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# Evaluation and refinement of zinc management options for field-specific nutrient management in eastern India

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In eastern India, zinc (Zn) has emerged as the most critical micronutrient impacting the yield of rice. Experiments were conducted for 2 years during the *Rabi* and *Kharif* rice seasons at 339 on-farm locations in five districts and four agroclimatic zones of Odisha state in eastern India to study the management of Zn in rice nurseries and the transplanted crop. At each location, five treatment plots were established in which nitrogen (N), phosphorus (P) and potassium (K) were applied to rice following site-specific nutrient management as guided by Rice Crop Manager (RCM), a web-based tool. In the three treatments, the rice nursery was treated with compost (4 t ha<sup>-1</sup>) or 50 or 100 kg Zn sulfate ha<sup>-1</sup> (on a nursery basis), while the transplanted crop was supplied with only N, P, and K. In the remaining two treatments, no compost or Zn was applied to the rice nursery, but 12.5 or 25 kg Zn sulfate ha<sup>-1</sup> was applied along with N, P, and K to the transplanted crop. Rice grain yield, system yield, and gross return above fertilizer cost (GRF) were significantly greater ( $p < 0.05$ ) with the application of 50 kg Zn sulfate ha<sup>-1</sup> than with the application of compost (farmer practices) to rice nurseries. Applying 100 kg Zn sulfate ha<sup>-1</sup> to the nursery or 12.5–25 kg Zn sulfate ha<sup>-1</sup> to transplanted rice did not increase yield or GRF. Higher yield, grain Zn content, and GHG emissions occurred in the *Rabi* season, with the lowest GHG emissions recorded when the nursery received 100 kg Zn sulfate ha<sup>-1</sup> in both seasons. The results of this study convincingly prove the usefulness of applying Zn along with site specific nutrient management (SSNM) in rice in eastern India to produce high yields and GRFs and reduce GHG emissions.

**Keywords** Rice yield, Zinc, On-farm trial, Greenhouse gas emissions, RCM, SSNM, Fertilizer recommendation

In India, zinc (Zn) is now considered the fourth most crucial yield-limiting nutrient after N, P, and K<sup>1</sup>. Analysis of 256,000 soils and 25,000 plant samples from all over India revealed that 48.5% of the soils and 44% of the plant samples were potentially Zn deficient and that this was the most common micronutrient problem affecting crop yields<sup>2</sup>. Periodic assessment of soil test data also suggested that Zn deficiency in the soils of India is likely to increase from 49 to 63% by the year 2025, as most of the marginal soils brought under cultivation show Zn deficiency<sup>3–5</sup>. The application of Zn in significant quantities and at the appropriate time is critical to achieving optimum rice yield because the production of rice may decrease by 25–50% under Zn deficiency<sup>6</sup>. Zn is also a major health risk factor in Asian countries where rice is the main meal, and Zn nutrition for human and animal health has recently received significant emphasis<sup>3,4,7</sup>. Compared to other parts of India, rice production in eastern India is frequently hampered by drought, floods, salinity, low soil fertility, and inadequate or insufficient fertilizer application<sup>8</sup>.

Zinc exists in the soil in various pools, including primary and secondary minerals, organic and inorganic precipitates, complexes, and exchangeable and adsorbed pools<sup>4,9</sup>. Widespread Zn deficiency in soils shows that both naturally occurring and applied Zn interact with both inorganic and organic components in the soil and determine its availability to crop plants<sup>10,11</sup>. A significant amount of Zn in the soil is bonded to iron oxides.

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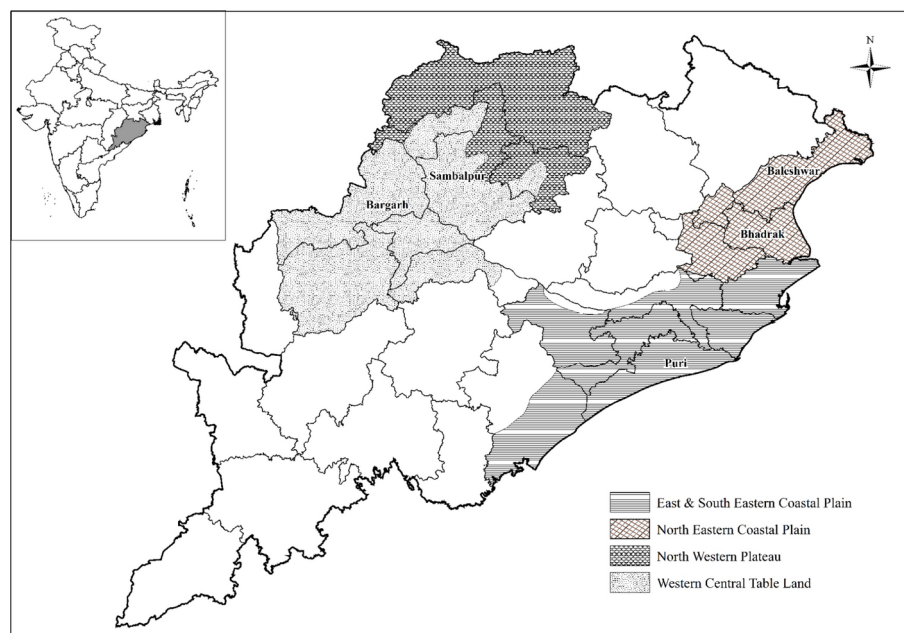
Under irrigated transplanted rice, these oxides are reduced upon submergence, resulting in lower concentrations of ionic forms that are more soluble. As a result, bound Zn is liberated and made accessible to crop plants.

The International Rice Research Institute (IRRI), in partnership with national partners from around Asia, developed the web-based decision support tool *Nutrient Manager for Rice*, which computes fertilizer rates and timings for a given field on the principles of site-specific nutrient management (SSNM)<sup>12</sup>. The IRRI modified the *Nutrient Manager for Rice* into another web-based tool, *Rice Crop Manager* (RCM), which provides crop management guidance in addition to nutrient management<sup>13</sup>. An on-farm study revealed that the components of SSNM using RCM increased rice production by 1.0–2.3 t/ha and enhanced profitability by US\$ 216–640 per ha compared to farmers' fertilizer practice (FFP) in West Africa<sup>14</sup>. Similar results were also obtained by various other workers in the Philippines<sup>15</sup> and India<sup>16</sup>. The site-specific fertilizer recommendations generated by the RCM in these studies produced high yield levels and reduced the risk of financial loss. Odisha is one of the major rice-producing states in eastern India, but its average yields are conspicuously lower (1.74 t per ha) compared to the national average (2.57 ton/ha) (IRRI News, 2020). A large portion of the rice in Odisha is grown on small and marginal plots of land with different crop management techniques and environmental challenges, such as drought and floods, which affect rice production and the need for additional fertilizers. Odisha may be well suited for SSNM as guided by RCM, with fertilizer application rates and timing adjusted for a target yield, rice variety, and crop management of a particular field rather than general fertilizer recommendations that do not take into account the spatial variability among rice fields<sup>16</sup>. However, Zn management in rice also needs to be matched with RCM-based SSNM. Zinc may be applied to rice nurseries or transplanted rice fields to meet the Zn needs of rice crops. The objective of the present study was to evaluate different scenarios of Zn management in rice nurseries or transplanted rice fields at on-farm locations when N, P and K are managed via SSNM assisted by RCM. We hypothesized that the practices involving application of Zn at nursery and/or transplanting stage would improve the productivity and GRF of rice. This study was conducted across a variety of rice-growing conditions in Odisha state of eastern India to assess the impacts of the agroclimatic zone, soil, cropping season and rice varieties.

