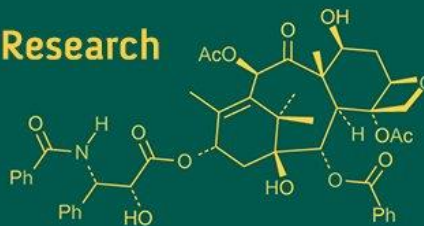


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Enhancement of spikelet fertility and grain yield in rice (*Oryza sativa* L.) through foliar application of plant growth regulators and micronutrients

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Abstract

Spikelet sterility is a major physiological constraint limiting rice productivity, particularly under high-rainfall, lateritic soil conditions. A field experiment was conducted during the *kharif* seasons of 2023 and 2024 at Education & Research Farm, Department of Agril. Botany, Dr. BSKKV, Dapoli, Maharashtra, to evaluate the effect of foliar application of plant growth regulators (PGRs) and micronutrients on spikelet fertility and grain yield of rice (*Oryza sativa* L.). The experiment was laid out in a factorial randomized block design with four PGR treatments [Control, Indole-3-acetic acid (IAA) @ 50 ppm, 6-Benzyl aminopurine (6-BA) @ 75 ppm, and Paclobutrazol (PBZ) @ 100 ppm] and three micronutrient treatments [Control, Boron @ 0.2%, and Zinc @ 0.3%], replicated thrice. Foliar sprays were applied at primordial initiation and flowering stages. Results revealed that foliar application of IAA @ 50 ppm and 6-BA @ 75 ppm significantly improved panicle length, number of spikelets per panicle, spikelet fertility, and grain yield per plant compared to the control. Among micronutrients, Zinc @ 0.3% recorded significantly higher spikelet fertility and grain yield than Boron and the control. Interaction effects indicated that IAA @ 50 ppm combined with Zinc @ 0.3% produced the highest spikelet fertility (88.11%) and grain yield per plant (22.66 g/plant), followed by 6-BA + Zinc. Paclobutrazol treatments were generally inferior for reproductive traits. The study demonstrates that foliar application of IAA or 6-BA in combination with Zinc is an effective strategy for enhancing spikelet fertility and grain yield of rice under high-rainfall ecosystems.

Keywords: Rice, spikelet fertility, plant growth regulators, indole-3-acetic acid, 6-benzyl aminopurine, zinc, boron, grain yield

Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops globally, serving as the primary staple food for more than half of the world's population. In Asia, particularly in India, rice plays a pivotal role in ensuring food security, sustaining rural livelihoods, and supporting agricultural sustainability. Although India ranks first in global rice production, the average productivity of rice remains comparatively low when measured against its yield potential and the productivity levels achieved in several other rice-growing countries. This yield gap is largely attributed to biotic and abiotic stresses, nutrient imbalances, and inefficiencies in crop management practices, particularly under rainfed and high-rainfall ecosystems. Among the various yield-limiting factors in rice, spikelet sterility leading to poor spikelet fertility is a major physiological constraint that significantly reduces grain yield. Grain yield in rice is primarily determined by the number of panicles per unit area, number of spikelets per panicle, spikelet fertility, and test weight. Of these components, spikelet fertility plays a decisive role, as even small reductions in the proportion of filled spikelets can result in substantial yield losses. Poor pollination, impaired fertilization, inadequate assimilate supply during reproductive stages, hormonal imbalance, and micronutrient deficiencies are among the major causes of spikelet sterility in rice.

In high-rainfall regions such as the Konkan belt of Maharashtra, rice cultivation faces unique agro-ecological challenges including excessive and erratic rainfall, nutrient leaching in lateritic soils, poor root aeration, and frequent pest and disease incidence. These adverse conditions often disrupt normal plant growth and reproductive development, resulting in increased spikelet sterility and reduced grain yield.

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Conventional soil fertilization practices frequently prove limiting under such environments due to heavy nutrient losses, especially of mobile nutrients and micronutrients, thereby necessitating alternative and more efficient nutrient and growth regulation strategies.

