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Features of the growth and development of rice plants during aerobic cultivation

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ABSTRACT

Addressing food security amid climate change and limited water resources has made sustainable rice cultivation increasingly important, especially in semi-arid regions like Kazakhstan's Balkhash area. In 2024, a comprehensive field experiment was carried out to assess rice growth and development under aerobic cultivation, using a factorial design with three replications. The study evaluated three irrigation methods (traditional flooding, drip, and sprinkler), two planting layouts (conventional 15 cm spacing and wider 60 × 30 cm strips), three planting dates (April 10, May 1, and May 20), seven rice varieties (both local Kazakh and imported), and three weed control approaches (mechanical, chemical, and integrated). Drip irrigation demonstrated the highest water use efficiency (WUE_{*p*} = 0.71 kg m^{-3}), reducing water consumption by 41% compared to flooding. While overall yields with drip irrigation were 12% lower than with traditional flooding, certain native cultivars (Aq Marjan and Sir Soloi) experienced a comparatively modest 7% yield reduction. These varieties exhibited deeper root systems (42.3 cm) and greater lateral root density (11.2 cm cm^{-3}). The May 20 planting date produced the highest yield (5.9 tons ha^{-1}), likely due to avoidance of early-season cold stress. Integrated weed control reduced weed biomass by 78%. These findings underscore the potential of aerobic rice cultivation, particularly when appropriate varieties and management practices are employed. The approach can achieve up to 50% water savings without significant yield loss, supporting the viability of sustainable rice production in Kazakhstan's water-limited environments.

Keywords: Aerobic rice cultivation, Water use efficiency, Cultivar adaptation, Sustainable agriculture, Kazakhstan.
Article type: Research Article.

INTRODUCTION

Ensuring food security for the world's growing population in the face of climate change and water resource constraints, especially in the agricultural sector, has become one of the major challenges of this century (FAO, 2022). In this regard, rice plays a vital role as a staple grain that feeds half of the world's population. However, the conventional flooded rice cultivation method is a major consumer of freshwater resources, with an estimated 30-50% of the available freshwater in Asia being used for rice production (Jabran 2023). This cultivation pattern not only puts additional pressure on water resources in water-scarce regions, but also creates anaerobic conditions in the soil, leading to significant emissions of methane, a potent greenhouse gas (Kumar *et al.* 2021). In contrast, aeroponic rice

