Journal of Agricultural Science and Technology (JAST), 29(5)
In Press, Pre-Proof Version

Evaluating Aerobic Rice Breeding Lines: Performance under Aerobic Conditions and Reproductive-Stage Drought Stress

Ali Moumeni[1]*, Mehrdad Amooghli Tabari[1], Abolfazl Faraji[2], Mostafa Yousefian[1], Vahid Khosravi[1], and Hadi Moumeni-Helali[1]

Abstract

Water scarcity and increasingly frequent droughts threaten rice production, highlighting the need for potentially water-saving cultivation systems. Aerobic rice—grown under non-flooded conditions—offers a sustainable alternative by reducing water demand while maintaining productivity. This study evaluated 23 advanced aerobic rice breeding lines derived from crosses among Iranian local cultivars and aerobic donors, alongside four check cultivars, under three cultivation systems: conventional flooded transplanting, reproductive-stage drought stress, and fully aerobic conditions. They were evaluated across three major rice-growing regions of Iran representing distinct agro-ecological zones. Agronomic traits, yield components, grain yield, and cooking quality parameters were measured and analyzed under each individual-environment and combined ANOVA. Because Bartlett's test indicated heterogeneous error variances, rank-based non-parametric stability statistics were used to assess consistency of genotype rankings across aerobic environments. Results revealed significant performance differences among lines under different conditions. C1-21 showed the highest grain yield among the breeding lines under reproductive-stage drought stress (3967 kg ha^{-1}), whereas C1-26, C1-21, and C1-1 (Amol) and C2-4, C2-14, and C1-9 (Gorgan) were the highest-yielding breeding lines under aerobic cultivation, compared with 1140 and 6967 kg ha^{-1} for the aerobic check Vandana, respectively. Grain quality parameters showed that most lines had intermediate amylose content (19-22%), desirable cooking elongation (1.65-1.99), and grain shapes similar to popular Iranian varieties. The results indicate that specific adaptation and rank-based stability should be considered separately when selecting lines for aerobic rice breeding.

Keywords: Aerobic rice, Breeding lines, Drought stress, Grain quality, Water-use efficiency.

[1] Rice Research Institute of Iran, Mazandaran Branch, Agricultural Research, Education and Extension Organization (AREEO), Amol, Islamic Republic of Iran.
[2] Gilan Agricultural and Natural Resources Research and Education Center, Agricultural Research, Education and Extension Organization (AREEO), Rasht, Islamic Republic of Iran.
*Corresponding author; e-mail: amoumeni@areeo.ac.ir

Introduction

Rice (*Oryza sativa* L.) is one of the most important staple food crops worldwide, providing the primary source of calories for more than half of the global population, particularly in Asia (FAO, 2021). Globally, rice contributes nearly 20% of total dietary energy intake, making its sustainable production essential for the food security (Bouman et al., 2007b). In Iran, rice is the second most important cereal crop after wheat and is mainly cultivated in the northern provinces such as Mazandaran, Guilan and Golestan, where it plays a crucial socio-economic and cultural role (Moumeni, 2014). However, many traditional Iranian cultivars, although highly preferred for their excellent cooking quality and aroma, are characterized by severe lodging, low harvest index, and high-water requirements, making them vulnerable under water-limited conditions.

Water scarcity is increasingly recognized as one of the most critical constraints to rice production worldwide. Conventional flooded rice cultivation requires large volumes of water, often exceeding 3000–5000 L kg^{-1} of grain produced (Bouman et al., 2005; Tuong and Bouman, 2003). Increasing competition for freshwater resources, declining groundwater levels, and climate change–induced variability in rainfall have rendered such systems unsustainable in many regions (Bouman et al., 2007a). In Iran, recurrent drought years and reduced surface water availability have intensified pressure on rice-growing systems, particularly during sensitive growth stages (Moumeni et al., 2021).

Reproductive-stage drought stress is among the most damaging forms of water deficit in rice, as it directly affects panicle exertion, pollen viability, spikelet fertility, and assimilate translocation (Lafitte et al., 2007; Serraj et al., 2011). Yield reductions due to drought stress at this stage can range from 20% to more than 50%, depending on genotype and stress severity (Kumar et al., 2014). Physiologically, drought stress during flowering increases spikelet sterility primarily through impaired anther dehiscence and reduced pollen germination (Zhang and Davies, 1990).