Foliar application of plant growth regulators (PGRs) has emerged as an effective agronomic approach to modulate physiological processes and improve reproductive efficiency in rice. Plant growth regulators such as Indole-3-acetic acid (IAA), 6-Benzyl Aminopurine (6-BA), and Paclobutrazol (PBZ) play critical roles in regulating cell division, elongation, tillering, panicle development, and assimilate partitioning. Auxins like IAA enhance root growth and vascular differentiation, improving nutrient uptake and supporting better panicle development. Cytokinin such as 6-BA delay leaf senescence, maintain higher photosynthetic activity, and promote spikelet differentiation and grain filling. Paclobutrazol, a growth retardant, alters plant architecture by restricting excessive vegetative growth, enhancing root development, and improving assimilate translocation towards reproductive organs, thereby contributing to improved spikelet fertility and yield stability. Micronutrients, particularly Zinc (Zn) and Boron (B), are equally crucial for normal growth and reproductive success in rice. Zinc is involved in enzyme activation, chlorophyll synthesis, auxin metabolism, and pollen viability, whereas Boron plays an essential role in cell wall formation, carbohydrate translocation, pollen germination, and pollen tube growth. Deficiencies of Zn and B are widespread in lateritic soils and frequently lead to poor tillering, reduced spikelet fertility, and lower grain yield. Foliar application of these micronutrients ensures rapid absorption and immediate physiological response, making it especially effective under high-rainfall conditions where soil-applied nutrients are prone to leaching losses.

Several studies have demonstrated that foliar application of plant growth regulators and micronutrients improves morphological traits, yield attributes, and grain yield in rice. More importantly, their combined or synergistic application has been reported to be superior to individual treatments, particularly in stress-prone environments, by enhancing reproductive efficiency and spikelet fertility. However, region-specific information on the integrated use of PGRs and micronutrients under high-rainfall, lateritic soil conditions of the Konkan region remains limited. Therefore, the present investigation entitled “Enhancement of Spikelet Fertility and Grain Yield in Rice (*Oryza sativa* L.) through Foliar Application of Plant Growth Regulators and Micronutrients” was undertaken to evaluate the individual and interactive effects of selected PGRs and micronutrients on spikelet fertility, yield attributes, and grain yield of rice, with the aim of developing efficient and sustainable management strategies for improving rice productivity under high-rainfall ecosystems.

Materials and Methods

Experimental Site and Climate

The field experiment entitled “Effect of Plant Growth Regulators and Micronutrients on Morpho-Physiological Traits, Growth and Yield of Rice (*Oryza sativa* L.)” was conducted during the kharif seasons of 2023 and 2024 at the Research and Education Farm, Department of Agricultural Botany, College of Agriculture, Dapoli, Maharashtra, India. The experimental site is located at 17°45' N latitude and

73°11' E longitude, at an altitude of approximately 250 m above mean sea level. The region experiences a tropical humid climate with high rainfall (4000-4300 mm) during the crop season. Mean temperature ranged from 22 to 34 °C with high relative humidity throughout the crop growth period.

Soil Characteristics

The experimental soil was lateritic in nature, belonging to the Gimhavana soil series (Fluventic Ustropepts). Composite soil samples (0-22.5 cm depth) were collected before transplanting and analyzed using standard procedures. The soil was slightly acidic (pH 5.5), medium in available nitrogen (179 kg ha⁻¹), low in available phosphorus (8.54 kg ha⁻¹), high in available potassium (383 kg ha⁻¹), and deficient in Zinc (0.23 mg kg⁻¹) and Boron (0.26 mg kg⁻¹).

Experimental Design and Treatments

The experiment was laid out in a Factorial Randomized Block Design (FRBD) with twelve treatment combinations and three replications. The treatments consisted of four plant growth regulator levels and three micronutrient levels. Plant Growth Regulators included viz.; (G): G₀-Control (no PGR), G₁-Indole-3-acetic acid (IAA) @ 50 ppm, G₂-6-Benzyl aminopurine (6-BA) @ 75 ppm, G₃-Paclobutrazol (PBZ) @ 100 ppm, while micronutrients (M) consist of M₀-Control (no micronutrient), M₁-Boron @ 0.2%, M₂-Zinc @ 0.3%. Rice variety Ratnagiri-5 was used for the study. Twenty-five-day-old seedlings were transplanted at a spacing of 20 × 15 cm. The recommended dose of fertilizers (100:50:50 kg N:P₂O₅:K₂O ha⁻¹) was applied uniformly to all treatments.