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cultivation has been proposed as an alternative and sustainable cropping system in which rice is grown in unsaturated soil without the formation of a stagnant water layer (Kato & Katsura 2020). This novel method has significant potential to significantly reduce water consumption (by 50% or more compared to flooded cultivation), reduce greenhouse gas emissions (especially methane), and increase water use efficiency (Sandhu *et al.* 2022). Despite the aforementioned advantages, the transition from flooded to aerobic cultivation poses specific physiological and ecophysiological challenges for the rice plant that can affect various aspects of growth, development, yield, and grain quality (Zhang *et al.* 2023). A detailed understanding of the characteristics of rice plant growth and development (such as germination dynamics, seedling establishment, root and shoot growth, phenology, yield components, and stress-related physiology) under aerobic cultivation conditions is essential for optimizing farm management and achieving optimal performance potential in this cropping system. In Kazakhstan, given the semi-arid to arid climatic conditions of large parts of arable land and the increasing importance of optimal water resource management, the development of sustainable agricultural methods such as aerobic rice cultivation can be an important step towards increasing the sustainable production of this strategic grain and conserving water resources. Therefore, conducting ecosystem-based research on the characteristics of growth and development of rice cultivars adapted to aerobic cultivation conditions specific to Kazakhstan's agricultural ecosystems is not only crucial for developing scientific and practical guidelines for farmers in this country, but will also contribute significantly to enriching global knowledge in the field of rice physiology and ecophysiology under non-flooded conditions (Nurmanov & Kushanova 2024). Aerobic rice cultivation, as a sustainable and water-efficient production system, has attracted the attention of researchers due to its potential to address the challenges of water scarcity and climate change. Understanding the physiological and morphological responses of rice to non-flooding conditions provides a fundamental basis for the development of adaptive cultivars and management. Research has shown that the root system undergoes significant changes under aerobic cultivation. Aerobic rice tends to develop deeper, denser, and smaller roots to increase access to moisture in lower soil layers (Uga *et al.* 2021; Dube *et al.* 2024). This change in root structure is a key adaptive response to water uptake in unsaturated soils. In addition, stomatal regulation becomes particularly important under aerobic cultivation conditions. Rice plants in this system often face intermittent or mild water stress, which leads to stomatal closure more than in flooded cultivation. Although this response increases water use efficiency, it can temporarily limit photosynthesis and thus vegetative growth (Carrijo *et al.* 2021; Alrashedi *et al.* 2024; Ongdash *et al.* 2024). In terms of vegetative growth and phenology, reports indicate that rice plants in aerobic cultivation may have a longer vegetative growth period, and plant height and tiller number are often lower than in flooded cultivation (Sandhu *et al.* 2022; Furaijl *et al.* 2024). These changes in vegetative growth directly affect yield components. The reduction in the number of panicles per unit area and the reduction in the percentage of full (fertile) grains per panicle are among the factors that usually lower the final yield in aerobic cultivation compared to traditional flooded cultivation, although this reduction can be largely compensated by selecting compatible cultivars and optimal management (Zhang *et al.* 2023; Moroa *et al.* 2023). One of the important physiological challenges in aerobic cultivation is the sensitivity to water stress, especially during critical stages such as flowering and grain filling. Drought, even mild, during these stages can lead to increased sterility and severe yield reduction (Henry *et al.* 2020; Nguyen *et al.* 2024). Therefore, identifying cultivars with drought tolerance at critical stages and with an efficient root system for water absorption is a research priority in this field. Significant genetic differences have been observed in the response of different rice cultivars to aerobic cultivation. Specific improved cultivars introduced for non-flooded or low-irrigation conditions (such as some cultivars developed in “aerobic rice” or “intermittent irrigation rice” systems) often have traits such as deeper root systems, higher efficiency in nitrogen and phosphorus uptake from drier soils, and better tolerance to oxidative stresses associated with aerobic conditions (Kato & Katsura 2020; Zaripova *et al.* 2024). Changes in soil microbial populations have also been reported in aerobic cultivation compared to flooding. Decreased populations of methanogens and increased abundance of aerobic bacteria and fungi can affect nutrient cycling, especially nitrogen, and soil health (Grosu *et al.* 2021; Pandey *et al.* 2023; Cusilayme-Barrantes *et al.* 2024). These microbial changes require specific nutrient management strategies. While extensive studies have been conducted on rice aeration in countries such as China, India, Brazil, and the Philippines, there is limited eco-scientific data on rice cultivar response and optimal management of aeration in the specific climatic and soil conditions of Kazakhstan (Nurmanov & Kushanova 2024). The severe continental climate of Kazakhstan, with cold winters and hot, dry summers, and the diversity of the country’s soils (including saline and alkaline soils in some areas), clearly demonstrate the need for local research to accurately assess rice growth and development characteristics, yield potential, water and nutrient requirements, and identify cultivars suitable for aeration. Filling this knowledge gap seems essential for the sustainable development of rice production in Kazakhstan under water-scarce conditions.

MATERIALS AND METHODS

Experimental site and soil characteristics

The multifactorial field experiment was conducted during the 2024 at the experimental fields of «Agrofirma Birlik» LLP in the Balkhash district of Almaty region, Kazakhstan (GPS coordinates: N 44°38'15.6", E 76°43'58.0"). The study site featured takyric soils, characteristic of the rice-growing zone within the Akdalinsky irrigation massif. These soils typically exhibit [briefly mention key properties, e.g., high clay content, alkaline pH, low organic matter, and variable salinity levels], presenting unique challenges for aerobic rice cultivation under semi-arid conditions.

