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Enhancing rice productivity through seed priming with gibberellic acid and zinc for direct seeding: Insights from Dakawa and Kyela, Tanzania

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Abstract:
Low rice productivity in sub-Saharan Africa is frequently associated with poor crop establishment, a challenge that is amplified under direct-seeded systems, where uneven emergence leads to suboptimal plant stands and reduced yield formation. Seed priming is a simple pre-sowing technique that can enhance early establishment and improve yield performance under farmer-relevant conditions. This study evaluated the effects of seed priming with gibberellic acid (GA_3), zinc (Zn), and their combination (GA_3+Zn) on grain yield and yield-related traits of direct-seeded rice under field conditions at two sites in Tanzania (Dakawa and Kyela). Five rice cultivars were assessed across five priming treatments in a factorial RCBD. Data were collected on phenology, growth, panicle traits, grain characteristics, and grain yield. Analysis of variance indicated significant ($p < 0.05$) effects of priming treatment on most agronomic traits at both sites. At Dakawa, GA+Zn priming produced the highest mean grain yield (6.3 t ha^{-1}) while GA and Zn priming also significantly outperformed the non-primed control (4.9 t ha^{-1}). At Kyela, Zn priming produced the highest mean yield (6.4 t ha^{-1}). Cultivar × priming interactions were generally non-significant for yield, suggesting broad applicability of priming across genotypes. The findings demonstrate that seed priming, particularly Zn-based and GA+Zn priming, can substantially improve grain yield and key developmental traits in direct-seeded rice. These results support wider evaluation and scaling of seed priming alongside cultivar selection to strengthen direct-seeded rice productivity.

Keywords: Agronomic traits; Cultivars; Crop improvement; Seed priming; Stress resilience.

1 INTRODUCTION

Rice (Oryza sativa L.) is a staple food crop that supports the diets and livelihoods of billions of people worldwide and remains a major contributor to rural incomes and national economies in many countries. Global rice production is heavily concentrated in Asia, with major producers such as China and India accounting for a large share of total output (Anagha *et al.*, 2024; Li *et al.*, 2024). In contrast, rice production systems in sub-Saharan Africa generally exhibit lower productivity and slower adoption of yield-enhancing technologies than leading Asian systems, despite increasing demand and expansion of cultivated areas (Ashraf *et al*., 2024).

In Tanzania, rice is a strategic food and cash crop that supports food security and provides livelihoods for millions of farming households. National average yields remain comparatively low (~2.5 t ha^{-1}), below the national target of 4.2 t ha^{-1} by 2025, indicating persistent yield gaps attributable to suboptimal crop establishment, nutrient constraints, and stress exposure during early growth stages (Senthilkumar *et al*., 2021).

Direct-seeded rice systems are increasingly promoted because they reduce labour requirements and shorten establishment time, but are frequently challenged by poor and uneven crop establishment, which can lead to weak plant stands and reduced yield component formation. Seed priming, a pre-sowing treatment that initiates key metabolic processes before planting has been shown to improve germination performance and early seedling vigour. Priming with gibberellic acid (GA_3) and zinc (Zn) has gained research attention due to their physiological roles in promoting early growth and stress adjustment. Gibberellins regulate reserve mobilization and elongation, while zinc supports enzyme function, antioxidant defense, and nutrient balance during early plant development (Adil *et al*., 2024; Dang *et al*., 2024; Dhillon *et al*., 2021; Nazir *et al*., 2024). Evidence from East African rice lowlands indicates that micronutrient constraints can limit intensification, suggesting a practical role for Zn interventions in improving rice productivity (Awio *et al*., 2021).

Against this background, the present study evaluated the effects of seed priming with GA_3, Zn, and GA_3+Zn on agronomic performance and grain yield of direct-seeded rice under field conditions in Dakawa (Eastern Tanzania) and Kyela (Southern Highlands). The study aimed to determine whether priming improves phenology, yield components, and grain yield across contrasting environments and cultivars, and to generate evidence to inform practical recommendations for strengthening the productivity of direct-seeded rice systems in Tanzania.

