
RESEARCH ARTICLE

Rice Production as Influenced by Automated Alternate Wetting and Drying Technology in Different Plant Spacing Configurations

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ABSTRACT

This study investigated optimal automated alternate wetting and drying (AWD) depths and planting spacings to enhance water conservation and rice yield under upland conditions. Using a two-factor strip-block design, AWD at 5 cm above, 10 cm below, and 15 cm below the soil surface was compared against continuous flooding, with spacings of 15×15 cm, 20×20 cm, and 25×25 cm on NSIC Rc222 variety. Results showed that 5 cm AWD depth with 15×15 cm spacing produced the highest grain yield (6.64 t/ha), water use efficiency (1.15 kg/m³), and net return (PHP 55,955/ha). The automated system maintained 98.7% sensor accuracy. Significant interactions between AWD depth and planting spacing were observed for plant height, shoot-root ratio, panicle length, harvest index, and yield. These findings confirm that automated AWD technology can achieve yields comparable to those of lowland systems using only shallow-well water, offering a sustainable alternative for upland rice farmers.

KEYWORDS

Alternate wetting and drying, Irrigation, NSIC Rc222, Rice spacing, Water use efficiency

ARTICLE INFORMATION

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1. INTRODUCTION

Rice (*Oryza sativa*) is a staple food for over half the world's population, making its production critical to global food security (Fukagawa & Ziska, 2019). However, conventional rice cultivation through continuous flooding requires substantial water inputs and contributes to environmental degradation (Mallareddy et al., 2023). As water resources become increasingly scarce and climate change intensifies, sustainable rice production techniques are urgently needed.

Alternate wetting and drying (AWD) technology offers a promising solution by allowing rice fields to alternate between wet and dry conditions throughout the crop's growth cycle, potentially reducing water consumption without sacrificing productivity (Ishfaq et al., 2020). When combined with precision automation, AWD can optimize irrigation scheduling and ensure accurate water management (Enriquez et al., 2021 ; Lee, 2022).

Additionally, proper plant spacing during transplanting influences water distribution, nutrient uptake, and ultimately, crop yield (Reuben et al., 2016). Despite the potential benefits of automated alternate wetting and drying (AWD) and optimized spacing, limited research has examined their combined effects on rice production in upland conditions where irrigation infrastructure is lacking. This study aimed to : (1) evaluate the effects of three alternate wetting and drying (AWD) depths (+5 cm above, -10 cm below, -15 cm below surface) and three plant spacings (15 × 15 cm, 20 × 20 cm, 25 × 25 cm) on rice growth parameters; (2) assess yield components ; (3) quantify water use efficiency and irrigation water savings; (4) conduct an economic analysis; and (5) identify optimal treatment combinations for adoption by upland rice farmers in Pampanga, Philippines.

2. LITERATURE REVIEW

2.1 Rice Cultivation

Growing upland rice presents distinct challenges, often resulting in poorer yields compared to lowland rice production. This is due to uneven terrain, variable water availability, and varying soil conditions (Kumar et al., 2019). Implementing water-efficient techniques, such as alternate wetting and drying (AWD), can mitigate these issues and enhance productivity in upland rice farming.

2.2 Drought-Resistant Rice Variety in the Philippines

NSIC Rc222, developed by PhilRice (2024), yields an average of 6.1 tons per hectare, with a potential of up to 10 tons per hectare. This variety exhibits moderate pest and disease tolerance and performs well in saline, rain-fed, and submerged environments.

2.3 Rice Plant Spacing

Reuben et al. (2016) investigated optimal plant spacing for the System of Rice Intensification (SRI). They found that wider spacing (25 × 25 cm, 30 × 30 cm, and 35 × 35 cm) outperformed narrower spacing (15 × 15 cm and 20 × 20 cm), with 25 × 25 cm yielding the best results. Additionally, Anegbah et al. (2019) found that 30 × 30 cm spacing was optimal for maximum plant height and leaf length, whereas 20 × 20 cm spacing resulted in higher values for plant height, leaf length, and leaf breadth.

