



Eurasian Journal of Soil Science

Journal homepage : <http://ejss.fesss.org>



Integrating provocative irrigation and stage-specific floodwater depth to enhance rice productivity and water-use efficiency in the saline Aral Sea Basin

Almasbek Berdibek ^a, Bakhytzhan Shayanbekova ^{a,*}, Akbope Aibekkyzy ^a,
Parida Sultanbekova ^b, Aigul Alibekova ^a, Galiya Omarova ^c, Adylkhan Balmakhanov ^a,
Gulzhan Kalmanova ^a, Bakhyt Seitmuratov ^d

^a Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan

^b M. Auezov South Kazakhstan University, Shymkent, Kazakhstan

^c National Institute of Water Management and Irrigation of M.H. Dulaty Taraz Regional University, Taraz, Kazakhstan

^d Regional Branch "Kainar" of LLP "Kazakh Research Institute of Fruit and Vegetable Growing", Kazakhstan

Article Info

Received : 12.05.2025

Accepted : 28.11.2025

Available online: 02.12.2025

Author(s)

A.Berdibek  
B.Shayanbekova *  
A.Aibekkyzy  
P.Sultanbekova  
A.Alibekova  
G.Omarova  
A.Balmakhanov  
G.Kalmanova  
B.Seitmuratov  

* Corresponding author

Abstract

Rice production in the Aral Sea basin is constrained by high water demand, severe soil salinity, and heavy weed pressure. This study evaluated an integrated irrigation strategy that combines provocative pre-sowing irrigation (Stale Seedbed Technique) with stage-specific regulation of floodwater depth, as a sustainable alternative to conventional continuous deep flooding. Field experiments were conducted over three seasons (2022–2024) on saline loam soils at the Karaul-Tyube Experimental Farm (Kyzylorda region, Kazakhstan), using two locally adapted rice varieties (Syr-Sulu and Avangard) in a randomized complete block design with four replications. Complementary pot experiments were used to isolate the effects of static water depths (5–25 cm) during key growth stages. Provocative irrigation (1100–1200 m³ ha⁻¹) applied before sowing induced massive germination of *Echinochloa* spp. (280–336 seedlings m⁻²) and *Phragmites australis* (45–62 seedlings m⁻²), enabling their mechanical removal and establishing nearly weed-free, herbicide-free rice stands. Simultaneously, pre-sowing leaching reduced salinity in the 0–40 cm layer from moderately–highly saline to slightly saline, with 0–10 cm dry residue decreasing four- to fivefold over the season. Stage-specific water management—shallow flooding (≈5 cm) during emergence and tillering, deeper water (≈20 cm) at panicle initiation, and moderate depths during ripening—significantly improved stand establishment, tiller number, spikelet fertility, and final grain yield. Compared with conventional continuous flooding, the optimized regime reduced seasonal irrigation input by 15–20% (≈3,500 m³ ha⁻¹) and improved specific water use by 150 m³ per 100 kg of grain, while increasing grain yield by 15.3–20.6%. Water balance analysis showed that these gains were achieved primarily by reducing non-productive percolation and eliminating drainage discharge losses. The integrated strategy provides a robust, scalable framework for water-efficient, herbicide-free rice cultivation in arid, salinity-affected regions.

Keywords: Rice, saline soils, provocative irrigation, floodwater depth, water-use efficiency.

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Introduction

Rice (*Oryza sativa* L.) is a global staple crop and a cornerstone of food security for more than half of the world's population (Mohidem et al., 2022). However, its productivity is severely constrained in arid and semi-arid regions due to its high water demand, heavy weed pressure, and widespread soil salinity problems (Zeng et al., 2003; Mallareddy et al., 2023; Sharifzadeh et al., 2024). Conventional continuous flooding—

although effective for suppressing weeds and moderating the microclimate—results in low water-use efficiency, while sustained reliance on chemical herbicides increases environmental risks such as contamination of irrigation return flows and natural water bodies (Voccia et al., 2024).

These challenges are especially acute in the Aral Sea basin, one of the most environmentally fragile and water-limited regions in the world. The Kyzylorda region of Kazakhstan, located in the lower Syr Darya basin, experiences extremely continental climatic conditions, limited precipitation, and high evaporative losses (Xie et al., 2023). Decades of unsustainable irrigation practices have further intensified secondary soil salinization—now affecting more than 60% of irrigated lands in Central Asia—and contributed to severe degradation of water resources (Qadir et al., 2009). Under such constraints, developing water-efficient and ecologically sound management strategies that simultaneously address weed control and salinity stress is essential for sustaining rice production in this region. Recent reclamation studies conducted on soda-saline and solonetz soils of the Aral Sea basin further highlight the severity of chemical degradation and the urgent need for integrated approaches. Naushabayev et al. (2024) demonstrated that the combined application of phosphogypsum, elemental sulfur and sulfuric acid significantly improved soil structure, reduced exchangeable sodium, and enhanced crop establishment in highly alkaline soils of southern Kazakhstan. Similar findings were reported by Duisenbayeva et al. (2023), who showed that chemical amelioration coupled with leaching irrigation effectively lowered ESP and facilitated the downward movement of soluble salts in saline-alkali soils. These studies collectively reinforce that early-season salt reduction is essential for successful crop establishment in Central Asian rice systems, and they provide a broader regional context for the present work, which evaluates a non-chemical, water-based approach to early-season desalination.

The standing water layer in lowland rice systems performs two essential agronomic functions: it suppresses weed emergence by acting as a physical barrier (Iwasa et al., 2025) and buffers temperature fluctuations to protect the crop during sensitive reproductive stages (Shimono et al., 2007). However, determining an optimal water depth is challenging because shallow and deep flooding impose contrasting physiological stresses. Shallow flooding (≤ 5 cm) generally favors seedling establishment and tillering, whereas deeper water reduces soil temperature, restricts oxygen availability, impedes tiller development, and may sharply reduce plant stand (Yoshida, 1981; Zeng et al., 2003). In contrast, deeper flooding is essential during the booting stage to minimize temperature-induced spikelet sterility and enhance weed suppression (Zeng et al., 2003; Shimono et al., 2007). This inherent trade-off underscores the limitations of traditional continuous deep flooding commonly practiced in the Aral Sea basin.

Addressing these conflicting water-depth requirements necessitates integrated approaches. One promising practice is the Provocative Irrigation strategy, a form of the stale seedbed technique, which applies irrigation before sowing to stimulate mass germination of weed seeds, followed by mechanical destruction. This decouples weed control from the main growing season and permits subsequent water management to be optimized strictly for crop physiological needs and improved water-use efficiency, rather than for weed suppression (Little et al., 2021; Savić et al., 2025). Despite its potential, the combined application of pre-sowing provocative irrigation with stage-specific water depth regulation (shallow during tillering, deep during booting, and moderate during ripening) has not been thoroughly evaluated under the saline, arid conditions of Central Asia.

Therefore, this study was designed to rigorously assess the effects of provocative irrigation on weed infestation and rice productivity when integrated with a dynamic, stage-specific water management regime. By comparing this optimized system with conventional continuous deep flooding using locally adapted rice cultivars grown on saline loam soils in the Kyzylorda region, the study aims to provide a scientifically grounded, sustainable irrigation strategy that enhances resource-use efficiency, reduces dependence on herbicides, and stabilizes rice yields in water-scarce, salinity-affected environments. We hypothesized that combining pre-sowing provocative irrigation with stage-specific regulation of floodwater depth would (i) reduce weed pressure, (ii) mitigate early-season salinity stress, (iii) increase water-use efficiency, and (iv) enhance grain yield under arid and saline conditions.

Material and Methods

Study Site and Environmental Characterization

The research was conducted over three consecutive growing seasons (2022–2024) at the Karaul-Tyube Experimental Farm, located in the eastern sector of the Right-Bank Kyzylorda Irrigation System in Kazakhstan (Figure 1). The climate of the Kyzylorda region is sharply continental, characterized by short, cold winters and long, hot, arid summers typical of the Aral Sea basin. These conditions generate intense

solar radiation, low relative humidity, and pronounced diurnal temperature fluctuations, which during the summer months ranged between 16 and 24 °C.