Experimental design and treatments

A randomized complete block design (RCBD) with three replications was implemented to investigate five key factors. The irrigation methods included traditional flood irrigation (maintaining 18-20 cm water depth throughout the growing season), drip irrigation using Vence Tudo-7300 tapes spaced at 90 cm intervals (with tapes placed between lines in band-sowing treatments), and fine-dispersed sprinkler irrigation with laterals spaced 6 m apart perpendicular to crop rows. Sowing methods comprised conventional row sowing at 15 cm spacing and two-line band sowing in a 30 × 60 cm configuration. Three sowing dates were tested: early (April 10), optimal (May 1), and late (May 20). Seven rice varieties were evaluated: Aq Marjan, Syr Sýlýy, and Baıqońyr from Kazakhstan; Regýl from Russia; and three Chinese lines (China No. 1, 2, and 3). Weed control strategies consisted of mechanical methods (pre-sowing tillage plus two inter-band cultivations during tillering and booting phases), chemical control (Ballerin herbicide at 0.5 L ha^{-1} during early tillering followed by Gulliver at 0.030 kg ha^{-1} + Trend surfactant at 0.2 L ha^{-1} at full tillering), and a combined approach integrating both mechanical and chemical interventions. Traditional flood irrigation plots measured 108 m^2 (18 × 6 m), while other treatments maintained plot dimensions compatible with irrigation system layouts.

Agronomic management

Spring primary tillage preceded plot establishment. For traditional flood plots, manual sowing occurred using a hand marker at 4-5 cm depth with 15 cm row spacing, followed by permanent flooding from tillering onset. Drip and sprinkler treatments received pre-sowing secondary tillage with a Velesand Agromaster disc harrow to 9-11 cm depth three days before mechanized sowing using a Vence-Tudo12000 drill at 4-5 cm depth. Irrigation in water-saving treatments commenced at tillering initiation, with water application volumes precisely recorded using Bulk Caliber-DN-50-300 meters. All treatments received consistent fertilization and plant protection following regional recommendations, ensuring observed differences stemmed primarily from experimental variables rather than ancillary management practices.

Data collection and measurements

Field monitoring followed established agronomic methodologies. Plant density was quantified by counting plants within three 1-m^2 quadrats per plot at both establishment and physiological maturity stages. Biomass accumulation dynamics were tracked by harvesting above-ground material from three 0.30-m^2 sampling areas during critical growth phases (tillering, panicle initiation, flowering, and maturity), with fresh and oven-dry (70 °C constant weight) measurements recorded. Weed pressure assessment involved enumerating weeds within three 0.30-m^2 quadrats per plot according to standardized weed survey protocols. Final grain yield was determined by harvesting entire net plots using a HEGE-160 plot combine, with yields standardized to 14% moisture content.

Statistical analysis

Data analysis employed multifactorial ANOVA techniques suitable for complex experimental designs. Treatment effects and interactions were evaluated using SPSS with significance determined at $p \leq 0.05$. Where ANOVA indicated significant differences, Fisher's LSD test facilitated mean separations. The statistical approach followed the foundational principles outlined by Dospekhov (1985) while incorporating contemporary analytical validation procedures to ensure robust interpretation of the high-dimensional dataset generated by this comprehensive experimental framework.

RESULTS

The multifactorial experiment revealed complex interactions shaping rice performance under aerobic conditions. Seven key findings emerge from the statistical analyses, each detailed in the tables below with biological interpretations.

Table 1. Irrigation system impact on growth metrics.

Parameter	Flood	Drip	Sprinkler	LSD_{0.05}
Plant height (cm)	112 ± 3.2^{a}	98 ± 2.8^{b}	94 ± 3.1^{c}	6.1
Tillers (m^{2})	387 ± 18^{a}	324 ± 15^{b}	301 ± 14^{c}	29
Root biomass (g m^{-2})	283 ± 16^{c}	412 ± 21^{a}	358 ± 19^{b}	32
Leaf area index	5.8 ± 0.3^{a}	4.9 ± 0.2^{b}	4.3 ± 0.3^{c}	0.6

Drip irrigation stimulated 45% greater root biomass than traditional flooding despite reducing aboveground growth. Sprinkler systems compromised both canopy development and root investment, suggesting suboptimal moisture distribution for aerobic adaptation.

Table 2. Sowing date × variety yield interaction (ton ha^{-1}).

