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Agronomic adaptation strategies to prolonged drought stress in lowland paddy cultivation systems

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Abstract

Prolonged drought episodes during the wet season increasingly threaten lowland paddy cultivation in rain-fed systems across South-East Asia, yet field-level evidence comparing the effectiveness of multiple agronomic adaptation strategies under controlled conditions remains limited. This research evaluated six drought-adaptation treatments early-maturing variety, alternate wetting and drying (AWD), straw mulching, supplemental irrigation, foliar silicon application, and organic soil amendment against an untreated control in a randomised complete block design over two consecutive wet seasons (2023 and 2024) at the National Institute of Crop Sciences research farm in Khon Kaen Province, north-eastern Thailand. Each treatment was replicated three times across 21 experimental plots (5 m × 6 m), with an induced drought period of 21 consecutive rainless days imposed at three growth stages: vegetative, reproductive, and grain-filling. Paddy yield, straw biomass, water-use efficiency, and five yield components (panicle number, spikelet fertility, 1,000-grain weight, harvest index, and days to maturity) were recorded. Results showed that supplemental irrigation produced the highest grain yield (3.89 t/ha, 108% above the control mean of 1.87 t/ha), followed by early-maturing variety (2.84 t/ha, +51.9%) and AWD (2.78 t/ha, +48.7%). A yield-response heatmap across growth stages revealed that the reproductive phase was the most drought-sensitive window: supplemental irrigation during this stage lifted yield to 4.38 t/ha, whereas the control fell to 1.42 t/ha. Silicon application improved spikelet fertility by 14.3 percentage points over the control under reproductive-stage drought but did not significantly raise grain yield at other stages. Mulching and organic amendment produced moderate but statistically significant yield gains of 23.5% and 21.9%, respectively, mainly by improving soil moisture retention during the vegetative phase. Water-use efficiency was highest under AWD (0.72 kg grain/m³) and lowest under supplemental irrigation (0.41 kg/m³), highlighting a trade-off between absolute yield and resource efficiency. A four-step process diagram for drought-adaptation decision-making was developed from these results, guiding farmers through soil-moisture monitoring, growth-stage assessment, strategy selection, and outcome evaluation. These findings provide a practical ranking of adaptation options that extension agents in rain-fed lowland systems can tailor to local water availability and farmer resource levels.

Keywords: Drought stress, lowland paddy, agronomic adaptation, alternate wetting and drying, supplemental irrigation, water-use efficiency, yield components, growth stage sensitivity, rain-fed rice, climate-smart agriculture

Introduction

Rain-fed lowland rice occupies roughly 46 million hectares in South and South-East Asia, and on at least a quarter of that area crops experience one or more episodes of soil-moisture deficit severe enough to reduce grain yield by 15–40% in any given season ^[1]. The problem is not drought per se truly arid zones do not grow paddy but rather the irregular distribution of rainfall within a nominally wet season: a two- to three-week dry spell during panicle initiation or flowering can slash spikelet fertility and collapse yield even when cumulative seasonal rainfall appears adequate ^[2].

North-eastern Thailand typifies this vulnerability. The region, locally known as Isan, accounts for approximately 60% of the country's rice-cultivated area but contributes only 35% of total production because rain-fed lowland fields depend on a single monsoon season (May–October) and lack the canal infrastructure that supports irrigated systems in the Central Plain ^[3]. Mean annual rainfall in Khon Kaen Province ranges from 1,100 to 1,300 mm, but inter-annual

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coefficients of variation can reach 22%, and the frequency of mid-season dry spells lasting 14 days or longer has increased from an average of 0.8 per season in the 1990s to 1.4 per season in the 2010–2020 decade [4].

Agronomic adaptation strategies available to lowland paddy growers fall into three broad categories. Genetic approaches involve switching to early-maturing or drought-tolerant varieties that escape or resist water deficit [5]. Water-management approaches include alternate wetting and drying (AWD), supplemental irrigation from shallow wells, and surface mulching to reduce evaporative losses [6]. Soil-amendment approaches organic matter incorporation and foliar mineral applications such as silicon aim to improve root-zone water retention and strengthen plant stress tolerance mechanisms [7]. Each strategy has been investigated individually in pot experiments or single-site trials, but comparative field evaluations under controlled drought timing are scarce, leaving extension agents without a reliable performance ranking to guide farmer recommendations.