Aerobic rice systems have emerged as a promising strategy to reduce water use in rice cultivation by growing rice under non-puddled and non-flooded conditions with intermittent irrigation (Bouman et al., 2005). Compared with conventional flooded systems, aerobic rice can reduce water use by 40–60% while maintaining acceptable yield levels (Peng et al., 2006). Considerable progress has been made in developing aerobic rice varieties at the International Rice Research Institute and national breeding programs, resulting in cultivars such as ‘Vandana’ that show improved performance under aerobic conditions (Atlin et al., 2006).

Despite these advances, many aerobic rice varieties suffer from yield penalties and inferior grain quality compared with traditional lowland cultivars, limiting their adoption in regions with strict quality preferences (Peng et al., 2006). In Iran, limited success has been achieved in identifying cultivars that combine adaptation to aerobic or drought-prone environments with the grain quality demanded by consumers. Most local cultivars remain highly sensitive to water deficit, particularly at the reproductive stage, and perform poorly under aerobic systems (Moumeni, 2014).

Therefore, a major gap exists in developing rice cultivars that simultaneously combine drought tolerance, aerobic adaptability, higher yield potential, and high grain quality suitable for Iranian markets. To address this gap, breeding populations were developed using crosses among Iranian traditional cultivars ('Tarom-Mazand' and 'Tarom-Mahalli') and aerobic / upland donor parents ('Vandana' and IR78908-193-B-3-B an IRRI-derived aerobic line). Through systematic selection under contrasting water regimes, advanced breeding lines were developed.

The objectives of this study were to: (i) evaluate the agronomic performance and grain yield of advanced aerobic rice breeding lines under aerobic, reproductive-stage drought stress and conventional flooded transplanted conditions and (ii) assess grain quality attributes of selected lines in comparison with commercial traditional/improved cultivars.

Materials and Methods

Plant Materials

The plant materials consisted of 23 advanced aerobic rice breeding lines derived from three breeding populations developed through crosses between Iranian local cultivars ('Tarom-Mazand' and 'Tarom-Mahalli') and aerobic / upland donor parents ('Vandana' and IR78908-193-B-3-B). The evaluated breeding lines were in the F7–F9 generations and were developed through pedigree selection under alternating aerobic and reproductive-stage drought stress conditions. Selection was initiated from segregating populations derived from crosses between Iranian local cultivars (Tarom-Mazand and Tarom-Mahalli) and aerobic donor parents (Vandana and IR78908-193-B-3-B). Advancement and selection were conducted over successive generations for earliness, plant type such as short plant stature, high tillering ability, complete panicle exertion, and lodging resistance; grain quality, and adaptation to water-limited environments. Table 1 presents the list and pedigree of the evaluated aerobic rice breeding lines and check cultivars. These lines were previously selected from a larger set based on early-maturity, yield potential, and preliminary

performance under aerobic and reproductive stage drought-stress conditions. Four rice cultivars—'Tarom-Mazand', 'Neda', 'Shiroudi', and 'Vandana'—were included as checks, representing local quality cultivars, drought-tolerant types, high-yielding improved varieties, and aerobic rice standards, respectively.

Experimental Design and Locations

Field experiments were conducted under three cultivation systems: (i) conventional flooded transplanted conditions, (ii) reproductive-stage drought stress under transplanted conditions, and (iii) fully aerobic cultivation. For consistency throughout the manuscript, the environments were coded as E1 = conventional flooded cultivation at Amol, E2 = reproductive-stage drought stress at Amol, E3 = aerobic cultivation at Amol, E4 = aerobic cultivation at Gorgan, and E5 = aerobic cultivation at Yasuj. The conventional flooded and reproductive-stage drought-stress trials were conducted at Amol, while the aerobic trials were conducted at Amol, Gorgan, and Yasuj. Mazandaran (Amol) is located at 36°28'N, 52°21'E, −20 m a.s.l., with a humid subtropical climate and annual rainfall of 800–1000 mm; Golestan (Gorgan) at 36°50'N, 54°26'E, 13 m a.s.l., with a semi-arid climate and annual rainfall of 400–600 mm; and Kohgiluyeh and Boyer-Ahmad (Yasuj) at 30°40'N, 51°35'E, 1840 m a.s.l., with a Mediterranean-type climate and annual rainfall of 500–700 mm. These locations were selected to represent contrasting water availability, temperature regimes, rainfall distribution, elevation, and soil characteristics. The transplanted experiments used 2.0 × 3.0 m plots as the experimental units, with a single seedling transplanted per hill; the aerobic experiments were conducted in six-row plots, with each row measuring 3 m in length and spaced 30 cm apart. Dry seeds were sown at 10-cm intervals within rows, with three to four seeds sown per hill. After emergence, two seedlings were retained per hill at all locations. All experiments, except E5 (Yasuj; one replication only), were arranged in a randomized complete block design with three blocks.

