grains per panicle and test weight were measured at maturity of the rice. The highest number of panicles per m^2 (300.28) was produced by 75% RD_N from chemical fertilizer + 25% RD_N from FYM + nano zinc spray treatment whereas application of 100% RDN from inorganic fertilizer + foliar spray of nano zinc recorded the highest number of filled grains per panicle (121.11) and maximum test weight (19.96). Maximum grain and straw yield were recorded with the application of 75% RD_N from chemical fertilizer + 25% RD_N from FYM + nano zinc spray which is recorded as an 8.82% and 11.85% increase in grain and straw yield respectively compared to that from 100% RD_N from chemical fertilizer–treated plot. It was also found that application of nano zinc over 100% inorganic fertilizer increased the grain yield of rice by 5.59% in comparison with the application of only 100% inorganic fertilizer, and application of only nano zinc recorded the rice grain yield of 4.01 t ha^{-1}, and it increased by 17.60% over control (Table 4; Fig. 3).

3.7 Effect on Soil Chemical Properties and Total Nutrient Uptake by Rice

Significant variations regarding soil organic carbon content, available nitrogen, available phosphorus and available zinc were found in the residual soil samples after the harvest of rice (Table 5). Higher soil organic carbon (%) was obtained in integrated nutrient management treated plots. Significantly highest soil available nitrogen and potassium (165.68 and 177.92 kg ha^{-1} respectively) was obtained with the application of 50% RD_N from chemical fertilizer + 50% RD_N from FYM + nano zinc spray, and it was increased by 9.49 and 2.71% respectively than solely chemically treated plot. An evaluation of the data revealed that available phosphorus in soil increased significantly in 50% RD_N from chemical fertilizer + 50% RD_N from FYM-treated plot (25.51 kg ha^{-1}), which was increased by 17.61% than 100% RD_N from inorganic fertilizer applied plot. Soil-available zinc was found to increase by 9.89% after harvest of rice in 50% RD_N from commercial inorganic fertilizer + 50% RD_N from FYM + nano zinc applied plots (1.00 mg kg^{-1}) than solely chemically treated plots.

Both grain and straw samples of rice from individual treatment were collected at maturity. The uptake of nutrients by grain and straw was then computed by multiplying grain and straw yield with respective nutrient contents (Figs. 4 and 5). Total uptake of nutrients varied significantly by different nutrient management practices (Table 5). Results revealed that 75% RD_N from chemical fertilizer + 25% RD_N from FYM + nano zinc spray–treated plot registered 14.24 and 18.19% increase in total nitrogen and potassium uptake respectively than 100% chemically treated plot. Significantly highest total phosphorus uptake was found with the application of 75% RD_N from chemical fertilizer + 25% RD_N from FYM in rice, resulting in 1.33% higher total phosphorus uptake than 100% RD_N from chemical fertilizer–treated plot. Maximum zinc concentration in brown rice was found in 75% RD_N from chemical fertilizer + 25% RD_N from FYM + nano zinc spray–treated plot which was at par with 100% RD_N from chemical fertilizer + nano zinc spray–treated plot and 50% RD_N from chemical fertilizer + 50% RD_N from FYM + nano zinc spray–treated plot.

3.8 Effect on Soil Microbial Population Count

Different nutrient combinations had a notable impact on the soil microbial population at all growth stages of rice (Table 6). The total number of microbial populations was found higher at 60 DAT than 30 DAT and at harvest stages. Application of 50% RD_N from inorganic fertilizer + 50% RD_N from FYM + nano zinc spray recorded the highest microbial population at 60 DAT which was increased by 32.16, 47.13 and 46.09% in bacterial, fungal and actinomycete population count respectively than 100% inorganic fertilizer treated plot.

3.9 Effect on soil Dehydrogenase Enzyme Estimation

Highest dehydrogenase enzyme activity in soil was found at 60 DAT due to abundance of microbial population (Table 7). It was found that at 60 DAT dehydrogenase enzyme activity increased by 5.85 and 8.44% in 50% RD_N from chemical fertilizer + 50% RD_N from FYM + nano zinc–treated plot than 100% RD_N from chemical fertilizer + nano zinc–treated plot and 100% RD_N from chemical fertilizer–treated plot respectively.

