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To cite this article: Firmin N Anago, Emile C Agbangba, Brice C T Oussou, Gustave D Dagbénobakin & Lucien G Amadji (2023): Magnesium and zinc fertilisation improves rice yield and yield component responses to nitrogen, phosphorus, and potassium, South African Journal of Plant and Soil, DOI: [10.1080/02571862.2023.2212190](https://doi.org/10.1080/02571862.2023.2212190)

To link to this article: <https://doi.org/10.1080/02571862.2023.2212190>

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 Published online: 26 Jul 2023.

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Magnesium and zinc fertilisation improves rice yield and yield component responses to nitrogen, phosphorus, and potassium

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The aim of this study was to assess the effects of magnesium (Mg) and zinc (Zn) on the response of rice to nitrogen (N), phosphorus (P), and potassium (K) application. Two sets of field experiments were carried out in Benin. A Box Behnken Design with eight replications per year with treatments of N, P, potassium (K), Mg, and Zn was used for the first experiment, while a randomised complete block design with five treatments varying in Mg and Zn was used for the second experiment. Co-application of major nutrients with Mg and/or Zn significantly increased rice yield and nutrient use efficiencies. Co-application of N and Mg increased grain yield, filled grain rate, and 1 000 grains weight by 53.5, 7.10, and 7.34%, respectively. Likewise, the co-application of N with Zn increased rice yield, panicles per plant, and spikelets per panicle by 35.69, 14.78, and 6.06%, respectively. When P was co-applied with Zn, grain yield, spikelets per panicle, and the 1 000 grains weight increased by 27.21, 5.71, and 6.20%, respectively. The co-application of K with Mg led to an increase of grain yield and filling of grain by 24.28, and 5.71%, respectively. This study revealed the positive effects of Mg and Zn on rice yield response to the application of N, P, and K.

Key words: agronomic efficiency, harvest index, micronutrients, secondary nutrients, rice fertilisation

Online supplementary material: Supplementary data for this article are available at <https://doi.org/10.1080/02571862.2023.2212190>

Introduction

The decline in the response of rice to the application of fertilisers may be attributed to nutrient deficiency owing to the inadequate or imbalanced application of fertilisers by farmers (Anago et al. 2020a). Globally, it is recognised that nitrogen (N), phosphorus (P) and potassium (K) fertilisers alone are not always sufficient to provide balanced nutrition for optimal rice yields and quality. The application of major nutrients has a major influence on rice crop yield and quality (Fageria 2014). However, this must be accompanied by the application of secondary and micronutrient elements. It is also important to reduce the amount of major nutrients applied in crop production to mitigate environmental problems. Losses of N by volatilisation and denitrification contribute to climate change, while the leaching of nitrates results in groundwater pollution and the eutrophication of surface waters (Cameron et al. 2013). The nutrients most widely supplied in Africa are N, P, and K, and many complete

fertilisers are made up of only these major nutrients. However, apart from the major nutrients, the application of other nutrients is required for optimal yield. Most of the commonly applied fertiliser in Sub-Saharan Africa (SSA) contains mainly N, P, and/or K, which do not replenish secondary nutrients and micronutrients such as calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), boron (B), and molybdenum (Mo) which often limit crop growth (Vanlauwe et al. 2015). Unfortunately, despite their importance, secondary nutrients and micronutrients have received less attention than macronutrients. Nutrient imbalances tend to be worse because of increased intensity in cropping, greater erosion, and the lack of inputs from organic or inorganic sources of nutrients.

The increased demands for secondary nutrients and micronutrients in high-yielding cultivars, intensification of cropping practices, and increasing production of crops on

marginal soils that were poor in those nutrients induce their expended deficiencies (Sathiyavani et al. 2017; Kihara et al. 2020). Secondary nutrients and micronutrients are needed in trace amounts but their adequate supply improves nutrient availability and positively affects crop yield. In Benin, the nutrient requirement for rainfed rice production was ranked as $N > Fe > Zn > K > Mg > P > Ca$ (Anago et al. 2020b). However, farmers apply N, P, K, and S fertilisers widely and the application of Mg and Zn is not common. This could explain the erratic evolution of average rice yields throughout the last decades, rarely exceeding $2\,500\text{ kg ha}^{-1}$ in rainfed systems, while the potential yield could reach $5\,000\text{--}7\,000\text{ kg ha}^{-1}$ according to variety (Anago et al. 2020a; FAOSTAT 2022). Deficiency of Mg is a frequently limiting factor for crop production due to low levels of exchangeable Mg in acidic soil, which negatively affects the sustainability of agricultural development (Wang et al. 2020). Magnesium deficiency has become a widespread problem that severely reduces the photosynthetic rates of crops, especially those grown in acidic soils (Chaudhry et al. 2021). Substantial literature is available on the importance of Mg for agricultural productivity and Mg deficiency in soils and crops (Cakmak and Kirkby 2008; Cakmak 2013; Ceylan et al. 2016). Zinc deficiency is also a major problem in soils (Khan et al. 2021) as although it is needed in low amounts it is often deficient in the soil. This deficiency brings about physiological stress in plants and animals owing to the dysfunction of several enzyme systems and other metabolic functions in which Zn is involved (Khan et al. 2021). Zinc deficiency is a major micronutrient issue that agriculture needs to address (Muthukumararaja and Sriramachandrasekharan 2012) and which has been reported in various parts of the world (Goloran et al. 2019). Recent research has shown that Mg and Zn increase the yield response of rice to N application (Guo et al. 2015). However, little is known about the effects of Mg and Zn on rice yield components' response to N application. Similarly, the effect of Mg and Zn on the response of rice to P and K applications is poorly understood. This knowledge gap leads to the following question: what is the effect of Mg and/or Zn on N, P, and K in improving rice yield and its parameters, harvest index, and agronomic efficiency? We hypothesised that Mg and Zn improved rice yield response to N, P, and K applications, due to their interactive effects on rice yield parameters. This study aims at assessing the effect of Mg and Zn on rice responses to N, P, and K applications.

Materials and methods

Soil characteristics

Two sets of experiments were conducted in the field in the villages of Yagbo ($02^{\circ}07'04.58''\text{E}$, $08^{\circ}7'19.3''\text{N}$) and Miniffi ($02^{\circ}18'08.93''\text{E}$, $07^{\circ}49'33.57''\text{N}$), Central Benin. The first set of experiments was carried out during the 2018 and 2019 rainy seasons and the second during the 2020 and 2021 rainy seasons. The soil of this area is classified as Luvisol (Kouélo et al. 2012; Azontonde et al. 2016). Thirty-two composite soil samples were collected with a soil auger at a depth of 0–20 cm diagonally across each of the experimental fields before basal fertiliser was applied in

both years. The soil samples were air-dried and crushed, and the physicochemical properties were assessed. The pH (water) was measured using the pH meter at a ratio of 1:2.5 soil:water. The organic matter and total N content were determined using the Walkley–Black and Kjeldahl methods, respectively (Dieckow et al. 2007). The available phosphorus was determined following the Bray-1 method (Boem et al. 2011). The exchangeable potassium and exchangeable capacity cations were determined by the ammonium acetate method of Metson at pH 7 and atomic absorption spectrophotometry (Sidi et al. 2015). Soil texture was analysed with the Robinson pipette method (Cathy et al. 2021). The average values of soil properties for the experimental plots across the two years are presented in Table 1.

Fertiliser dosage method

First experiment (2018 and 2019)

A Box-Behnken design experiment (Ferreira et al. 2007) with five factors (N, P, K, Mg, and Zn) was carried out. Each factor had three levels based on the lowest and highest application rates in recent literature: 0, 125, and 250 kg N ha^{-1} (Bai et al. 2019; Hu et al. 2019; Kong et al. 2019); 0, 100, and $200\text{ kg P}_2\text{O}_5\text{ ha}^{-1}$ (George et al. 2001; Fageria et al. 2014); 0, 60, and $120\text{ kg K}_2\text{O ha}^{-1}$ (Saha et al. 2009; Reis et al. 2018; Fryer et al. 2019); 0, 15, and 30 kg MgO ha^{-1} (Choudhury and Khanif 2001; De Bauw et al. 2019); and 0, 15, and 30 kg Zn ha^{-1} (Guo et al. 2015; Chen et al. 2017). In this study, N, P, K, Mg, and Zn were broadcast as urea at 46% of N, Triple Super Phosphate (TSP) at 46% of P_2O_5 , potassium chloride (KCl) at 60% of K_2O , magnesium sulfate (MgSO_4) at 23.5% of MgO and zinc sulfate (ZnSO_4) at 35% of Zn, respectively.