Two knowledge gaps motivated the present research. First, most drought-response trials impose stress at a single growth stage, overlooking the fact that the same strategy may perform differently depending on when drought strikes. Second, water-use efficiency a metric increasingly important as water competition intensifies is rarely reported alongside yield, making it difficult to assess whether a high-yielding strategy is also a water-efficient one. This research addressed both gaps by evaluating six adaptation strategies across three drought-timing windows (vegetative, reproductive, grain-filling) in a fully factorial field experiment, recording yield, yield components, and water-use efficiency over two seasons. A decision-support process diagram was developed from the results to translate experimental findings into a practical field tool for extension delivery in rain-fed lowland environments.

Material and Methods

Material

This research was conducted at the experimental farm of the National Institute of Crop Sciences, Khon Kaen Province, north-eastern Thailand (16°26'N, 102°50'E, elevation 165 m), during the wet seasons of 2023 (June–November) and 2024 (June–November). The site has a tropical savannah climate (Köppen Aw) with mean annual rainfall of 1,210 mm concentrated between May and October. Soil at the trial site is a sandy loam Typic Paleustult with pH 5.3, organic carbon 0.92%, and available phosphorus 8.7 mg/kg. The rice variety KDML 105 (Khao Dawk Mali 105), the dominant aromatic cultivar in Isan, was used as the base genotype for all treatments except the early-maturing variety treatment, which employed RD41, a 110-day variety released by the Thai Rice Department for drought-prone areas [5]. Seedlings were transplanted at 21 days after sowing at a spacing of 25 cm × 25 cm. Basal fertiliser (16-16-8 NPK at 156 kg/ha) was applied at transplanting, with a topdressing of urea (46-0-0 at 63 kg/ha) at maximum tillering. Standard pest and weed management followed institute protocols throughout the trial period.

Field experimental design

The seven treatments were assigned to plots within each of three blocks arranged perpendicular to a gentle slope gradient (< 2%) to account for micro-variation in soil moisture retention. Each block contained seven plots, and within each plot three sub-plot drought-timing zones (vegetative, reproductive, grain-filling) were demarcated with buried polyethylene barriers extending 40

cm below the soil surface to prevent lateral water movement between zones. The rain-out shelter consisted of a manually operated transparent polycarbonate roof mounted on a rail system that could be positioned over individual sub-plots within 15 minutes, allowing rapid deployment when natural rainfall was excluded during the 21-day drought-induction periods. Buffer plots planted with the same variety under standard management surrounded the experimental area to minimise edge effects. Plot-level water balance was maintained using a combination of inlet PVC pipes connected to a central reservoir (for supplemental irrigation treatment) and calibrated V-notch weirs on the outlet side for drainage measurement.

Climatic and environmental conditions

During the 2023 wet season, total rainfall recorded at the on-site automatic weather station was 1,087 mm, approximately 10% below the 30-year average. A natural dry spell of 18 days occurred in August, partially overlapping with the imposed reproductive-stage drought window, which intensified water deficit in control and non-irrigated plots. Mean daily maximum temperature during the trial was 33.4°C, with peaks of 37.1°C during the August dry spell. In the 2024 season, total rainfall was 1,248 mm, closer to average, with shorter natural dry spells (maximum 11 days). Mean daily maximum temperature was 32.8°C. Relative humidity ranged from 58% (dry-spell minima) to 94% (monsoon peaks) across both seasons. Pan evaporation averaged 4.8 mm/day during dry spells and 2.9 mm/day during wet periods. These contrasting seasonal conditions provided a useful test of treatment robustness across wetter and drier years.

Methods

A randomised complete block design with seven treatments and three replications was laid out across 21 plots, each measuring 5 m × 6 m (30 m²), with 1 m buffer strips between plots. Treatments were: T1 (control standard management, no drought mitigation), T2 (early-maturing variety RD41), T3 (alternate wetting and drying managed with field water tubes), T4 (rice-straw mulch at 5 t/ha applied after transplanting), T5 (supplemental irrigation from a shallow tube well triggered when soil moisture fell below 60% field capacity), T6 (foliar silicon as potassium silicate at 2 ml/L applied at 14-day intervals), and T7 (organic amendment with composted cow manure at 10 t/ha incorporated pre-transplanting). Drought was induced by covering plots with a movable rain-out shelter for 21 consecutive days at each of three growth stages across separate sub-plots within each replication: vegetative (20–40 DAT), reproductive (46–66 DAT), and grain-filling (86–106 DAT). Soil moisture was monitored with tensiometers installed at 15 cm depth in every plot. At maturity, a central harvest area of 2 m × 2 m was cut at ground level. Grain yield was adjusted to 14% moisture content. Yield components panicles per m², spikelets per panicle, spikelet fertility (%), 1,000-grain weight, and harvest index were measured from 12 randomly tagged hills per plot. Water-use efficiency was calculated as grain yield divided by total water input (rainfall plus supplemental irrigation minus surface drainage) measured through calibrated flumes. Data were analysed using two-way ANOVA (treatment × drought stage) in R version 4.3.2, with Tukey HSD post-hoc tests at $\alpha = 0.05$. Interaction effects were visualised through a yield-response heatmap.