Drought Stress, Soil Water Monitoring and Crop Management

Meteorological data including mean temperature and rainfall were collected from local meteorological stations throughout the growing season. Soil parameters were determined before planting (Table 2). Under conventional flooded conditions, irrigation was continuously maintained until two weeks before harvest. To impose reproductive-stage drought stress, the fields were

irrigated under normal conditions for approximately four weeks after transplanting, until around panicle initiation. The fields were then drained, and irrigation was withheld to induce drought stress during the reproductive stage, following the procedures described by Torres and Henry (2018). Soil water status was monitored by measuring soil moisture at 20–30 cm depth using gravimetric and volumetric methods. Soil matric potential was determined from weekly tensiometer readings and converted according to the soil water retention relationship described by van Genuchten (1980). Water table depth and soil water content were monitored weekly. In the aerobic cultivation experiment, irrigation was applied immediately after sowing using polyethylene drip tapes (20 mm diameter, 20 cm emitter spacing, and 40 cm lateral spacing). To ensure proper germination, irrigation was performed every 3–4 days until the emergence of the second fully expanded leaf, maintaining soil moisture near saturation. Subsequent irrigations were applied every 5–7 days. Weed management was performed by manual weeding and pre- and post-emergence herbicide application, including Nominee®, Council®, and Propanil. Fertilization in all experiments included 150 kg ha^{-1} urea, 100 kg ha^{-1} phosphorus, and 50 kg ha^{-1} potassium fertilizers, with 50% of urea and all phosphorus and potassium applied at sowing and transplanting. The remaining 50% of urea was applied as nitrogen top-dressing at the maximum tillering and panicle initiation/ exertion stages. Irrigation water applied in the environments was measured volumetrically using water meters installed at each location.

Data Collection

Data were recorded for days to 50% flowering (days), plant height (cm), number of productive tillers (no. $plant^{-1}$), panicle length (cm), number of filled and unfilled grains per panicle (no. $panicle^{-1}$), thousand-grain weight (g), brown grain length and width (mm), grain length of milled rice before and after cooking (mm), elongation ratio, grain shape, and grain yield (kg ha^{-1}). Grain quality traits, including amylose content (%) (Juliano, 1971) and alkali spreading value (Little et al., 1958), were measured using standard laboratory procedures. Disease resistance to rice blast (Yeh and Bonman, 1986) and tolerance to stem borer (IRRI, 2013) were evaluated in separate nurseries.

Statistical Analysis

Analysis of variance (ANOVA) was performed for individual environments and across environments using the general linear model. Individual-environment analyses were performed for E1–E4. E5 (Yasuj) had only one replication, so an independent experimental error term could not be estimated; it was therefore not analyzed individually and was not included in the combined ANOVA, and its genotype means were used only in the rank-based analysis. Combined analysis across the four environments (E1–E4) was conducted to evaluate genotype, environment, genotype × environment interaction effects and to compare genotype performance and ranking across contrasting cultivation and water-management conditions. Homogeneity of error variances among the replicated environments was evaluated using Bartlett's test. Because significant heterogeneity was detected, parametric stability procedures that rely on a common error variance were not used as the primary stability criterion. Grain-yield stability was assessed using Thennarasu's NP(1)–NP(4) statistics, which are based on genotype ranks across environments, and Kang's rank-sum method. In this study, a genotype was considered high-yielding when its mean grain yield ranked among the upper-performing genotypes for the target environment(s), whereas stability referred specifically to consistency of genotype ranking across the aerobic environments, with lower NP values indicating greater rank consistency. Thus, high yield and stability were not treated as synonymous. Mean comparisons were performed using LSD at the 5% probability level. Genotype means within each individual environment (E1–E4), together with the corresponding LSD values, are presented in Supplementary Table S1 using the same E1–E5 environment coding adopted throughout the manuscript; the E5 values are descriptive only. Statistical analyses were conducted using SAS software (SAS, 2013). Missing observations in a limited number of experimental units resulted in slight differences among residual degrees of freedom across environments. Degrees of freedom were adjusted accordingly during analysis. AMMI was not used as the primary stability analysis because the significant Bartlett test indicated heterogeneity of residual variances among environments. Moreover, E5 (Yasuj) had only one replication and consequently could not provide an independent error estimate for inclusion in an inferential multi-environment AMMI analysis. Therefore, given the variance heterogeneity and the structure of the available data, rank-based non-parametric stability analysis was considered a more appropriate approach for evaluating genotype stability and changes in genotype ranking across environments, consistent with the considerations of Aryana and Wangiyana (2016).