Second experiment (2020 and 2021)

The experiment was conducted in a randomised complete block design. The following five treatments were replicated four times in each village: complete fertiliser (T4) treatment composed of 106, 90.6, 58.5, 14.1, and 11.8 kg ha^{-1} of N, P_2O_5 , K_2O , MgO, and Zn, respectively (optimal combination rates of fertiliser obtained from first experiment results); exclusion of Mg and Zn from T4 (i.e. $T1 = T4 - (\text{Mg} + \text{Zn})$), exclusion of Zn from T4 ($T2 = T4 - \text{Zn}$), exclusion of Mg from T4 ($T3 = T4 - \text{Mg}$); and control T0 with no fertiliser.

Field experiment, plant sample, and data collection

Seeds of the rice cultivar Nerica 4, also called WAB 450-I-B-P-91-HB, obtained from Africa Rice in Ivory Coast were used as planting material in both experiments. In the first experiment, the size of each elementary plot was $3\text{ m} \times 4\text{ m}$ (12 m^2). The experiments, with 46 combinations of nutrients, were replicated four times at Yagbo and four times at Miniffi during the rice growing season from August to November 2018. The experiment was repeated in adjacent fields in 2019. In the second experiment, the land was laid out in 25 m^2 ($5 \times 5\text{ m}^2$) plots. The five treatments were replicated four times in a randomised complete block design at Yagbo also at Miniffi during the rice growing season from August to November 2020 and 2021.

In both experiments, rice was planted through direct seeding between the 1st and 5th of August of each year

Table 1: Physicochemical properties of soil at experimental sites over the study period

Parameters	2018			2019			2020			2021		
	Yagbo	Miniffi	Yagbo	Miniffi	Yagbo	Miniffi	Yagbo	Miniffi	Yagbo	Miniffi	Yagbo	Miniffi
Clay (%)	14.75 ± 2.4	14.95 ± 1.39	15.28 ± 4.73	13.19 ± 2.98	12.74 ± 0.41	13.94 ± 0.56	14.74 ± 0.4	13.94 ± 0.56	14.74 ± 0.4	12.4 ± 0.5	14.74 ± 0.4	12.4 ± 0.5
Loam (%)	24.18 ± 6.47	25.85 ± 3.96	26.68 ± 1.86	22.66 ± 2.48	22.22 ± 2.98	23.6 ± 3.05	21.22 ± 2.8	23.6 ± 3.05	21.22 ± 2.8	22.6 ± 3.5	21.22 ± 2.8	22.6 ± 3.5
Sandy (%)	60.85 ± 6.40	59.14 ± 3.95	58.03 ± 9.36	64.19 ± 4.61	65.4 ± 3.39	63.0 ± 2.89	66.4 ± 3.9	63.0 ± 2.89	66.4 ± 3.9	64.0 ± 2.9	66.4 ± 3.9	64.0 ± 2.9
Organic C (g kg ⁻¹)	9.6 ± 0.8	12.0 ± 1.2	8.3 ± 1.3	9.3 ± 0.4	13.2 ± 0.25	10.6 ± 0.18	11.2 ± 0.5	10.6 ± 0.18	11.2 ± 0.5	12.6 ± 0.8	11.2 ± 0.5	12.6 ± 0.8
Total N (g kg ⁻¹)	0.73 ± 0.04	0.88 ± 0.08	0.6 ± 0.01	0.79 ± 0.09	0.8 ± 0.04	0.7 ± 0.06	0.7 ± 0.05	0.7 ± 0.06	0.7 ± 0.05	0.6 ± 0.05	0.7 ± 0.05	0.6 ± 0.05
C/N (%)	13.28 ± 1.21	13.70 ± 0.78	8.4 ± 1.95	12.03 ± 2.07	16.5 ± 3.4	15.14 ± 3.6	14.5 ± 2.4	15.14 ± 3.6	14.5 ± 2.4	16.4 ± 4.6	14.5 ± 2.4	16.4 ± 4.6
pH (water)	5.5 ± 0.2	5.9 ± 0.3	5.4 ± 0.2	5.3 ± 0.1	6.4 ± 0.2	5.8 ± 0.1	6.4 ± 0.2	5.8 ± 0.1	6.4 ± 0.2	5.8 ± 0.1	6.4 ± 0.2	5.8 ± 0.1
Ca (Cmol kg ⁻¹)	2.67 ± 0.55	3.84 ± 0.57	2.64 ± 1.1	5.13 ± 1.05	3.9 ± 0.9	3.5 ± 0.8	3.4 ± 0.2	3.5 ± 0.8	3.4 ± 0.2	5.1 ± 0.3	3.4 ± 0.2	5.1 ± 0.3
Mg (Cmol kg ⁻¹)	0.83 ± 0.25	1.26 ± 0.19	0.59 ± 0.08	0.83 ± 0.06	0.7 ± 0.06	0.9 ± 0.08	0.5 ± 0.04	0.9 ± 0.08	0.5 ± 0.04	0.7 ± 0.05	0.5 ± 0.04	0.7 ± 0.05
Zn (mg kg ⁻¹)	0.54 ± 0.16	0.64 ± 0.25	0.48 ± 0.18	0.61 ± 0.23	0.4 ± 0.08	0.5 ± 0.04	0.5 ± 0.05	0.5 ± 0.04	0.5 ± 0.05	0.4 ± 0.03	0.5 ± 0.05	0.4 ± 0.03
Exchangeable K (Cmol kg ⁻¹)	0.2 ± 0.04	0.32 ± 0.04	0.15 ± 0.03	0.29 ± 0.07	0.2 ± 0.03	0.3 ± 0.07	0.3 ± 0.05	0.3 ± 0.07	0.3 ± 0.05	0.3 ± 0.07	0.3 ± 0.05	0.3 ± 0.07
Sum. Cations (Cmol kg ⁻¹)	3.88 ± 0.85	5.724 ± 0.9	3.51 ± 1.25	6.42 ± 1.06	7.4 ± 1.4	7.8 ± 0.2	6.4 ± 1.2	7.8 ± 0.2	6.4 ± 1.2	8.2 ± 0.2	6.4 ± 1.2	8.2 ± 0.2
ECC (Cmol kg ⁻¹)	7.98 ± 1.16	8.78 ± 0.88	4.96 ± 0.96	8.46 ± 0.46	5.6 ± 0.6	7.6 ± 0.6	4.2 ± 0.5	7.6 ± 0.6	4.2 ± 0.5	8.2 ± 0.7	4.2 ± 0.5	8.2 ± 0.7
% V = S/T * 100 (%)	48.0 ± 5.0	64.5 ± 4.5	71.7 ± 4.3	75.3 ± 8.1	70.7 ± 4.3	65.3 ± 8.1	60.7 ± 5.3	65.3 ± 8.1	60.7 ± 5.3	55.3 ± 9.1	60.7 ± 5.3	55.3 ± 9.1
Bray 1 P [mg kg ⁻¹]	5.25 ± 1.62	9.5 ± 2.25	6.7 ± 1.74	6.6 ± 0.88	5.5 ± 1.7	7.1 ± 0.8	6.2 ± 1.3	7.1 ± 0.8	6.2 ± 1.3	5.1 ± 0.5	6.2 ± 1.3	5.1 ± 0.5

with three seeds per hole. Seedlings were thinned to one plant per hole after emergence at a density of 250 000 plants ha⁻¹ and 20 cm × 20 cm spacing. Total rates of P, K, Mg, and Zn were applied 15 days after sowing, at the beginning of the tillering stage, while N rates were split into two equal rates and were applied 15 and 45 days after sowing, at the beginning of tillering and at panicle-initiation stages, respectively.