Weather patterns varied considerably across the three years. In 2022, climatic conditions were close to long-term regional averages, although the preceding winter months were colder than normal. The 2023 growing season was exceptionally arid and hot: total rainfall from April to September was only 17 mm, falling 20 mm below the long-term average. Moreover, the mean July temperature exceeded the long-term average by 1.7 °C, and relative humidity during the growing season averaged 37%, compared with the normative 41%. In contrast, 2024 began with notable rainfall in early April, briefly increasing humidity, but the remainder of the season was marked by severe drought, with no measurable precipitation throughout the main summer months.

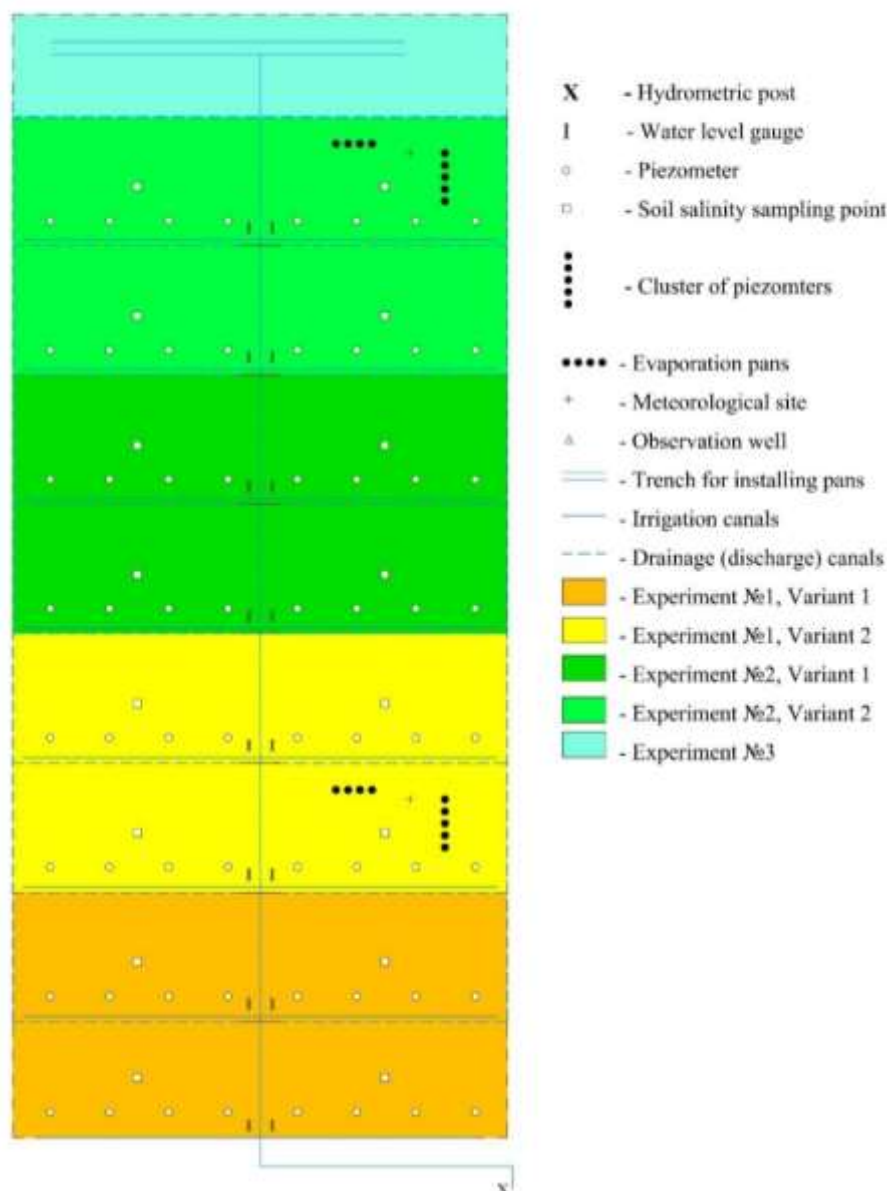


Figure 1. Schematic layout of the experimental plot

Soil Characteristics and Hydro-physical Parameters

The soils at the experimental site were classified as medium-textured loams containing stratified interlayers of sandy loams and fine sands throughout the profile. A distinct sandy horizon occurred at a depth of 22–25 cm beneath the upper loamy layer, and this stratification played an important role in the vertical redistribution of moisture and salts during the growing season. The primary hydro-physical properties of the soil included a bulk density ranging from 1.48 to 1.60 g cm⁻³ and a particle density between 2.66 and 2.70 g cm⁻³, resulting in a total porosity of 43–47%. The field capacity varied from 24.3 to 31.5%, consistent with the medium-textured nature of the profile. The aeration zone exhibited a filtration coefficient of 0.40 m day⁻¹, reflecting the moderate permeability of the loam-sand stratified layers. Groundwater was

encountered at depths fluctuating between 2.0 and 3.0 m, and analyses showed that it was highly saline, with mineralization values ranging from 4.0 to 7.0 g L⁻¹. Soil salinity in the 0–40 cm layer also exhibited substantial variation, measuring between 0.429% and 0.853% depending on micro-topographic position and moisture conditions. Chemically, the soil reaction was slightly alkaline, with a pH ranging from 7.4 to 7.8, while the nutrient status was notably poor; available phosphorus in the plow layer was only 3.6–3.7 mg per 100 g of soil, indicating an overall low fertility typical of long-term irrigated arid-zone soils.

Experimental Design and Treatments

The field study was designed as a Randomized Complete Block Design (RCBD) with four replications. Two locally adapted rice varieties, Syr-Sulu and Avangard, were grown in all experiments. The experimental framework incorporated two main factors—weed control strategy and water depth management—and was implemented across three distinct trials. The average size of the paddy units was 1.8 ha, while individual plot sizes ranged from 0.4 to 3.0 ha.

Experiment 1: Effect of Stale Seedbed Technique (Provocative Irrigation) on Weed Infestation

This experiment compared two crop establishment strategies:

Variant 1 (Control): Conventional rice cultivation without any pre-sowing weed management.

Variant 2 (Provocative): Included a pre-sowing provocative irrigation (1100–1200 m³ ha⁻¹) applied in early May to stimulate weed-seed germination. Spring preparatory work consisted of chiseling at 12–15 cm depth and surface leveling. Following the induced mass weed emergence, a shallow tillage (8–10 cm depth) was conducted to eliminate germinated seedlings before sowing. Weed infestation density was quantified using 1 m² quadrats immediately after the provocative irrigation event.

Experiment 2: Rice Productivity under Phase-Specific Water Layer Depths

This trial assessed the physiological responses and yield performance of both varieties under two contrasting irrigation regimes:

Regime	Growth Stage	Water Depth	Objective
Conventional Control	Sowing to Emergence	10–12 cm	Local Standard Practice
	Emergence to Tillering	5–7 cm	Promoting initial growth
	Tillering through Dough Stage	12–15 cm	Continuous Flooding
Experimental (Differentiated)	Sowing to Germination	15–18 cm	Salinity Leaching and Establishment
	Emergence to Tillering	5–7 cm	Promote Lateral Shoot Initiation
	Tillering to Stem Elongation (Booting)	20–25 cm	Thermal Buffering and Weed Suppression
	Stem Elongation through Dough Stage	10–15 cm	Stable Grain Filling

Experiment 3: Growth and Development of Rice Varieties under Static Water Depths (Pot Experiment)

To isolate the direct effects of water depth on early growth, a controlled pot experiment was performed with four replications using 10 L vessels. Water depth was maintained at fixed levels (5, 10, 15, 20, and 25 cm) across key growth stages. Seedlings were thinned post-emergence to 10 healthy plants per vessel. Soil temperature was recorded daily at 5 cm depth at three intervals (08:00, 13:00, 18:00) using Savinov soil thermometers.