4 Discussion

Conjunctive use of organic and inorganic sources of nutrients resulted in significant increase in growth parameters. Accessibility of nutrients during the whole crop growth period because of steady release of nutrients from organic source helps to improve accumulation of dry matter and production of fertile tillers from which higher number of panicles per unit area was achieved that finally converts into yield. Efficacy of organic manure with inorganic fertilizer application in growth and yield of rice was also reported by Mondal et al. (2015), Karki et al. (2018) Moe et al. (2019), Ram et al. (2020) and Mangaraj et al. (2022). In an experiment, Ullah et al. (2019) found better results in yield components like number of panicles per plant, length of panicle, 1000-grain weight with the application of 50% RD_N from inorganic fertilizer + 50% in the form of FYM whereas Borah et al. (2016) reported 75% RD_N in the form of FYM or vermicompost with 25% recommended rate of fertilizers produced rice plant with greater growth and yield attributes which accelerate to increase grain yield by 89.6% over control. In a research, Islam et al. (2019) specified that balanced supply of nutrients increased chlorophyll content of leaf, LAI and NAR which eventually led to more accumulation of dry matter and yield of rice. Higher leaf area index might be due to an adequate supply of nutrients and also higher nutrient absorption through the foliar spray of zinc by the plants. Related findings were noticed by Torabian et al. (2015). Application of nano zinc as foliar treatment significantly increases total chlorophyll concentration per unit of leaf area which was supported by the conclusions of Kheir et al. (2019), Bala et al. (2019) and Yan et al. (2021). In the present study, application of zinc in nanoform was proven to be quite effective in order to enhance plant growth parameters. The zinc nanoparticles were characterized by FTIR, XRD, SEM and EDX methods before they were applied. Use of these methods (FTIR, XRD, SEM and EDX) to identify and characterize zinc nanoparticles was reported by several other researchers as well (Hall et al. 2007; Mourdikoudis et al. 2018; Modena et al. 2019). Integrated nutrient management practices ameliorated the physicochemical properties of soil which encouraged prolific root attributes like length of root, dry weight of root and root volume that ultimately helped plants in better uptake of water and nutrients from lower layers of soil. Betterment of root morphological characteristics of rice plant for incorporation of organic manure into soil was also observed by Yang et al. (2004), Ullah et al. (2019) and Ajaykumar and Sivakumar (2020). Kheyri et al. (2019) reported that slow release of nutrients by nano-ZnO application during the crop growth period increases rice growth as well as yield. A significant impact of foliar application of ZnO NPs on the yield-contributing characteristics of rice, i.e., number of panicles per m^2, number of grains per panicle, in comparison with the non-sprayed treatment was noticed by Bala et al. (2019) and Kheir et al. (2019). Nutrients from chemical fertilizer are immediately utilizable to plants because of quick solubility in soil solution whereas organic manures help in enhancing the availability of nutrients for a longer period due to the slow decomposition of manures. As a result, improved organic carbon content, soil-available nutrients after the harvest of rice and uptake of nutrients by the plant were observed in the combined use of inorganic and organic fertilizer–treated plots. The beneficial effect of conjoint use of organic manure along with inorganic fertilizer in improving soil chemical properties was supported by Naher and Paul (2017), Abid et al. (2020), Rollon et al. (2021) and Urmi et al. (2022). Ghoneim (2016) observed that zinc as foliar spray increased zinc concentration in soil as compared to control. Bala et al. (2019) also observed that the application of ZnO NPs as foliar treatment significantly affected soil zinc content. Better uptake of nutrients by the plant due to integrated nutrient management was also observed by Banik and Sharma (2009), Mitra and Mandal (2012), Mondal et al. (2016) and Ram et al. (2020). The decrease in phosphorus content at harvest stage both in grain and straw and total phosphorus uptake was found with the application of zinc because of the antagonistic effect of zinc on P absorption. This result was also supported by Fageria et al. (2011) and Ghoneim (2016). More zinc concentration in rice grain due to foliar spray of nano zinc was also reported by Adhikary et al. (2020). A profound increase in microbial population was observed in organic manure addition with inorganic fertilizer and foliar spray of nano zinc-applied plots as compared to the only chemical fertilizer application because organic matter serves as a source of the nourishment and also as a substance for decomposition and mineralization of nutrients which creates a favourable condition for the growth of microbes in the soil. Similar findings were also observed by Bahadur et al. (2012), Kumari et al. (2017) and Kumar et al. (2018). Raliya and Tarafdar (2013) had noticed an increment in the microbial population after using of nano zinc oxide particles. Dehydrogenase enzyme activity acts as a measure of comprehensive microbial activity in soil. Greater dehydrogenase enzyme activity was noticed in integrated nutrient management treatments because degradation of added organic material supposed to provide intra- and extra-cellular enzymes that eventually increase microbial activity in the soil. This result finds conformity with the discussions of Kumari et al. (2017), Patra et al. (2020) and Kumar et al. (2021).

5 Conclusion

Addition of good quality organic matter in soil improves soil biological properties which are regarded as an indicator of high-quality soil. In spite of providing good amount of nutrients required by the plants for growth and development, inorganic fertilizers also cause numerous menaces to the soil and environment. Modern agro-techniques like nanotechnology particularly nanofertilizers play vital role in reducing problems connected with nutrient and fertilizer management in the field of agriculture. The effect of nano zinc application was found more pronounced under integrated nutrient management system as compared to sole application of chemical fertilizers in terms of yield of rice crop though they were found statistically at par. These effects may be more distinct under long-term INM practice. Therefore, it may be concluded that integrated nutrient management practice with foliar application of nutrients is a tool which aims to minimize the dose of chemical fertilizer in soil that creates favourable soil physiochemical properties and healthy environment and helps to attain desired crop productivity with proper maintaining of soil fertility by protecting soil nutrient balance in the long run as a whole for sustainability in agricultural production.

Acknowledgements The authors would like to sincerely thank the laboratory and field staff of Bidhan Chandra Krishi Viswavidyalaya, for their technical assistance in the inorganic analyses.

Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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