At maturity, 10 plants were sampled randomly per plot. The number of panicles per plant was counted and they were then detached from the plant by hand. The panicles were dried in an oven at 65 °C until at constant weight. The spikelets were detached from the panicle and counted. The filled grain was separated from the unfilled grain by visual observation plus pinching with fingers. All rice plants in plots of 1 m × 1 m density were randomly collected in three locations to measure the grain and straw yield. Plant samples were separated into straw and panicles. Panicles were hand-threshed and spikelets were separated. The fresh straw and grain weights were recorded and sub-samples were oven dried at 65 °C until constant weight for dry matter. The yield was determined using the formula below:

$$\text{Yield (kg ha}^{-1}\text{)} = (\text{P} \times \text{DM} \times 10000) \text{ where DM (\%)} \\ = \left(\frac{\text{Pd}}{\text{Pf}} \right) \times 100 \quad (1)$$

where Pf and Pd are the weights of the fresh and dry matter of the straw sample, respectively

P is total weight of straw biomass harvested on 1 m².

For rice grain yield at 14% of water content, the formula is that found in Janier and Maidin (2011):

$$\text{Rice grain yield (kg ha}^{-1}\text{)} = (\text{P} \times \text{DM} \\ \times 8600) \text{ with DM (\%)} \\ = \left(\frac{\text{Pd}}{\text{Pf}} \right) \times 100 \quad (2)$$

Pf and Pd are fresh and dry matter of the sample of rice paddy respectively; and P is the total weight of rice grain harvested on 1 m².

All dried samples from the second experiment were ground to powder, passed through a 0.25 mm sieve, and digested with a mixture of concentrated H₂SO₄ and H₂O₂ (Wolf 1982). Nitrogen concentrations were determined by the Kjeldahl method (Vinklářková et al. 2015). Magnesium, Zn, and K concentrations were determined using an Atomic Absorption Spectrophotometer (Butcher 2005). Phosphorus concentration was determined using the vanadate–molybdate method with a spectral photometer 1100 (Neves et al. 2008). Nutrient uptake was determined by multiplying dry matter weight with their respective nutrient concentrations in different above-ground parts.

Statistical analysis

Statistical data analysis was performed using analysis of variance with a general linear mixed-effect model using the package nlme (Pinheiro et al. 2020) in R software version 3.6.2 (R Core Team 2019). The year, fertiliser applications,

and treatments were considered as fixed effects while locations and replications were considered random effects. The mean values were compared by Tukey's HSD (honestly significant difference) test at the 0.05 probability level using the lsmeans package (Russell 2018a). When the interactions between major nutrients (N, P, K) and Mg or Zn were significant for grain yield and yield components, data were presented with means across the three levels of Mg or Zn.

Fitted response-surface contour plots for the rice grain yield were done with the rsm (R response-surface methods) package (Russell 2018b). The agronomic efficiency (AE) was calculated using the formula in Equation 3 (Golla 2021), where AEI = agronomic efficiency of nutrient I (N, P and K). The harvest index was calculated following Jiang et al. (2019) as shown in Equation 4. Nutrient recovery efficiency (NRE) was calculated following Golla (2021) as shown in Equation 5.

$$AEI = \frac{\text{rice grain yield with I application} - \text{rice grain yield with I omission}}{\text{I rate applied}} \quad (3)$$

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{All aboveground yield}} \times 100 \quad (4)$$

$$NRE = \frac{(\text{total nutrient uptake of nutrient fertilized plot} - \text{total nutrient uptake of control plot}) \times 100}{\text{applied nutrient rate of fertilized plot}} \quad (5)$$

Results

Rice yield responses to N, P, K, Mg, and Zn application

Rice grain yield and yield components were significantly ($p < 0.05$) affected by the N, P, K, Mg, and Zn treatments as well as the interactive effects between N and Mg, N and Zn, P and Zn, K, and Mg. However, the interactive effects between P and Mg, K and Zn were insignificant for paddy yield (Table 2). The straw yield was significantly ($p < 0.05$) influenced by N, P, K, Zn and the interactive effect between N and Zn, whereas the interactive effects between N and Mg, P and Mg, P and Zn, K and Mg, K and Zn were insignificant for straw yield (Table 2).

Effect of Mg on response of rice to N application

Application of N and Mg significantly increased grain yield, and combined application of N and Mg showed higher grain yield than the application of N or Mg alone (Figure 1a). The co-application of N and Mg at 15 kg ha⁻¹ increased grain yield response to applications of 125 and 250 kg N ha⁻¹ by 53.5 and 36.62%, respectively, while N co-applied with 30 kg MgO ha⁻¹ increased responses by 33.67 and 25.12%, respectively, compared to the sole application of N (Figure 1a). Co-application of 125 and 250 kg N ha⁻¹ with 15 kg MgO ha⁻¹ led to an increase of grain yield by 109.78 and 81.46% respectively, and 76.2 and 60.61% with 30 kg MgO ha⁻¹, respectively. The increased grain yield responses were mainly due to the differences in 1 000

Table 2: Analysis of variance for grain yield and yield components

Source of variation	Panicles per plant	Spikelets per panicle	Filled grain rate	1 000 grains weight	Grain yield	Straw yield
Year	ns	ns	ns	ns	ns	ns
N	**	***	**	**	***	***
P	ns	*	ns	**	***	***
K	**	ns	**	ns	**	*
Mg	ns	ns	ns	*	**	ns
Zn	**	ns	ns	ns	**	*
N × Mg	ns	**	**	**	*	ns
N × Zn	*	**	ns	ns	**	*
P × Mg	ns	ns	ns	ns	ns	ns
P × Zn	ns	**	ns	*	**	ns
K × Mg	ns	ns	**	ns	***	ns
K × Zn	ns	ns	ns	ns	ns	ns
Mg × Zn	ns	ns	ns	**	*	ns
Year × N	ns	ns	ns	ns	ns	ns
Year × P	ns	ns	ns	ns	ns	ns
Year × K	ns	ns	ns	ns	ns	ns
Year × Mg	ns	ns	ns	ns	ns	ns
Year × Zn	ns	ns	ns	ns	ns	ns

* = $p > 0.05$ ** = $p > 0.01$ *** = $p > 0.001$
ns = not significant at $p < 0.05$

grain weight (Figure 1c), spikelets per panicle (Figure 1d), and filled grain rates (Figure 1e) across N rates treatments co-applied with Mg. The number of spikelets per panicle increased with an increase in N rate and when N was co-applied with 15 MgO kg ha⁻¹. However, the filled grain rate and 1 000 grain weights decreased with an increase in the N rate. The interactive effect between N and Mg was insignificant for straw yield (Figure 1b).

Compared to zero-N treatment, sole applications of 125 and 250 kg N ha⁻¹ increased the rice harvest indices by 43.05 and 33.21%, respectively. However, the co-application of 125 and 250 kg N ha⁻¹ and 15 kg MgO ha⁻¹ increased the rice harvest indices by 71.35 and 50.56%, respectively, while with 30 kg MgO ha⁻¹, the same rates of N application led to increases in the rice harvest indices of 26.50 and 12.61%, respectively, compared to zero-N treatment.

The agronomic efficiency of N decreased by approximately 60% when the N application rates increased from 125 to 250 kg ha⁻¹. The co-application of N with 15 kg MgO ha⁻¹ increased the agronomic efficiency of applications of 125 and 250 kg N ha⁻¹ by 69.92 and 36.85%, respectively, while with 30 kg MgO ha⁻¹, the agronomic efficiency of the same rates of N application increased by 28.49 and 8.97%, respectively.