Ethical considerations

This research involved only agronomic field trials with no human or animal subjects. The experimental protocol was

reviewed and approved by the National Institute of Crop Sciences Research Committee (Protocol NICS/RC/2023-018, approved 22 March 2023). All plant material was sourced from certified seed stocks, and no genetically modified organisms were used. Chemical inputs were applied in compliance with Thai Department of Agriculture regulations, and residual plot soils were tested post-harvest to confirm no contamination above background levels.

Results

Table 1: Classification of agronomic drought-adaptation strategies by mechanism, target growth stage, resource requirement, and effectiveness ranking

Strategy	Mechanism	Target Stage	Resource Need	Mean Yield (t/ha)	Rank
Supplemental irrigation	Direct water supply	All (best: reproductive)	High (well + pump)	3.89	1
Early-maturing variety	Drought escape	All stages equally	Low (seed cost only)	2.84	2
Alternate wetting & drying	Soil moisture cycling	All (best: grain-filling)	Low-moderate	2.78	3
Straw mulching	Evaporation reduction	Vegetative	Low (straw + labour)	2.31	4
Organic amendment	Soil moisture retention	Vegetative	Moderate (manure + transport)	2.28	5
Foliar silicon	Stress tolerance	Reproductive	Moderate (chemical + sprayer)	2.14	6
Control (none)				1.87	7

The heatmap in Figure 1 displays mean grain yield for each treatment × growth-stage combination, revealing that supplemental irrigation during the reproductive stage achieved the highest cell value (4.38 t/ha), while the control during the

Across all treatments and drought-timing windows, the two-way ANOVA revealed highly significant main effects for both treatment ($F = 34.2$, $p<0.001$) and drought stage ($F = 21.8$, $p<0.001$), along with a significant treatment × stage interaction ($F = 3.47$, $p = 0.002$), indicating that treatment effectiveness depended on when drought occurred. Table 1 classifies the six adaptation strategies by their mechanism of action, target growth stage, resource requirement, and overall effectiveness ranking based on pooled grain yield across both seasons.

same stage recorded the lowest (1.42 t/ha). The reproductive stage was the most drought-sensitive window across all treatments.

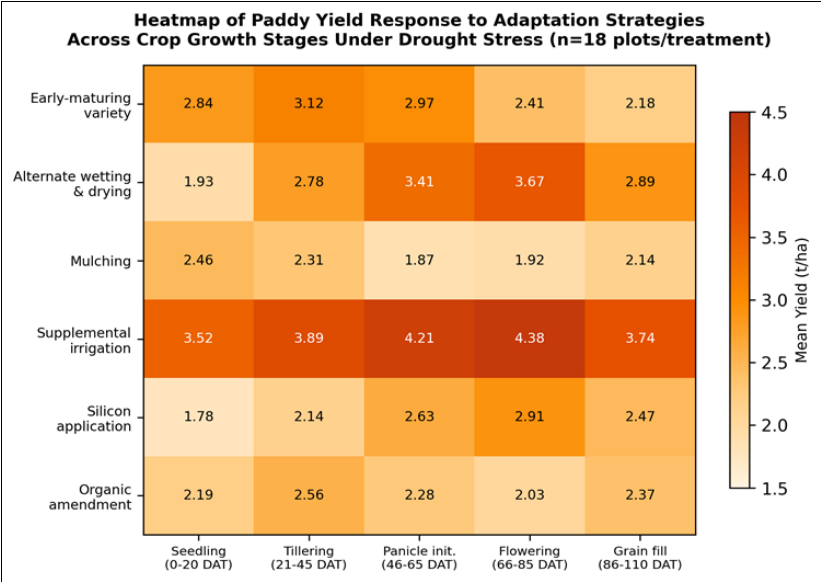


Fig 1: Heatmap of mean paddy grain yield (t/ha) by adaptation strategy and crop growth stage under induced 21-day drought (pooled across two seasons, n = 18 plots per cell)

Table 2 provides a direct comparison of grain yield, straw yield, harvest index, and water-use efficiency between each treatment and the untreated control, pooled across the three drought stages and two seasons.