Irrigation and Analytical Protocols

Irrigation water for the experiments was supplied from established field canals that formed part of the Right-Bank Kyzylorda irrigation system. The drainage infrastructure consisted of field and on-farm ditches ranging from 1.2 to 1.5 m deep, larger collectors between 2.5 and 3.0 m deep, and subsurface drains placed at depths of 1.8–2.0 m to facilitate the removal of excess percolated water and maintain appropriate groundwater levels. Water discharge into the paddies was measured precisely using calibrated sluice gates and Cipoletti weirs. To determine the water balance components, dedicated lysimetric vessels installed within the rice fields were used to quantify surface evaporation, plant transpiration, and deep percolation. Soil and water samples were collected and analyzed following international standard procedures. Soil moisture content was determined gravimetrically according to [ISO 11461:2001](#) and [ISO 16586:2003](#), while field capacity was measured using laboratory water-retention methods described in [ISO 11274:2019](#). Bulk density was assessed using the core sampling technique, and particle-size distribution was measured through both pipette and laser diffraction analyses following [ISO 11277:2020](#). Total nitrogen was quantified by dry combustion using an elemental analyzer ([ISO 13878:1998](#)), and available phosphorus was extracted

using the Mehlich-3 method. Soil pH was measured potentiometrically in a 1:5 soil-to-solution suspension (ISO 10390:2021). Soil salinity was determined by measuring the electrical conductivity of saturated paste extracts, providing a reliable indicator of salt accumulation dynamics in the profile. These analytical procedures collectively ensured a comprehensive assessment of both irrigation performance and soil physicochemical responses under the contrasting water management regimes.

Data Analysis

Measurements included soil hydro-physical and salt regime dynamics, groundwater fluctuations, total irrigation water use, crop phenology, and yield components (productive tillers plant⁻¹, grains panicle⁻¹, 1000-grain weight).

All data were subjected to Two-Way Analysis of Variance (ANOVA) to evaluate the effects of irrigation strategy, rice variety, and their interaction. Differences between treatment means were identified using Duncan's Multiple Range Test at $p < 0.05$.

Result

Effect of Pre-Sowing Provocative Irrigation on Soil Hydro-Dynamics and Desalination

Soil Moisture Dynamics

Initial monitoring conducted in early April revealed that soil moisture levels in the upper arable horizons were relatively high at the beginning of the season. As temperatures increased and relative humidity declined, a progressive reduction in soil moisture was observed across all horizons. By late April—prior to any experimental intervention—moisture levels in both treatment variants (Conventional, Variant 1; and Optimized, Variant 2) had decreased uniformly in the 0–5 cm, 5–10 cm, and 10–20 cm layers, approaching values close to the hygroscopic minimum.

The application of pre-sowing provocative irrigation on 10 May in Variant 2 produced a pronounced and immediate change in the soil moisture profile. This leaching irrigation effectively increased and stabilized the moisture content, maintaining it at 60–70% of field capacity (FC) across the upper horizons for 10–15 days prior to rice seeding. Such stabilization during the pre-sowing window is critical, as it creates favorable conditions for seedbed preparation, uniform germination, and early crop establishment.

In sharp contrast, the topsoil of the control plots (Variant 1), which received no pre-sowing irrigation, continued to dry rapidly due to increasing evaporative demand. The moisture content in these plots fell well below the levels needed to sustain either microbial activity or adequate physical conditions for germination. This divergence in moisture behavior between the two variants is illustrated clearly in Figure 2, which compares the daily dynamics of soil moisture across the 0–5, 5–10, and 10–20 cm horizons.

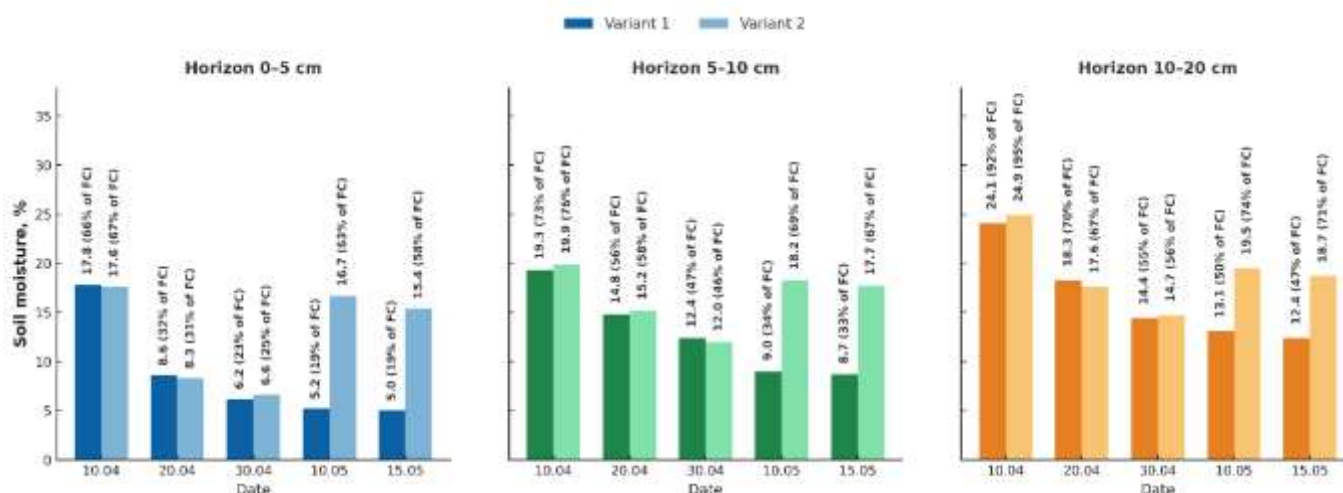


Figure 2. Dynamics of soil moisture before rice sowing

Soil Salinity Dynamics and Desalination

The pre-sowing leaching irrigation had a pronounced and measurable effect on soil salinity patterns across the upper soil horizons (Figure 3). Prior to irrigation, the 0–20 cm layer contained the highest levels of soluble salts, with total dry residue values ranging from 0.72% to 0.85%. This represented a clear concentration gradient, whereby salt levels progressively declined with depth. The chloride (Cl⁻)

distribution followed a similar pattern, decreasing from a maximum of 0.212% in the surface layer to only 0.041% in the deeper subsoil.

Following the application of provocative irrigation in Variant 2, a substantial desalination of the 0–40 cm layer was observed. The downward displacement of soluble salts effectively mitigated the initial salinity stress, shifting the soil from a highly saline to a weakly saline condition. This leaching-induced improvement persisted throughout the full duration of the rice growing season, as confirmed by sequential monitoring and the values presented in Table 1.

By the end of the season in October, total dry residue in the 0–10 cm horizon had decreased dramatically in both variants. In the Conventional regime (Variant 1), dry residue declined from 0.853% to 0.212%, representing a reduction of approximately fourfold. In the Optimized regime (Variant 2), the decrease was similar in magnitude, from 0.837% to 0.193%, corresponding to a reduction of roughly fivefold. Chloride concentrations exhibited an even more pronounced response, decreasing by a factor of 5–7 in the surface horizons of both treatments by the end of the cultivation period. These desalination patterns are consistent with regional reclamation findings on salt-affected soils of the Kyzylorda and Turkestan regions. Chemical amelioration trials using phosphogypsum and sulfuric acid (Naushabayev et al., 2024) or elemental sulfur and drainage-leaching combinations (Duisenbayeva et al., 2023) similarly documented substantial reductions in chloride and sulfate concentrations within the 0–40 cm root zone. However, unlike these chemically driven interventions, the present study demonstrates that comparable levels of early-season desalination can be achieved solely through a properly timed pre-sowing leaching irrigation, without the use of external amendments. This highlights the agronomic significance and economic advantage of provocative irrigation as a low-input strategy for salinity mitigation.

This pattern of extended desalination demonstrates that the combined effects of pre-sowing leaching and subsequent ponded conditions were sufficient to convert soils classified initially as moderately saline into soils with only slight salinity. The consistent reduction in major ion concentrations—including chloride, sulfate, and exchangeable cations—further confirms the effectiveness of the irrigation strategy in modifying the soil chemical environment in favor of rice establishment and growth.