Effect of Zinc on the response of rice to Nitrogen application

Application of N and Zn significantly increased grain yield and the combined application of N and Zn showed a higher grain yield than the sole application of N or Zn (Figure 2a). The co-application of N with 15 kg Zn ha⁻¹ increased rice response to applications of 125 and 250 kg N ha⁻¹ by 35.69 and 28.09% of grain yield (Figure 2a) and 12.69 and 11.16% of straw yield (Figure 2b), respectively, compared to the sole

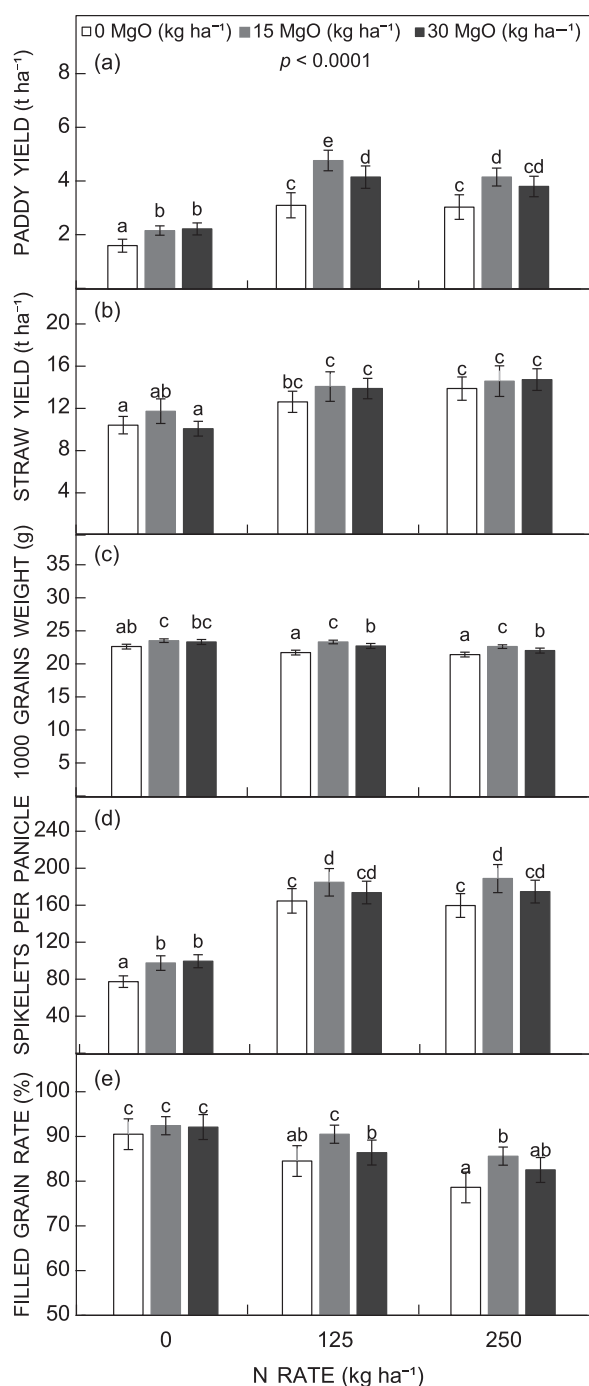


Figure 1: Responses of (a) rice grain yield, (b) spikelet number per panicle, (c) filled grain rate, and (d) 1 000 grains weight, to Nitrogen application rates across different rates of Magnesium application. Data were averaged across the two years. Error bars indicate \pm SE

application of N. However, the co-application of N and 30 kg Zn ha⁻¹ led to increased rice responses to the applications of 125 and 250 kg N ha⁻¹ of up to 20.87 and 18.68% of grain yield and 14.33 and 12.71% of straw yield, respectively, compared to sole application of N. The yield response to the co-application of N with Zn rates was explained by the difference in panicles per plant (Figure 2c) and spikelets

per panicle (Figure 2d) across N rates treatments co-applied with Zn.

The sole application of N at 125 and 250 kg ha⁻¹ increased the rice harvest indices by 48.08 and 33.87% respectively, compared to zero N application. When 125 and 250 kg N ha⁻¹ were used with 15 kg Zn ha⁻¹, the rice harvest indices increased by 57.97 and 48.27%, respectively, and by 47.02 and 30.24% with 30 kg Zn ha⁻¹, respectively, compared to zero N treatment. The results showed that the co-application of N with Zn increased the agronomic efficiency of applications of 125 and 250 kg N ha⁻¹ by up to 37.6 and 48.3% for 15 kg Zn ha⁻¹, respectively, and 18.31 and 6.29% for 30 kg Zn ha⁻¹, respectively.

Effect of Zn on the response of rice to P application

Application of P and Zn significantly increased grain yield and the combined application of both showed higher grain yields than the sole application of P or Zn (Figure 3a). Compared to zero P treatment, the sole application of P increased paddy yield by 37.28%, and when 100 kg P₂O₅ ha⁻¹ was co-applied with 15 and 30 kg Zn ha⁻¹ it increased paddy yields by 48.37% and 31.26%, respectively. When P was co-applied with 15 and 30 kg Zn ha⁻¹, paddy yield response to P treatments increased by 27.21–27.58% and 8.09–11.63%, respectively, compared to P application alone. The yield response to the co-application of P with Zn was explained by the difference in spikelets per panicle (Figure 3b) and 1 000 grains weight (Figure 3c) across P treatments co-applied with Zn. The interactive effect of P and Zn was insignificant for straw yield.

Sole application of 100 and 200 kg P₂O₅ ha⁻¹ increased the rice harvest indices by 28.91 and 26.41%, respectively. Co-application of 15 kg Zn ha⁻¹ with 100 and 200 kg P₂O₅ ha⁻¹ increased the rice harvest indices by 33.05 and 31.92%, respectively, compared to zero P treatment. Furthermore, when 100 and 200 kg P₂O₅ ha⁻¹ were co-applied with 30 kg Zn ha⁻¹, the rice harvest indices increased by 16.08 and 15.98%, respectively, compared to zero P treatment.

The application of P at 200 kg P₂O₅ ha⁻¹ decreased the P agronomic efficiency compared to that observed with 100 kg P₂O₅ ha⁻¹. Combined application of 15 kg Zn ha⁻¹ with 100 and 200 kg P₂O₅ ha⁻¹ led to increases in P agronomic efficiency of 37.99 and 55.39%, respectively, compared to the sole application of P. The co-application of 100 and 200 kg P₂O₅ ha⁻¹ with 30 kg Zn ha⁻¹ decreased P agronomic efficiency by 19.77 and 17.24%, respectively, compared to the sole application of P.

Effect of Mg on the response of rice to K application

The combined application of K and Mg led to higher grain yields than the sole application of K or Mg (Figure 4a). The sole application of 60 kg K₂O ha⁻¹ increased paddy yield by 21.79%, and increased paddy yield by 43.98 and 20.85% when it was co-applied with 15 and 30 kg MgO ha⁻¹, respectively. However, co-application of K with Mg at 15 and 30 kg MgO ha⁻¹ led to an increase of grain yield response to K treatments by 24.28–28.14% and 16.15–17.24%, respectively, compared to sole K application (Figure 4a). The yield response to the co-application of K

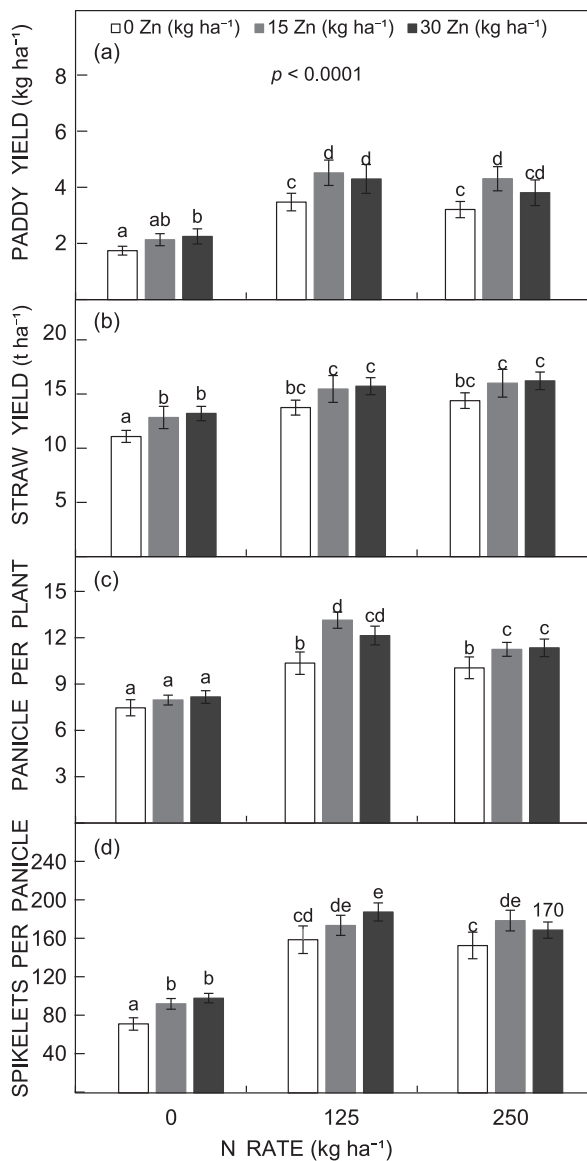


Figure 2: Responses of (a) grain and (b) straw yield, (c) panicle number per plant and (d) spikelet number per panicle, to Nitrogen application rates across different rates of Zinc application. Data were averaged across the two years. Error bars indicate \pm SE

with Mg was explained by the difference in filled grain rate across K treatments co-applied with Mg (Figure 4b).