Foliar Application of Plant Growth Regulators and Micronutrients

Foliar application of plant growth regulators and micronutrients was carried out twice, first at 60 days after sowing (DAS) corresponding to the primordial initiation stage and second at 80 DAS at the flowering stage. The required concentrations of PGRs and micronutrients were prepared using distilled water and applied uniformly with a knapsack sprayer during morning hours to ensure proper absorption.

Crop Management Practices

All recommended agronomic practices were followed uniformly for raising the crop. Irrigation was maintained at a shallow water depth throughout the growing period. Weeding was done manually as and when required. No serious incidence of pests or diseases was observed during the experimental period.

Observations Recorded

Five plants were randomly selected and tagged from each plot for recording observations. Morphological parameters such as plant height, number of tillers per plant, number of leaves per plant, dry matter accumulation in root, stem, leaf and panicle, and total dry matter production were recorded at 50, 75, 100 DAS and at harvest.

Yield attributes including panicle length, number of panicles per plant, number of spikelets per panicle, spikelet fertility, grain yield per plant, total biomass, test weight, grain yield (q ha⁻¹), and harvest index were recorded at harvest.

Statistical Analysis

The data collected during both the years were subjected to analysis of variance (ANOVA) appropriate to Factorial Randomized Block Design, as described by Panse and Sukhatme (1985) ^[13]. Treatment means were compared using Critical Difference (CD) at 5 percent level of significance.

Results and Discussion

The observations recorded were analyzed statistically and presented and discussed under the following heads:

Effect of Plant growth regulators on Yield and Yield attributes

Effect of plant growth regulators on panicle length (cm) in rice

The significantly higher panicle length was recorded with

foliar application of IAA @ 50 ppm (G_1) (18.79, 18.34 and 18.57 cm during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G_2) (18.61, 18.10 and 18.35 cm) and significantly superior to the control (17.44 cm) (Table 1). The minimum panicle length was observed under PBZ @ 100 ppm (G_3) (17.19 cm in pooled data). The increase in panicle length under IAA and 6-BA treatments may be attributed to enhanced cell division, elongation, and improved assimilate translocation towards developing panicles. Auxins promote vascular differentiation and panicle elongation, while cytokinins delay leaf senescence and support continuous assimilate supply during reproductive growth. Similar increases in panicle length with foliar application of IAA and 6-BA were reported by Kumar *et al.* (2019) ^[8] and Zhang *et al.* (2020) ^[21].

Table 1: Effect of plant growth regulators and micronutrients on panicle length (cm), test weight (g) in rice during *kharif* 2023, 2024 & pooled analysis

Sr. No.	Treatments	Panicle length (cm)			Test weight (g)		
		2023	2024	Pooled	2023	2024	Pooled
(A)	Foliar application of plant growth regulators						
G_0	No application of PGRs	17.79	17.10	17.44	12.01	12.50	12.25
G_1	IAA @ 50 ppm	18.79	18.34	18.57	12.59	12.80	12.69
G_2	6-BA @ 75ppm	18.61	18.10	18.35	12.63	12.91	12.77
G_3	PBZ @ 100 ppm	17.45	16.92	17.19	12.22	12.65	12.43
	SE (m)±	0.06	0.12	0.06	0.06	0.05	0.03
	CD at 5%	0.17	0.34	0.17	0.17	0.14	0.09
(B)	Foliar application of micronutrients						
M_0	No application of MNTs	17.90	17.38	17.64	12.14	12.61	12.38
M_1	Boron @ 0.2%	18.20	17.56	17.88	12.49	12.79	12.64
M_2	Zinc @ 0.3%	18.38	17.90	18.14	12.44	12.75	12.60
	SE (m)±	0.05	0.10	0.05	0.05	0.04	0.03
	CD at 5%	0.14	0.30	0.14	0.15	0.12	0.08
(C)	Interaction (G x M)						
	SE (m)±	0.10	0.20	0.10	0.10	0.08	0.05
	CD at 5%	NS	NS	NS	NS	NS	NS
	GM	18.16	17.61	17.89	12.36	12.72	12.54