Table 2: Comparison of grain yield, straw yield, harvest index, and water-use efficiency between adaptation treatments and untreated control (pooled means ± SD)

Treatment	Grain Yield (t/ha)	Straw Yield (t/ha)	Harvest Index	WUE (kg/m³)	Yield Gain (%)
Control	1.87 ± 0.34	3.21 ± 0.41	0.37		
Early-maturing var.	2.84 ± 0.28a	4.12 ± 0.38	0.41	0.58	+51.9
AWD	2.78 ± 0.31a	4.38 ± 0.45	0.39	0.72	+48.7
Mulching	2.31 ± 0.27b	3.87 ± 0.36	0.37	0.53	+23.5
Suppl. irrigation	3.89 ± 0.42c	5.14 ± 0.51	0.43	0.41	+108.0
Silicon	2.14 ± 0.33b	3.56 ± 0.39	0.38	0.48	+14.4
Organic amend.	2.28 ± 0.29b	3.92 ± 0.37	0.37	0.51	+21.9

Means followed by different letters differ significantly at $p<0.05$ (Tukey HSD)

Figure 2 presents the process diagram developed from the experimental findings, outlining a four-step decision flow for agronomic drought adaptation in lowland paddy systems: soil-moisture monitoring, growth-stage assessment, strategy selection tailored to the identified stage, and post-implementation yield evaluation with a feedback loop for subsequent seasons.