The harvest indices of rice were increased by 17.82 and 17.54% with the sole application of K at 60 and 120 kg K₂O ha⁻¹, respectively. However, when 60 and 120 kg K₂O ha⁻¹ were co-applied with 15 kg MgO ha⁻¹, the harvest indices were increased by 31.87 and 15.21% respectively, and by 16.05 and 9.45% respectively when co-applied with 30 kg MgO ha⁻¹, compared to zero-K treatment.

The application of 120 kg K₂O ha⁻¹ decreased the K agronomic efficiency compared to that observed with 60 kg K₂O ha⁻¹. Compared to the sole application of K, when co-applied with 15 kg MgO ha⁻¹, K agronomic efficiency increased by 57.52 and 8.47% for 60 and 120 kg K₂O ha⁻¹ applications, respectively. Furthermore, 60 kg K₂O ha⁻¹

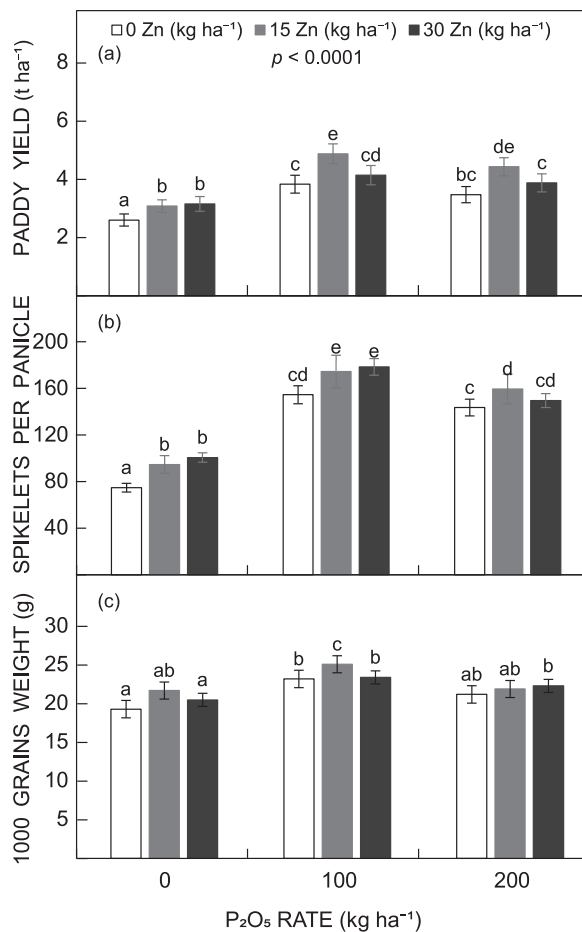


Figure 3: Responses of (a) rice grain yield, (b) spikelet number per panicle, and (c) 1 000 grains weight, to Phosphorus application rates across different rates of Zinc application. Data were averaged across the two years. Error bars indicate \pm SE

co-applied with 30 kg MgO ha⁻¹ increased K agronomic efficiency by 14.61%, while the co-application of 120 K₂O kg ha⁻¹ with 30 kg MgO ha⁻¹ decreased the K agronomic efficiency by 13.21%.

Interactive effect of Mg and Zn on rice plant under N, P, and K

The combined application of Mg and Zn showed a higher grain yield than the sole application of Mg or Zn under N, P, and K (Figure 5). The interactive effect of Mg and Zn was significant on rice yield and grain weight. Sole application of Mg or Zn significantly increased grain yield through increasing grain weight and number of panicles per plant, respectively. The effect of co-application of Mg with Zn under N, P, and K on the rice yield response was mainly expressed by the difference in 1 000 grain weights across Mg and Zn rates. Thus, compared to zero MgO treatment, sole applications of 15 and 30 kg MgO ha⁻¹ increased grain yield by 10.01 and 1.5%, respectively. Co-application of 15 and 30 kg MgO ha⁻¹ with Zn led to increases in grain yield of 15.75 and 27.73%, respectively,

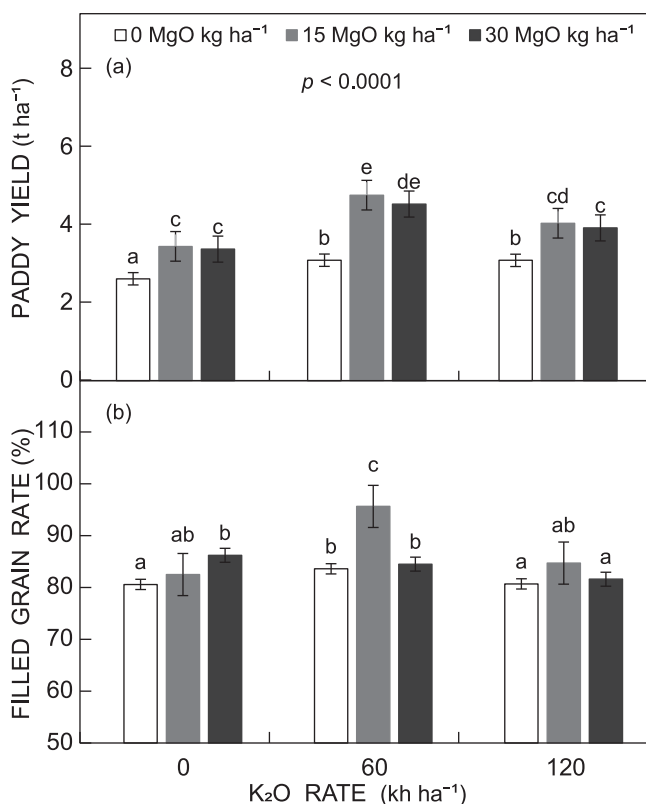


Figure 4: Responses of (a) rice grain yield and (b) filled grain rate to Potassium application rates across different rates of Magnesium application. Data were averaged across the two years. Error bars indicate \pm SE

with an application of 15 kg Zn ha⁻¹, and 16.86 and 38.27%, respectively, with 30 kg Zn ha⁻¹.

Nutrient uptake and recovery efficiency

The combination of fertilisers significantly ($p < 0.0001$) influenced nutrient concentrations and uptakes in rice grain

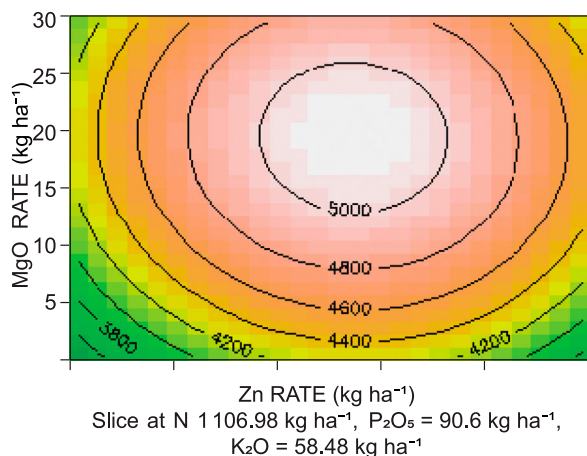


Figure 5: Effects of Magnesium and Zinc on grain yield of field experiments over two years (2018 and 2019)

and straw (Figure 6 and Table 3). Compared to the control, fertiliser application (all treatments) significantly increased N concentrations in rice grain, while no significant increases were observed in straw concentrations of N (Figure 6a). Combinations of Mg or Zn with N, P, and K (T2, T3) did not induce significant increases in N rice grain concentrations, compared to the sole NPK (T1) application (Figure 6a). The combination of Mg and Zn with N, P, and K (T4) significantly increased N rice grain concentrations to 12 and 22% in 2020 and 2021, respectively. In addition, compared to the sole NPK application, Mg and Zn significantly increased N uptake in rice grains by 15–18 and 23–28%, respectively. When applied together, Mg and Zn increased N uptake in rice grain by up to 36–54%. Rice grains contained higher levels of P than did rice straw and applications of NPK (T1), and NPK + Mg (T2) did not induce significant increases in grain or straw P concentrations (Figure 6b). However, treatments involving Zn (T3 and T4) induced significant increases in grain P concentration and uptake (Figure 6b, Table 3) compared to control and sole NPK (T1) applications. Zinc increased grain P concentrations by 44–47%. In addition, all treatments with fertiliser applications significantly increased P uptake in rice grain and straw (Table 3). Rice grain K concentrations were lower than those of straw, and the lowest concentrations were recorded with fertiliser application treatments without Mg (Figure 6c). Magnesium and Zn concentrations in both rice grain and straw were significantly increased with treatments involving Mg (Figure 6d) and Zn (Figure 6d), respectively. Co-application of N, P, K, Mg, and Zn fertiliser (Treatment T4) significantly increased N, P, K, Mg, and Zn uptake even though some nutrient concentrations in grain and straw did not increase compared to control or NPK (Treatment T1) fertiliser. These uptake responses to fertiliser application were mainly explained by the increased yield responses to the co-application of N, P, K, Mg, and Zn (Table 3). The results show that Mg and Zn significantly increased N, P, and K recovery efficiency compared to the control or sole NPK application (Table 3).