Effect of plant growth regulators on test weight (g) in rice

Foliar application of plant growth regulators significantly influenced the test weight of rice during both the years and in pooled analysis (Table 1). The significantly higher test weight was recorded with 6-BA @ 75 ppm (G_2) (12.63, 12.91 and 12.77 g during 2023, 2024 and pooled data, respectively), which was at par with IAA @ 50 ppm (G_1) (12.59, 12.80 and 12.69 g) and significantly superior to the control (12.25 g). The lowest test weight was observed under PBZ @ 100 ppm (G_3) (12.43 g in pooled data). The improvement in test weight under 6-BA and IAA treatments may be attributed to enhanced grain filling due to delayed senescence, sustained photosynthetic activity, and improved assimilate translocation towards developing grains. Cytokinin play a vital role in maintaining sink strength during the grain-filling period, while auxins regulate carbohydrate metabolism and nutrient transport. These findings are in close conformity with Chakraborty *et al.* (2018) ^[3], who reported significant improvement in test weight with foliar application of 6-BA, and Meleha *et al.* (2023) ^[11], who observed increased 1000-grain weight in rice following foliar application of IAA under stress conditions.

Effect of plant growth regulators on no. of fertile spikelets per panicle in rice

Foliar application of plant growth regulators significantly influenced the number of fertile spikelets per panicle during both the years and in pooled analysis (Table 2). The significantly higher number of fertile spikelets per panicle was recorded with IAA @ 50 ppm (G_1) (230.5, 224.4 and 227.4 during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G_2) (222.0, 217.8 and 219.9) and significantly superior to the control (182.4). The minimum number of fertile spikelets per panicle was observed under PBZ @ 100 ppm (G_3) (177.9 in pooled data). The increase in fertile spikelets under IAA and 6-BA treatments may be attributed to improved spikelet differentiation, enhanced assimilate translocation, and better hormonal balance during reproductive stages. Auxins promote vascular differentiation and nutrient flow to developing spikelets, while cytokinins enhance sink strength and reduce spikelet abortion. Similar improvements in fertile spikelet number with foliar application of IAA and 6-BA in rice were reported by Zhang *et al.* (2020) ^[21] and Kumar *et al.* (2019) ^[8].

Table 2: Effect of plant growth regulators and micronutrients on no. of fertile & total spikelets per panicle in rice during *kharif* 2023, 2024 & pooled analysis

Sr. No.	Treatments	No. of fertile spikelet per panicle			No. of total spikelets per panicle		
		2023	2024	Pooled	2023	2024	Pooled
(A)	Foliar application of plant growth regulators						
G ₀	No application of PGRs	186.1	178.7	182.4	251.7	246.4	249.1
G ₁	IAA @ 50 ppm	230.5	224.4	227.4	269.4	267.0	268.2
G ₂	6-BA @ 75ppm	222.0	217.8	219.9	264.6	262.3	263.4
G ₃	PBZ @ 100 ppm	180.8	174.9	177.9	239.9	235.0	237.5
	SE (m)±	0.87	0.75	0.53	0.4	0.64	0.3
	CD at 5%	2.55	2.19	1.55	1.19	1.88	0.89
(B)	Foliar application of micronutrients						
M ₀	No application of MNTs	191.9	187.4	189.6	253.7	249.0	251.3
M ₁	Boron @ 0.2%	208.7	201.0	204.8	256.6	253.7	255.2
M ₂	Zinc @ 0.3%	214.0	208.4	211.2	258.8	255.3	257.1
	SE (m)±	0.75	0.65	0.46	0.35	0.56	0.26
	CD at 5%	2.20	1.90	1.34	1.03	1.63	0.77
(C)	Interaction (G x M)						
	SE (m)±	1.50	1.29	0.92	0.7	1.11	0.52
	CD at 5%	4.31	3.71	2.62	NS	NS	NS
	GM	204.8	198.9	201.9	256.4	252.7	254.5