2 Materials and Methods

2.1 Study sites

Field experiments were conducted at Dakawa (Morogoro Region, Eastern Tanzania) and Kyela (Mbeya Region, Southern Highlands, Tanzania), during the 2023/2024 cropping season. The experiment evaluated the agronomic effects of seed priming on direct-seeded rice under field conditions.

2.2 Soil sampling and analysis

Before field preparation, soil samples were collected from each site using a random zigzag sampling method at 0-30 cm depth. Several sub-samples per site were composited into a representative sample (~1.5 kg) for laboratory analysis. Soil parameters determined included pH, electrical conductivity (EC), organic carbon (OC), total nitrogen (N), particle size distribution, and available nutrients. All analyses followed standard procedures (Okalebo *et al*., 2002) (Table 1).

2.3 Experimental design and treatments

The study employed a two-factor factorial arrangement at each site under a randomised complete block design (RCBD) with three replications. The factors were: (i) Cultivar (five levels): KALAMATA, SATO1, TARI RIC2, TARI RIC3, and TXD 306; and (ii) Priming treatment (five levels): GA_3, Zn, GA_3+Zn, water (hydropriming), and non-primed control. This produced 25 treatment combinations replicated three times per site.

2.4 Implementation of field experiments

GA_3 was prepared at 0.1g in distilled water. Zinc priming used Zn at 0.5% w/v (50g). For the combined treatment, GA_3 (0.1g) and Zn (50g w/v) were prepared together. For each cultivar, 1 kg of seed was soaked in 1 L of the respective solution for 24 hours. Seeds were drained, shade-dried, and direct drilled at 2–3 cm depth using 25 cm × 25 cm spacing. DAP was applied at planting to supply 40 kg P ha^{-1} and 36 kg N ha^{-1}; total nitrogen was targeted at 100 kg N ha^{-1} with the remainder applied as urea in two equal splits at tillering and booting (Senthilkumar *et al*., 2021).

2.5 Data collection and yield assessment

Phenological and agronomic parameters recorded included days to 50% flowering, days to maturity, plant height (cm), tiller density (tillers m^{-2}), panicle length (cm), and panicle density (panicles m^{-2}). Yield component traits measured included filled grains per panicle, unfilled grains per panicle, and 1000-grain weight (g). Grain yield was harvested from a net plot area of 8 m^2 and converted to t ha^{-1}.

2.6 Statistical analysis

Data were analysed using two-way ANOVA appropriate for a factorial RCBD. Within each site, cultivar, priming treatment, and their interaction were fixed effects, and block was a random effect. When significant differences were detected ($p \leq 0.05$), means were separated using Tukey's Honestly Significant Difference (HSD) test (Gomez & Gomez, 1984) at the 5% significance level. Mean separation letters are reported in all tables; means sharing the same letter do not differ significantly at $p \leq 0.05$.

3 Results

3.1 Soil chemical characteristics of the study sites

Soil characteristics differed markedly between Kyela and Dakawa (Table1). The Kyela soil was strongly acidic (pH 4.36) compared with Dakawa (pH 5.85), while both sites were non-saline. Kyela had higher organic carbon (1.6%) and greater clay and silt content (textural class: clay loam), while Dakawa had higher total nitrogen (0.21%), available phosphorus (15 mg kg^{-1}), and extractable iron (101.4 mg kg^{-1}). Zinc was higher at Kyela (2.7 mg kg^{-1}) than at Dakawa (2.0 mg kg^{-1}). These contrasting soil environments provided a useful basis for assessing the generalisability of priming effects across sites.