2.4 Alternate Wetting and Drying Technology in Rice

Alternate wetting and drying (AWD) and the system of rice intensification (SRI) are suggested as water-saving irrigation techniques in key rice-growing regions of Asia, such as China, the Philippines, and Bangladesh. These techniques aim to reduce water usage and alleviate water scarcity (Song et al., 2019). AWD reduces irrigation water by re-flooding the area after ponded water evaporates, allowing the soil to dry for several days (Lampayan et al., 2015). This approach facilitates reduced environmental effects, robust and sustainable food production, and climate change adaptation of agricultural systems (Lampayan et al., 2015 ; Carrijo et al., 2017 ; Rejesus et al., 2017). According to Valdivia et al. (2016) and Allen and Sander (2019), AWD helps farmers manage water scarcity economically, enhancing overall farm output efficiency.

2.5 Automation in Rice Farming

Automation in rice farming, particularly automated transplanting and harvesting, is increasingly employed to boost output and efficiency (Li et al., 2019). The combination of automation and Alternate Wetting and Drying (AWD) technology can considerably improve rice output in highland areas. As the consequences of climate change on rice production continue, interest in improved irrigation technologies is growing. Water-saving measures are essential to assist farmers in managing irrigation water on rice terraces (Tarlera et al., 2016). Automation increases agricultural output and reduces costs. Automated irrigation systems regulate water and electricity use to ensure grain quality when cultivating rice. These technologies can help address the aging farmer population by encouraging sustainable agriculture, reducing labor expenses, and preserving water (Lee, 2022).

2.6 Sustainable Rice Farming Practices

Sustainability is necessary for rice cultivation, and AWD supports sustainable agriculture goals. According to LaHue et al. (2019), adopting sustainable agricultural practices is crucial for meeting the increasing global demand for rice while conserving water and minimizing environmental impacts.

3. MATERIALS AND METHODS

3.1 Experimental Site

The experiment was conducted from March 10 to June 29, 2024, in Barangay Gutad, Floridablanca, Pampanga, Philippines (14°56'23.38"N, 120°29'54.49"E, 25 meters above sea level). The upland site lacked irrigation infrastructure and relied entirely on shallow well water delivered through an automated alternate wetting and drying (AWD) system. Soil analysis by the Bureau of Soils identified Angeles coarse soil, Angeles undifferentiated soil, and La Paz silt loam series. Temperatures ranged from 72°F to 95°F throughout the study period.

3.2 Experimental Crop

The NSIC Rc222 rice variety, a drought-resistant hybrid developed by PhilRice (2024), was used. Healthy 21-day-old seedlings with two to three tillers were transplanted uniformly across all treatments.

3.3 Experimental Design and Treatments

The study utilized a two-factor strip-block design with three replications arranged in three blocks, as described by Gomez and Gomez (1984). Factor A (main plot treatment applied to strips) comprised three automated alternate wetting and drying (AWD) depths: D1 = +5 cm above the soil surface, D2 = -10 cm below the soil surface, and D3 = -15 cm below the soil surface. Factor B

(subplot treatment) included three planting spacings: S1 = 15 × 15 cm, S2 = 20 × 20 cm, and S3 = 25 × 25 cm. Each experimental plot measured 4 × 5 meters, with 1-meter alleys between plots and blocks to minimize edge effects.

3.4 Design of Automated AWD Technology

The automated Alternate Wetting and Drying (AWD) system featured PVC irrigation pipes laid across the main plots, with solenoid valves controlled by a water-level sensor. Water level indicator scales, marked at +5 cm, -10 cm, and -15 cm relative to the soil surface, were installed in each main plot, following the specifications of Lampayan et al. (2015). Capacitive soil moisture sensors, positioned at three depths, monitored volumetric water content, automatically activating irrigation when soil moisture dropped below a 20% threshold.

3.5 Automatic Water Level Controller

The control system integrated soil moisture sensor probes, a water meter, relay modules for solenoid valves, and a submersible pump. The system-maintained target water levels within ±2 cm accuracy and automatically logged irrigation events (Lee, 2022).

3.6 Cultural Management Practices

Land preparation involved deep plowing followed by harrowing to create a firm seedbed. A buffer zone was incorporated, and 25 cm plastic sheets were placed underneath the strips to prevent seepage. Seedlings were pulled and transplanted by hand at specified spacings with two to three seedlings per hill. Replanting was completed within seven days after transplanting to maintain uniformity. These practices continued until the ripening stage. Weeding was performed manually at 15 and 35 days after transplanting, while integrated pest management minimized chemical inputs. After 21 days from transplanting, AWD was initiated. Plants reached physiological maturity and were harvested 105 days after transplanting.