## Materials and methods

### Site characterization

Experiments were conducted with rice at on-farm locations during the *Kharif* seasons of 2018 and 2019 and the *Rabi* seasons of 2018–2019 and 2019–2020. The *Kharif* season rice crop is grown from July to October during the southwest monsoon season. The *Rabi* season crop is grown from October to March during mild winters. The average annual rainfall of the state is 145.12 cm, which is mainly concentrated over a period of three months during the monsoon season. The average maximum temperature is the highest in April–May and reaches 40 °C, whereas the average minimum temperature is low (20 °C) in December–January. Low temperatures during December and January coincided with the early vegetative period of the *Rabi* rice crop. During the *Rabi* season, the relative humidity is near 70%. However, it increased gradually in the *Kharif* season. The experimental sites were distributed across five districts and four agroclimatic zones of major rice cropping areas in Odisha state of eastern India (Fig. 1). The soils in the region are lateritic, red, and yellow in the northwestern plateau, with low soil fertility, alluvial deltaic soils, and coastal saline soils in the northeastern coastal plain; red-yellow and black



**Fig. 1.** Map of Odisha state in India showing the five districts and four agroclimatic zones with field trials (Software used to develop the map: ArcGIS version 10.3).

soils in the west-central table land; and coastal saline, alluvial, black and red soils in the east and southeastern coastal plain. The plants in the experiments were irrigated and rained in the *Kharif* season, but they were irrigated in the *Rabi* season.

Experimental design

A total of 339 on-farm experiments (including both the *Kharif* and *Rabi* cropping seasons) were conducted at different locations in five districts of Odisha state. Each trial consisted of five plots, each measuring between 60 and 980 m<sup>2</sup>. The variability or bias was addressed by including large sample sizes. The following five non-replicated treatments were randomly allocated to the five plots in each experiment:

- 1. RCM<sub>T</sub>C (T<sub>1</sub>): SSNM/RCM-based NPK in the transplanted crop + compost in the rice nursery (4000 kg compost ha<sup>-1</sup> nursery area) as farmers’ practice.
- 2. RCM<sub>T</sub>Z<sub>1/2n</sub> (T<sub>2</sub>): SSNM/RCM-based NPK in transplanted crop + Half recommended dose of Zn in the rice nursery (50 kg ZnSO<sub>4</sub> ha<sup>-1</sup> nursery area). No compost was applied.
- 3. RCM<sub>T</sub>Z<sub>n</sub> (T<sub>3</sub>): SSNM/RCM-based NPK in transplanted crop + Full recommended dose of zinc in the rice nursery (100 kg ZnSO<sub>4</sub> ha<sup>-1</sup> nursery area). No compost was applied.
- 4. RCM<sub>T</sub>Z<sub>1/2t</sub> (T<sub>4</sub>): SSNM/RCM-based NPK in transplanted crop + Half recommended dose of zinc in the transplanted crop (12.5 kg ZnSO<sub>4</sub> ha<sup>-1</sup> transplanted area). No compost or Zn was applied to the rice nursery.
- 5. RCM<sub>T</sub>Z<sub>t</sub> (T<sub>5</sub>): SSNM/RCM-based NPK in transplanted crop + Full recommended dose of zinc in the transplanted crop (25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> transplanted area). No compost or Zn was applied to the rice nursery.

An earthen levee encircled each plot to stop the transport of nutrients between plots. This study included 20 registered varieties of rice whose agronomic parameters varied between the two cropping seasons (Table 1).

Farmers at all 339 locations underwent an RCM (<http://webapps.irri.org/in/od/rcm>) based discussion before crop establishment and to record size, rice variety, anticipated age of seedlings at transplanting, irrigation method (irrigated or rainfed), rice yield in previous years with the same or a similar variety, percentage of above-ground residues from the previous crop still in the field, and choice of fertilizer sources. To reach a target yield goal, the RCM computes a field-specific fertilizer recommendation using the data provided by each farmer. This RCM recommendation included the rates and time for applying the sources of fertilizer that the farmer had selected. For each field location, distinct N, P, and K suggestions for RCM treatment were made. Usually, the RCM raises the historical yield that the farmer mentioned during the RCM interview as the target output. When transplanting is postponed, the RCM also alters the target yield downward, which restricts the upward adjustment of the yield for low-yielding rice varieties<sup>16</sup>. In 12% of the field experiments in our analysis, the goal yield was therefore lower than the farmer’s reported historical production. In this study, the target yield for RCM ranged between 3.0 and 6.0 t ha<sup>-1</sup>.

Application of N, P, K, and Zn in the RCM-based SSNM treatments

The anticipated increase in yield from applied N was divided by the target agronomic efficiency of additional fertilizer N by the RCM to compute the fertilizer N rate for a target yield. The results of the nutrient omission plot method trials were used to calibrate the estimated yield increases from managed N as a measure of target yield. The increase in yield from applied N that was estimated from nutrient omission plot trials conducted in Odisha was used by the RCM in the present study to calculate the fertilizer N rate. This method resulted in a linear increase in the predicted fertilizer N rate with RCM, from 57 kg N ha<sup>-1</sup> (target yield 3 t ha<sup>-1</sup>) to 123 kg N ha<sup>-1</sup> (target yield 6 t ha<sup>-1</sup>). In three stages, namely, the early vegetative stage, mid-tillering (MT), and panicle initiation (PI), fertilizer N with RCM was applied. The MT and PI stages are crucial for fertilizer N application; however, the length of the growth cycle of the rice variety and the age of the transplanted seedlings determine how long it takes to reach these crucial phases after transplanting. RCM suggested days after transplanting (DAT) for each fertilizer N application using data gathered from the farmer about the variety and age of transplanted plants. It then accessed information on the growth duration of the chosen variety, which was kept in a database.

At transplanting, P fertilizer with RCM guidance was applied as a basal dose. It was estimated using information on the balance of nutrient input and output in a particular field with variances in the amounts of P taken by mature crops and the crop residues that were retained. The projected amount of additional K the rice crop would absorb to reach the desired yield was divided by the improved recovery efficiency of K to determine the RCM-based fertilizer K rate. At transplanting, K fertilizer was applied as a basal dose. K was applied at a 100% basal rate when the total rate was less than 33 kg ha<sup>-1</sup>. A total of 50% of the total K fertilizer was applied basally at transplanting, and 50% was applied at the PI stage if it was greater than 33 kg ha<sup>-1</sup>. Depending on how long each rice variety would take to mature, different N, P, and K applications were applied at various intervals. These were applied between 0 and 5 DAT for the types with a short duration and 0–21 DAT for those with a long duration.