Table 1: Soil properties of the study sites

Soil property	Kyela site		Dakawa site	
	Value	**Rating (Landon, 1991)**	**Value**	**Rating (Landon, 1991)**
pH	4.36	Extremely acid	5.85	Medium acid
EC (mhos cm^{-1})	0.015	Non-saline	0.014	Non-saline
OC (%)	1.6	Medium	0.08	Very low
N (%)	0.14	Medium	0.21	High
Clay (%)	32	High	20.23	Medium
Silt (%)	40	High	9.58	Low
Sand (%)	28	Medium	0.62	Very low
Textural class	Clay Loam	-	Clay	-
P (mg kg^{-1})	12.1	Medium	15	High
Zn (mg kg^{-1})	2.7	High	2.0	Medium
Fe (mg kg^{-1})	78.2	High	101.4	Very high
Ca (cmol(+) kg^{-1})	2.47	Low	8.0	High
Mg (cmol(+) kg^{-1})	8.32	Very high	3.0	Medium
K (cmol(+) kg^{-1})	0.31	Low	0.4	Medium
Na (cmol(+) kg^{-1})	0.06	Low	0.1	Low

EC = electrical conductivity; CEC = cation exchange capacity; OC = organic carbon; ESP = exchangeable sodium percentage.

3.2 ANOVA summary: effects of cultivar, priming, and their interaction

At Kyela, (Table 2) the ANOVA showed that both cultivar and priming treatment significantly influenced most measured traits, including days to 50% flowering, panicle length, panicle density, plant height, tiller density, filled grains, maturity days, 1000-grain weight, and grain yield ($p < 0.05$). Priming and cultivar effects were not significant for unproductive tillers at Kyela, and a significant cultivar × priming interaction was detected for plant height and unproductive tillers ($p < 0.05$), indicating trait-specific genotype responsiveness to priming at this site.

At Dakawa, priming significantly influenced most traits, including flowering time, panicle density, plant height, tiller density, filled grains, maturity, and grain yield. Cultivar effects were significant for flowering time, maturity, and plant height, but not for several yield-component traits or grain yield per se. The cultivar × priming interaction was significant only for plant height at Dakawa ($p < 0.001$), indicating that cultivar-dependent priming response was trait-specific rather than general.

Varietal effects were significant at $p < 0.001$ for Days to 50% flowering, Plant height, and Maturity days, but not for Panicle length, Panicles (m^{-2}), Tillers (m^{-2}), Filled grains, or Yield ($t\ ha^{-1}$) ($p > 0.05$). Priming effects were significant at $p < 0.001$ for Days to 50% flowering, Panicles (m^{-2}), Plant height, Tillers (m^{-2}), Maturity days, and Yield ($t\ ha^{-1}$), and at $p < 0.05$ for Filled grains, but not for Panicle length ($p > 0.05$). The varieties × priming interaction was significant at $p < 0.001$ for Plant height only; none of the remaining traits showed a significant interaction ($p>0.05$).

Table 2: ANOVA summary on the effects of cultivar, priming, and their interaction at Kyela

Source of variation	**df**	**Days to 50% flowering**	**Panicle length**	**Panicles (m^{-2})**	**Plant height**	**Tillers (m^{-2})**	**Filled grains**	**Maturity days**	**1000-GW**	**Yield (ha)**
Replication	2	0.30	3.47	17326	41.2	17589	12235	0.3	4.1	0.75
Varieties	4	409.0***	76.05***	77581**	18111.1***	76395**	194535***	408.95***	115.9***	3.67*
Priming	4	119.4***	17.49***	8064***	175.7***	8066***	11212***	119.4***	6.1***	1.29**
Varieties × Priming	16	7.4	1.10	760	26.4***	803	944	7.4	0.5	0.40
Residual	40	3.9	0.83	1169	13.5	1198	1210	3.9	0.4	0.25

*Note: *, **, *** significant at p<0.05, p<0.01, p<0.001 respectively*

Table 3: ANOVA summary on the effects of cultivar, priming, and their interaction at Dakawa

Source of variation	**df**	**Days to 50% flowering**	**Panicle length**	**Panicles (m^{-2})**	**Plant height**	**Tillers (m^{-2})**	**Filled grains**	**Maturity days**	**Yield (ha)**
Replication	2	0.01	9.1	23251	28.5	31457	57.9	0.01	1.0
Varieties	4	409.0***	9.8	7043	4515.2***	10596	1144.4	408.95***	2.1
Priming	4	142.0***	6.1	44585***	921.2***	43523***	1952.8*	141.98***	14.5***

Varieties × Priming	16	4.5	13.9	6695	207.9***	8105	1207.4	4.5	0.9
Residual	40	2.5	12.69	3664	25.8	4342	715.2	2.5	1.6