Effect of plant growth regulators on no. of total spikelets per panicle in rice

The number of total spikelets per panicle was significantly influenced by foliar application of plant growth regulators during both the years and in pooled analysis (Table 2). The maximum number of total spikelets per panicle was recorded with IAA @ 50 ppm (G₁) (269.4, 267.0 and 268.2 during 2023, 2024 and pooled data, respectively), followed by 6-BA @ 75 ppm (G₂) (263.4 in pooled data), both being significantly superior to the control (249.1). The lowest number of total spikelets per panicle was observed under PBZ @ 100 ppm (G₃) (237.5 in pooled data). The increase in total spikelets under IAA and 6-BA may be attributed to enhanced panicle branching, increased meristematic activity, and improved spikelet initiation. Cytokinins are particularly known to promote panicle differentiation and

spikelet primordia formation. These results are in conformity with the findings of Zhang *et al.* (2020) ^[21] in rice and Kumar *et al.* (2019) ^[8] in cereal crops.

Effect of plant growth regulators on spikelet fertility in rice

Foliar application of plant growth regulators significantly influenced spikelet fertility during both the years and in pooled analysis (Table 3). The significantly higher spikelet fertility was recorded with IAA @ 50 ppm (G₁) (85.52, 84.02 and 84.77% during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G₂) (83.87, 83.02 and 83.44%) and significantly superior to the control (73.21%). The lowest spikelet fertility was observed under PBZ @ 100 ppm (G₃) (74.88% in pooled data).

Table 3: Effect of plant growth regulators and micronutrients on spikelet fertility (%) & grain yield (g) per plant in rice during *kharif* 2023, 2024 & pooled analysis

Sr. No.	Treatments	Spikelet fertility (%)			Grain yield (g) per plant		
		2023	2024	Pooled	2023	2024	Pooled
(A)	Foliar application of plant growth regulators						
G ₀	No application of PGRs	73.93	72.48	73.21	19.36	18.28	18.82
G ₁	IAA @ 50 ppm	85.52	84.02	84.77	22.37	21.31	21.84
G ₂	6-BA @ 75ppm	83.87	83.02	83.44	21.87	20.74	21.31
G ₃	PBZ @ 100 ppm	75.37	74.39	74.88	20.49	19.30	19.90
	SE (m)±	0.32	0.32	0.21	0.12	0.11	0.09
	CD at 5%	0.93	0.94	0.62	0.36	0.32	0.26
(B)	Foliar application of micronutrients						
M ₀	No application of MNTs	75.48	75.03	75.25	20.23	19.21	19.72
M ₁	Boron @ 0.2%	81.10	79.04	80.07	21.21	19.89	20.55
M ₂	Zinc @ 0.3%	82.44	81.37	81.91	21.64	20.63	21.13
	SE (m)±	0.27	0.28	0.18	0.11	0.10	0.08
	CD at 5%	0.80	0.81	0.54	0.31	0.28	0.22
(C)	Interaction (G x M)						
	SE (m)±	0.55	0.55	0.37	0.21	0.19	0.15
	CD at 5%	1.56	1.59	1.05	0.61	0.55	0.44
	GM	79.67	78.48	79.07	21.02	19.91	20.47

The improvement in spikelet fertility under IAA and 6-BA treatments may be attributed to reduced floret abortion, enhanced pollen viability, and improved assimilate translocation during anthesis and grain-setting stages. Auxin application improves fertilization efficiency under stress conditions, while cytokinins delay senescence and strengthen sink activity. These findings are in close agreement with Wei *et al.* (2016) [19] and Chen *et al.* (2016) [4], who reported significant increases in spikelet fertility and grain number with foliar application of 6-BA. Similarly, Kumar *et al.* (2023) [9] observed a marked improvement in spikelet fertility of rice following exogenous IAA application under heat stress.