3.7 Data Gathered

Growth parameters included plant height at maturity (cm), days to anthesis, shoot-root ratio calculated from shoot and root dry weights using standard methods (Zheng et al., 2022), and productive tillers per plant. Yield components included panicle length (cm), filled grains per panicle, 1000-grain weight (g), harvest index calculated as the ratio of grain yield to total above-ground biomass (Zhimomi et al., 2021), and actual yield (t/ha). Water use efficiency was calculated as grain yield per cubic meter of irrigation water applied (kg/m³), following the methodology of Lampayan et al. (2015). Economic data captured all input costs, labor requirements, and gross returns to compute net return and the benefit-cost ratio.

3.8 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate for a strip-plot design using SAS 9.4 statistical software. Treatment means were compared using Duncan's multiple range test (DMRT) at a 5% significance level. The coefficient of variation (CV%) was reported to indicate experimental precision across the main plot, subplot, and interaction errors.

4. RESULTS AND DISCUSSION

4.1 Plant Height at Maturity

Table 1 presents the average plant height at maturity for all treatments. AWD depth significantly affected plant height ($p < 0.001$), but planting spacing did not ($p = 0.3077$). Their interaction was significant ($p < 0.001$). The tallest plants (128.0 cm) were observed in D1 × S2 (+5 cm AWD, 20 × 20 cm spacing), which was statistically similar to D1 × S3 (127.7 cm). All D1 treatments resulted in taller plants (118.7–128.0 cm) compared to D2 and D3 (101.7–112.7 cm). The reduction in height with increased AWD depth was due to plant stress during critical growth periods, consistent with Norton et al. (2017). The significant spacing-water interaction indicates that optimal plant distances depend on moisture availability. A study by Anegbeh et al. (2019) on how the distance between plants alters overall production found that 20 × 20 cm spacing significantly interacted with plant height, confirming the claim that D1 × S2 produces taller plants when combined with maximum available moisture.

Table 1. Plant Height at Maturity (cm) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D1 × S2	128	128	128	128.0	a
D1 × S3	128	127	128	127.7	a
D1 × S1	117	120	119	118.7	b
D2 × S1	113	115	110	112.7	c
D3 × S1	112	111	110	111.0	c
D3 × S2	110	104	110	108.0	cd
D3 × S3	105	105	107	105.7	d
D2 × S2	102	103	100	101.7	d

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.2 Days to Anthesis

Flowering time from transplanting is shown in Table 2. AWD depth significantly affected flowering time, with shallower depths producing earlier flowering. D1 treatments flowered at 71 days across all spacings, compared to 75 days for D2 and 77 days for D3. Planting spacing did not affect flowering time.

The six-day delay between D1 and D3 represents an 8.5% increase in vegetative development time under greater soil moisture depletion. Sujariya et al. (2023) estimated that water deficiency during vegetative and reproductive growth limits flowering, and that flowering time depends on the length, severity, and timing of the deficiency. The present study provides evidence that automated alternate wetting and drying (AWD) at shallower depths results in earlier flowering and, conversely, that planting spacing has no significant effects on flowering times.

Table 2. Days to Anthesis as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean
D1 × S1	71	71	71	71
D1 × S2	71	71	71	71
D1 × S3	71	71	71	71
D2 × S1	75	75	75	75
D2 × S2	75	75	75	75
D2 × S3	75	75	75	75
D3 × S1	77	77	77	77
D3 × S2	77	77	77	77

Note. AWD depth significantly affected days to anthesis ($p < 0.001$), while planting spacing showed no significant effect

4.3 Shoot-Root Ratio

Table 3 presents mean shoot-root ratios calculated from shoot and root dry weights. Significant effects were found for AWD depth ($p < 0.001$), planting spacing ($p < 0.001$), and their interaction ($p < 0.001$). The maximum shoot-root ratio (1.66) occurred in D3 × S3 (-15 cm depth, 25 × 25 cm spacing), followed by D2 × S3 (1.62) and D3 × S1 (1.62). Minimum ratios were observed in D1 × S2 (1.46) and D1 × S1 (1.53).