*Note: *, **, *** significant at p<0.05, p<0.01, p<0.001 respectively*

3.3 Main effects of cultivar on phenology and growth traits

Cultivar had a significant ($p < 0.001$) effect on days to 50% flowering and maturity at both sites (Table 4). TARI RIC2 was consistently the earliest-flowering cultivar (74.8 days at Kyela; 72.8 days at Dakawa) and earliest maturing (109.8 and 107.8 days, respectively), classifying it as a short duration variety suited to intensive cropping systems. In contrast, KALAMATA and TARI RIC3 showed the latest maturity at both sites (>120 days at Kyela; >120 days at Dakawa). Plant height differed significantly among cultivars at both sites; KALAMATA was markedly taller (174.5 cm at Kyela; 132.7 cm at Dakawa) than the other four cultivars, which ranged from 91 to 99 cm at Dakawa and 94 to 99 cm at Kyela. At Kyela, cultivar also significantly influenced tiller density, panicle density, panicle length, filled grains per panicle, and grain yield. TXD306 recorded the highest mean yield at Kyela (6.7 t ha^{-1}), followed by SATO1 (6.4 t ha^{-1}). At Dakawa, cultivar differences were not significant for yield, tillers, panicles, or filled grains, although trends favoured TARI RIC3 (5.8 t ha^{-1}) and TXD306 (5.6 t ha^{-1}).

Table 4: Main effects of cultivar on growth and yield attributes of rice at Dakawa and Kyela sites

Kyela site

Cultivar	Days to 50% flowering	Tillers (m^{-2})	Panicles (m^{-2})	Plant height (cm)	Panicle length (cm)	Filled grains $panicle^{-1}$	Maturity days	1000-GW (g)	Yield (t ha^{-1})
KALAMATA	87.67^{a}	244.07^{c}	242.00^{c}	174.53^{a}	30.19^{b}	507.93^{a}	122.67^{a}	88.40^{a}	5.68^{b}
SATO1	83.07^{c}	343.33^{b}	342.73^{b}	98.06^{b}	32.71^{a}	285.00^{b}	118.07^{c}	79.00^{a}	6.38^{a}
TARI RIC2	74.80^{d}	386.67^{a}	385.87^{a}	98.51^{b}	25.20^{d}	289.20^{b}	109.80^{d}	79.47^{a}	5.50^{b}
TARI RIC3	87.07^{a}	418.80^{a}	417.60^{a}	94.53^{b}	30.00^{c}	231.80^{c}	122.07^{a}	76.87^{a}	5.75^{b}
TXD306	85.27^{b}	409.87^{a}	409.80^{a}	96.54^{b}	30.85^{b}	235.67^{c}	120.27^{b}	57.40^{b}	6.65^{a}
Grand Mean	83.57	360.55	359.60	112.43	29.79	309.92	118.57	76.23	5.99
S.E. (±)	0.489	12.338	12.343	1.033	0.188	9.277	0.489	5.267	0.143
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	<0.001

Dakawa site

Cultivar	Days to 50% flowering	Tillers (m^{-2})	Panicles (m^{-2})	Plant height (cm)	Panicle length (cm)	Filled grains $panicle^{-1}$	Maturity days	1000-GW (g)	Yield (t ha^{-1})
KALAMATA	85.67^{a}	315.13^{a}	296.13^{a}	132.66^{a}	20.77^{a}	117.20^{a}	120.67^{a}	35.07^{a}	4.88^{a}
SATO1	81.07^{c}	360.20^{a}	334.60^{a}	91.58^{b}	22.15^{a}	108.20^{a}	116.07^{c}	31.93^{a}	5.19^{a}