To prevent farmers from making changes or being biased, researchers controlled all fertilizer applications for all treatments. All management procedures other than fertilizer application, including land preparation, variety,

Duration	Variety
Short	Khandagiri, Parijata
Medium	Sindhu, 113, MD 264, MTU 1001, MTU 1010, Hira, Silky, 1156, Binadhan 11, Lalat, 468, Hardil
Long	Swarna, Pooja, Swarna Sub1

Table 1. Rice varieties across four agroclimatic zones (ACZs).

crop establishment, residue management, water management, and crop protection practices, were selected and carried out by the farmer and were the same for the five treatments.

Measurements and analyses

At physiological maturity, the crop was harvested from different plots in the experiments from an area of 5 m × 5 m (25 m<sup>2</sup>), and the GY was estimated at 14% moisture content using Eq. (1):

GY at 14% moisture content (t ha<sup>-1</sup>) =  $\frac{[100 - \text{actual moisture content (\%)}]}{100 - 14} \times \text{GY at harvest (t ha}^{-1})$  (1)

The cost of each fertilizer applied in the farmer’s field was estimated by the amount of fertilizer applied and the average farmgate prices of the selected districts in different seasons. The average prices of urea, DAP, MOP, compost, and zinc sulfate were 0.27 US\$ kg<sup>-1</sup>, 0.075 US\$ kg<sup>-1</sup>, 0.14 US\$ kg<sup>-1</sup>, 0.12 US\$ kg<sup>-1</sup>, and 1.25 US\$ kg<sup>-1</sup>, respectively. The total fertilizer cost (TFC) was calculated as the sum of all fertilizers applied. The prices are reported in US\$ at the exchange rate of 1 US\$ = 80 Indian rupees (INR). Gross return was computed using the average farmgate prices for unmilled rice across districts. The average farmgate price used in the present study was 0.25 US\$ ha<sup>-1</sup>. The gross return above fertilizer cost (GRF) in US\$ ha<sup>-1</sup> was determined as follows:

GRF = GR – TFC (2)

The difference in GRF between treatments was used to evaluate the added net benefit of Zn compared to that of compost.

The partial factor productivity (PFP) of additional N was computed as

Partial factor productivity (PFP, kg grain per kg N) =  $1000 \times \frac{\text{Grain yield (t ha}^{-1})}{\text{Fertilizer N (kg ha}^{-1})}$  (3)

All data were examined using independent mixed models for each response variable: fertilizer rate (N, P, K and Zn), yield, TFC, PFP, and additional net benefit. The parameters of treatments across the agroclimatic zone and across the seasons were included in the model as fixed effects based on the evaluated hypotheses. Interactions between components were treated as fixed effects, whereas farmer field trials were treated as random. Tukey tests for pairwise variations between more than two means and Dunnett’s tests for pairwise differences between these two means were used for post hoc comparisons at the α = 0.05 level of significance. The analysis was done in the SPSS programming language<sup>17</sup>.

The annual GHG emissions linked to the production of rice were computed using the Cool Farm Tool<sup>18</sup>. The programme considers context-specific elements such as pedo-climatic traits, production inputs, and other field- and farm-level management methods, which affect GHG emissions. The output from the Cool Farm Tool is the total GHG emissions per unit area and per unit of the product.

Ethics declaration

We confirm that all methods were carried out in accordance with relevant guidelines and regulations of the IRRI. All experimental protocols are developed and approved. We also confirm that informed consent of farmers was taken to set experiment/trial in their field. This is not a study involving farmer’s interview but involves general discussion. As we were doing this trial on Rice–Wheat growing farmers’ field so the farmers were discussed for some primary practices and varieties for us to follow up during the crop establishment.

Results

Evaluation of nutrient rates under various treatments across rice-growing seasons

Rice nursery

The data shown in Table 2 elucidate the rates of total N, P, K, and Zn fertilizers in various treatments across seasons (*Kharif* and *Rabi*) during the years 2018–2020 in rice nurseries. In the RCM<sub>1</sub>C treatment (T<sub>1</sub>), compost

Parameter	Treatment or contrast	Kharif		Rabi	
		2018	2019	2018–2019	2019–2020
No. of experiments		95	82	75	87
Total Zn (kg ha <sup>-1</sup> )	RCM <sub>1</sub> C (T <sub>1</sub> )	0.30 <sup>b</sup>	0.30 <sup>b</sup>	0.30 <sup>b</sup>	0.30 <sup>b</sup>
	RCM <sub>1</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	10.5 <sup>c</sup>	10.5 <sup>c</sup>	10.5 <sup>c</sup>	10.5 <sup>c</sup>
	RCM <sub>1</sub> Z <sub>n</sub> (T <sub>3</sub> )	21.0 <sup>d</sup>	21.0 <sup>d</sup>	21.0 <sup>d</sup>	21.0 <sup>d</sup>
	RCM <sub>1</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	RCM <sub>1</sub> Z <sub>t</sub> (T <sub>5</sub> )	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	Season		ns		
	Year		ns		

**Table 2.** Rates of Zn fertilizers applied to rice nurseries across different seasons and years under different treatments. Values in columns with the same letter do not significantly differ at 5% level. ns: Not significant.

supplied approximately 80, 20 and 80 kg ha<sup>-1</sup> of N, P and K, respectively. In all the other four treatments, P and K were not applied to the RNs. The total Zn concentration in treatment T<sub>1</sub> was significantly lower than that in treatments RCM<sub>T</sub>Z<sub>1/2n</sub> (T<sub>2</sub>) and RCM<sub>T</sub>Zn (T<sub>3</sub>), which received 10.5 and 21 kg Zn ha<sup>-1</sup>, respectively. No Zn was applied to rice nurseries in the RCM<sub>T</sub>Z<sub>1/2t</sub> (T<sub>4</sub>) and RCM<sub>T</sub>Zt (T<sub>5</sub>) treatments.

#### Transplanted rice fields

The data shown in Table 3 show the rates of total N, P, K, and Zn applied through fertilizers in the different treatments across seasons and years in the transplanted rice fields. Total N, P, and K were significantly similar among the treatments, but N and K differed across the seasons and across the years at  $P > 0.01$ ; they were greater (%) in the *Rabi* season than in the *Kharif* season; and they were greater in the first year (2018–2019) than in the second year (2019–2020) but were statistically similar for P and Zn across the seasons and years. The total Zn fertilizer rate significantly differed among the treatments. The amount was the lowest in the RCM<sub>T</sub>C (T<sub>1</sub>), RCM<sub>T</sub>Z<sub>1/2n</sub> (T<sub>2</sub>), and RCM<sub>T</sub>Zn (T<sub>3</sub>) treatments. The total Zn fertilizer rate was greatest in the RCM<sub>T</sub>Zt (T<sub>5</sub>) treatment, followed by the RCM<sub>T</sub>Z<sub>1/2t</sub> (T<sub>4</sub>) treatment, irrespective of season and year.

