Tropentag 2026
September 16-18, 2026
Conference on International Research on Food Security, Natural Resource Management and Rural Development
organised by the Universities of Göttingen and Kassel, Göttingen, Germany

Comparative adaptive responses of improved and indigenous lowland rice to water management under Nigeria's derived-Savannah

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Introduction

Rice is a staple crop across sub-Saharan Africa, but its production in irrigated and rainfed lowland systems is increasingly constrained by competition for freshwater. Continuous flooding, the conventional practice for lowland rice, can consume 2,500–5,000 L of water per kilogram of grain produced, far more than most other cereals (Bouman and Tuong, 2001). Alternate wetting and drying (AWD) is widely promoted as a water-saving alternative in which fields dry to a defined soil or field-water threshold between irrigations rather than being kept continuously flooded (Bouman et al., 2007). A meta-analysis across 56 studies found AWD reduces irrigation water input by 10–45% relative to continuous flooding, with the yield effect depending on drying severity, timing and genotype (Carrijo et al., 2017).

AWD outcomes vary across environments and genotypes (Carrijo et al., 2017). West African evidence demonstrates both its inland-valley productivity potential and its agroclimatic suitability but remains geographically limited and provides little genotype-specific physiological evidence for Nigeria's derived-savannah lowlands (Blango et al., 2019; Akpoti et al., 2021). It is not established whether improved lowland varieties bred for the West African mega-environment [ARICA 3, NERICA® L-19, WITA 4 (Nwilene et al., 2008)] and locally adapted landraces such as Ofada differ in yield, water-productivity and physiological responses to a vegetative-stage drying regime, given that the varieties differ in canopy architecture, rooting and phenology.

This study quantified irrigation water saving, grain yield, water productivity and selected physiological responses (chlorophyll content, root volume, growth rate) of three improved lowland rice varieties and the Ofada landrace under continuous flooding and scheduled five-day intermittent irrigation and tested whether responses were consistent across varieties.

Material and Methods

A pot experiment was conducted in a screenhouse at the Federal University of Agriculture, Abeokuta, south-western Nigeria (derived-savannah agroecological zone), using pots filled with hydromorphic inland-valley soil. Four lowland rice varieties namely ARICA 3, NERICA® L-19 and WITA 4 (improved), and Ofada (indigenous landrace) were grown under two water regimes: continuous flooding (CF, 5 cm standing water throughout) and a scheduled five-day intermittent irrigation regime (AWD-type; pots re-irrigated every five days during the vegetative stage, with both regimes flooded identically from panicle initiation onward). Single seedlings of five transplanting ages (9, 12, 15, 18 and 21 days after emergence) were transplanted in a completely randomised design with a 4 × 2 × 5 factorial treatment structure, three replicates and two experimental runs, giving 240 treatment replicate series. Each series was followed across four sequential destructive harvests (active tillering, maximum tillering, flowering, physiological maturity); a separate physical pot sharing the series label was sampled at each stage, giving up to 960 physical pots in total, while grain yield and final irrigation-water totals came from the maturity pot of each series only.

Irrigation water applied per pot was logged volumetrically throughout cultivation and totalled at final harvest. Grain yield per plant, panicle number per plant and harvest index (HI) were recorded at maturity (grain yield by hand threshing), and water productivity was computed as grain yield ÷ total irrigation water applied (g grain L^{-1}). Leaf chlorophyll content (SPAD units) and root volume (water-displacement method) were measured at each of the four destructive harvest stages (active tillering, maximum tillering, flowering, maturity) from the stage specific pot. Absolute growth rate (AGR) was calculated, as $AGR = \Delta W/\Delta t$ in above-ground dry weight between successive destructive-harvest stages: active tillering→maximum tillering, maximum tillering→flowering and flowering→maturity. These interval names follow directly from the four harvest stage labels.

All means, percentage changes and P-values were computed directly from the series-level dataset (n=240 series) in Python (pandas, SciPy, statsmodels). Two model structures were used. (i) For outcomes recorded once per series i.e. yield, water applied, water productivity, panicle number, harvest index, and chlorophyll, root volume and growth rate at flowering a fixed-effects Type II ANOVA (OLS) was fitted: variety, water regime and their interaction. The model is a standard fixed-effects ANOVA on series means. (ii) For absolute growth rate, computed for three intervals per series, a linear mixed-effects model (REML, long format, three rows per series) was fitted with variety, water, interval and their interactions as fixed effects, age (categorical) and run (categorical blocking factor) as additive terms and series as a random intercept. In a preliminary model adding water×age and water×run terms to the variety×water model, neither interaction was significant for yield, water applied or water productivity (all P>0.13), so means are pooled across age and run (Figure 1); for chlorophyll, the variety × water × age interaction was significant, so age-specific means are reported separately (Table 4). Within-variety CF-vs-AWD contrasts used Welch's t-test with Holm correction across the four varieties.