Cultivar	Days to 50% flowering	Tillers (m^{-2})	Panicles (m^{-2})	Plant height (cm)	Panicle length (cm)	Filled grains panicle^{-1}	Maturity days	1000-GW (g)	Yield (t ha^{-1})
TARI RIC2	72.80^{d}	374.13^{a}	342.93^{a}	95.38^{b}	22.97^{a}	120.60^{a}	107.80^{d}	32.07^{a}	5.58^{a}
TARI RIC3	85.07^{a}	350.67^{a}	323.13^{a}	94.03^{b}	21.58^{a}	99.20^{a}	120.07^{a}	33.67^{a}	5.82^{a}
TXD306	83.27^{b}	384.00^{a}	352.27^{a}	95.02^{b}	21.65^{a}	117.20^{a}	118.27^{b}	32.53^{a}	5.59^{a}
Grand Mean	81.57	356.83	329.81	101.73	21.82	112.48	116.57	33.05	5.41
S.E. (±)	0.423	17.780	16.537	1.294	0.976	6.965	0.423	1.979	0.342
p-value	<0.001	0.079	0.162	<0.001	0.605	0.197	<0.001	0.778	0.320

Means within a column followed by different letters differ significantly at p ≤ 0.05 (Tukey HSD test); GW = grain weight.

3.4 Main effects of priming on phenology and growth traits

Across sites, priming significantly influenced rice phenology and growth (Table 5). At Kyela, GA, Zn, and GA+Zn priming significantly reduced days to 50% flowering relative to water priming and the non-primed control, with GA+Zn producing the earliest flowering (81.0 days) compared with the non-primed control (86.2 days). Similar trends were observed at Dakawa, where GA+Zn produced the earliest flowering (78.3 days) and differed significantly from the non-primed control (84.3 days) and water priming (85.3 days). Priming also significantly increased tiller density and panicle density at both sites (Table 3.5). GA+Zn produced the highest tiller counts at Dakawa (404.1 m^{-2}) and Kyela (385.3 m^{-2}), and these were significantly higher than the non-primed control (294.5 and 336.1 m^{-2}, respectively). Plant height was similarly improved by priming at both sites. Panicle length was not significantly affected by priming at Dakawa ($p = 0.75$), but was significant at Kyela ($p < 0.001$), with Zn and GA priming producing longer panicles than water or non-primed seeds.

Table 5: Growth responses of rice as affected by seed priming at Dakawa and Kyela sites

Kyela site

Priming type	Days to flowering	50% Tillers (m^{-2})	Panicle length (cm)	Panicles (m^{-2})	Plant height (cm)
GA	82.87^{b}	364.47^{a}	30.05^{a}	363.53^{a}	114.47^{a}
Zn	80.93^{b}	379.80^{a}	30.27^{a}	378.80^{a}	116.05^{a}
GA+Zn	81.00^{b}	385.33^{a}	30.37^{a}	384.40^{a}	114.00^{a}
Water	86.87^{a}	337.07^{a}	29.35^{b}	336.73^{a}	109.63^{b}
Non-primed	86.20^{a}	336.07^{a}	28.91^{b}	334.53^{b}	108.03^{b}
Grand Mean	83.57	360.55	29.79	359.60	112.43
S.E. (±)	0.489	12.338	0.188	12.343	1.033
p-value	<0.001	0.013	<0.001	0.013	<0.001

Dakawa site

Priming type	Days to 50% flowering	Tillers (m^{-2})	Panicle length (cm)	Panicles (m^{-2})	Plant height (cm)
GA	80.60[b]	400.53[a]	22.54[a]	379.07[a]	106.44[a]
Zn	79.40[b]	382.33[a]	21.46[a]	354.53[a]	108.51[a]
GA+Zn	78.27[c]	404.07[a]	21.88[a]	373.60[a]	107.29[a]
Water	85.27[a]	302.67[b]	22.29[a]	271.73[b]	92.38[b]
Non-primed	84.33[a]	294.53[b]	20.95[a]	270.13[b]	94.04[b]
Grand Mean	81.57	356.83	21.82	329.81	101.73
S.E. (±)	0.423	17.780	0.976	16.537	1.294
p-value	<0.001	<0.001	0.789	<0.001	<0.001

Key: GA = Gibberellic acid; Zn = Zinc; Means within a column followed by different letters differ significantly at $p \leq 0.05$ (Tukey HSD test).