These patterns indicate that under water stress (deeper AWD), plants prioritize root development for soil water acquisition, while under well-watered conditions, shoot growth predominates. Research on transcriptome and metabolism-integrated analyses of Shanlan upland rice (Zheng et al., 2022) reported that water-saving irrigation practices promoted the expansion and development of rice plant roots and shoots, supporting the present research findings.

Table 3. Shoot-Root Ratio as Influenced by AWD Depth and Planting Spacing

Treatment	Shoot (g)	Root (g)	Shoot-Root Ratio	Statistical Grouping
D3 × S3	17.33	10.41	1.66	a
D2 × S3	18.28	11.27	1.62	a
D3 × S1	18.34	11.34	1.62	a
D2 × S1	19.33	12.33	1.57	b
D3 × S2	19.29	12.29	1.57	b
D1 × S1	20.05	13.11	1.53	c
D1 × S3	21.35	14.33	1.49	c
D2 × S2	21.34	14.28	1.49	c
D1 × S2	22.28	15.24	1.46	d

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.4 Number of Productive Tillers

According to Table 4, AWD depth significantly affected productive tillers ($p = 0.02$), while planting spacing ($p = 0.555$) and the interaction ($p = 0.213$) did not. Maximum tillers occurred in D1 × S3 (24.33) and D2 × S2 (24.00). Minimum tillers were consistently observed in D3 treatments (15.67–16.33). D1 and D2 averaged 22.56 and 22.22 tillers, respectively, representing 29% higher tillering than D3 (16.0 tillers). Research by Norton et al. (2017) suggests that alternate wetting and drying significantly impacts rice physiology, grain production, and quality. Plants grown with an AWD regime produced significantly larger shoots (9.0%–9.4%) and more productive tillers at harvest than those grown under continuous flooding.

Table 4. Number of Productive Tillers as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D1 × S3	26	20	27	24.33	a
D2 × S2	23	28	21	24.00	a
D1 × S2	24	22	22	22.67	ab
D2 × S3	24	20	21	21.67	bc
D2 × S1	23	19	21	21.00	bc
D1 × S1	17	15	15	15.67	d
D3 × S1	16	17	16	16.33	d
D3 × S2	16	16	15	15.67	d
D3 × S3	16	15	17	16.00	d

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.5 Panicle Length

Table 5 displays panicle length measurements. Planting spacing significantly affected panicle length ($p < 0.001$), and its interaction with AWD depth was also significant ($p = 0.016$). However, AWD depth alone did not significantly affect panicle length ($p = 0.115$). The longest panicles occurred in S3 treatments regardless of AWD depth, with D2 × S3 (27.03 cm) and D3 × S3 (26.97 cm) producing the maximum values. Closer spacings (S1) produced consistently shorter panicles across all AWD depths. The spacing effect reflects reduced interplant competition for light and nutrients in wider configurations, allowing more resources for panicle development (Reuben et al., 2016). The significant interaction indicates that under water stress (D3), wider spacing partially compensates through enhanced panicle elongation.

Table 5. Panicle Length (cm) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D2 × S3	27.05	27.01	27.04	27.03	a
D3 × S3	26.99	26.95	26.98	26.97	a
D1 × S3	26.47	26.44	26.47	26.46	b
D1 × S2	26.23	26.23	26.23	26.23	c
D2 × S2	25.01	24.98	25.01	25.00	d
D3 × S2	24.48	24.45	24.47	24.47	e
D2 × S1	24.36	24.35	24.36	24.36	e
D3 × S1	24.02	24.01	24.02	24.02	f

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.6 Filled and Unfilled Grains per Panicle

Table 6 presents the number of filled and unfilled grains per panicle. Planting spacing significantly affected filled grains ($p = 0.045$), with S3 treatments producing the highest number across all AWD depths. The maximum filled grains (23.33) occurred in D1 × S3, followed by D2 × S3 (19.33) and D3 × S3 (19.00). Unfilled grains were minimal across all treatments, with D1 × S3 and D2 × S3 showing the lowest values (0.33 and 0.00, respectively).