Discussion

This study shows that the co-application of N with Mg and Zn significantly increases grain yield responses. When N is supplied as urea to the soil, it is converted to ammonium and susceptible to volatilisation loss (Liu et al. 2019). The co-application of Mg and N as urea prevents this loss by forming ammonium chloride or nitrate (Fenn et al. 1981). In addition, Mg is an integral part of ribosomes, which are the central component of chlorophyll (Shrestha et al. 2020). Eggink et al. (2001) reported that the stronger co-ordination bonds between the Mg atom and amino acid sidechain ligand in chlorophyll-binding apoproteins enhance their import into the chloroplast and the assembly of light-harvesting complexes. However, N is a primary component of amino acids, protein building blocks, nucleic acids, and chlorophyll (Shrestha et al. 2020). This strong relationship between Mg and N in apoprotein binding and light absorption, which is used to convert carbon dioxide and

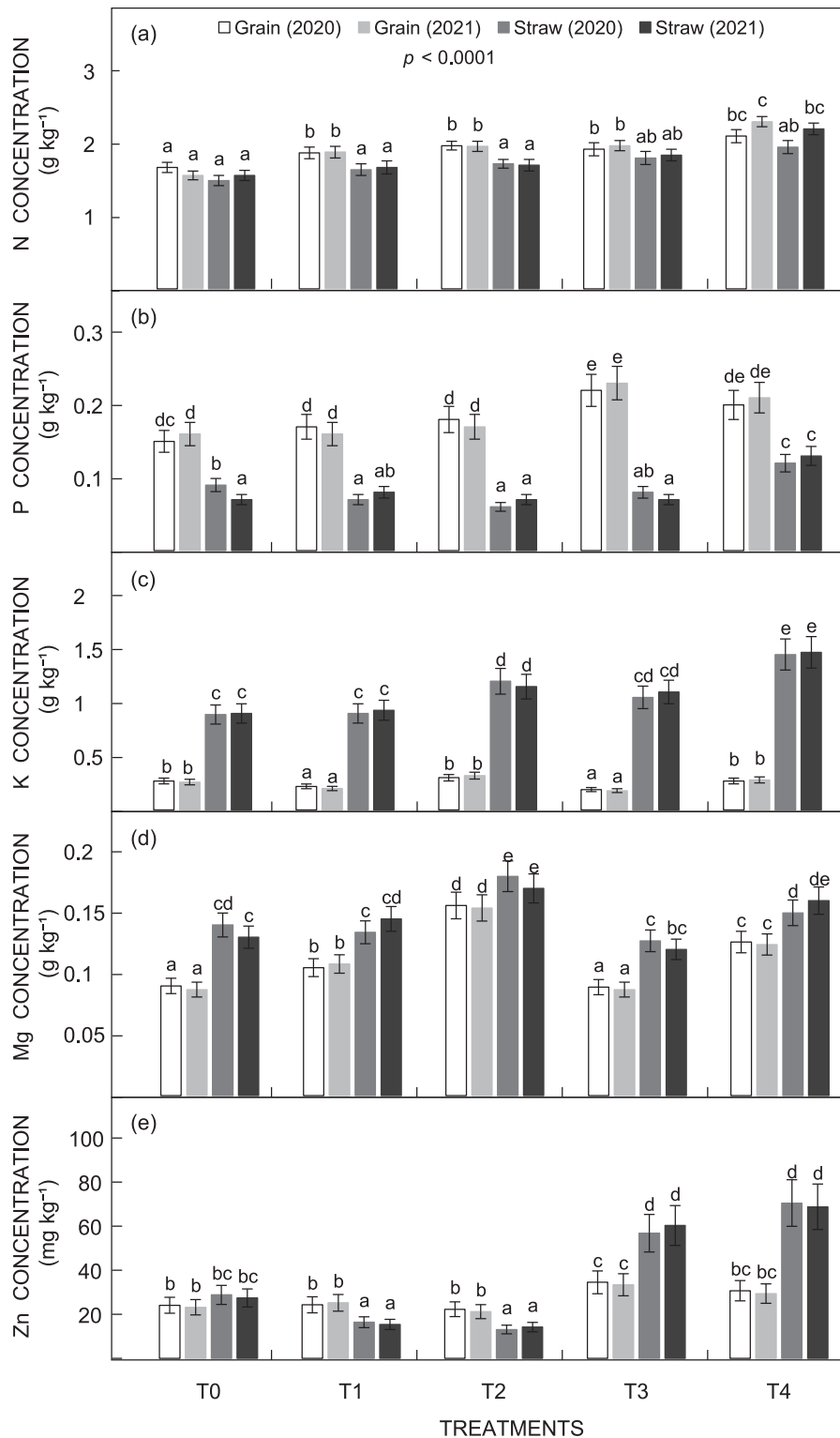


Figure 6: Effects of the combinations of Magnesium and Zinc treatments with NPK fertiliser on (a) grain and straw Nitrogen, (b) Phosphorus, (c) Potassium, (d) Magnesium and (e) Zinc concentrations for the two study periods. The same letters above the error bars and for same variable indicate means are not significantly different ($p > 0.05$) according to the Student Newman–Keuls test.

Abbreviations:

T0 = Control

T1 = 106 kg N ha^{-1} + 90.6 kg P2O5 ha^{-1} + 58.5 kg K2O ha^{-1}

T2 = 106 kg N ha^{-1} + 90.6 kg P2O5 ha^{-1} + 58.5 kg K2O ha^{-1} + 14.14 kg MgO ha^{-1}

T3 = 106 kg N ha^{-1} + 90.6 kg P2O5 ha^{-1} + 58.5 kg K2O ha^{-1} + 11.8 kg Zn ha^{-1}

T4 = 106 kg N ha^{-1} + 90.6 kg P2O5 ha^{-1} + 58.5 kg K2O ha^{-1} + 14.14 kg MgO ha^{-1} + 11.8 kg Zn ha^{-1}

Table 3: Nutrient uptake in grain and straw across the treatment combinations of Magnesium and Zinc applied with NPK fertiliser