Effect of plant growth regulators on grain yield (g) per plant in rice

Grain yield per plant was significantly influenced by foliar application of plant growth regulators during both years and in pooled analysis (Table 3). The significantly higher grain yield per plant was recorded with IAA @ 50 ppm (G₁) (22.37, 21.31 and 21.84 g during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G₂) (21.31 g in pooled data) and significantly superior to the control (18.82 g). The lowest grain yield was observed under PBZ @ 100 ppm (G₃) (19.90 g in pooled data). The enhanced grain yield under IAA and 6-BA treatments may be attributed to improved spikelet fertility, enhanced grain filling, and better source-sink balance. Auxins promote tillering and assimilate translocation, while cytokinin enhance panicle initiation and grain development. These findings are in conformity with Ruchitha *et al.* (2020) [17], Pan *et al.* (2021) [12], and Renuka *et al.* (2024) [16], who reported significant yield improvements in rice following foliar application of IAA and 6-BA under normal and stress conditions.

Effect of Micronutrients on Yield and Yield Attributes

Effect of micronutrients on panicle length (cm) in rice

Foliar application of micronutrients significantly influenced panicle length during both years and in pooled analysis. Application of Zinc @ 0.3% (M₂) recorded the highest panicle length (18.38, 17.90 and 18.14 cm during 2023, 2024 and pooled data, respectively), which was significantly superior to the no-micronutrient control (17.64 cm). This was followed by Boron @ 0.2% (M₁), which recorded a pooled panicle length of 17.88 cm. The improvement in panicle length due to Zinc may be attributed to its role in enzyme activation, auxin metabolism, and protein synthesis, which support active meristematic growth. Boron enhances cell wall formation, carbohydrate translocation, and reproductive development, thereby contributing to panicle elongation. These findings are in conformity with the results of Baishya *et al.* (2019) [2] and Ahmad *et al.* (2022) [1].

Effect of micronutrients on test weight (g) in rice

Foliar application of micronutrients exerted a significant effect on test weight during both the experimental years and in pooled data (Table 1). The highest test weight was recorded with Boron @ 0.2% (M₁) (12.49, 12.79 and 12.64 g during 2023, 2024 and pooled data, respectively), which was closely followed by Zinc @ 0.3% (M₂) (12.44, 12.75 and 12.60 g), both being significantly superior to the no-micronutrient control (12.38 g). The increase in test weight

due to Boron and Zinc application may be attributed to their crucial role in pollen viability, carbohydrate translocation, enzyme activation, and grain development. Zinc enhances starch synthesis and protein metabolism, while Boron facilitates sugar transport and proper grain filling. These results corroborate the findings of Khan *et al.* (2019) [6] and Krishna *et al.* (2023) [7], who reported significant improvements in 1000-grain weight and grain yield with foliar application of Zinc and Boron in cereals.

Effect of micronutrients on no. of fertile spikelets per panicle in rice

Foliar application of micronutrients significantly increased the number of fertile spikelets per panicle over the control during both the years and in pooled analysis (Table 2). The maximum number of fertile spikelets per panicle was recorded with Zinc @ 0.3% (M₂) (214.0, 208.4 and 211.2), followed by Boron @ 0.2% (M₁) (204.8 in pooled data), both being significantly superior to the no-micronutrient control (189.6). The improvement in fertile spikelet number due to Zinc and Boron application may be attributed to their role in pollen viability, enzyme activation, carbohydrate translocation, and fertilization efficiency. Zinc enhances auxin metabolism and spikelet survival, while Boron is essential for pollen tube growth and successful fertilization. These findings are supported by Khan *et al.* (2019) [6] and Krishna *et al.* (2023) [7].

Effect of micronutrients on no. of total spikelets per panicle in rice

Foliar application of micronutrients significantly influenced the number of total spikelets per panicle during both the years and in pooled data (Table 2). The highest number of total spikelets per panicle was recorded with Zinc @ 0.3% (M₂) (258.8, 255.3 and 257.1), followed by Boron @ 0.2% (M₁) (255.2 in pooled data), both being significantly superior to the control (251.3). The increase in total spikelet number with Zinc and Boron application may be attributed to improved nutrient availability, enhanced enzymatic activity, and better panicle development. Zinc supports spikelet initiation through its role in auxin synthesis, while Boron contributes to carbohydrate transport and reproductive growth. These findings are in agreement with Khan *et al.* (2019) [6] and Krishna *et al.* (2023) [7].