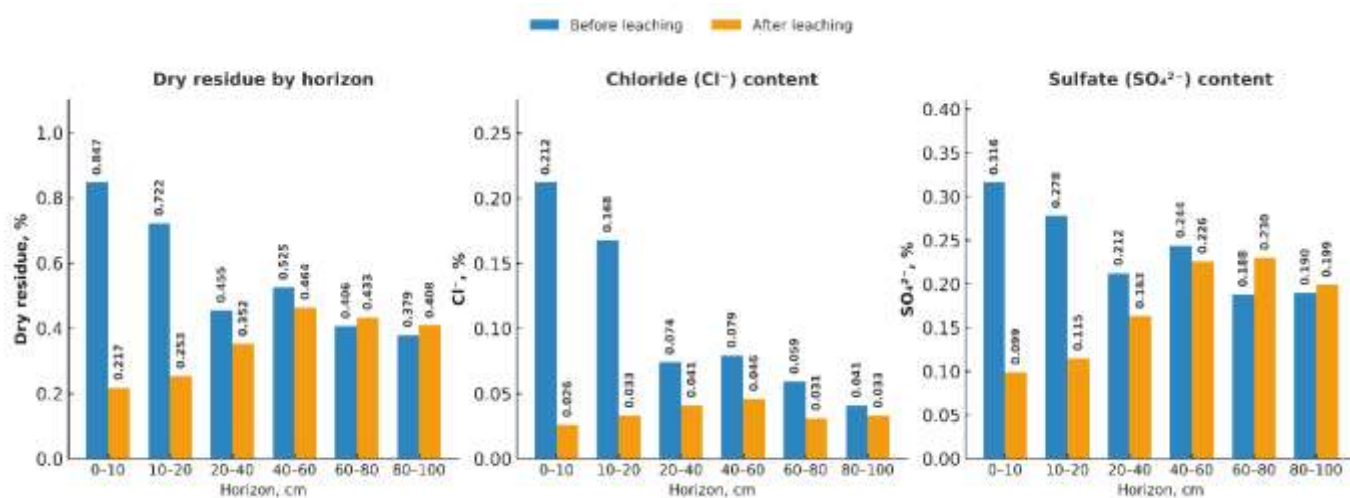


Figure 3. Dynamics of salt content in soils

Table 1. Changes in ion content in the 0–40 cm soil layer during the rice growing season (%)

Variant	Sampling Date	Depth (cm)	Dry residue (%)	HCO ₃ ⁻ (%)	Cl ⁻ (%)	SO ₄ ²⁻ (%)	Ca ²⁺ (%)	Mg ²⁺ (%)	Na ⁺ +K ⁺ (%)
1	25 Apr (start)	0–10	0.853	0.013	0.129	0.432	0.035	0.012	0.232
		10–20	0.720	0.012	0.168	0.312	0.140	0.015	0.073
		20–40	0.429	0.016	0.049	0.240	0.080	0.018	0.026
	14 Oct (end)	0–10	0.212	0.030	0.028	0.095	0.034	0.012	0.013
		10–20	0.361	0.024	0.024	0.205	0.050	0.008	0.050
		20–40	0.289	0.024	0.030	0.155	0.040	0.018	0.022
2	24 Apr (start)	0–10	0.837	0.019	0.257	0.288	0.140	0.019	0.114
		10–20	0.840	0.018	0.237	0.312	0.120	0.021	0.132
		20–40	0.446	0.026	0.049	0.240	0.045	0.020	0.066
	10 Oct (end)	0–10	0.193	0.024	0.036	0.077	0.035	0.009	0.012
		10–20	0.363	0.022	0.033	0.199	0.055	0.009	0.045
		20–40	0.289*	0.024*	0.030*	0.155*	0.040*	0.018*	0.022*

Weed Management and Early Crop Establishment

Weed Emergence under Provocative Irrigation

The provocative irrigation applied as part of the Stale Seedbed Technique proved highly effective in stimulating the mass germination of dominant paddy weed species prior to rice sowing (Figure 4). In the plots receiving provocative irrigation (Variant 2), a substantial and uniform emergence of weed seedlings was observed. Densities of Proso millet (*Echinochloa* spp.) ranged from 280 to 336 seedlings m^{-2} , while Reed weed (*Phragmites australis*) emergence varied between 45 and 62 seedlings m^{-2} during the 2022–2024 seasons. This intentionally induced flush of weeds represented a critical component of the strategy, enabling their removal before rice establishment.

In stark contrast, the control plots managed under conventional irrigation (Variant 1) exhibited only limited spontaneous weed emergence. In these plots, *Echinochloa* densities were restricted to 15–26 seedlings m^{-2} , and *Phragmites australis* emergence ranged only from 23 to 28 seedlings m^{-2} over the same period. This difference highlights the capacity of provocative irrigation to expose a much larger proportion of the weed seedbank to germination stimuli.

Following the induced emergence in Variant 2, shallow tillage effectively destroyed nearly all germinated seedlings, resulting in a substantially cleaner seedbed. Consequently, rice stands established under provocative irrigation developed with minimal weed interference and did not require chemical herbicide applications, demonstrating both agronomic and environmental advantages. The contrasting weed emergence patterns between the two irrigation strategies are clearly illustrated in Figure 4, which summarizes annual and average weed densities across the experimental years.

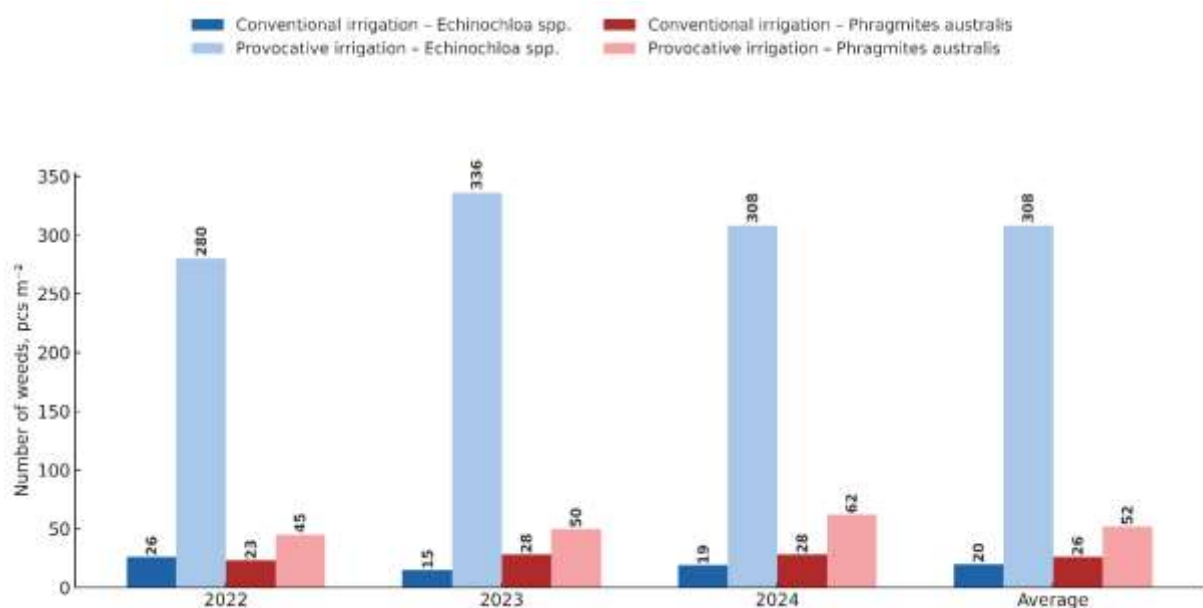


Figure 4. Weed seedling emergence before rice sowing under conventional and provocative irrigation treatments (2022–2024).

Impact of Water Depth on Physiological Development and Yield Components

Impact of Water Depth on Emergence Stage

Water depth during the emergence phase (Sowing to Emergence) was identified as a decisive factor influencing seedling establishment. The results clearly showed that deeper flooding produced adverse effects on both soil temperature and field emergence. As shown in Table 2, maintaining a shallow water layer of 5 cm resulted in a higher average daily soil surface temperature (22.5 °C) compared with the markedly cooler conditions recorded under a 20 cm water depth (20.7 °C). This reduction in soil temperature under deeper water layers had a direct and negative impact on rice emergence.

Correspondingly, field emergence percentages declined sharply as water depth increased. In the Avangard variety, emergence decreased dramatically from 32.9% at 5 cm to only 9.0% at 20 cm, indicating a substantial loss in establishment capacity under deeper flooding. The Syr-Sulu variety exhibited comparatively greater tolerance, yet still showed a clear decline in emergence from 34.5% at 5 cm to 20.4% at 20 cm. These contrasting responses between the two varieties highlight both the general sensitivity of rice seedlings to deep flooding and the relative resilience of Syr-Sulu during the emergence phase.

Deeper flooding also extended the duration required for seedlings to emerge. Under shallow water depths of 5–10 cm, the interval from initial flooding to seedling emergence was approximately 13 days. However, at a depth of 20 cm, this period lengthened considerably to 15–16 days. Such delays are agronomically significant because prolonged emergence increases the vulnerability of seedlings to environmental stresses and reduces final stand uniformity.