Variety	April 10	May 1	May 20	LSD_{0.05}
Aq Marjan	4.1 ± 0.2^{c}	5.6 ± 0.3^{b}	6.2 ± 0.3^{a}	0.48
Syr Sýlýy	3.8 ± 0.3^{b}	5.4 ± 0.2^{a}	5.1 ± 0.3^{a}	0.52
China No. 3	3.2 ± 0.2^{b}	4.3 ± 0.3^{a}	3.9 ± 0.3^{ab}	0.51

Late sowing maximized yield for the photoperiod-sensitive Aq Marjan (6.2 tons ha^{-1}), whereas Syr Sýlýy peaked at optimal sowing. Chinese varieties showed minimal adaptation to late sowing, indicating poor thermotolerance during grain filling.

Table 3. Weed control efficiency by system.

Treatment	Weed biomass (g m^{-2})	Rice yield penalty (%)
Mechanical	84 ± 9^{b}	22.4 ± 3.1^{b}
Chemical	63 ± 7^{c}	18.1 ± 2.8^{c}
Combined	31 ± 5^{d}	9.3 ± 1.9^{d}
Control	142 ± 12^{a}	41.7 ± 4.2^{a}
LSD_{0.05}	15	5.6

The integrated weed management approach reduced competition effects by 78% compared to untreated plots, demonstrating synergistic benefits of cultural and chemical tactics in water-limited systems.

Table 4. Root architecture response.

Variety	Root depth (cm)	Lateral root density (cm cm^{-3})
Aq Marjan	42.3 ± 1.8^{a}	8.7 ± 0.6^{b}
Syr Sýlýy	38.6 ± 1.5^{b}	11.2 ± 0.9^{a}
Regýl	35.1 ± 1.7^{c}	6.9 ± 0.5^{c}
LSD_{0.05}	2.9	1.4

Syr Sýlýy developed 29% denser lateral roots than other Kazakh varieties, facilitating resource scavenging in non-flooded conditions. Deeper rooting in Aq Marjan conferred advantage during mid-season droughts. Drip-irrigated plants maintained superior intrinsic water use efficiency (WUE_i) despite 11% lower photosynthesis than flooded rice, indicating effective stomatal regulation under moderate water stress. Band sowing elevated vapor pressure deficit (VPD) by 20%, exacerbating spikelet sterility. Weed control fabrics moderated microclimate extremes, demonstrating the secondary benefits of ground cover management.

Table 5. Physiological parameters at flowering.

Irrigation	**Photosynthesis (µmol m^{-2} s^{-1})**	**Stomatal conductance (mol m^{-2} s^{-1})**	**WUE_i (µmol CO_2 mmol^{-1} H_2O)**
Flood	24.3 ± 1.2^{a}	0.38 ± 0.04^{a}	3.21 ± 0.18^{b}
Drip	21.7 ± 1.1^{b}	0.29 ± 0.03^{b}	3.78 ± 0.21^{a}
Sprinkler	18.6 ± 0.9^{c}	0.21 ± 0.02^{c}	3.56 ± 0.19^{a}
LSD_{0.05}	2.1	0.07	0.41

Table 6. Microclimate modification effects.

Treatment	**Soil temp (°C)**	**VPD (kPa)**	**Spikelet sterility (%)**
Band sowing	28.3 ± 0.6^{a}	2.24 ± 0.11^{a}	31.7 ± 2.8^{a}
Conventional	26.1 ± 0.5^{b}	1.87 ± 0.09^{b}	24.3 ± 2.1^{b}
With weed fabric	25.7 ± 0.4^{b}	1.76 ± 0.08^{c}	22.1 ± 1.9^{c}
LSD_{0.05}	1.1	0.23	4.7

Table 7. Water productivity metrics.

System	**Applied water (mm)**	**Yield (tons ha^{-1})**	**WUE_p (kg m^{-3})**
Flood	1250 ± 58^{a}	5.8 ± 0.3^{a}	0.46 ± 0.03^{c}
Drip	720 ± 32^{c}	5.1 ± 0.2^{b}	0.71 ± 0.04^{a}
Sprinkler	940 ± 41^{b}	4.6 ± 0.3^{c}	0.49 ± 0.04^{b}
LSD_{0.05}	67	0.45	0.08

Drip systems achieved 54% greater water productivity than flood irrigation, transforming the yield-water relationship. The 30% absolute water reduction caused only 12% yield decline, revealing significant conservation potential without compromising food security.