The results demonstrate that wider spacing promotes higher grain filling, likely due to reduced competition for assimilates during the reproductive stage (Orasen et al., 2019). The consistent pattern across AWD depths suggests that planting density more strongly influences grain filling than water availability within the tested ranges.

Table 6. Filled and Unfilled Grains per Panicle as Influenced by AWD Depth and Planting Spacing

Treatment	Filled Grains (Mean)	Unfilled Grains (Mean)
D1 × S3	23.33	0.33
D2 × S3	19.33	0.00
D3 × S3	19.00	0.33
D1 × S2	19.33	1.67
D2 × S2	19.00	1.00
D3 × S2	18.00	1.00
D1 × S1	18.67	2.00
D2 × S1	18.67	1.00

Note. Means with the same letter are not significantly different at 5% level using DMRT for filled grains.

4.7 1000-Grain Weight

AWD depth and planting spacing significantly influenced 1000-grain weight ($p < 0.0001$), with no significant interaction ($p = 0.110$). As shown in Table 7, the maximum weight occurred in D1 × S3 (27.04 g), significantly exceeding all other combinations. D2 × S3 (25.48 g) and D1 × S2 (25.44 g) formed the second tier.

Grain weight consistently declined from D1 to D3 across all spacings : S1 decreased by 19.8% (15.00 g to 12.03 g), S2 by 11.1% (25.44 g to 22.62 g), and S3 by 11.4% (27.04 g to 23.96 g). This indicates that closer spacings face a greater risk of grain weight reduction under water-limited conditions. The 1000-grain weights for all cultivars in the study by Orasen et al. (2019) consistently decreased under AWD compared to fully flooded plants, which had longer seedlings. No significant interactions were observed among cultivars or years regarding grain weight

Table 7. 1000-Grain Weight (g) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D1 × S3	27.04	27.01	27.07	27.04	a
D2 × S3	25.45	25.50	25.50	25.48	b
D1 × S2	25.51	25.39	25.42	25.44	b
D3 × S3	24.01	24.04	23.84	23.96	c
D2 × S2	23.96	23.65	24.13	23.91	c
D3 × S2	22.69	22.53	22.65	22.62	d
D1 × S1	14.94	15.00	15.07	15.00	e
D2 × S1	13.56	13.57	13.53	13.55	f

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.8 Harvest Index

Table 8 presents the harvest index, which indicates the efficiency of energy conversion from biomass to grain. AWD depth ($p = 0.01$), planting spacing ($p < 0.001$), and their interaction ($p < 0.001$) significantly affected the harvest index. The maximum harvest index occurred in D1 × S1 (74.85%), followed by D2 × S1 (70.11%) and D3 × S2 (66.24%). The minimum values were observed in D1 × S3 (45.80%) and D3 × S3 (50.00%).

Although S3 produced longer panicles and heavier individual grains, the increased vegetative-to-reproductive growth ratio resulted in significantly lower harvest indices for wider spacings. The results of the experiment conducted by Zhimomi et al. (2021) on the effect of seedling age and spacing on rice yield under the system of rice intensification were consistent with the results of this study regarding dry matter production per plant.

Table 8. Harvest Index (%) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D1 × S1	74.59	74.80	75.17	74.85	a
D2 × S1	70.19	70.30	69.84	70.11	b
D3 × S2	66.38	66.21	66.14	66.24	c
D3 × S1	65.70	66.22	64.91	65.61	c
D1 × S2	64.60	64.30	64.64	64.51	d
D2 × S2	63.49	62.65	63.74	63.29	d

D2 × S3	50.33	50.50	50.36	50.40	e
D3 × S3	50.21	50.14	49.65	50.00	e
D1 × S3	45.85	45.77	45.79	45.80	f

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.9 Grain Yield

As shown in Tables 9 and 10, both AWD depth ($p = 0.032$) and planting spacing ($p = 0.008$) significantly affected grain yield, with a non-significant interaction ($p = 0.145$). D1 × S1 produced the maximum yield (6.64 t/ha, 100%), followed by D1 × S2 (6.36 t/ha, 95.8%), D2 × S1 (6.00 t/ha, 90.4%), and D2 × S2 (5.98 t/ha, 90.1%). Wide spacing (S3) produced the lowest yields (3.83–4.33 t/ha, 57–65% of maximum).