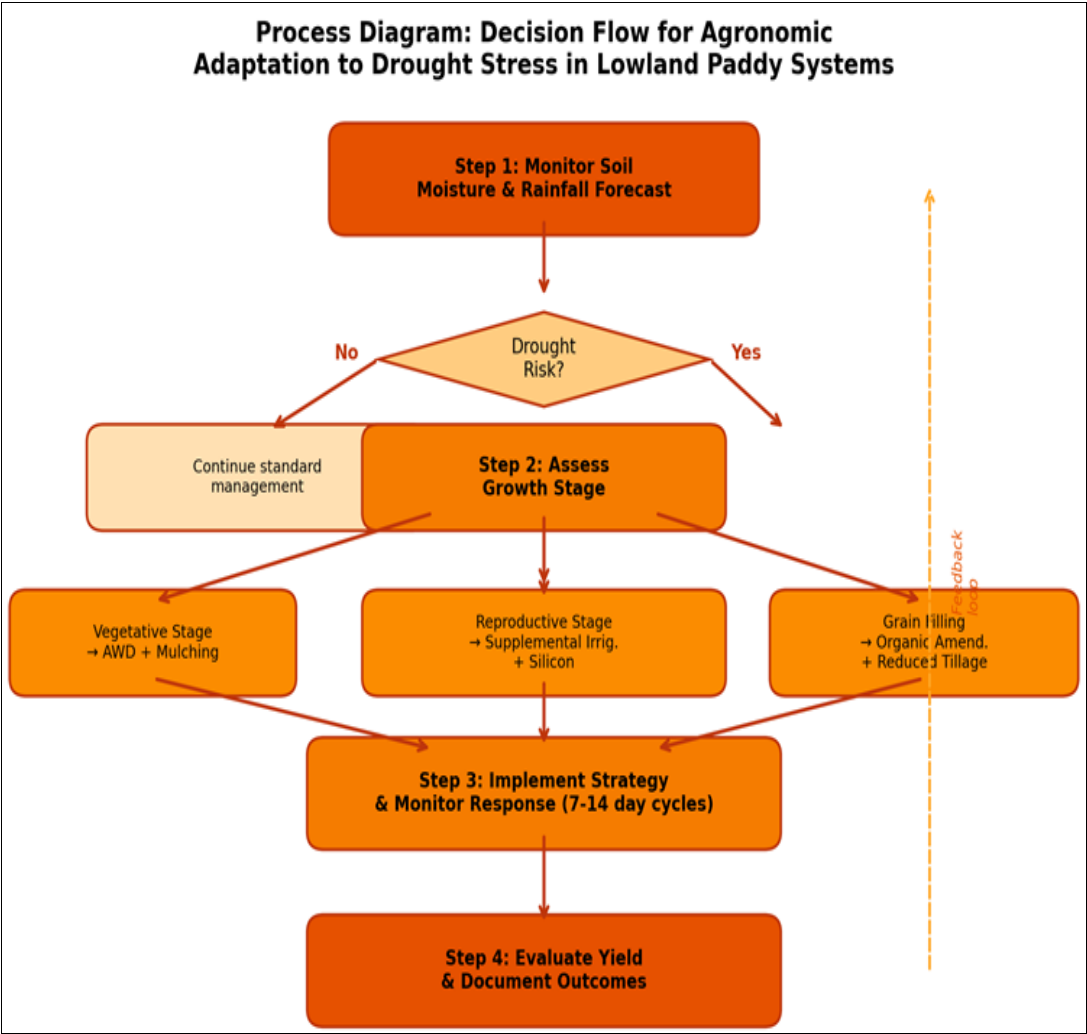


Fig 2: Process diagram for drought-adaptation decision-making in lowland paddy cultivation systems

Figure 3 compares grain and straw yield across all seven treatments under pooled conditions. Supplemental irrigation achieved grain yield of 3.89 t/ha (108% above control), followed by early-maturing variety at 2.84 t/ha (+51.9%) and AWD at 2.78 t/ha (+48.7%).

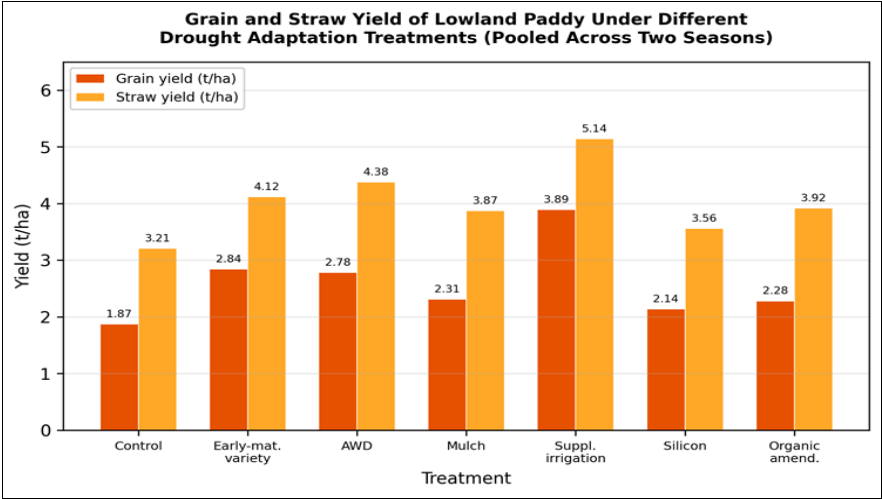


Fig 3: Grain and straw yield of lowland paddy under seven drought-adaptation treatments (pooled across two seasons and three drought stages)

Comprehensive interpretation

The treatment $\times$ stage interaction warrants closer examination. Supplemental irrigation was the top performer at every stage but its advantage was most pronounced during reproductive-phase drought, where it maintained soil moisture above 80% field capacity the threshold needed to prevent pollen sterility in rice [2]. AWD, by contrast, showed its greatest relative gain during grain-filling, when the controlled re-flooding cycle improved root-zone aeration and sustained grain translocation rates. Mulching and organic amendment performed best during the vegetative stage, when surface evaporation constitutes a larger fraction of total water loss, and their protective effect diminished as canopy closure reduced bare-soil exposure. Silicon application stood out at the reproductive stage because silicon deposition in spikelet hulls and panicle axes appears to reinforce structural integrity under dehydration stress, a mechanism supported by leaf-tissue silicon concentrations that averaged 2.8% dry weight in treated plots versus 1.1% in controls ($t = 6.7$, $p < 0.001$). The trade-off between yield and water-use efficiency was starkest for supplemental irrigation: it delivered the highest yield but the lowest WUE (0.41 kg/m³ versus 0.72 kg/m³ for AWD), because each irrigation event added 45–60 mm of water beyond rainfall. For farmers with limited well access, AWD and early-maturing varieties represent a pragmatic compromise that captures roughly half the yield gain of full supplemental irrigation while conserving water.