Results and Discussion

Irrigation water applied, grain yield and water productivity

Across all four varieties, the scheduled intermittent irrigation regime reduced irrigation water applied from a mean of 105.5 L pot^{-1} under CF to 90.2 L pot^{-1} (−14.5%; P<0.001), while simultaneously increasing grain yield per plant from 56.3 to 61.8 g (+9.8%; P<0.001) and water productivity from 0.535 to 0.686 g grain L^{-1} (+28.2%; P<0.001; Figure 1). The variety × water-regime interaction was not significant (P>0.05) for any of the three outcomes (water applied, P=0.54; yield, P=0.60; water productivity, P=0.70), and within-variety Holm-adjusted Welch contrasts confirmed the water-saving and yield benefit in all four varieties individually (all P<0.001). This indicates that the response was broadly consistent across the improved varieties and the indigenous landrace, rather than being confined to a subset of genotypes.

This water saving (14.5%) falls toward the lower end of the 10–45% range reported in Carrijo et al.'s (2017) meta-analysis, possibly reflecting the comparatively short, calendar based five-day interval used rather than a deeper, field-water-status-triggered threshold (Bouman et al., 2007); establishing actual drying severity would require direct soil-water measurements. That the yield response was positive rather than negative in all four varieties, including Ofada, is notable given that yield penalties are more often reported under more severe drying (Carrijo et al., 2017), suggesting the water-saving and yield objectives were not in direct trade-off within this vegetative-stage window.

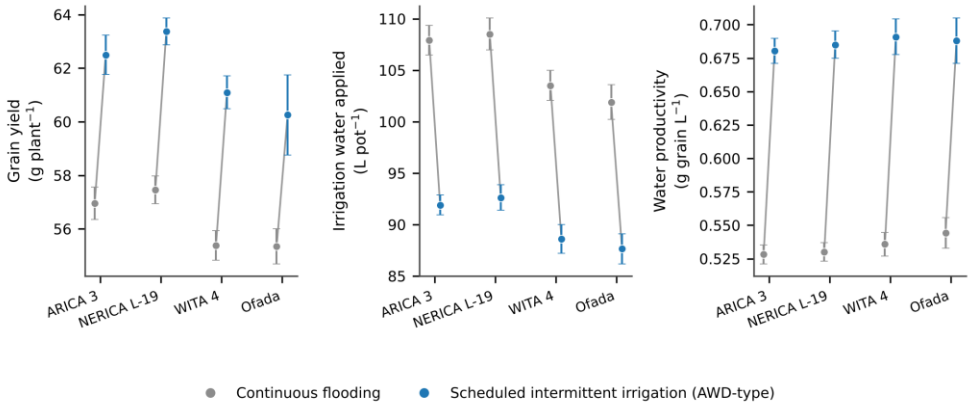


Figure 1: Grain yield per plant, irrigation water applied and water productivity (mean ± 95% CI; n=30 per variety × water-regime cell) by variety under continuous flooding and scheduled intermittent irrigation (AWD-type).

Variety means (Table 1) show the same direction of response in all four varieties. Panicle number per plant rose under the scheduled regime in every variety (+23 to +33%; within-variety Holm P<0.001; variety × water P=0.057), whereas harvest index fell by 7–8% (Holm P<0.001 in each; interaction P=0.21). Because grain yield rose while harvest index fell, total above-ground biomass must have increased proportionally more than grain yield.

Table 1: Variety agronomic responses, shown as CF mean / AWD mean (percentage change AWD relative to CF), pooled across seedling age and run

Variety	Grain yield (g plant^{-1})	Water applied (L pot^{-1})	Water productivity (g L^{-1})	Panicles plant^{-1}	Harvest index (%)
ARICA 3	57.0 / 62.5 (+9.7)	107.9 / 91.9 (−14.8)	0.528 / 0.680 (+28.8)	10.6 / 13.6 (+27.6)	46.5 / 43.4 (−6.8)
NERICA® L-19	57.5 / 63.4 (+10.3)	108.5 / 92.6 (−14.6)	0.530 / 0.685 (+29.2)	10.4 / 12.7 (+22.5)	44.5 / 41.6 (−6.6)
WITA 4	55.4 / 61.1	103.5 / 88.6	0.536 / 0.691	10.1 / 13.5	45.0 / 41.7

	(+10.3)		(−14.4)		(+28.9)		(+33.3)		(−7.2)	
Ofada	55.4 / (+8.9)	60.3	101.9 / (−14.0)	87.6	0.544 / (+26.4)	0.688	8.4 / (+29.9)	10.9	49.1 / (−8.3)	45.0

Physiological responses

In contrast to the consistent agronomic response, physiological responses to the scheduled irrigation regime were more variety-specific (Table 3). Leaf chlorophyll content at flowering showed a significant variety × water-regime interaction (P=0.002) and in addition, a significant variety × water-regime × seedling-age interaction (P=0.031): pooling across seedling age is therefore not fully justified for this trait, and the pooled variety means in Table 2 are descriptive summaries. Age-specific responses (Table 3) show the chlorophyll response varied with transplanting age within variety, for example Ofada ranged from −16.1% at 12 DAE to +3.2% at 21 DAE. Root volume at flowering was numerically lower in ARICA 3 and NERICA® L-19 but higher in WITA 4 and Ofada; the interaction was not significant (P=0.061), so these differences remain inconclusive. Absolute growth rate between maximum tillering and flowering increased significantly in ARICA 3 (Holm P<0.001), NERICA® L-19 (P=0.005) and Ofada (P=0.002) but not WITA 4 (P=0.27), with a significant overall interaction (P=0.015).