#### Evaluation of nutrient rates under various treatments across agro-climatic zones

The performance of different doses and times of Zn application with RCM recommendations was examined across four agro-climatic zones (ACZs) in two seasons for two years (Table 4). Four ACZs of Odisha state, i.e., the eastern and southeastern coastal plains, northeastern coastal plain, northwestern plateau, and western central land, were studied. The highest nutrient application rate was in the western central table land, followed by the northeastern coastal plain and the eastern and southeastern coastal plain, and the lowest nutrient application rate was in the northwestern plateau. The nutrient application rate was greater (3.5–4.7% in N, 3.1–0.4% in P<sub>2</sub>O<sub>5</sub> and 2.3–10.5% in K<sub>2</sub>O) in *Rabi* the season than in the *Kharif* season, irrespective of the ACZ and year. The total N, P, and K rates were determined according to the soil nutrient status as well as the previous fertilizer applied by

Parameter	Treatment or contrast	Kharif		Rabi	
		2018	2019	2018–2019	2019–2020
Number of experiments		95	82	75	87
Total N (kg ha <sup>-1</sup> )	RCM <sub>T</sub> C (T <sub>1</sub> )	118.2 <sup>ns</sup>	109.9 <sup>ns</sup>	117.2 <sup>ns</sup>	113.2 <sup>ns</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	112.7	106.9	119.8	111.2
	RCM <sub>T</sub> Zn (T <sub>3</sub> )	113.1	100.4	118.5	109.2
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	117.3	112.5	125.9	110.1
	RCM <sub>T</sub> Zt (T <sub>5</sub> )	115.9	110.3	124.3	115.7
	Season		ns		
	Year		ns		
Total P <sub>2</sub> O <sub>5</sub> (kg ha <sup>-1</sup> )	RCM <sub>T</sub> C (T <sub>1</sub> )	28.7 <sup>ns</sup>	29.7 <sup>ns</sup>	26.5 <sup>ns</sup>	28.0 <sup>ns</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	26.2	27.1	30.6	31.4
	RCM <sub>T</sub> Zn (T <sub>3</sub> )	29.7	26.0	30.1	31.2
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	28.4	30.9	30.7	27.7
	RCM <sub>T</sub> Zt (T <sub>5</sub> )	28.3	30.0	28.4	30.0
	Season		ns		
	Year		ns		
Total K <sub>2</sub> O (kg ha <sup>-1</sup> )	RCM <sub>T</sub> C (T <sub>1</sub> )	34.0 <sup>ns</sup>	34.5 <sup>ns</sup>	37.6 <sup>ns</sup>	36.2 <sup>ns</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	31.3	33.7	45.5	35.7
	RCM <sub>T</sub> Zn (T <sub>3</sub> )	38.1	33.2	40.6	34.7
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	39.0	35.9	38.9	33.2
	RCM <sub>T</sub> Zt (T <sub>5</sub> )	36.6	33.8	37.5	35.3
	Season		ns		
	Year		ns		
Total Zn (kg ha <sup>-1</sup> )	RCM <sub>T</sub> C (T <sub>1</sub> )	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	RCM <sub>T</sub> Zn (T <sub>3</sub> )	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	2.63 <sup>b</sup>	2.63 <sup>b</sup>	2.63 <sup>b</sup>	2.63 <sup>b</sup>
	RCM <sub>T</sub> Zt (T <sub>5</sub> )	5.25 <sup>c</sup>	5.25 <sup>c</sup>	5.25 <sup>c</sup>	5.25 <sup>c</sup>
	Season		ns		
	Year		ns		

**Table 3.** Rates of N, P, K, and Zn fertilizers applied across seasons and years under various treatments in transplanted rice fields. The values with the same letter in a column for a nutrient do not differ significantly; <sup>ns</sup>–nonsignificant; \*, \*\*, and \*\*\* indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively.

Nutrient	Season	Year	Treatment	Nutrient rate (kg ha <sup>-1</sup> )			
				East and south eastern coastal plain	North eastern coastal plain	Northwestern plateau	Western central land
Total N <sup>a</sup>	Kharif	2018	RCM <sub>T</sub> C (T <sub>1</sub> )	114.2***	114.8 <sup>ns</sup>	102.4 <sup>ns</sup>	139.2 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	105.2	121.9	105.3	124.4
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	112.4	122.9	113.8	125.3
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	119.2	116.5	113.7	124.6
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	118.5	117.1	112.7	117.8
		2019	RCM <sub>T</sub> C (T <sub>1</sub> )	118.1 <sup>ns</sup>	123.6 <sup>ns</sup>	119.5 <sup>ns</sup>	127.5 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	116.7	131.5	126.6	129.3
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	117.8	132.5	128.1	129.5
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	115.7	136.1	123.8	136.3
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	116.8	133.6	130.2	132.9
	Rabi	2018–2019	RCM <sub>T</sub> C (T <sub>1</sub> )	105.9 <sup>ns</sup>	113.5 <sup>ns</sup>	104.4 <sup>ns</sup>	118.5 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	106.2	116.6	99.3	95.2
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	103.0	106.8	73.2	118.7
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	105.1	117.1	109.5	118.7
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	89.9	113.5	110.8	117.4
		2019–2020	RCM <sub>T</sub> C (T <sub>1</sub> )	107.5 <sup>ns</sup>	116.1 <sup>ns</sup>	117.3 <sup>ns</sup>	119.7 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	104.6	117.7	121.3	121.3
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	105.8	118.1	124.7	126.2
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	106.6	113.5	124.8	123.2
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	103.4	127.9	128.3	127.4
P <sub>2</sub> O <sub>5</sub> <sup>a</sup>	Kharif	2018	RCM <sub>T</sub> C (T <sub>1</sub> )	25.9**	32.2 <sup>ns</sup>	23.0 <sup>ns</sup>	32.6 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	22.2	34.1	22.5	26.9
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	29.6	38.3	24.5	25.5
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	28.6	30.7	25.8	29.4
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	30.7	31.8	24.1	26.8
		2019	RCM <sub>T</sub> C (T <sub>1</sub> )	24.2 <sup>ns</sup>	26.8 <sup>ns</sup>	24.5 <sup>ns</sup>	26.3 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	27.6	28.3	26.5	27.2
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	25.9	31.6	31.4	32.4
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	28.3	33.1	32.1	33.4
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	24.8	32.8	32.8	33.4
	Rabi	2018–2019	RCM <sub>T</sub> C (T <sub>1</sub> )	29.7 <sup>ns</sup>	31.5 <sup>ns</sup>	25.5 <sup>ns</sup>	31.2 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	27.3	31.0	25.6	23.0
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	24.6	30.6	26.5	31.6
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	29.6	32.3	28.1	31.6
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	24.2	31.7	27.2	30.6
		2019–2020	RCM <sub>T</sub> C (T <sub>1</sub> )	25.5**	27.8 <sup>ns</sup>	28.5 <sup>ns</sup>	29.8 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	29.9	32.2	31.1	33.1
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	30.2	32.8	31.8	33.2
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	27.8	27.6	33.6	35.8
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	23.9	36.0	34.8	35.6
Continued							