Taken together, these results demonstrate that under continuous flooding conditions, minimizing flood depth during emergence is essential for maximizing field establishment. This requirement is particularly important for less water-tolerant varieties such as Avangard, which exhibit pronounced reductions in emergence when water depths exceed optimal physiological thresholds.

Table 2. Effect of different floodwater depths on soil surface temperature and field emergence of two rice varieties (Syr-Sulu and Avangard).

Parameter	Syr-Sulu (5 cm)	Syr-Sulu (10 cm)	Syr-Sulu (15 cm)	Syr-Sulu (20 cm)	Avangard (5 cm)	Avangard (10 cm)	Avangard (15 cm)	Avangard (20 cm)
Average daily soil surface temperature (°C)	22.5	21.7	21.0	20.7	22.5	21.7	21.0	20.7
Number of germinated seeds (no.)	57	49	45	42	43	36	31	26
Number of emerged seedlings (no.)	24	23	18	14	23	20	10	6
Field emergence (%)	34.5	32.5	26.4	20.4	32.9	26.1	14.8	9.0
Duration from flooding to emergence (days)	13	13	14	15	14	14	15	16

Impact of Water Depth on Tillering Stage

The depth of the floodwater layer during the tillering phase exerted a clear and substantial influence on the dynamics and intensity of tiller formation. Across treatments, deeper water levels (15–20 cm) consistently delayed the initiation of secondary shoots by several days when compared with the shallow 5 cm water depth. This delay is primarily associated with the lower soil temperatures observed at the tillering node under deeper flooding conditions. As shown in Table 3, the Syr-Sulu variety entered the tillering phase approximately three days later under a 20 cm water depth (around July 2) than under the 5 cm treatment, where tillering began in late June.

The number of productive tillers per plant was also negatively affected by increased water depth. Under the 5 cm treatment, Syr-Sulu formed an average of 2.0 productive tillers per plant. This value declined to 1.5–1.8 under the deeper 15–20 cm water layers. Avangard exhibited a similar pattern, producing 1.7 productive tillers per plant at 5 cm, compared with only 1.3–1.5 productive tillers under the deeper flooding conditions. The underlying physiological mechanism corresponds well with soil temperature measurements: the average daily temperature in the tillering zone was notably lower under 20 cm of water (22.2 °C in June) compared to 24.3 °C under the 5 cm treatment. Reduced soil temperature at greater water depths likely suppressed metabolic processes at the basal nodes, thereby inhibiting the initiation of lateral shoots.

Taken together, these findings provide strong evidence that shallow floodwater during the tillering period enhances tiller formation, promotes earlier initiation of secondary shoots, and results in a greater number of productive tillers per plant for both rice varieties. These outcomes underscore the importance of stage-specific water depth management to optimize vegetative growth in rice production systems.

Table 3. Effect of floodwater depth during the tillering stage on soil temperature, tillering dynamics, and productive tiller formation in the rice varieties Syr-Sulu and Avangard

Water depth (cm)	Avg. soil temp June (°C)	Avg. soil temp July (°C)	Tillering phase period – Syr-Sulu (start–end)	Tillering phase period – Avangard (start–end)	Total tillers per plant – Syr-Sulu	Total tillers per plant – Avangard	Productive tillers per plant – Syr-Sulu	Productive tillers per plant – Avangard
5	24.3	27.3	26.06–30.06 (June)	30.06–03.07 (June–July)	2.4	2.1	2.0	1.7
10	23.5	26.6	27.06–03.07 (June–July)	30.06–04.07 (June–July)	2.2	1.9	1.8	1.6
15	22.5	26.1	27.06–30.06 (June)	01.07–05.07 (July)	1.7	1.4	1.5	1.3
20	22.2	25.7	29.06–02.07 (June–July)	02.07–06.07 (July)	2.0	1.7	1.8	1.5

Impact of Water Depth on Panicle Initiation (Booting) Stage

In contrast to the earlier growth stages, where deeper flooding tended to suppress vegetative development, increasing the water depth during the panicle initiation (booting) phase enhanced vegetative vigor and improved key yield components. Leaf area responded positively to increased water depth, reaching its maximum at an intermediate depth of 20 cm (Table 4). For the Syr-Sulu variety, leaf area expanded from 280.1 cm² per plant under a 10 cm water layer to 310.5 cm² per plant at 20 cm. A similar trend was observed for Avangard, where leaf area increased from 207.1 cm² at 10 cm to 268.8 cm² at 20 cm. This expansion in leaf surface area suggests that deeper flooding during booting enhances canopy development, likely through improved microclimatic buffering and moderated temperature fluctuations.

Yield components exhibited a parallel response to increased water depth. As the water layer deepened from 10 cm to 20–25 cm, panicles became longer and produced a higher number of grains. Syr-Sulu recorded an increase from 64 to 76 grains per panicle between 10 cm and 20 cm water depth, while Avangard demonstrated a rise from 50 to 62 grains. Moreover, the proportion of unfilled grains decreased appreciably under deeper flooding. For Syr-Sulu, sterility declined from 8.0% at 10 cm to 5.8% at 20 cm, and for Avangard, the lowest sterility value (3.2%) was also observed at the 20 cm depth. These findings indicate that a deeper water layer during the booting stage supports spikelet fertility and contributes to enhanced grain set.

Collectively, the results indicate that maintaining a deeper water layer (up to 20 cm) during the booting phase significantly improves panicle development and yield-related traits. The likely mechanism is the thermal buffering effect of deeper water, which stabilizes the microenvironment around the developing panicle and helps mitigate temperature-induced stress at this sensitive stage.

Table 4. Effect of water layer depth during the panicle initiation–grain filling period on leaf area, panicle structure, and yield components of the rice varieties Syr-Sulu and Avangard

Indicator	Syr-Sulu (10 cm)	Syr-Sulu (15 cm)	Syr-Sulu (20 cm)	Syr-Sulu (25 cm)	Avangard (10 cm)	Avangard (15 cm)	Avangard (20 cm)	Avangard (25 cm)
Leaf area per plant (cm ²)	280.1	308.8	310.5	301.3	207.1	239.8	268.8	246.2
Panicle length (cm)	16.7	17.2	17.6	17.4	16.8	16.9	17.9	17.7
Grains per panicle (no.)	64	66	76	76	50	52	62	57
Unfilled grains (%)	8.0	7.4	5.8	6.5	6.1	6.1	3.2	4.0
Panicle weight (g)	1.5	1.5	1.7	1.8	1.2	1.3	1.5	1.4

Phase-Specific Water Depth Effects on Grain Yield (Pot Experiment)

Emergence Stage Impact on Yield

The controlled pot experiment provided a clear assessment of how floodwater depth during the emergence phase influences final grain yield and its associated components (Tables 5–8). The results demonstrated that maintaining a shallow water depth during the early emergence stage was essential for maximizing grain yield. As shown in Table 5, grain yield per pot declined progressively and significantly as the water depth increased from 5 cm to 20 cm. In the Syr-Sulu variety, grain yield decreased from 53.6 g pot⁻¹ at 5 cm to 43.3 g pot⁻¹ at 20 cm, with a least significant difference (LSD_{0.05}) of 1.3 g pot⁻¹. The Avangard variety showed an even more pronounced sensitivity: yield fell from 33.8 g pot⁻¹ under 5 cm flooding to only 23.4 g pot⁻¹ at 20 cm, with an LSD_{0.05} of 1.5 g pot⁻¹.

This reduction in yield with increasing water depth was primarily driven by a decline in the number of productive tillers per pot, indicating that deep flooding during emergence suppresses early vegetative development. Interestingly, although productive tiller number decreased at greater depths, spikelet sterility exhibited the opposite trend. For example, in Syr-Sulu, sterility declined markedly from 14.1% at 5 cm to 5.1% at 20 cm, suggesting that deeper water during emergence may reduce temperature-induced sterility but at the cost of reduced overall yield potential. Despite this minor compensatory effect, the shallow 5 cm water depth provided the highest yield potential for both rice varieties, confirming that minimal flooding during emergence is optimal for achieving strong physiological establishment and maximizing grain production.

Table 5. Effect of water depth during the emergence stage on grain yield and yield components in the rice varieties Syr-Sulu and Avangard (Pot Experiment).