Effect of micronutrients on spikelet fertility in rice

Foliar application of micronutrients significantly enhanced spikelet fertility during both the years and in pooled data (Table 3). Application of Zinc @ 0.3% (M₂) recorded the highest spikelet fertility (82.44, 81.37 and 81.91%), followed by Boron @ 0.2% (M₁) (80.07% in pooled data), both being significantly superior to the no-micronutrient control (75.25%). The increase in spikelet fertility due to Zinc and Boron application may be attributed to improved pollen formation, pollen tube growth, and stigma receptivity. Zinc plays a crucial role in enzyme activation and auxin metabolism, whereas Boron is essential for fertilization and grain setting. These results corroborate the findings of Shivay *et al.* (2008) [18] and Raghuveer Rao *et al.* (2013) [15], who reported significant reductions in spikelet sterility and improved grain setting with foliar application of Zinc and Boron in rice.

Effect of micronutrients on grain yield (g) per plant in rice

Foliar application of micronutrients significantly increased grain yield per plant during both years and in pooled analysis (Table 2). Application of Zinc @ 0.3% (M₂) resulted in the highest grain yield per plant (21.64, 20.63 and 21.13 g), followed by Boron @ 0.2% (M₁) (20.55 g in pooled data), both being significantly superior to the control (19.72 g). The improvement in grain yield due to Zinc and Boron application may be attributed to enhanced spikelet fertility, improved grain filling, and efficient nutrient remobilization during reproductive stages. These results are in agreement with Meena *et al.* (2020) [10], who reported substantial yield enhancement in cereals with foliar application of Zinc and Boron.

Interaction Effect of Plant growth regulators and Micronutrients

Interaction effect of PGRs & micronutrients on panicle length (cm) in rice

The interaction effect between plant growth regulators and micronutrients was found to be non-significant during both the years and in pooled analysis (Table 1).

Interaction effect of PGRs & micronutrients on test weight (g) in rice

The interaction effect between plant growth regulators and micronutrients on test weight was found to be non-significant during both years and in pooled analysis (Table 1).

Interaction effect of PGRs & micronutrients on no. of fertile spikelets per panicle

The interaction between plant growth regulators (PGRs) and micronutrients significantly influenced the number of fertile spikelets per panicle during both years and in pooled analysis (Table 4). Among treatment combinations, IAA @ 50 ppm with Zinc @ 0.3% (G₁M₂) recorded the maximum fertile spikelets (241.0, 236.7 and 238.9 in 2023, 2024 and pooled data, respectively), followed by 6-BA @ 75 ppm

with Zinc (G₂M₂). The lowest fertile spikelet count was consistently observed under the control (G₀M₀) and PBZ-based combinations. The synergistic response of IAA and Zinc may be attributed to enhanced pollen viability, improved carbohydrate translocation and reduced spikelet abortion through auxin-mediated sink strengthening and Zinc-regulated enzyme activity. Similar interactive benefits of cytokinins/auxins with micronutrients on spikelet fertility have been reported by Kumar *et al.* (2023) [9], Shivay *et al.* (2008) [18] and Raghuveer Rao *et al.* (2013) [15], supporting the present findings.

Table 4: Interaction effect of plant growth regulators and micronutrients on no of fertile spikelets in rice

MNTs PGRs	No of fertile spikelets per panicle in rice								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	176.1	188.8	193.3	163.9	184.7	187.6	170.0	186.8	190.4
G ₁	215.7	234.6	241.0	213.0	223.4	236.7	214.4	229.0	238.9
G ₂	203.9	228.1	234.0	207.1	218.4	227.9	205.5	223.2	231.0
G ₃	171.7	183.3	187.6	165.7	177.4	181.5	168.7	180.3	184.5
SE (m)±	1.50			1.29			0.92		
CD at 5%	4.31			3.71			2.62		

Interaction effect of PGRs & micronutrients on no. of total spikelets per panicle

The interaction effect between plant growth regulators and micronutrients on no. of total spikelets per panicle was found to be non-significant during both years and in pooled analysis.