Table 2: Physiological responses at flowering under continuous flooding (CF) and scheduled intermittent irrigation (AWD)

Trait (at flowering)	**Variety**	**CF mean**	**AWD mean**	**Δ (%)**	**Holm P**	**V×W P**
Chlorophyll (SPAD)[1]	ARICA 3	44.7	41.1	−8.0	<0.001	
	NERICA® L-19	42.5	43.3	+1.8	0.55	0.002
	WITA 4	41.8	43.0	+2.9	0.55	
	Ofada	43.8	42.2	−3.7	0.55	
Root volume (mL)	ARICA 3	40.7	30.0	−26.3	0.44	
	NERICA® L-19	49.3	38.3	−22.3	0.44	0.061
	WITA 4	49.0	53.5	+9.2	1.00	
	Ofada	38.7	42.5	+10.0	1.00	
Growth rate, max. tillering–flowering (g pl^{-1} d^{-1})	ARICA 3	1.84	2.67	+45.2	<0.001	
	NERICA® L-19	2.02	2.79	+37.7	0.005	0.015
	WITA 4	1.97	2.12	+7.6	0.27	
	Ofada	1.52	2.01	+32.2	0.002	

[1]Chlorophyll pooled means are descriptive only; see Table 4 for the significant age-dependent pattern (V×W×A, P=0.031)

Table 3: Chlorophyll response to scheduled irrigation (% change relative to CF) by variety and seedling age at transplanting (DAE = days after emergence).

Variety	**9 DAE**	**12 DAE**	**15 DAE**	**18 DAE**	**21 DAE**
ARICA 3	−12.7	−1.3	−16.3	−2.8	−6.0
NERICA® L-19	+2.7	−2.0	+9.6	−6.2	+6.2
WITA 4	+4.7	−2.1	+2.8	+0.2	+9.3
Ofada	−7.5	−16.1	+0.4	+1.4	+3.2

Developmental timing of the growth response

Absolute growth rate was significantly higher under the scheduled regime than under CF, averaged across all three developmental intervals (P<0.001; Figure 2). The largest numerical gain occurred between maximum tillering and flowering (1.84 vs 2.40 g $plant^{-1}$ day^{-1}), but a joint Wald test of the water-regime × interval interaction (mixed model, series as random intercept) was not significant (P=0.065), so this cannot be identified as a uniquely critical window but better described as the interval with the largest numerical, though not statistically confirmed, response.

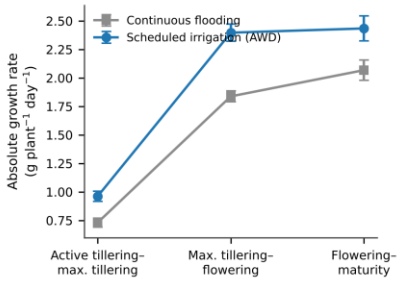


Figure 2: Absolute growth rate (mean ± 1 SE, averaged across varieties) under continuous flooding and scheduled intermittent irrigation, by developmental interval

The gain in grain yield (+9.8%) was smaller than the gain in panicle number (+23 to +33%) and harvest index declined, so the extra grain per plant was associated with more panicles rather than with a higher proportion of biomass allocated to grain. The results point to a consistent water-saving and yield benefit, accompanied by differing and for chlorophyll, age-dependent physiological responses among varieties. This is consistent with emerging West African evidence that AWD-type management can be productive in inland-valley environments (Blango et al., 2019) and agroclimatically viable more widely (Akpoti et al., 2021), underlining that genotype- and age-specific evaluation, not a single blanket recommendation, is needed when extending it to new agroecologies such as Nigeria's derived savannah.

Conclusions and Outlook

Under controlled pot conditions, a scheduled five-day vegetative-stage intermittent-irrigation regime reduced irrigation water applied by 14.5% while increasing grain yield per plant by 9.8% and water productivity by 28.2%, with no significant variety × water-regime interaction for irrigation input, grain yield or water productivity across the three improved varieties and the Ofada landrace. Similar agronomic benefits were accompanied by differing physiological responses among varieties, with chlorophyll responses also depending on seedling age. Because these findings derive from a controlled pot experiment with a calendar-based rather than soil-water-status-triggered drying schedule, field validation under monitored soil-water conditions, across seasons and locations in Nigeria's derived-savannah lowlands, is recommended before extending the practice to farmers. The reduced irrigation input may offer an untested methane-mitigation co-benefit; future work should quantify greenhouse-gas fluxes directly.

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