Nutrient	Season	Year	Treatment	Nutrient rate (kg ha <sup>-1</sup> )			
				East and south eastern coastal plain	North eastern coastal plain	Northwestern plateau	Western central land
K <sub>2</sub> O <sup>a</sup>	Kharif	2018	RCM <sub>T</sub> C (T <sub>1</sub> )	31.6***	41.6 <sup>ns</sup>	25.5*	35.0*
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	26.2	40.6	27.1	32.5
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	44.5	51.2	29.1	23.3
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	52.9	42.5	29.8	28.3
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	53.7	35.6	27.3	28.3
		2019	RCM <sub>T</sub> C (T <sub>1</sub> )	30.0 <sup>ns</sup>	35.0 <sup>ns</sup>	32.3 <sup>ns</sup>	32.5 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	33.0	34.6	34.1	33.3
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	30.0	39.1	36.6	34.1
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	30.0	47.8	39.8	36.8
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	30.0	46.9	43.2	44.2
	Rabi	2018–2019	RCM <sub>T</sub> C (T <sub>1</sub> )	32.9 <sup>ns</sup>	35.2 <sup>ns</sup>	31.2 <sup>ns</sup>	41.2 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	32.6	36.4	30.0	30.0
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	32.8	38.6	23.3	41.2
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	32.4	37.2	35.7	41.2
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	27.7	36.8	30.0	40.0
		2019–2020	RCM <sub>T</sub> C (T <sub>1</sub> )	33.3 <sup>ns</sup>	36.6 <sup>ns</sup>	35.6 <sup>ns</sup>	34.7 <sup>ns</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	33.0	38.4	34.3	36.5
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	31.8	42.5	40.5	39.9
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	33.6	32.7	36.5	35.3
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	32.1	38.4	39.3	40.1

**Table 4.** Agro-climatic zone (ACZs) wise N, P, K, and Zn fertilizers' application rate in transplanted rice fields. <sup>ns</sup> = not significant ( $P > 0.05$ ); \*, \*\*, and \*\*\* indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively, between the groups; <sup>a</sup> fertilizer was applied.

the farmers in their fields. These data were used by the RCM to calculate the total N, P, and K fertilizers applied in different plots at any given location for this study.

### Evaluation of grain yield and gross return above the fertilizer nutrient rate under various treatments across rice-growing seasons

#### Grain yield

The grain yield was significantly greater in treatment T<sub>5</sub> (RCM<sub>T</sub>Z<sub>t</sub>), where N, P, and K were applied through RCM and a full dose of Zn was applied in the transplanted field, than in treatment T<sub>1</sub> (RCM<sub>T</sub>C), where NPK was applied through RCM and compost was applied to the nursery. However, the grain yield in T<sub>5</sub> was *on par* with those in T<sub>2</sub> (RCM<sub>T</sub>Z<sub>1/2n</sub>), T<sub>3</sub> (RCM<sub>T</sub>Z<sub>n</sub>) and T<sub>4</sub> (RCM<sub>T</sub>Z<sub>1/2t</sub>) irrespective of year and season (Tables 5 and 6). The ranges of increase in grain yield for T<sub>2</sub>, T<sub>3</sub>, T<sub>4</sub> and T<sub>5</sub> over T<sub>1</sub> were 0.09–0.48 t ha<sup>-1</sup>, 0.31–0.51 t ha<sup>-1</sup>, 0.39–0.50 t ha<sup>-1</sup> and 0.48–0.92 t ha<sup>-1</sup>, respectively. The grain yield was greater in the *Rabi* season than in the *Kharif* season; however, the difference was not significant across the years. The system yield for both years and the average yield are shown in Fig. 2. The mean system yield was significantly greater for T<sub>5</sub> than for T<sub>1</sub> and *was on par* with those for T<sub>2</sub>, T<sub>3</sub>, and T<sub>4</sub>.

#### Gross return above fertilizer cost (GRF)

For grain yield, the GRF was significantly greater in the RCM<sub>T</sub>Z<sub>t</sub> (T<sub>5</sub>) treatment, in which a rice nursery was raised without the application of compost or Zn and N, P, and K were applied as guided by RCM, and a full dose of Zn was applied in the transplanted field over the T<sub>1</sub> treatment (RCM<sub>T</sub>C), where although N, P, and K were applied following RCM, the nursery was raised using compost. The GRFs for treatments T<sub>3</sub> (RCM<sub>T</sub>Z<sub>n</sub>), T<sub>2</sub> (RCM<sub>T</sub>Z<sub>1/2n</sub>) and T<sub>4</sub> (RCM<sub>T</sub>Z<sub>1/2t</sub>) were *on par* with that of T<sub>5</sub>, irrespective of year or season (Table 5). The ranges of increase in the GRFs for T<sub>2</sub>, T<sub>3</sub>, T<sub>4</sub> and T<sub>5</sub> over T<sub>1</sub> were 20.1–105.6 US\$ ha<sup>-1</sup>, 69.2–111.5 US\$ ha<sup>-1</sup>, 22.2–94.0 US\$ ha<sup>-1</sup> and 84.1–118.5 US\$ ha<sup>-1</sup>, respectively.

### Analysis of variance for effect on grain yield and gross return above fertilizer (GRF)

Analysis of variance (ANOVA), as shown in Table 7, revealed a significant impact of source of variance (SOV) on grain yield and the GRF. There was a significant effect of ACZ, season, and treatment on grain yield and the GRF. Similarly, the interaction effect of ACZ and treatment had a significant influence on grain yield and the GRF. However, the interaction of season and treatment did not influence these parameters, while the three-way interactions of ACZ, season and treatment had a significant impact on grain yield and GRF.

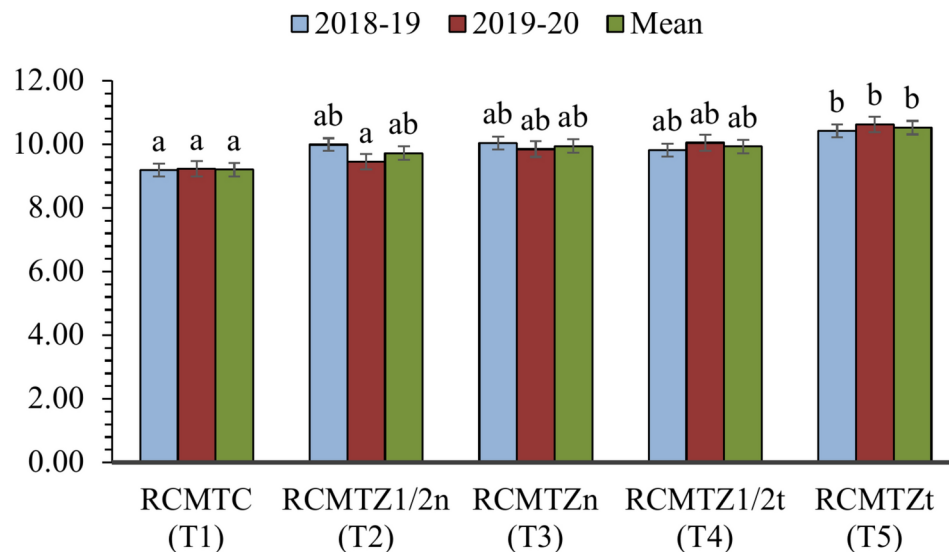
Parameter	Treatment or contrast	Kharif		Rabi	
		2018	2019	2018–2019	2019–2020
Trials (n)		95	82	75	87
Grain yield (t ha <sup>-1</sup> )	RCM <sub>T</sub> C (T <sub>1</sub> )	4.79 <sup>a</sup>	4.34 <sup>a</sup>	4.40 <sup>a</sup>	4.89 <sup>a</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	5.27 <sup>b</sup>	4.43 <sup>ab</sup>	4.72 <sup>ab</sup>	5.02 <sup>abc</sup>
	RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	5.30 <sup>b</sup>	4.65 <sup>b</sup>	4.74 <sup>ab</sup>	5.20 <sup>bc</sup>
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	4.92 <sup>ab</sup>	4.73 <sup>b</sup>	4.90 <sup>ab</sup>	5.32 <sup>bc</sup>
	RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	5.34 <sup>b</sup>	4.82 <sup>b</sup>	5.08 <sup>b</sup>	5.81 <sup>c</sup>
	Season		**		
	Year		ns		
GRF (US\$ ha <sup>-1</sup> )	RCM <sub>T</sub> C (T <sub>1</sub> )	1042.9 <sup>a</sup>	943.9 <sup>a</sup>	994.3 <sup>a</sup>	1102.2 <sup>a</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	1148.5 <sup>ab</sup>	964.0 <sup>ab</sup>	1064.0 <sup>b</sup>	1129.7 <sup>b</sup>
	RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	1154.4 <sup>b</sup>	1013.1 <sup>b</sup>	1071.2 <sup>b</sup>	1172.6 <sup>b</sup>
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	1070.1 <sup>ab</sup>	1025.9 <sup>b</sup>	1016.5 <sup>b</sup>	1196.2 <sup>b</sup>
	RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	1161.4 <sup>b</sup>	1028.0 <sup>b</sup>	1108.7 <sup>b</sup>	1206.6 <sup>b</sup>
	Season		**		
	Year		ns		