Interaction effect of PGRs & micronutrients on spikelet fertility in rice

The interaction between plant growth regulators and micronutrients exerted a significant influence on spikelet fertility during both years and in pooled analysis (Table 5). The highest spikelet fertility was recorded with IAA @ 50 ppm + Zinc @ 0.3% (G₁M₂) (88.62, 87.60 and 88.11% in 2023, 2024 and pooled data, respectively), followed by 6-BA @ 75 ppm + Zinc (G₂M₂).

Table 5: Interaction effect of plant growth regulators and micronutrients spikelet fertility (%) in rice

MNTs PGRs	Spikelet fertility (%) in rice								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	70.34	75.09	76.36	67.95	74.40	75.09	69.15	74.74	75.72
G ₁	81.26	86.68	88.62	81.08	83.39	87.60	81.17	85.04	88.11
G ₂	78.08	86.11	87.42	80.03	82.94	86.09	79.05	84.52	86.76
G ₃	72.24	76.51	77.35	71.05	75.42	76.70	71.64	75.97	77.03
SE (m)±	0.55			0.55			0.37		
CD at 5%	1.56			1.59			1.05		

The lowest fertility was observed under the control (G₀M₀) treatment. The enhanced fertility under IAA-Zn and 6-BA-Zn combinations may be attributed to improved pollen viability, stigma receptivity and assimilate translocation, resulting in reduced spikelet sterility. Similar synergistic effects of auxins or cytokinins with Boron and Zinc on spikelet fertility in rice have been reported by Raghuveer Rao *et al.* (2013) [15], Zhang *et al.* (2013) [20] and Khampuang *et al.* (2024) [5], corroborating the present findings.

Interaction effect of PGRs & micronutrients on grain yield (g) per plant in rice

The interaction between plant growth regulators and micronutrients significantly influenced grain yield per plant during both years and in pooled analysis (Table 6). The highest grain yield was recorded with IAA @ 50 ppm + Zinc @ 0.3% (G₁M₂) (23.29, 22.03 and 22.66 g plant⁻¹ in 2023, 2024 and pooled data, respectively), followed by 6-BA @ 75 ppm + Zinc (G₂M₂). The lowest yield was observed under the control treatment (G₀M₀). The superiority of IAA + Zn and 6-BA + Zn combinations may

be attributed to improved assimilate partitioning, enhanced sink strength and efficient grain filling. Similar synergistic effects of PGRs with Zinc or Boron on grain yield have been reported in maize, wheat and rice by Patel *et al.* (2018) ^[14], Kumar *et al.* (2019) ^[8] and Zhang *et al.* (2021) ^[22], supporting the present findings.

Table 6: Interaction effect of plant growth regulators and micronutrients grain yield (g) per plant in rice

MNTs PGRs	Grain yield (g) per plant								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	19.16	19.34	19.57	17.50	18.52	18.81	18.33	18.93	19.19
G ₁	21.26	22.57	23.29	20.47	21.43	22.03	20.86	22.00	22.66
G ₂	20.76	22.23	22.63	19.96	20.36	21.91	20.36	21.29	22.27
G ₃	19.73	20.69	21.05	18.91	19.24	19.75	19.32	19.97	20.40
SE (m)±	0.21			0.19			0.15		
CD at 5%	0.61			0.55			0.44		

Conclusion

Foliar application of plant growth regulators and micronutrients significantly enhanced spikelet fertility and grain yield in rice under high-rainfall, lateritic soil conditions. Among the treatments, IAA @ 50 ppm and 6-BA @ 75 ppm markedly improved panicle traits, spikelet fertility and grain yield, while Zinc @ 0.3% and Boron @ 0.2% effectively enhanced reproductive efficiency and grain filling. The IAA @ 50 ppm + Zinc @ 0.3% combination proved most effective, exhibiting a strong synergistic effect by maximizing fertile spikelets, spikelet fertility and grain yield per plant. These improvements were primarily attributed to enhanced assimilate partitioning, improved pollen viability and strengthened source-sink relationships. The study demonstrates that integrated foliar application of PGRs and micronutrients is an efficient and sustainable strategy for improving rice productivity in high-rainfall ecosystems.

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