3.5 Main effects of priming on yield components and grain yield

Priming significantly improved filled grains per panicle and maturity timing, while unfilled grains per panicle were not significantly affected at either site (Table 6). At Kyela, GA+Zn and Zn priming produced the highest filled grains (336.9 and 334.1 panicle^{-1}, respectively), which differed significantly from the non-primed control (274.6 panicle^{-1}; $p < 0.001$). At Dakawa, filled grains also differed across priming treatments ($p = 0.042$), though differences were smaller in magnitude. Priming significantly advanced maturity at both sites; GA+Zn-primed plants matured earliest (116.0 days at Kyela; 113.3 days at Dakawa) while non-primed plants matured latest.

Table 6: Yield components of rice as affected by seed priming at Dakawa and Kyela sites

Priming type	Kyela site		
	Filled grains panicle^{-1}	**Maturity days**	**Unfilled grains panicle^{-1}**
GA	314.33[a]	117.87[b]	81.40[a]
Zn	334.07[a]	115.93[b]	76.13[a]
GA+Zn	336.93[a]	116.00[b]	71.53[a]
Water	289.67[b]	121.87[a]	73.47[a]
Non-primed	274.60[b]	121.20[a]	78.60[a]
Grand mean	309.92	118.57	76.23
p-value	<0.001	<0.001	0.693

Dakawa site

Priming type	Filled grains panicle⁻¹	Maturity days	Unfilled grains panicle⁻¹
GA	107.27[a]	115.60[b]	22.13[a]
Zn	95.53[a]	114.40[b]	18.53[a]
GA+Zn	114.53[a]	113.27[c]	21.13[a]
Water	122.40[a]	120.27[a]	20.73[a]
Non-primed	122.67[a]	119.33[a]	21.87[a]
Grand mean	112.48	116.57	20.88
p-value	0.042	<0.001	0.882

Key: GA = Gibberellic acid; Zn = Zinc; Means within a column followed by different letters differ significantly at $p \leq 0.05$ (Tukey HSD test).

Grain yield differed significantly among priming treatments at both sites ($p < 0.001$ at Dakawa; $p = 0.005$ at Kyela; Table 7). At Kyela, Zn priming produced the highest mean yield (6.4 t ha^{-1}), significantly superior to water priming (5.8 t ha^{-1}) and the non-primed control (5.7 t ha^{-1}). At Dakawa, GA+Zn and GA priming produced the highest yields (6.3 and 6.2 t ha^{-1}, respectively), while water priming (4.1 t ha^{-1}) and the non-primed control (4.7 t ha^{-1}) yielded significantly less. These results show a 34% yield advantage (GA+Zn over non-primed) at Dakawa and a 12% advantage (Zn over non-primed) at Kyela, confirming the agronomic value of priming under direct-seeded conditions. The 1000-grain weight was stable across priming treatments at Dakawa (non-significant, $p = 0.970$), but significant at Kyela ($p < 0.001$), indicating that environmental conditions modulate the expression of grain size responses to priming.

Table 7: Grain yield and associated traits of rice as affected by seed priming at Dakawa and Kyela sites

Kyela site

Priming type	1000-grain weight (g)	Unproductive tillers (m^{-2})	Yield (t ha^{-1})
GA	81.40[a]	0.93[a]	5.99[a]
Zn	76.13[a]	1.00[a]	6.43[a]
GA+Zn	71.53[a]	0.93[a]	6.08[a]
Water	73.47[b]	0.33[a]	5.81[b]
Non-primed	72.60[b]	1.53[a]	5.66[b]
Grand Mean	76.23	0.95	5.99
S.E. (±)	5.267	0.418	0.143
p-value	<0.001	0.399	0.005

Dakawa site

Priming type	1000-grain weight (g)	Unproductive tillers (m^{-2})	Yield (t ha^{-1})
GA	33.47[a]	21.47[a]	6.16[a]

Priming type	1000-grain weight (g)	Unproductive tillers (m^{-2})	Yield ($t\ ha^{-1}$)
Zn	33.80[a]	27.80[a]	5.89[a]
GA+Zn	32.00[a]	30.47[a]	6.27[a]
Water	33.33[a]	30.93[a]	4.08[b]
Non-primed	32.67[a]	24.40[a]	4.67[b]
Grand Mean	33.05	27.01	5.41
S.E. (±)	1.979	4.023	0.342
p-value	0.970	0.411	<0.001

Key: GA = Gibberellic acid; Zn = Zinc; Means within a column followed by different letters differ significantly at $p \leq 0.05$ (Tukey HSD test).