**Table 5.** Grain yield and gross return above fertilizer cost (GRF) across seasons (*Kharif* and *Rabi*) and years under various treatments. Values in a column with the same letter do not differ significantly; ns = not significant ( $P > 0.05$ ); \*, \*\*, and \*\*\* indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively, between the groups.

Parameters	Season	Year	Treatment or contrast	East and south eastern coastal plain	North eastern coastal plateau	North western plateau	Western central table land
Trials (n)	<i>Kharif</i>	2018		25	25	30	15
		2019		25	24	20	13
	<i>Rabi</i>	2018–2019		25	25	15	10
		2019–2020		25	25	20	17
Grain yield (t ha <sup>-1</sup> )	<i>Kharif</i>	2018	RCM <sub>T</sub> C (T <sub>1</sub> )	4.64 <sup>b</sup>	4.09 <sup>ab</sup>	4.76 <sup>b</sup>	5.91 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	4.70 <sup>ab</sup>	5.55 <sup>a</sup>	5.26 <sup>ab</sup>	5.78 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	4.92 <sup>ab</sup>	5.72 <sup>a</sup>	5.24 <sup>ab</sup>	5.35 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	5.04 <sup>ab</sup>	3.19 <sup>ab</sup>	5.88 <sup>ab</sup>	5.67 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	5.12 <sup>a</sup>	5.12 <sup>a</sup>	5.49 <sup>a</sup>	5.78 <sup>a</sup>
		2019	RCM <sub>T</sub> C (T <sub>1</sub> )	4.20 <sup>ab</sup>	4.50 <sup>b</sup>	4.90 <sup>ab</sup>	4.81 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	4.39 <sup>ab</sup>	5.04 <sup>ab</sup>	5.10 <sup>ab</sup>	5.27 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	4.41 <sup>ab</sup>	5.07 <sup>ab</sup>	5.04 <sup>ab</sup>	4.98 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	4.42 <sup>ab</sup>	4.60 <sup>ab</sup>	4.65 <sup>ab</sup>	5.03 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	5.07 <sup>a</sup>	5.10 <sup>a</sup>	5.96 <sup>a</sup>	5.81 <sup>a</sup>
	<i>Rabi</i>	2018–2019	RCM <sub>T</sub> C (T <sub>1</sub> )	2.93 <sup>a</sup>	4.90 <sup>b</sup>	5.33 <sup>a</sup>	5.04 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	2.87 <sup>a</sup>	5.30 <sup>ab</sup>	5.21 <sup>a</sup>	5.03 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	3.01 <sup>a</sup>	5.60 <sup>ab</sup>	5.34 <sup>a</sup>	5.42 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	3.23 <sup>a</sup>	5.29 <sup>ab</sup>	5.10 <sup>a</sup>	5.29 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	2.58 <sup>a</sup>	5.71 <sup>b</sup>	5.55 <sup>a</sup>	5.43 <sup>a</sup>
		2019–2020	RCM <sub>T</sub> C (T <sub>1</sub> )	4.63 <sup>b</sup>	5.10 <sup>ab</sup>	4.92 <sup>ab</sup>	4.65 <sup>a</sup>
			RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	4.65 <sup>ab</sup>	5.38 <sup>ab</sup>	5.05 <sup>ab</sup>	5.02 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	4.92 <sup>ab</sup>	5.49 <sup>ab</sup>	5.13 <sup>ab</sup>	5.17 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	4.95 <sup>ab</sup>	5.70 <sup>ab</sup>	5.09 <sup>ab</sup>	5.11 <sup>ab</sup>
			RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	5.05 <sup>a</sup>	6.58 <sup>a</sup>	5.36 <sup>a</sup>	5.41 <sup>a</sup>

**Table 6.** Measured rice grain yield for different fertilizer applications in two seasons (*Kharif* and *Rabi*) across four agro-climatic zones (ACZs) in Odisha, India. Similar letters represent statistically nonsignificant differences; ns: Nonsignificant differences.





**Fig. 2.** System yield ( $\text{t ha}^{-1}$ ) under the different treatments during 2018–19 and 2019–20. Columns with the same letter do not differ significantly at  $\alpha = 0.05$

Source of variance	df <sup>a</sup>	Significance	
		Grain yield	GRF
ACZ <sup>b</sup>	3	***	***
Season <sup>c</sup>	1	**	**
Treatment (T) <sup>d</sup>	4	***	***
ACZ*Treatment	12	**	**
Season*Treatment	4	ns	ns
ACZ*Season*Treatment	12	***	***

**Table 7.** Analysis of variance for effect of agroclimatic zone (ACZ) and fertilizer treatment on gross return of fertilizer (GRF) and measured rice grain yield. ns = not significant ( $P > 0.05$ ). \*\* and \*\*\* indicate significance at the 0.01 and 0.001 probability levels, respectively. <sup>a</sup>df = degrees of freedom. <sup>b</sup>ACZ = agroclimatic zone; ACZ is the eastern and southeastern coastal plain, northeastern coastal plain, northwestern plateau, and western central table land. <sup>c</sup>Seasons are *Kharif* and *Rabi* from 2018 to 2020. <sup>d</sup>Treatments are as described in Tables 1 and 2.

### Evaluation of additional net benefit and partial factor productivity (PFP) from different treatments

#### Additional net benefit

The additional net benefit was significantly greater for  $T_5$  than for  $T_4$  (*Kharif* 2018 or *Rabi* 2018–19) and  $T_2$  (*Kharif* 2019 or *Rabi* 2019–20) (Table 8). Treatment  $T_5$  was performed on par with treatment  $T_3$ . The ranges of additional net benefits during *Kharif* 2018, *Kharif* 2019, *Rabi* 2018–19 and *Rabi* 2019–20 were 27.2–118.5 US\$  $\text{ha}^{-1}$ , 20.1–84.1 US\$  $\text{ha}^{-1}$ , 22.2–114.4 US\$  $\text{ha}^{-1}$  and 27.5–104.4 US\$  $\text{ha}^{-1}$ , respectively. There was a significant difference in the additional net benefits across the seasons and years.