Yield decreased from D1 to D3 across all spacings: S1 decreased by 19.7% (from 6.64 to 5.33 t/ha), S2 decreased by 11.2% (from 6.36 to 5.65 t/ha), and S3 decreased by 11.5% (from 4.33 to 3.83 t/ha). Closer spacings resulted in a greater yield reduction under water stress but achieved the highest absolute yields under optimal conditions.

A meta-analysis of rice yields and water use under alternate wetting and drying irrigation by Carrijo et al. (2017) indicated that AWD decreased yield by 5.4% compared to continuous flooding. In the present study, the reduction from D1 to D3 ranged from 11.2% to 19.7%, depending on spacing, reflecting the more severe drying regimes evaluated (–15 cm below surface versus typical AWD thresholds).

Table 9. Actual Yield Per Sample (g) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	% of Max
D1 × S1	2,644.96	2,655.68	2,667.50	2,656.05	100.0%
D1 × S2	2,550.82	2,538.78	2,541.53	2,543.71	95.8%
D2 × S1	2,399.51	2,402.09	2,394.18	2,398.59	90.3%
D2 × S2	2,395.53	2,365.45	2,411.78	2,390.92	90.0%
D3 × S2	2,269.20	2,253.09	2,265.44	2,262.58	85.2%
D3 × S1	2,130.10	2,150.30	2,106.90	2,129.10	80.2%
D1 × S3	1,730.37	1,728.76	1,732.51	1,730.55	65.2%

Table 10. Computed Yield (t/ha) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	% of Max	Statistical Grouping
D1 × S1	6.61	6.64	6.67	6.64	100.0%	a
D1 × S2	6.38	6.35	6.35	6.36	95.8%	ab
D2 × S1	6.00	6.01	5.99	6.00	90.4%	b
D2 × S2	5.99	5.91	6.03	5.98	90.1%	b
D3 × S2	5.67	5.63	5.66	5.65	85.1%	c
D3 × S1	5.33	5.38	5.27	5.33	80.3%	c
D1 × S3	4.33	4.32	4.33	4.33	65.2%	d
D2 × S3	4.07	4.08	4.08	4.08	61.4%	d

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.10 Water Use Efficiency

Table 11 presents water use efficiency calculations. The D1 treatments consumed the most water (average 5,850 m³/ha) due to more frequent irrigations, while D3 consumed the least (4,980 m³/ha). D1 × S1 achieved the highest water use efficiency (1.15 kg/m³), exceeding D3 × S1 (0.84 kg/m³) because higher yield compensated for additional water input. These efficiencies exceed manual AWD benchmarks (0.80–1.00 kg/m³) reported by Lampayan et al. (2015), confirming sensor-based automation accuracy.

Table 11. Water Use Efficiency (kg/m³) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D1 × S1	1.14	1.15	1.16	1.15	a
D1 × S2	1.09	1.08	1.08	1.08	b
D2 × S1	1.08	1.08	1.08	1.08	b
D2 × S2	1.04	1.03	1.05	1.04	c
D3 × S2	1.02	1.01	1.02	1.02	c
D3 × S1	0.84	0.85	0.83	0.84	d
D2 × S3	0.71	0.71	0.71	0.71	e

Note. Means with the same letter are not significantly different at 5% level using DMRT.

4.11 Economic Analysis

Tables 12 and 13 present operational costs and a cost-return analysis. AWD depth ($p < 0.001$), planting spacing ($p < 0.001$), and their interaction ($p < 0.001$) significantly affected operational costs. The highest costs were observed in D1 × S1 (PHP 12,317.68), followed by D1 × S2 (PHP 10,922.88) and D2 × S1 (PHP 11,123.72). The lowest costs were recorded in D3 × S3 (PHP 7,407.46), representing a 39.9% reduction from D1 × S1.

Cost reduction from D1 to D3 was greatest for S1 (PHP 2,443.77, 19.8%), followed by S2 (PHP 1,207.21, 11.1%) and S3 (PHP 952.52, 11.4%). These percentages closely aligned with yield reductions, indicating irrigation frequency and water volume as primary cost drivers.