3.6 Cultivar × priming interaction

The interaction between cultivar and seed priming significantly influenced plant height at both the Kyela and Dakawa sites (p = 0.001), indicating that cultivars responded differently to the various priming treatments. Across both environments, the local cultivar KALAMATA consistently produced significantly taller plants than the improved cultivars (TXD306, TARI RIC2, TARI RIC3, and SATO1). At Kyela, KALAMATA primed with Zn (180.89 cm) and GA (177.89 cm) recorded the greatest plant heights and did not differ significantly from GA+Zn (177.33 cm) or water priming (170.77 cm), whereas the non-primed treatment resulted in a comparatively lower height (165.78 cm). Similarly, at Dakawa, Zn (151.9 cm) and GA+Zn (149.6 cm) produced the tallest KALAMATA plants, followed by GA (141.3 cm), while the non-primed (118.9 cm) and water-primed (101.6 cm) treatments were significantly shorter. In contrast, the improved cultivars exhibited relatively modest plant heights ranging from 89.67 to 103.11 cm at Kyela and 84.8 to 103.4 cm at Dakawa, with only small differences among priming treatments.

Table 8: Interaction effects of cultivar and priming treatment on plant height (cm) at Kyela and Dakawa sites

Cultivar × Priming	Plant height (cm) (Kyela)	Plant height (cm) Dakawa
TXD306 GA	98.22[c]	103.4[c]
TXD306 GA+Zn	100.28[c]	97.5[c]
TXD306 non-primed	94.33[c]	86.4[d]
TXD306 Water	89.67[d]	89.0[d]
TXD306 Zn	100.22[c]	98.8[c]
TARI RIC2 GA	98.44[c]	94.6[c]
TARI RIC2 GA+Zn	102.37[c]	99.3[c]
TARI RIC2 non-primed	91.62[c]	92.2[c]
TARI RIC2 Water	97.00[c]	91.6[c]

TARI RIC2 Zn	103.11^{c}	99.1^{c}
TARI RIC3 GA	99.00^{c}	96.7^{c}
TARI RIC3 GA+Zn	90.44^{c}	97.9^{c}
TARI RIC3 non-primed	92.99^{c}	84.8^{e}
TARI RIC3 Water	93.89^{c}	92.8^{c}
TARI RIC3 Zn	96.33^{c}	98.0^{c}
SATO1 GA	98.78^{c}	96.2^{c}
SATO1 GA+Zn	99.56^{c}	92.1^{c}
SATO1 non-primed	95.44^{c}	87.9^{d}
SATO1 Water	96.83^{c}	86.9^{d}
SATO1 Zn	99.68^{c}	94.7^{c}
KALAMATA GA	177.89^{a}	141.3^{a}
KALAMATA GA+Zn	177.33^{a}	149.6^{a}
KALAMATA non-primed	165.78^{b}	118.9^{b}
KALAMATA Water	170.77^{a}	101.6^{c}
KALAMATA Zn	180.89^{a}	151.9^{a}
Grand Mean	112.43	103.0
S.E. (±)	2.310	4.093
p-value	<0.001	<0.001

Means within a column sharing different letters differ significantly at $p \leq 0.05$ (Tukey HSD test). S.E. = standard error of the mean.

4 Discussion

The findings from Kyela and Dakawa demonstrate that seed priming with gibberellic acid (GA_3), zinc (Zn), and their combination (GA_3+Zn) significantly improved rice growth, phenological development, and grain yield under direct-seeded field conditions. Across both environments, priming treatments consistently reduced days to 50% flowering and maturity while enhancing tiller density, panicle production, and grain filling compared with water-primed and non-primed controls. These results confirm seed priming as an effective physiological enhancement strategy capable of improving crop establishment and productivity, particularly in direct-seeded rice systems where early stand development strongly determines final yield performance (Farooq *et al*., 2019; Ganie *et al*., 2024).