#### Partial factor productivity (PFP)

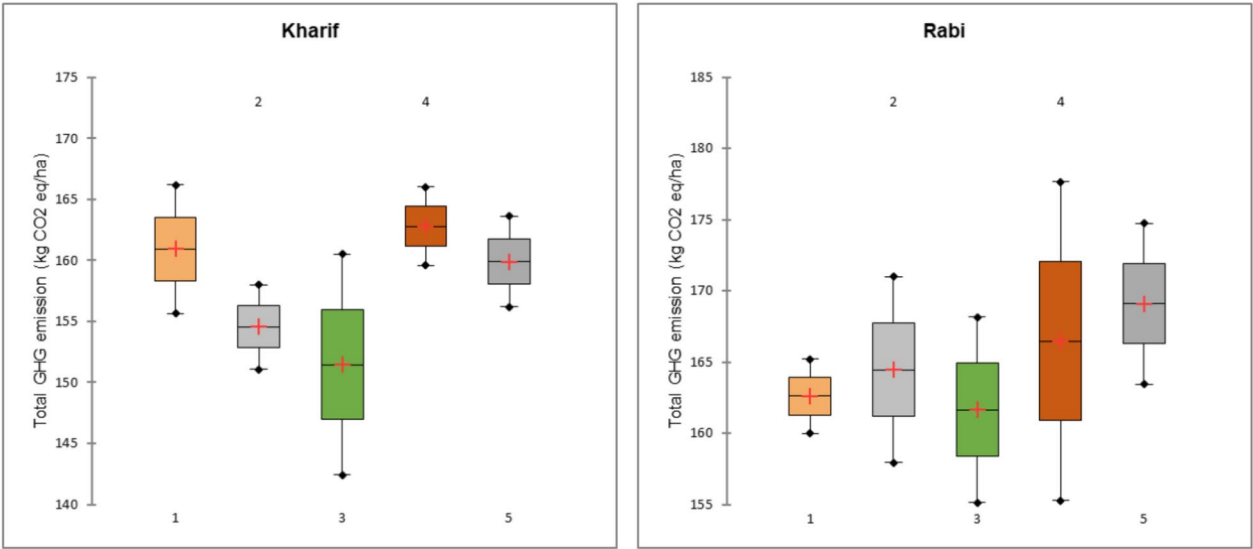
The partial factor productivity was significantly greater for  $T_5$  than for  $T_1$  and was on par with that for  $T_3$ , irrespective of season and year (Table 8). The ranges of PFP during *Kharif* 2018, *Kharif* 2019, *Rabi* 2018–19 and *Rabi* 2019–20 were 40.5–46.9 kg of grain per kg N, 39.5–46.3 kg of grain per kg N, 37.5–40.9 kg of grain per kg N and 43.2–50.2 kg of grain per kg N, respectively. There was no significant difference in the PFR across seasons or years.

### Evaluation of total greenhouse gas (GHG) emissions from different treatments

Total GHG emissions were estimated for both seasons across the years (Fig. 3). The total GHG emissions in the *Kharif* season ranged from 150 to 163 kg  $\text{CO}_2$  eq.  $\text{ha}^{-1}$ , while in the *Rabi* season, the total GHG emissions ranged from 162 to 170 kg  $\text{CO}_2$  eq.  $\text{ha}^{-1}$ , with greater emissions occurring during the *Rabi* season than during the *Kharif* season. During the *Kharif* season,  $T_4$  had the highest GHG emissions, followed by  $T_1$ ,  $T_5$ ,  $T_2$  and  $T_3$ . During the *Rabi* season,  $T_5$  exhibited the highest GHG emissions, followed by  $T_4$ ,  $T_2$ , and  $T_1$ , and the lowest GHG emissions occurred in  $T_3$ .

Parameter	Treatment or contrast	Kharif		Rabi	
		2018	2019	2018–2019	2019–2020
Trails (n)		95	82	75	87
Additional net benefit (US\$ ha <sup>−1</sup> )	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> ) vs. RCM <sub>T</sub> C (T <sub>1</sub> )	105.6 <sup>b</sup>	20.1 <sup>a</sup>	69.7 <sup>b</sup>	27.5 <sup>a</sup>
	RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> ) vs. RCM <sub>T</sub> C (T <sub>1</sub> )	111.5 <sup>b</sup>	69.2 <sup>ab</sup>	76.9 <sup>bc</sup>	70.4 <sup>b</sup>
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> ) vs. RCM <sub>T</sub> C (T <sub>1</sub> )	27.2 <sup>a</sup>	82.0 <sup>b</sup>	22.2 <sup>a</sup>	94.0 <sup>bc</sup>
	RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> ) vs. RCM <sub>T</sub> C (T <sub>1</sub> )	118.5 <sup>b</sup>	84.1 <sup>b</sup>	114.4 <sup>c</sup>	104.4 <sup>c</sup>
	Season		*		
	Year		*		
PFP (kg of grain per kg N)	RCM <sub>T</sub> C (T <sub>1</sub> )	40.5 <sup>a</sup>	39.5 <sup>a</sup>	37.5 <sup>a</sup>	43.2 <sup>a</sup>
	RCM <sub>T</sub> Z <sub>1/2n</sub> (T <sub>2</sub> )	46.8 <sup>b</sup>	41.4 <sup>a</sup>	39.4 <sup>ab</sup>	45.1 <sup>b</sup>
	RCM <sub>T</sub> Z <sub>n</sub> (T <sub>3</sub> )	46.9 <sup>b</sup>	46.3 <sup>b</sup>	40.0 <sup>ab</sup>	47.6 <sup>bc</sup>
	RCM <sub>T</sub> Z <sub>1/2t</sub> (T <sub>4</sub> )	41.9 <sup>ab</sup>	42.0 <sup>ab</sup>	38.9 <sup>a</sup>	48.3 <sup>bc</sup>
	RCM <sub>T</sub> Z <sub>t</sub> (T <sub>5</sub> )	46.1 <sup>b</sup>	43.7 <sup>ab</sup>	40.9 <sup>b</sup>	50.2 <sup>c</sup>
	Season		ns		
	Year		ns		

**Table 8.** Additional net benefit and partial factor productivity (PFP) across seasons (*Kharif* and *Rabi*) and years under various treatments. Similar letters represent statistically nonsignificant differences; \*, \*\*, and \*\*\* indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively, between the groups.



**Fig. 3.** Total GHG emissions for both seasons during the study years [1. RCM<sub>T</sub>C (T<sub>1</sub>); 2. RCM<sub>T</sub>Z<sub>1/2n</sub> (T<sub>2</sub>); 3. RCM<sub>T</sub>Z<sub>n</sub> (T<sub>3</sub>); 4. RCM<sub>T</sub>Z<sub>1/2t</sub> (T<sub>4</sub>); 5. RCM<sub>T</sub>Z<sub>t</sub> (T<sub>5</sub>)].