Variety	Water depth (cm)	Grain yield (g/pot)	Productive tillers (no.)	Tillering coefficient	Panicle length (cm)	Grains per panicle (no.)	Panicle weight (g)	Unfilled grains (%)
Syr-Sulu	5	53.6	31	3.1	17.5	73	1.8	14.1
	10	49.6	28	2.8	17.3	63	1.8	13.7
	15	47.7	26	2.6	17.0	68	1.6	7.2
	20	43.3	25	2.5	17.0	69	1.4	5.1
Avangard	5	33.8	16	1.6	18.4	60	2.0	15.9
	10	28.3	15	1.5	18.0	58	1.9	13.2
	15	26.1	13	1.3	17.5	58	1.8	13.2
	20	23.4	13	1.3	17.3	51	1.6	10.7

Tillering Stage Impact on Yield

During the active tillering phase, maintaining a shallow water layer of approximately 5 cm resulted in the highest grain yields, reinforcing the importance of minimal flooding during early vegetative development (Table 6). In the Syr-Sulu variety, grain yield reached 53.6 g pot⁻¹ under the 5 cm water depth, whereas increasing the water layer to 20 cm reduced yield to 45.0 g pot⁻¹ (LSD_{0.05} = 3.8 g pot⁻¹). This reduction in yield was closely associated with the variety's tillering capacity. Under shallow flooding, Syr-Sulu produced 35 productive tillers per pot, corresponding to a tillering coefficient of 3.5, while deeper flooding at 20 cm resulted in only 25 productive tillers (coefficient 2.6). These results demonstrate that deeper water levels suppress lateral shoot initiation and reduce the number of effective tillers capable of contributing to final yield.

A notable difference from the emergence stage was the effect of water depth on spikelet sterility. While deeper water during emergence tended to reduce sterility, the opposite trend was observed during the tillering phase. For example, Syr-Sulu exhibited a spikelet sterility of 5.6% at 5 cm water depth, which increased substantially to 11.3% under 20 cm flooding. This suggests that excessive water depth during tillering not only restricts tiller formation but also negatively affects grain filling and spikelet fertility.

The Avangard variety exhibited similar patterns: grain yield declined from 35.1 g pot⁻¹ at 5 cm to 28.4 g pot⁻¹ at 20 cm (LSD_{0.05} = 3.0 g pot⁻¹), and the number of productive tillers decreased consistently with increasing water depth. Collectively, these findings highlight the detrimental impact of deep flooding during tillering on both vegetative and reproductive parameters, further affirming that maintaining a shallow water layer is essential for ensuring optimal yield performance.

Table 6. Effect of water depth during the tillering stage on grain yield and yield components in the rice varieties Syr-Sulu and Avangard (Pot Experiment).

Variety	Water depth (cm)	Grain yield (g/pot)	Productive tillers (no.)	Tillering coefficient	Panicle length (cm)	Grains per panicle (no.)	Panicle weight (g)	Unfilled grains (%)
Syr-Sulu	5	53.6	35	3.5	18.7	70	2.0	5.6
	10	49.0	31	3.1	16.4	69	1.8	6.0
	15	47.8	26	2.6	16.1	68	1.8	9.9
	20	45.0	25	2.6	16.1	63	1.7	11.3
Avangard	5	35.1	29	2.9	17.1	62	1.6	5.0
	10	34.3	21	2.1	16.9	60	1.6	8.9
	15	30.0	19	1.9	16.6	57	1.5	8.3
	20	28.4	17	1.7	16.6	55	1.4	9.1

Panicle Initiation Stage Impact on Yield

In clear contrast to the earlier growth stages, the panicle initiation (booting) phase showed an opposite response to water depth, with deeper flooding—approximately 20 cm—proving optimal for maximizing grain yield (Table 7). For the Syr-Sulu variety, grain yield reached 51.2 g pot⁻¹ under the 20 cm water layer, exceeding the yield obtained under 10 cm (49.5 g pot⁻¹). A similar trend was observed in Avangard, where yield increased from 31.7 g pot⁻¹ at 10 cm to 35.6 g pot⁻¹ at 20 cm. These improvements in yield were primarily attributed to enhanced panicle fertility under deeper water conditions.

Increasing the floodwater depth from 10 cm to 20 cm substantially increased the number of filled grains per panicle. In Syr-Sulu, this increase amounted to an additional 17 filled grains, while in Avangard, sterility declined dramatically—dropping from 8.3% at 10 cm to only 3.8% at 20 cm. These data highlight the strong positive influence of deeper flooding on spikelet fertility at this sensitive developmental stage. Although

extremely deep flooding at 25 cm caused a slight reduction in yield relative to the 20 cm treatment, it still maintained relatively high fertility levels, positioning the 20 cm depth as the most physiologically advantageous for panicle initiation.

Collectively, these results demonstrate that deeper water layers during the booting stage enhance microclimatic stability, reduce temperature-induced sterility, and support improved grain filling, thereby establishing 20 cm as the optimal flood depth for maximizing yield potential during this critical reproductive phase.

Table 7. Effect of water depth during the panicle initiation (booting) stage on grain yield and yield components in the rice varieties Syr-Sulu and Avangard (Pot Experiment).

Variety	Water depth (cm)	Grain yield (g/pot)	Productive tillers (no.)	Tillering coefficient	Panicle length (cm)	Grains per panicle (no.)	Panicle weight (g)	Unfilled grains (%)
Syr-Sulu	10	49.5	30	3.0	16.4	64	1.7	12.9
	15	48.7	29	2.9	16.8	66	1.8	11.8
	20	51.2	28	2.8	17.6	81	2.0	9.0
	25	48.4	26	2.6	17.4	82	1.9	9.4
Avangard	10	31.7	21	2.1	16.8	47	1.3	8.3
	15	33.4	23	2.3	17.4	52	1.4	6.0
	20	35.6	23	2.3	17.9	54	1.6	3.8
	25	33.7	20	2.0	17.7	50	1.5	2.9

Ripening Stage Impact on Yield

During the final ripening stage (from heading through wax maturity), excessively deep flooding—particularly at 20 cm—had a detrimental effect on grain yield, reversing the positive influence that deeper water layers exhibited during the earlier panicle initiation stage (Table 8). The highest yield values were consistently obtained under moderate water depths of 5–10 cm, demonstrating that late-season flooding requires a more conservative approach. For the Syr-Sulu variety, grain yield reached 54.1 g pot⁻¹ at 5 cm water depth but declined sharply to 40.2 g pot⁻¹ under a 20 cm water layer. A similar pattern was observed for Avangard, which produced its highest yield of 38.9 g pot⁻¹ at 10 cm before decreasing to 34.3 g pot⁻¹ at 20 cm.

These reductions in yield at deeper water levels likely reflect late-season stresses, including increased susceptibility to lodging, reduced oxygen diffusion, or compromised physiological functioning of the maturing panicle. As plants approach physiological maturity, their structural integrity and metabolic efficiency become more sensitive to excessive flooding, which may hinder assimilate translocation, weaken culm strength, or delay normal grain desiccation processes. Thus, while deeper flooding is beneficial during the booting stage for protecting developing spikelets, it becomes counterproductive during ripening, when moderate water depths support optimal grain filling and minimize stress.

Table 8. Effect of water depth during the ripening stage on grain yield and yield components in the rice varieties Syr-Sulu and Avangard (Pot Experiment).

Variety	Water depth (cm)	Grain yield (g/pot)	Productive tillers (no.)	Tillering coefficient	Panicle length (cm)	Grains per panicle (no.)	Panicle weight (g)	Unfilled grains (%)
Syr-Sulu	5	54.1	26	2.6	17.2	77	2.0	8.1
	10	47.6	28	2.8	17.3	75	1.9	5.4
	15	46.6	27	2.7	17.0	73	1.8	5.3
	20	40.2	25	2.5	16.9	70	1.6	6.6
Avangard	5	36.3	21	2.1	18.2	59	1.7	6.1
	10	38.9	23	2.3	18.7	62	1.9	7.3
	15	37.8	22	2.2	18.1	61	1.6	7.3
	20	34.3	18	1.8	17.7	60	1.6	8.5

Final Yield and Water Use Efficiency (Field Experiment Results)

Mineralization Dynamics of Irrigation Water

The mineralization of irrigation water within the rice checks exhibited a consistent increase in salinity from the beginning to the end of the growing season (Table 9). At the emergence stage, water mineralization levels were nearly identical between the two irrigation regimes, each registering approximately 1.330 g L⁻¹. As the season advanced, however, clear differences emerged between the treatments. Under the conventional continuous flooding system (Variant 1), water mineralization increased more sharply, reaching

2.184 g L⁻¹ by the maturation stage. In contrast, the optimized, phase-specific water management regime (Variant 2) showed a more moderate increase, with mineralization at 2.022 g L⁻¹ during maturation. This divergence suggests that the dynamic water depth regulation in Variant 2 was more effective at limiting the accumulation of salts within the water column.