The yield gains observed in this study were mainly associated with improvements in yield component traits rather than changes in grain size, with 1000-grain weight non-significant at Dakawa and differing only modestly at Kyela. Primed seeds produced higher tiller and panicle densities, increasing sink capacity and contributing to greater filled grain numbers per panicle. This agrees with previous reports indicating that priming accelerates metabolic activation during early germination, leading to more vigorous crop development and improved reproductive efficiency (Biswas *et al*., 2023; Farooq *et al*., 2019). At both sites, GA_3 and GA_3+Zn treatments promoted earlier flowering, consistent with the role of gibberellins in stimulating reserve mobilization, cell elongation, and accelerated vegetative progression (Liu *et al*., 2024; Nazir *et al*., 2024).

Zinc priming contributed substantially to yield enhancement by increasing filled grain numbers and panicle density at both sites. Zinc plays a critical role in enzymatic function, antioxidant defence, and nutrient balance during early plant development, and its effects are often pronounced in acidic soils where micronutrient availability may be constrained (Awio *et al*., 2021; Dang *et al*., 2024). The Kyela site, with its strongly acidic soil (pH 4.36) and lower available nutrients, showed particularly high responses to Zn priming, where it produced the highest mean yield (6.4 t ha^{-1}). This is consistent with findings that Zn seed priming can improve grain yield and biofortification in rice under both submerged and aerobic conditions (Rehman *et al*., 2021). The improved performance of Zn-primed treatments highlights zinc priming as a practical, low-cost agronomic intervention for improving rice productivity under low-input conditions.

Although varietal differences were significant for many agronomic traits, cultivar × priming interactions were generally weak for grain yield, indicating that priming benefits were broadly consistent across cultivars. This supports priming as a universally applicable management practice rather than one restricted to specific genetic backgrounds. The presence of significant interaction effects for plant height (both sites) and unproductive tillers (Kyela) implies that cultivar responsiveness may vary for vegetative traits, potentially reflecting differences in growth habit and hormonal sensitivity among genotypes (Farooq *et al*., 2019; Ganie *et al*., 2024). The contrasting soil environments also influenced the magnitude of the response: Kyela's more acidic, lower-fertility soils may have constrained the response to GA priming, while Zn priming proved most effective, possibly by directly relieving a Zn-related physiological limitation at that site.

5 Conclusions and Recommendations

This study confirms that seed priming with gibberellic acid (GA_3), zinc (Zn), and their combination (GA_3+Zn) is an effective strategy for improving growth, phenology, and grain yield of direct-seeded rice across contrasting soil and environmental conditions. Priming consistently reduced days to flowering and maturity while significantly increasing tiller density, panicle number, and filled grains per panicle, leading to grain yield gains of up to 34% over non-primed controls. The non-significance of cultivar × priming interactions for grain yield indicates that priming benefits are largely universal across the tested rice varieties, strengthening the case for broad adoption. Based on these findings, the following recommendations are made:

(i) Seed priming with GA+Zn or Zn is recommended as a low-cost agronomic practice for direct-seeded rice, particularly in acidic and low-fertility soils of the type found at Kyela; (ii) Priming should be combined with responsive cultivars TXD306 and SATO1 showed the highest yields at Kyela, while TARI RIC3 and TXD306 were superior at Dakawa; (iii) TARI RIC2 is recommended for intensification systems requiring early maturity, given its consistent early maturing trait across both sites; (iv) Water priming (hydropriming) alone is not recommended as a yield enhancing strategy, as it showed no significant yield advantage over the non-primed control; (v) Further multi-season and on-farm evaluations are advised to support wider adoption and refine priming protocols across diverse Tanzanian rice environments.

6 Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

7 Author contributions

MAB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, writing original draft, Writing review & editing. DGM: Supervision, Validation, Visualization, Writing, review & editing. BVM: Supervision, Validation, Visualization, Writing review & editing.

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9 Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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