Parameters	T0		T1		T2		T3		T4		
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	
Yields (kg ha ⁻¹)	Grain	1980 ± 165 ^a	2134 ± 214 ^a	4090 ± 335 ^b	4045 ± 305 ^b	4580 ± 285 ^c	4457 ± 401 ^c	4670 ± 462 ^c	4768 ± 309 ^{cd}	4952 ± 455 ^d	5087 ± 523 ^d
	Straw	6590 ± 365 ^a	6457 ± 485 ^a	10058 ± 785 ^b	10163 ± 670 ^b	9540 ± 598 ^b	10034 ± 694 ^b	9670 ± 734 ^b	9879 ± 582 ^b	10586 ± 805 ^b	10678 ± 785 ^b
N uptake (kg ha ⁻¹)	Grain	3.31 ± 0.27 ^a	3.33 ± 0.33 ^a	7.65 ± 0.62 ^b	7.60 ± 0.57 ^b	9.02 ± 0.56 ^c	8.74 ± 0.78 ^c	8.97 ± 0.88 ^c	9.39 ± 0.6 ^{cd}	10.4 ± 0.95 ^{de}	11.70 ± 1.2 ^e
	Straw	9.82 ± 0.54 ^a	10.1 ± 0.75 ^a	16.50 ± 1.28 ^b	16.97 ± 1.11 ^b	16.41 ± 1.2 ^b	17.06 ± 1.1 ^b	17.41 ± 1.2 ^b	18.18 ± 1.7 ^{bc}	20.64 ± 1.5 ^c	23.49 ± 1.7 ^d
	Total	13.13 ± 0.4 ^a	13.4 ± 0.54 ^a	24.14 ± 0.9 ^b	24.58 ± 0.85 ^b	25.4 ± 0.9 ^{bc}	25.79 ± 0.78 ^{bc}	26.37 ± 1.1 ^c	27.57 ± 1.3 ^c	31.04 ± 1.4 ^d	35.19 ± 1.6 ^e
N recovery efficiency	–	–	10.39 ± 1.8 ^a	10.54 ± 1.6 ^a	11.61 ± 1.9 ^a	11.69 ± 2.3 ^a	12.5 ± 2.6 ^{ab}	13.37 ± 2.3 ^b	16.9 ± 2.7 ^c	20.56 ± 3.2 ^d	
P uptake (kg ha ⁻¹)	Grain	0.3 ± 0.02 ^a	0.34 ± 0.03 ^a	0.68 ± 0.05 ^b	0.65 ± 0.04 ^b	0.82 ± 0.05 ^c	0.76 ± 0.07 ^c	1.03 ± 0.1 ^d	1.1 ± 0.07 ^d	0.99 ± 0.09 ^d	1.07 ± 0.1 ^d
	Straw	0.59 ± 0.03 ^b	0.45 ± 0.03 ^a	0.7 ± 0.05 ^c	0.81 ± 0.05 ^d	0.57 ± 0.03 ^b	0.70 ± 0.05 ^c	0.8 ± 0.06 ^{cd}	0.69 ± 0.04 ^c	1.27 ± 0.09 ^e	1.39 ± 0.1 ^e
	Total	0.89 ± 0.3 ^b	0.79 ± 0.3 ^a	1.40 ± 0.5 ^c	1.46 ± 0.5 ^d	1.40 ± 0.4 ^d	1.46 ± 0.6 ^d	1.80 ± 0.4 ^c	1.79 ± 0.6 ^c	2.26 ± 0.9 ^e	2.46 ± 0.1 ^e
P recovery efficiency	–	–	1.28 ± 0.2 ^a	1.67 ± 0.24 ^b	1.27 ± 0.18 ^a	1.67 ± 0.21 ^b	2.29 ± 0.34 ^c	2.50 ± 0.28 ^c	3.44 ± 0.32 ^d	4.17 ± 0.34 ^e	
K uptake (kg ha ⁻¹)	Grain	0.53 ± 0.04 ^a	0.55 ± 0.05 ^a	0.90 ± 0.07 ^b	0.81 ± 0.06 ^b	1.37 ± 0.08 ^c	1.43 ± 0.12 ^c	0.89 ± 0.08 ^b	0.86 ± 0.05 ^b	1.34 ± 0.12 ^c	1.42 ± 0.14 ^c
	Straw	5.87 ± 0.3 ^a	5.81 ± 0.4 ^a	9.05 ± 0.7 ^b	9.45 ± 0.6 ^b	11.45 ± 0.7 ^c	11.54 ± 0.8 ^c	10.15 ± 0.7 ^c	10.87 ± 0.6 ^c	15.35 ± 1.16 ^d	15.70 ± 1.15 ^d
	Total	6.40 ± 0.4 ^a	6.37 ± 0.5 ^a	9.95 ± 0.7 ^b	10.26 ± 0.6 ^b	12.82 ± 0.7 ^c	12.97 ± 0.1 ^c	11.04 ± 0.8 ^b	11.73 ± 0.6 ^c	16.69 ± 0.7 ^d	17.12 ± 0.8 ^d
K recovery efficiency	–	–	7.32 ± 0.84 ^a	8.03 ± 0.98 ^a	13.24 ± 1.8 ^c	13.61 ± 1.5 ^c	9.57 ± 1.2 ^b	11.05 ± 1.4 ^b	21.21 ± 2.3 ^d	22.18 ± 2.1 ^d	
Mg uptake (kg ha ⁻¹)	Grain	0.18 ± 0.01 ^a	0.19 ± 0.02 ^a	0.43 ± 0.03 ^b	0.44 ± 0.03 ^b	0.71 ± 0.04 ^d	0.69 ± 0.06 ^{cd}	0.42 ± 0.04 ^b	0.41 ± 0.02 ^b	0.62 ± 0.05 ^c	0.63 ± 0.06 ^c
	Straw	0.92 ± 0.05 ^a	0.84 ± 0.06 ^a	1.35 ± 0.1 ^b	1.47 ± 0.1 ^b	1.72 ± 0.1 ^c	1.71 ± 0.11 ^c	1.23 ± 0.09 ^b	1.19 ± 0.07 ^b	1.59 ± 0.12 ^c	1.71 ± 0.13 ^c
	Total	1.10 ± 0.3 ^a	1.03 ± 0.4 ^a	1.78 ± 0.2 ^b	1.91 ± 0.2 ^b	2.43 ± 0.3 ^c	2.39 ± 0.8 ^c	1.64 ± 0.7 ^b	1.60 ± 0.5 ^b	2.21 ± 0.9 ^c	2.34 ± 0.2 ^c
Mg recovery efficiency	–	–	–	–	15.69 ± 2.4 ^b	16.12 ± 2.1 ^b	–	–	13.10 ± 1.67 ^a	15.50 ± 2.2 ^b	
Zn uptake (kg ha ⁻¹)	Grain	0.05 ± 0.00 ^a	0.05 ± 0.00 ^a	0.10 ± 0.01 ^b	0.10 ± 0.01 ^b	0.10 ± 0.01 ^b	0.09 ± 0.01 ^b	0.16 ± 0.02 ^c	0.16 ± 0.01 ^c	0.15 ± 0.01 ^c	0.15 ± 0.01 ^c
	Straw	0.19 ± 0.01 ^c	0.18 ± 0.01 ^{bc}	0.16 ± 0.01 ^b	0.16 ± 0.01 ^b	0.12 ± 0.01 ^a	0.14 ± 0.01 ^a	0.55 ± 0.04 ^d	0.60 ± 0.03 ^d	0.75 ± 0.06 ^e	0.73 ± 0.05 ^e
	Total	0.24 ± 0.01 ^a	0.23 ± 0.01 ^a	0.26 ± 0.01 ^b	0.26 ± 0.01 ^b	0.23 ± 0.01 ^a	0.24 ± 0.01 ^a	0.71 ± 0.03 ^c	0.75 ± 0.02 ^c	0.90 ± 0.04 ^d	0.88 ± 0.03 ^d
Zn recovery efficiency	–	–	–	–	–	–	4.01 ± 0.5 ^a	4.48 ± 0.3 ^a	5.60 ± 0.7 ^b	5.57 ± 0.8 ^b	

On same line, means with the same superscript letters are not significantly different ($p > 0.05$) according to Tukey's honestly significant difference test

T0 = Control

T1 = 106 kg N ha⁻¹ + 90.6 kg P2O5 ha⁻¹ + 58.5 kg K2O ha⁻¹

T2 = 106 kg N ha⁻¹ + 90.6 kg P2O5 ha⁻¹ + 58.5 kg K2O ha⁻¹ + 14.14 kg MgO ha⁻¹

T3 = 106 kg N ha⁻¹ + 90.6 kg P2O5 ha⁻¹ + 58.5 kg K2O ha⁻¹ + 11.8 kg Zn ha⁻¹

T4 = 106 kg N ha⁻¹ + 90.6 kg P2O5 ha⁻¹ + 58.5 kg K2O ha⁻¹ + 14.14 kg MgO ha⁻¹ + 11.8 kg Zn ha⁻¹

water into glucose through photosynthesis, could explain the positive effects of the co-application of N and Mg on rice yield, yield component, and N uptake observed in the present study. Our results are consistent with Choudhury and Khanif (2001) who reported a significant increase in rice grain yield due to N and Mg co-application. This finding suggests that improving rice yield responses to N fertiliser by adding Mg was mainly caused by the positive interactive effect of N and Mg on spikelets per panicle, filled grain rate, and 1 000 grains weight. The decrease in rice grain yield under high N conditions was mainly caused by low grain filling and grain weight (Fu et al. 2019; Hou et al. 2019). These decreases in filled grain rate and 1 000 grains weight with an increase in N rate were reduced when N was co-applied with Mg. This study reveals that the co-application of N and Mg improves the dry matter accumulation at grain filling through the increase in filled grain rate and 1 000 grains weight.