**Discussion**  
**Nutrient (N, P, K, and Zn) recommendation using RCM**

The amount of fertilizer applied to rice varies between fields depending on crop and soil management practices and the nutrient supply capacity of the soil and rice variety. Soil characteristics like texture, organic matter, and pH affect nutrient availability and retention, influencing crop nutrient demands. Management practices such as irrigation and cropping history alter soil nutrient levels and dynamics, impacting fertilization requirements<sup>16</sup>. In the present study, N, P, and K fertilizers applied to different treatment plots were estimated using a web-based RCM tool following the principles of the SSNM. The SSNM for rice developed Dobermann et al.<sup>19</sup> was limited to the macronutrients N, P, and K. The use of nutrient recommendations through RCM always has a rice yield advantage because fertilizers are estimated to achieve a target yield<sup>16</sup>. Increasing areas under RCM-guided soil and crop management practices have been found to be comparatively superior to those under farmer fertilizer practices<sup>14–16</sup>, but refining, evaluation, and out-scaling are still the key targets for RCM outreach. The scalability and accuracy of RCM are influenced by farmer literacy, technological access, and regional soil characteristics, as farmers need adequate knowledge, access to digital tools, and accurate soil data for effective use of the tool<sup>20</sup>. While studying RCM in intensively cultivated areas such as rice–rice and rice–wheat cropping systems, Zn deficiency was noted with a significant yield loss ranging in 20.2–23.7% in rice<sup>21</sup>, hence, Zn was included as an

important component for nutrient recommendation through RCM. Currently, the recommendation for Zn is blanket application of 25 kg Zn sulfate ha<sup>-1</sup> in the transplanted field. Although the application of Zn has been found to improve rice yields, it leads to a substantial increase in the cost of cultivation for rice crop production. The present study therefore revolves around the refinement and evaluation of Zn management when coupled with RCM-guided fertilizer management in eastern India.

As in the case of managing nutrients using RCM in a field-specific manner, farmers in the regions were interviewed about Zn management in rice prior to the commencement of the cropping season. In accordance with what each farmer stated during an interview, Zn sulphate was applied as a fertilizer. Most farmers did not use Zn; only 5% of the farmers applied Zn to rice fields. It was attempted to understand how far the yield variations among farmers were linked with Zn management.

### Zinc management in rice fields

Zinc is an essential micronutrient that influences rice growth and yields mainly by affecting N assimilation and protein and lipid metabolism<sup>11,22</sup>. A low Zn supply limits the ability of plants to convert amino acids to protein. Therefore, when the Zn supply in the soil is limited, plant growth is restricted. Zn deficiency in rice has been reported worldwide<sup>23,24</sup>. Zn availability in fields is influenced by several factors, such as soil Zn status, soil pH, organic matter, soil temperature, moisture, and root spreading<sup>10</sup>. The common problem of Zn deficiency is typically poor by continuous flooding, which alters the pH and Eh of the soil and affects the availability of Zn by regulating the forms of Zn in the soil.

To ensure a favorable crop response to Zn fertilizer treatment and to achieve a healthy and productive crop, other nutrients must be applied at appropriate levels. Zn application in rice nurseries and transplanted fields has been reported to be effective for Zn management in rice fields<sup>25</sup>. The results from the present study showed that although compost was applied in the nursery, Zn applied in the nursery and transplanted field at either half dose or full dose had a higher rice yield and a greater positive GRF than the compost-based treatment. The synergistic effects of Zn application on rice growth, yield and economics were also proved by several workers<sup>26,27</sup>. The additional net benefit and PFP were also greater for Zn applied in the nursery and in the transplanted field when either a half dose or full dose of the compost was applied in the nursery. Two years of studies were not able to establish a significant yield difference between Zn management practices in the nursery and transplanted fields. Long-term studies may distinguish between the impacts of nursery application and transplanted field application.

The application of Zn can increase rice crop yield by 9–12% in different climatic zones and soil types<sup>28</sup>. This study also revealed a significant impact of season and ACZ on rice yield and GRF. The improved Zn fertilizer management with RCM resulted in a greater yield in the *Rabi* season. This may be due to the continuous application for two years each season. Based on general nutrient recommendations, the use of Zn for one crop in a cropping system is effective for 2–3 crops. An efficient amount of Zn applied to the soil helps increase the amount of amino acids in rice (Kalwe et al., 2001). RCM-Zn had an additional net benefit and PFP over the other farm practices. This can result in improved economic sustainability for farmers in eastern India.

### Refinement of zinc application for RCM

The ultimate goal of this study was to generate datasets for refining RCMs for Zn management in rice in eastern India. Considering seasons, ACZ and varieties for collecting datasets will allow suitable modifications of the RCM algorithm for better soil and crop management in rice for both nursery and transplanted fields as demonstrated in the current findings. This refinement of RCMs can improve the productivity of rice crops in the region as well as reduce the cost of cultivation by reducing the amount of Zn applied and adding net benefits to farmers which was also proved in the current investigation.

### Greenhouse gas emissions from RCM-based rice fields

Zn application at a half or full dose along with RCM-based NPK to the transplanted fields resulted in high GHG emissions. However, Zn applied to the nursery along with RCM-based NPK had lower GHG emissions. Chivenge et al. (2020) reported that transplanted rice cultivation practices involving intense agricultural practices and high-yielding varieties resulted in high amounts of GHG emissions in the atmosphere. Studies have reported that compared with other agricultural practices, SSNM in cereals significantly reduces GHG emissions<sup>29</sup>. The treatments in this study are SSNM-based and could be expected to reduce GHG emissions over the FFP.

The application of urea as fertilizer N, crop residue burning, and tillage practices in rice fields increase CO<sub>2</sub> emissions<sup>30</sup>. The majority of C in urea is released as CO<sub>2</sub>. Urea fertilizer includes 12 g C for every 28 g N, and its global warming potential is 1.6 kg CO<sub>2</sub> kg<sup>-1</sup><sup>31</sup>. The RCM-based NPK was preferred for applying fertilizers, and their cost was determined according to the target yield based on the SSNM. This reduces the financial risk of farmers<sup>16</sup>. Therefore, RCMZn should prove to be the best alternative and most sustainable fertilizer management method for farmers in eastern India.

### Conclusion

An evaluation of Zn management in eastern India's rice revealed that Zn is essential for growth and yield. High yield levels can be achieved by managing Zn either in nurseries or the transplanted crop, aligned with site-specific nutrient management practices. The application of compost at a rate of 4 t ha<sup>-1</sup> to rice nurseries by farmers is insufficient to satisfy their Zn requirements. Experiments conducted at 339 on-farm locations revealed that that Zn sulfate must be applied to rice nurseries at least at 50 kg Zn sulfate ha<sup>-1</sup> (on a nursery basis) or to transplanted rice crops at 12.5 kg Zn sulfate ha<sup>-1</sup> to produce higher yields and higher net returns in rice in eastern India. The RCM algorithm can be enhanced to facilitate the management of Zn, N, P, and K in eastern

India by incorporating data from the *Rabi* and *Kharif* seasons, ACZs, and rice varieties to assess the compatibility of potential Zn management options.

## Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. All data generated or analysed during this study are included in this published article.

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### Author contributions

SS and AKM conceptualize and executed the experiment. AKM and GPP analysed the data, wrote the main manuscript, and AKM, RP, PB and SS edited and finalized the manuscript.

### Declarations

### Competing interests

The authors declare no competing interests.

### Additional information

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