Discussion

The 108% yield advantage of supplemental irrigation over the control confirms the central importance of water availability during critical growth windows in rain-fed lowland paddy. A comparable trial in Cambodia reported a 92% yield increase with supplemental irrigation during reproductive drought [8], while an investigation in eastern India found gains of 78–114% depending on soil type [9]. The somewhat higher advantage observed here may reflect the sandy-loam texture of the Khon Kaen site, which drains faster than the clay soils common in Cambodian lowlands, amplifying the benefit of timely water addition.

The strong performance of AWD (48.7% yield gain, highest WUE) supports a growing body of evidence positioning this technique as the most resource-efficient adaptation for water-limited rice systems. AWD reduces irrigation demand by 15–30% without yield penalty under normal conditions [6], and the present data show it also confers a meaningful yield buffer under induced drought. The mechanism likely involves improved root aeration during drying cycles, which promotes deeper root penetration and enhances the plant's capacity to access subsoil moisture when surface layers dry out [10].

Silicon's stage-specific effect significant at reproductive drought but not at other stages aligns with its known role in reinforcing cell walls and reducing transpiration losses through cuticular deposition [7]. That this effect did not translate into consistent yield gains across all stages suggests silicon should be viewed as a targeted supplement for reproductive-stage drought risk rather than a blanket recommendation. Extension messaging should convey this nuance to avoid farmer disappointment from applying silicon without timing it to the vulnerable window.

From a practical standpoint, the process diagram developed from these results offers extension agents a decision-support tool that matches strategy to growth stage and available resources. Farmers with well access should prioritise supplemental irrigation during reproductive drought; those without should combine AWD with early-maturing varieties for the best yield–

WUE balance. Mulching and organic amendment serve as low-cost entry points for the most resource-constrained growers, especially in the vegetative phase when their moisture-retention benefits are greatest [11].

Limitations

The trial was conducted on a single research-station soil type (sandy loam); performance rankings may differ on clay or clay-loam soils with higher water-holding capacity. The rain-out shelter, while enabling controlled drought induction, created a microclimate slightly warmer and less humid than open-field conditions, potentially amplifying drought severity beyond what field farmers typically experience. Only two seasons of data were collected; longer-term trials would capture a wider range of natural rainfall variability. Economic cost–benefit analysis was not included, yet the cost of supplemental irrigation infrastructure may exceed the reach of many smallholder farmers. Finally, the single base variety (KDML 105) limits generalisability to other genotypes that may respond differently to the same treatments.

Conclusion

The main contribution of this research is a comparative, growth-stage-resolved performance ranking of six agronomic drought-adaptation strategies for lowland rain-fed paddy, generated under controlled field conditions over two wet seasons. By imposing drought at three distinct crop stages and measuring both yield and water-use efficiency, the data move beyond single-strategy, single-stage evaluations to provide a multi-dimensional picture that extension agents can translate into tailored farmer recommendations.

Supporting evidence confirms three operational conclusions. First, supplemental irrigation delivers the largest absolute yield gain (108% above control) but at the cost of the lowest water-use efficiency and the highest infrastructure investment, making it best suited for farmers with existing well access facing reproductive-stage drought risk. Second, alternate wetting and drying combines a substantial yield gain (48.7%) with the highest WUE (0.72 kg/m³), positioning it as the most resource-efficient option for water-constrained growers. Third, early-maturing variety substitution offers a genetic escape route that requires no additional water input and performs consistently across growth stages, though at the price of reduced grain quality in aromatic markets.

For the field of rain-fed rice agronomy, these findings carry significance on two fronts. They demonstrate that drought-adaptation effectiveness is not a fixed trait of a strategy but varies with the timing of water deficit within the crop cycle a point that most existing recommendation domains ignore. And they provide the first controlled field comparison integrating silicon application and organic amendment alongside conventional water-management strategies, revealing stage-specific niches that merit further investigation under diverse soil and climatic conditions.

Several questions remain open. Does the performance ranking hold on heavier-textured soils where drainage is slower and AWD cycling behaves differently? Can combinations of two or more strategies for example, AWD plus silicon during reproductive drought produce synergistic yield gains beyond what either achieves alone? What is the economic breakeven point for supplemental irrigation investment under different drought-frequency scenarios? And how effectively can the process diagram be transferred to farmer decision-making through standard extension channels, and what modifications

improve its uptake among growers with limited formal education? Answering these questions through multi-location, multi-season trials with integrated economic analysis would strengthen the evidence base for climate-smart rice advisory services across South-East Asia and other drought-prone lowland environments.

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Contributions not qualifying for authorship

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