A clear positive interaction between N and Zn fertilisers on rice grain and straw yield was demonstrated under the experimental conditions. Guo et al. (2015) also observed this positive influence of the co-application of N and Zn on rice grain yield. This study indicates that Zn improves the panicles per plant and the spikelets per panicle responses to N rates application. There are significant losses of urea-derived N through NH_3 volatilisation and NO_3^- leaching due to the rapid hydrolysis of the amide N as a result of its reaction with the enzyme urease (Blennerhassett et al. 2006). This induces a decrease in the urea-N use efficiency and the response of crops to N. The positive influence of Zn on N application in this study could be partially explained by the inhibitory effects of ZnSO_4 on urease activity (Gonzalez et al. 2019). In addition, Zn is the cofactor for various enzyme systems that are active in N metabolism including alcohol dehydrogenase and glutamate dehydrogenase (Shrestha et al. 2020). Consequently, Zn deficiency significantly reduces the alcohol dehydrogenase function and thus the metabolism of N. These influences of Zn on N metabolism could explain the positive effect of the co-application of N and Zn on rice yield and yield component responses to N application. Previous studies suggest that the use of ZnSO_4 in conjunction with urea significantly increased both total N uptake and the efficiency of urea N fertilisation in a forage crop (Guimarães et al. 2016). This interaction could be due to the role of Zn as a constituent of carbonic anhydrase and other enzymes which are required for protein synthesis and carbohydrate metabolism (Marschner 2012). Consequently, an appropriate combination of N, Mg, and Zn not only improved the grain yield but also reduced the required N application rate. This co-application would therefore also reduce the environmental problems caused by the high level of use of N fertilisers (water pollution and greenhouse gases).

An appropriate rate of Zn application improved the rice grain yield responses to P application through the number of spikelets per panicle and the 1 000 grains weight. Mousavi (2011) reported that large amounts of Zn reduce the uptake of P and Fe, ATP synthesis, chloroplast activity, and photosynthesis. Nevertheless, these experiments have indicated that within the normal rates of P and Zn

application, the interaction between them was synergistic, and optimum rice yields were obtained (Debnath et al. 2015). An imbalance between P and Zn can cause metabolic disorders in plant cells (Wijebandara 2007). Such effects are due to (i) the reduction in Zn translocation through the endodermis and epidermis of roots, causing a reduction in its absorption by plants (Safaya 1976; Raimundo et al. 2014); (ii) a simple dilution effect on the Zn concentration in the tops caused by the growth response due to P (Watanabe 1965); (iii) physiological effects such as P interference in the utilisation of Zn by the plant (Malik et al. 2011) and (iv) the precipitation of Zn by P in conductive tissues (Biddulph 1953). The co-application of P and Zn at an adequate rate would correct the deficiency that could be induced by the sole application of P and could enhance Zn absorption by rice plants. In the plant, P deficiency results in over-accumulation of Zn in shoots, and inversely, Zn deficiency leads to over-accumulation of P in the aerial part of plants (Xie et al. 2019). Thus, a balance between P and Zn improves absorption of both P and Zn and can then explain the positive effect of co-application of P and Zn on rice yield and yield components observed in this study.

The present study reveals that Mg improves the rice grain yield responses to K application rates through the improvement of filling of grain although an appropriate combination rate of both fertilisers is needed. The application of K alone decreases Mg uptake due to the competition of both nutrients for metabolically produced binding compounds or active sites present on the plasma membrane (Xie et al. 2021). In rice plants, Mg absorption by roots is through the Mg^{2+} transporter gene and a non-selective ion channel, which is also capable of transporting K in root cells (Shabala and Hariadi 2005). However, under most conditions, the majority of K is taken up by the high-affinity plant K^+ transporter gene (Xie et al. 2021). This transporter is responsible for K transport but it has also been suggested that it facilitates Mg transport in plants (Horie et al. 2011; Kobayashi and Tanoi 2015). In rice roots, under Mg deficiency, the high-affinity K^+ transporter gene is upregulated; under K deficiency, expression of the Mg^{2+} transporter gene is upregulated (Cai et al. 2012). This mechanism, using competition for active sites or transporters, could partly explain the significantly interactive effect of K and Mg on rice yield observed in this study. In addition, K and Mg have synergistic effects on physiological processes such as photosynthesis, carbohydrate allocation, and nitrogen metabolism, and Mg can partially replace K in some functions (Xie et al. 2021). Because of the antagonistic and synergistic interaction effects of K and Mg in the processes of their absorption, translocation, distribution, and physiological processes, K and Mg imbalances in soils limit the growth and yields of rice. Such results are also reported by Carmeis et al. (2017) who observed that Mg uptake per unit of rice root length was reduced with an increasing rate of K without Mg application.

This study highlights the fact that co-application of NPK with Mg and Zn improves paddy yield and also rice biofortification in Mg and Zn. In Africa, intensive rice farming focuses on the single application of N, P, and K

(Vanlauwe et al. 2015). The present study revealed that the sole application of NPK increased Mg and Zn uptake from soil to paddy and straw. Unfortunately, this uptake of Mg and Zn is not spontaneously replenished in the soil (Anago et al. 2020a). Therefore, intensive rice cropping systems in which only NPK fertilisers are used become very deficient in Mg and Zn (Chaudhry et al. 2021; Khan et al. 2021). Magnesium deficiency leads to reduced chlorophyll biosynthesis which in turn disrupts photosynthetic activity, causes oxidative DNA damage, oxidative protein damage, inhibition of sucrose transport from source to sink tissues, and compact root growth which disrupts nutrient absorption (Igamberdiev and Kleczkowski 2001; Yu-Chuan et al. 2008; Hörtensteiner 2009; Yang et al. 2012; Chaudhry et al. 2021). Our study shows that the co-application of NPK with Mg could solve these Mg deficiency issues and significantly increase the response of rice yield to NPK application and nutrient uptake. However, rice crops are highly susceptible to Zn deficiency, which could be induced by the application of NPK fertiliser alone over time (Khan et al. 2021). In rice, Zn deficiency-responsive genes that are involved in the root system, photosynthesis, metal transport, and phyto-siderophore biosynthesis have been identified (Bandyopadhyay et al. 2017). Therefore, Zn deficiency induced by the exclusive application of NPK fertiliser disturbs root growth, photosynthetic activity, and metal transport. As a component of the ribosome, Zn deficiency induces DNA damage which causes abnormal development of leaves and reduces the general growth of the plant (Sotta et al. 2019). The results of this study show that the application of NPK with Zn avoids these metabolic dysfunctions and increases rice yield response to N, P, and K fertilisers. The co-application of an adequate rate of N, P, K, Mg, and Zn should be recommended for improving rice growth and yield, to alleviate the imbalance in soil exchangeable Mg and Zn on continuously cropped soil treated only with applications of N, P, and K.

Conclusion

The present study revealed the positive interactive effects of each major nutrient (nitrogen, phosphorus, and potassium) with magnesium and/or zinc on various yield parameters including grain yield, panicle number per plant, spikelet number per plant, filled grain rate, and 1 000 grains weight. Magnesium and zinc improved rice yield response to nitrogen application through increasing panicle number per plant, spikelet number per panicle, filled grain rate, and 1 000 grains weight. Grain yield response to phosphorus application consistently increased with the addition of appropriate zinc levels, as shown by increased numbers of spikelets per panicle and 1 000 grains weight. However, the rice grain yield response to potassium application increased when it was co-applied with magnesium due to an increase in filled grain rate. The co-application of the major nutrients with magnesium and/or zinc also improved the use efficiency of each major nutrient. These results indicated that the application of adequate amounts of nitrogen, phosphorus, potassium, magnesium, and zinc are necessary to achieve optimal grain yield in rice.

Acknowledgments — The authors are grateful to the Islamic Development Bank (IDB) through Smallholder Agricultural Production Enhancement Program (SAPEP) for financial support and the opportunity to carry out this study.

Geolocation

Yagbo (02°07'04.58" E, 08°7'19.3" N)
Miniffi (02°18'08.93" E, 07°49'33.57" N)

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