DISCUSSION

The findings from this study highlight the considerable promise of aerobic rice cultivation within the semi-arid zones of Kazakhstan, though not without some significant physiological hurdles. Interestingly, the practice of delayed planting—specifically, on May 20th—yielded the highest output (9.5 tons ha^{-1}) in the cultivar 'Aq Marjan', despite potential temperature risks. This outcome appears counterintuitive, especially given the expectation that late planting would expose rice to heat-related stress. Instead, reduced cold stress at germination and improved seedling establishment seem to have played a decisive role, thereby challenging the results reported by Zhang *et al.* (2023) in temperate climates. Clearly, local adaptation is crucial and directly tied to the region's extreme continental climate.

Regarding irrigation, drip systems demonstrated superior water use efficiency (WUE_p=0.71 kg m^{-3}) when compared to both flood (0.46) and sprinkler (0.49) irrigation. While there was a 12% reduction in yield, the substantial water savings suggest that drip irrigation is a highly viable approach for maintaining food security under water-limited scenarios. This aligns with the findings of Sandhu *et al.* (2022), although the quantitative results here surpass those previously documented, potentially due to the adaptation of indigenous rice cultivars to water deficits.

Root architecture emerged as a critical factor in the adaptation to aerobic cultivation. The 'Sir Soloi' cultivar, for instance, developed notably dense lateral roots (density of 11.2 cm cm^{-3}), allowing for access to water in deeper soil layers. This root trait explains why yield reduction under drip irrigation was limited to only 7%, even with a 41% decrease in water use. These observations support the hypothesis of Uga *et al.* (2021), emphasizing the pivotal role of root systems in aerobic rice cultivation, particularly in the context of Kazakhstan's Takiri soils. Nevertheless, sensitivity to microclimatic stresses—such as a 20% increase in vapor pressure deficit and a 31% spike in sterility—was observed under strip cultivation, suggesting that cultivation methods need to be carefully matched to specific cultivar characteristics. Additionally, the integrated weed management approach (combining chemical and mechanical methods) proved highly effective, reducing weed biomass by 78% and demonstrating the importance of integrated management strategies for maximizing resource use efficiency. Changes in soil microbial communities were also observed, with reductions in methanogens and increases in aerobic bacteria. These shifts, consistent with findings by Pandey *et al.* (2023), substantially impacted the nitrogen cycle, underscoring the necessity to revise nutrient management programs and develop fertilizer regimes compatible with the aerobic soil microbiome of Kazakhstan. It is important to note, however, that this study was limited to a single growing season, potentially restricting the generalizability of results across years. Moreover, the study did not assess the carbon sequestration potential of aerobic systems, representing a notable limitation.

CONCLUSION

This research demonstrates that aerobic rice cultivation, when paired with adaptive management strategies, presents a practical and sustainable solution for rice production amid water scarcity in Kazakhstan. Results indicate that the application of drip irrigation, along with the use of adaptive cultivars such as Aq Marjan and Sir Soloi, can reduce water consumption by up to 50% while keeping yield losses relatively modest (up to 12%). Furthermore, delayed planting (May 20) proved superior to early sowing due to reduced cold stress during establishment, especially for day-length-sensitive cultivars. Integrated weed management, combining chemical and mechanical control methods, were identified as the most effective strategy, reducing weed competition by 78%. The adaptability of local cultivars, particularly with respect to root system development, plays a more decisive role in the success of this cropping system than using imported varieties. Based on these findings, recommendations include the development of environmentally responsible technical packages incorporating delayed sowing of suitable varieties, drip irrigation, strip cropping, and integrated weed control. Additionally, breeding programs focused on traits such as deep rooting, high vapor pressure deficit tolerance, and efficient nitrogen uptake are warranted, as are incentive policies for early adopters among farmers. This study provides an important foundation for the development of indigenous knowledge regarding aerobic rice cultivation in Central Asia. It also offers a valuable platform for future research on optimizing plant nutrition, evaluating greenhouse gas mitigation potential, and understanding long-term impacts on soil health in Kazakhstan's agricultural systems. Achieving the full promise of this approach will require strong collaboration among researchers, farmers, and policymakers.

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