Ion-specific measurements reinforced this pattern. Chloride (Cl⁻) and sulfate (SO₄²⁻) concentrations were consistently lower in Variant 2 at the later growth stages, reflecting both reduced salt accumulation and enhanced stability in water quality under the phase-specific irrigation strategy. These findings indicate that Variant 2 minimized salinization risk by moderating water depth during critical growth stages, particularly during booting and grain maturation when excessive evaporation under deep water layers can accelerate salt concentration.

Additional field evaluations examining the effect of periodic surface water discharge (drainage releases) revealed that such discharges caused negligible reduction in water mineralization relative to treatments without discharge. However, this practice introduced several negative consequences, including reductions in water temperature and frequent fluctuations in water depth. These fluctuations destabilized the microenvironment of the rice plants, ultimately leading to lower grain yields and increased overall irrigation requirements. Therefore, in fields where adequate drainage infrastructure already exists, the implementation of periodic drainage releases is not recommended due to their detrimental impact on water-use efficiency and yield stability.

Table 9. Mineralization of irrigation water in rice checks at different growth stages (g L⁻¹).

Growth stage	Variant	Water Mineralization (g L ⁻¹)	Cl ⁻ (g L ⁻¹)	SO ₄ ²⁻ (g L ⁻¹)
Emergence	1	1.330	0.098	0.740
	2	1.338	0.099	0.743
Tillering	1	1.523	0.136	0.799
	2	1.529	0.131	0.793
Booting (stem elongation)	1	1.960	0.227	0.869
	2	1.730	0.187	0.839
Maturation	1	2.184	0.273	0.909
	2	2.022	0.240	0.876

Irrigation Water Use Efficiency and Variety Performance

Maintaining an optimal, stage-differentiated water layer substantially improved the efficiency of irrigation water use and reduced total seasonal water consumption per hectare. The optimized regime (Variant 2) demonstrated a clear advantage over the conventional continuous flooding regime (Variant 1), reducing total irrigation water application by approximately 15–20% across both rice varieties. For Avangard, total seasonal irrigation volume decreased from 24,380 m³ ha⁻¹ under the control regime to 20,760 m³ ha⁻¹ under the optimized regime, representing a saving of 3,620 m³ ha⁻¹. Similarly, Syr-Sulu required 21,520 m³ ha⁻¹ under conventional continuous flooding, whereas the optimized schedule reduced this demand to 18,050 m³ ha⁻¹, resulting in a saving of 3,470 m³ ha⁻¹.

These reductions in overall irrigation requirement were also reflected in the specific water use—defined as the volume of irrigation water required to produce 100 kg of grain yield. Under the optimized regime, specific water use decreased markedly to 350 m³ per 100 kg for Syr-Sulu and 420 m³ per 100 kg for Avangard. Relative to the conventional regime, this represents an improvement of 150 m³ per 100 kg of grain yield for both varieties. Such enhancements in water-use efficiency underscore the agronomic and environmental benefits of implementing a phased, growth-stage-specific water management strategy in rice systems, particularly in arid and water-limited regions.

Table 10. Average irrigation norm and specific water use for rice under two contrasting water regimes (Syr-Sulu / Avangard).

Variant	Average Irrigation Norm (m ³ ha ⁻¹)	Specific Water Use (m ³ per 100 kg yield)
1 (Control)	21,520 / 24,380	500 / 570
2 (Optimized)	18,050 / 20,760	350 / 420
Difference vs. Var 1	3,470 / 3,620	150 / 150

Water Balance of the Rice Field

Detailed water balance calculations (Table 11) further confirmed the effectiveness of the optimized irrigation strategy. Under the conventional continuous flooding regime (Variant 1), the dominant components of water consumption were percolation, evaporation, and plant transpiration. Percolation (filtration) constituted 33.5–39.9% of the total water inflow, making it the single largest pathway of water loss. Evaporation accounted for 21.2–24.4%, while transpiration represented 18.4–21.6% of the total inflow.

These proportions highlight the inherently high water demand of traditional continuous flooding systems and the substantial inefficiencies associated with uncontrolled deep-water layers throughout the growing season.

By contrast, the optimized irrigation regime (Variant 2) eliminated the need for surface drainage discharge, a component that accounted for 13.8% of the total outflow under the conventional treatment. In Variant 2, drainage discharge was 0%, demonstrating the precision with which water levels were maintained and highlighting a major source of the 15–20% reduction in total irrigation requirement. The phase-specific water management not only reduced unnecessary water accumulation but also stabilized soil moisture and minimized fluctuations in field water depth, leading to more favorable physiological conditions for rice growth.

The overall closure error of the water balance—ranging from 1.3% to 5.3% across treatments and varieties—indicates a high level of accuracy in inflow and outflow measurements, confirming the reliability of the field water balance assessments. The consistency of these results across both rice varieties, Syr-Sulu and Avangard, demonstrates that the optimized regime improved water distribution and retention, reduced non-productive losses, and contributed directly to enhanced water-use efficiency.

Table 11. Water balance of rice fields under two irrigation regimes for the varieties Syr-Sulu and Avangard.

Indicator	Var 1 (Syr-Sulu) (m3/ha)	Var 1 (Syr-Sulu) (%)	Var 2 (Syr-Sulu) (m3/ha)	Var 2 (Syr-Sulu) (%)	Var 1 (Avangard) (m3/ha)	Var 1 (Avangard) (%)	Var 2 (Avangard) (m3/ha)	Var 2 (Avangard) (%)
Inflow:								
– Water supply (irrigation)	21.48	99.80	18.01	99.80	24.34	99.80	20.72	99.80
– Rainfall	40.00	0.20	40.00	0.20	40.00	0.20	40.00	0.20
Total Inflow	21.52	100.00	18.05	100.00	24.38	100.00	20.76	100.00
Outflow:								
– Soil saturation	2.69	12.10	2.70	14.20	2.95	12.10	2.95	14.20
– Evaporation	4.71	21.20	4.61	24.30	5.12	21.20	5.02	24.30
– Transpiration	4.09	18.40	4.11	21.60	4.38	18.40	4.40	21.60
– Percolation (filtration)	7.66	34.50	7.58	39.90	8.20	34.50	8.12	39.90
– Drainage discharge	3.07	13.80	0.00	0.00	3.37	13.80	0.00	0.00
Total Outflow	22.22	100.00	19.00	100.00	24.02	100.00	20.49	100.00
Balance Error (In-Out)	–700	–3.2	–950	–5.3	+360	+1.5	+270	+1.3

Discussion

This study investigated an integrated water management strategy designed to address the key constraints of rice production in the arid, saline environment of the Aral Sea basin, specifically focusing on weed infestation, water scarcity, and yield stability. The central hypothesis—that phase-specific water depth regulation combined with pre-sowing intervention could optimize these limiting factors—was strongly supported by the results obtained across three years of field and pot experimentation.

Weed and Salinity Management through Pre-Sowing Intervention

The initial component of the optimized strategy—provocative pre-sowing irrigation (Stale Seedbed Technique)—fulfilled a dual agronomic function. First, it effectively stimulated mass germination of the predominant paddy weeds, primarily *Echinochloa* spp. (280–336 seedlings m⁻²) and *Phragmites australis* (45–62 seedlings m⁻²) (Figures 2, 4). The subsequent mechanical elimination of these emerged weed seedlings prior to sowing resulted in nearly weed-free rice stands and eliminated the need for chemical herbicide application. This weed control mechanism aligns with integrated weed management principles that recommend cultural practices to reduce the weed seedbank prior to crop establishment (Ismail et al., 2012). It also avoids environmental risks associated with herbicide use, including resistance development and contamination of water bodies—particularly problematic in the fragile ecosystem of the Aral Sea region (Voccia et al., 2024; Bartrem et al., 2025).