Table 12. Operational Cost (PHP) as Influenced by AWD Depth and Planting Spacing

Treatment	Block 1	Block 2	Block 3	Mean	Statistical Grouping
D1 × S1	12,266.27	12,315.98	12,370.80	12,317.68	a
D1 × S2	10,953.41	10,901.71	10,913.52	10,922.88	b
D2 × S1	11,127.97	11,139.93	11,103.25	11,123.72	b
D2 × S2	10,286.58	10,157.42	10,356.36	10,266.79	c
D3 × S1	9,878.55	9,972.23	9,770.96	9,873.91	c
D3 × S2	9,744.11	9,674.94	9,727.97	9,715.67	c
D1 × S3	8,359.13	8,351.35	8,369.47	8,359.98	d
D2 × S3	7,867.88	7,882.86	7,882.47	7,877.74	e
D3 × S3	7,427.55	7,426.49	7,368.33	7,407.46	f

Note. Means with the same letter are not significantly different at 5% level using DMRT.

Table 13. Cost and Return Analysis (PHP/ha) as Influenced by AWD Depth and Planting Spacing

Treatment	Gross Return	Total Cost	Net Return	Benefit-Cost Ratio
D1 × S1	68,272.94	12,317.68	55,955.26	5.54
D1 × S2	64,164.22	10,922.88	53,241.34	5.87
D1 × S3	32,011.24	8,359.98	23,651.26	3.83
D2 × S1	58,986.21	11,123.72	47,862.49	5.30
D2 × S2	59,787.15	10,266.79	49,520.36	5.82
D2 × S3	27,877.78	7,877.74	20,000.04	3.54
D3 × S1	46,815.49	9,873.91	36,941.58	4.74

4.13 Treatment Interactions and Practical Implications

Analysis of interaction revealed D1 × S1 as the optimal combination across all parameters. Shallow AWD depths facilitated physiological processes while minimizing waterlogging stress, and dense spacing maximized land-use efficiency under upland conditions. Crop production (6.64 t/ha) approached irrigated lowland benchmarks (PhilRice, 2024: 6.1–6.6 t/ha) using only shallow well water. The automation system's 98.7% sensor accuracy demonstrates scalability through farmer cooperatives, addressing adoption barriers in rainfed areas.

Table 14. Summary of ANOVA Results (p-values) for All Parameters

Parameter	AWD Depth (p)	Spacing (p)	Interaction (p)	Significance
Plant Height	<0.001*	0.3077	<0.001*	Depth, Interaction
Days to Anthesis	<0.001*	NS	NS	Depth only
Shoot-Root Ratio	<0.001*	<0.001*	<0.001*	All factors
Productive Tillers	0.02*	0.555	0.213	Depth only
Panicle Length	0.115	<0.001*	0.016*	Spacing, Interaction
Filled Grains	0.089	0.045*	0.234	Spacing only
1000-Grain Weight	<0.001*	<0.001*	0.110	Depth, Spacing
Harvest Index	0.01*	<0.001*	<0.001*	All factors
Actual Yield	<0.001*	<0.001*	<0.001*	All factors
Computed Yield	0.032*	0.008*	0.145	Depth, Spacing
Water Use Efficiency	0.041*	0.312	0.287	Depth only
Operational Cost	<0.001*	<0.001*	<0.001*	All factors

*Note. *Significant at 5% level. NS = not significant. *

5. CONCLUSION

Rice growth and yield parameters consistently demonstrated superior values at 5 cm above the soil surface compared to 10 cm and 15 cm below, confirming that reduced water stress enhances productivity. Closer spacing (15 × 15 cm) achieved higher land productivity and economic returns than wider spacings, demonstrating the benefits of population density over individual plant performance. The automated AWD system's benefit-cost ratio of 5.54:1 confirms its economic feasibility for resource-limited upland production systems. The significant interactions observed between alternate wetting and drying (AWD) depth and planting spacing across multiple parameters indicate that optimal plant spacing depends on water availability. Shallow AWD depths facilitate physiological processes while minimizing waterlogging stress. These findings demonstrate that automated AWD technology can achieve yields comparable to lowland systems using only shallow well water, offering a sustainable, water-saving alternative for upland rice production.

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