Second, the provocative irrigation acted as an efficient leaching event. Prior to irrigation, the 0–20 cm soil layer exhibited high soluble salt concentrations—up to 0.853% dry residue. The downward movement of salts following leaching effectively reduced salinity in the root zone, shifting the soil's classification from highly saline to weakly saline (Figure 3). This early-season desalination is crucial because rice is highly

sensitive to salt stress during seedling establishment and early vegetative growth (Zeng and Shannon, 2000; Grattan et al., 2002). The trend of continuing desalination under ponded conditions throughout the season further underscores the importance of controlled water movement in ameliorating salinity stress in marginal soils (Table 8).

The desalination response observed in this study is also in line with broader regional reclamation research. Earlier work on soda-saline solonetz soils has shown that removing Na-dominance through Ca^{2+} -based amendments (phosphogypsum, sulfuric acid or elemental sulfur) combined with controlled leaching effectively improves soil physical properties and crop establishment (Duisenbayeva et al., 2023; Naushabayev et al., 2024). While these approaches rely on chemical amendments to trigger ionic replacement and salt displacement, our results demonstrate that a strategically timed water-based intervention can produce similar early-season improvements in root-zone salinity. This provides a new, non-chemical pathway for managing salinity in the rice-based systems of the Aral Sea basin, particularly where resource constraints or environmental considerations limit the use of mineral ameliorants.

Stage-Specific Water Depth Effects on Stand Establishment and Tillering

The experimental results demonstrated unequivocally that optimal floodwater depth is strongly stage-dependent, consistent with global research on rice hydrodynamics (Carrijo et al., 2017). During the emergence phase, maintaining a shallow 5 cm water layer was essential for maximizing stand establishment and final yield potential. This treatment preserved significantly warmer seedbed temperatures (22.5 °C at 5 cm versus 20.7 °C at 20 cm), which enhanced both the speed and rate of emergence (Table 1). The negative effect of deeper flooding was particularly evident for Avangard, whose emergence declined from 32.9% at 5 cm to only 9.0% at 20 cm. Such declines are consistent with known inhibitory effects of deep flooding, including reduced soil temperature and increased risk of hypoxia, which suppress germination and early seedling vigor (Zeng et al., 2003; Chamara et al., 2018).

During the tillering phase, the superiority of shallow water (5 cm) was again evident. Increasing the flood depth to 15–20 cm delayed the onset of tillering and reduced the number of productive tillers per plant. For example, productive tillers in Syr-Sulu declined from 2.0 per plant at 5 cm to 1.5 per plant at 15 cm (Table 2). Since panicle number is a primary determinant of rice yield, suppression of tillering significantly limits the crop's sink capacity and, consequently, its final yield potential (Table 5). The physiological basis of this response lies in the cooling effect of deeper water on the tillering node, which slows metabolic processes and reduces lateral shoot initiation (Yoshida, 1981).

Reproductive Stage: Thermal Buffering and Maximizing Fertility

In contrast to the early vegetative stages, the reproductive phase—particularly panicle initiation (booting)—responded most favorably to a moderately deep water layer of approximately 20 cm. This depth enhanced leaf area development, increased grains per panicle (e.g., Syr-Sulu: 76 at 20 cm vs. 64 at 10 cm), and significantly reduced spikelet sterility (Table 3, 6). Avangard exhibited an especially strong response, with sterility falling from 8.3% at 10 cm to only 3.8% at 20 cm.

These responses are consistent with the need for thermal buffering during the temperature-sensitive reproductive phase. The deeper floodwater layer stabilizes the microclimate surrounding the developing panicle primordia, protecting it from high-temperature events that can induce floret abortion (Shimono et al., 2007; Jagadish, 2020). Therefore, deeper water at booting was a critical contributor to improved spikelet fertility and ultimately higher grain yield.

Collectively, the results validate a tripartite water management schedule:

1. Shallow water during emergence for warm seedbeds and rapid stand establishment.
2. Shallow-to-moderate water during tillering to maximize vegetative sink potential.
3. Moderately deep water (up to 20 cm) during booting to protect developing spikelets.
4. Moderate water during ripening to avoid lodging and grain-filling disruption.

Water Use Efficiency and Field Water Balance

The optimized, stage-differentiated water regime (Variant 2) provided substantial gains in water productivity. Seasonal irrigation demand was reduced by 15–20%, corresponding to water savings of approximately 3,500 m³ ha⁻¹ (e.g., 24,380 m³ ha⁻¹ to 20,760 m³ ha⁻¹ for Avangard) (Table 10). These reductions were directly reflected in improved specific water use, with a 150 m³ per 100 kg grain improvement for both varieties.

The field water balance (Table 11) clarified the mechanisms behind these savings:

1. Under the conventional regime, percolation (filtration) was the largest water loss pathway, accounting for 33.5–39.9% of total inflow.
2. The optimized regime reduced this unproductive loss by minimizing excessive ponding during the vegetative and ripening stages, while still maintaining necessary transpiration losses (18–22%), which directly drive yield formation (Bouman and Tuong, 2001).
3. The optimized strategy eliminated the 13.8% loss through drainage discharge observed in the conventional system, without compromising water quality or increasing mineralization (Table 9, 11).

Together, these findings highlight the operational, agronomic, and environmental benefits of stage-specific water regulation, particularly in water-scarce and salinity-prone environments. This research offers a comprehensive, field-validated, and environmentally aligned strategy for high-yield rice production in the Aral Sea basin. By integrating pre-sowing weed control and desalination with a nuanced, stage-specific floodwater management regime, it effectively addresses the region's major constraints—salinity, water scarcity, and weed pressure—while enhancing yield potential by 15–20%. The findings provide a practical and scalable framework for modernizing rice irrigation practices in arid, saline landscapes.

Conclusion

This study conclusively demonstrates that an integrated, resource-efficient water management strategy—combining provocative pre-sowing irrigation with stage-specific regulation of floodwater depth—provides a superior and sustainable alternative to the conventional practice of continuous deep flooding in the arid, saline environment of the Aral Sea basin. The first component, provocative irrigation, proved to be an effective ecological tool by inducing massive germination of the dominant paddy weeds (*Echinochloa* spp. and *Phragmites australis*), thereby enabling their complete mechanical removal prior to crop establishment. This facilitated herbicide-free rice cultivation without compromising crop vigor while simultaneously reducing salinity in the critical root zone, thus lowering both environmental risk and soil-borne stress during early seedling growth (Zeng and Shannon, 2000).

The results unequivocally demonstrate that optimal floodwater depth must be dynamically aligned with the physiological requirements of the crop. During the early vegetative stages—emergence through tillering—a shallow 5 cm water layer was essential for maximizing stand establishment and productive tiller formation. This depth minimized the combined stresses of low soil temperature and hypoxia, resulting in substantially higher emergence rates (up to a 70% improvement over the 20 cm depth for Avangard) and supporting vigorous above-ground biomass accumulation (Table 1, 2). In contrast, during the temperature-sensitive reproductive phase, especially panicle initiation and flowering, temporarily increasing the water depth to 20 cm was critical. This deeper water column provided an effective thermal buffer, protecting developing spikelets from temperature shocks that induce sterility, which in turn increased the number of filled grains per panicle and enhanced final grain yield (Jagadish, 2020; Table 3).

Importantly, the precise control of water depth translated directly into significant environmental and economic benefits. Implementation of the stage-specific irrigation regime (Variant 2) reduced total seasonal irrigation demand by approximately 20%—equivalent to a water saving of about 3,500 m³ ha⁻¹—compared with conventional deep flooding. These savings were achieved primarily by suppressing unproductive deep percolation losses, the dominant pathway of water outflow under high hydrostatic pressure (Bouman and Tuong, 2001), while maintaining adequate transpiration to support yield formation. Despite reduced water input, the optimized regime simultaneously increased overall grain yield by 15.3–20.6%, indicating that water-use efficiency gains were achieved in tandem with productivity improvements.

In summary, the findings highlight a robust, scalable, and ecologically aligned strategy for sustainable rice production in water-limited and saline environments. The integration of provocative irrigation with stage-specific floodwater regulation enables effective weed suppression without chemical herbicides, conserves substantial volumes of irrigation water, and significantly boosts grain yield. Adoption of this optimized irrigation regime is therefore critical for enhancing resource-use efficiency, improving yield stability, and strengthening climate-resilient rice production systems in arid and saline environments. The findings are also complementary to recent studies that applied chemical ameliorants for reclaiming saline-alkali soils in Central Asia, yet the present work demonstrates that comparable early-season desalination can be achieved through a water-based approach alone, offering a scalable, low-cost alternative for salinity management.

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