Results

Soil Water Dynamics and Stress Characterization

During reproductive-stage drought stress, which was initiated four weeks after transplanting, around the panicle initiation stage and continued through panicle emergence and grain filling until maturation, the water table declined from approximately +5 cm above the soil surface under flooded conditions to more than 50 cm below the soil surface at flowering and grain-filling stages (Figure 1). Soil water tension increased from approximately 0 cmHg to more than 90 cmHg during stress development. Soil water status declined from saturated conditions to severe water deficit conditions, with matric potential approaching approximately −14 bar (~14000 pressure head) during panicle emergence and grain filling (Figure 2). These measurements confirmed successful imposition of reproductive-stage drought stress. Seasonal irrigation water consumption in aerobic environments was approximately 4500, 7000 and 7000 m^3 ha^{-1} in Amol, Gorgan and Yasuj, respectively. At Amol (E1-E3), where flooded and aerobic systems were evaluated, aerobic cultivation used approximately 47% less irrigation water than the flooded system (4500 vs. 8500 m^3 ha^{-1}). Because flooded trials were not conducted at Gorgan and Yasuj in this study, no within-location flooded-versus-aerobic water-use reduction is inferred for E4 or E5.

Performance under Individual Environments: Aerobic and Reproductive-Stage Drought Stress

The analysis of variance for individual environments under flooded, reproductive-stage drought stress, and aerobic conditions is summarized in Table 3, while mean values of all evaluated traits across individual environments are presented in Supplementary Table S1. The environment codes in Table 3 correspond to E1 = flooded Amol, E2 = reproductive-stage drought Amol, E3 = aerobic Amol, and E4 = aerobic Gorgan; E5 = aerobic Yasuj is represented in the multi-environment genotype-mean data. Genotypic differences in grain yield were highly significant ($P \leq 0.01$) in E1 and E3 and significant ($P \leq 0.05$) in E2 and E4 (Table 3), indicating substantial variability among the evaluated breeding lines. Under conventional flooded conditions, grain yield ranged from 3353 to 6680 kg ha^{-1}. However, under reproductive-stage drought stress, the percentage change in yield relative to flooded conditions differed among genotypes. For example, C1-26 and Vandana showed reductions of 45.7% and 46.5% in grain yield, respectively, whereas C1-21 showed a 2.2%

increase and had the highest grain yield among the breeding lines under reproductive-stage drought stress (3967 kg ha^{-1}; Table S1).

Mean plant height was lower under drought stress (134.2 cm in E2 vs. 150.3 cm in E1; Table 3), a descriptive reduction of about 11%. Tall traditional cultivars such as 'Tarom-Mazand' and 'Tarom-Mahalli' showed greater height reduction, whereas semi-dwarf aerobic-derived lines maintained more stable plant height. The mean number of productive tillers per plant was also lower under drought stress (11.7 in E2 vs. 12.8 in E1; Table 3), though to a lesser extent than plant height.

Spikelet filling was also affected by reproductive-stage drought stress: the mean number of filled grains per panicle was 95.1 in E1 and 91.4 in E2, whereas the mean number of unfilled spikelets per panicle increased from 20.6 to 27.2 (Table 3). These are descriptive comparisons of environment means, and the magnitude of the change varied among genotypes (Supplementary Table S1). Lines derived from crosses with the aerobic donor 'Vandana' tended to maintain a higher number of filled grains under stress (Supplementary Table S1).

Under fully aerobic cultivation, grain yield varied widely among the genotypes, ranging from 1140 to 7767 kg ha^{-1} across the aerobic environments (E3 and E4; Supplementary Table S1).

Combined Analysis across Environments

Results of the combined analysis of variance across the four environments (E1-E4) are presented in Table 4. Combined analysis of variance across the four environments revealed highly significant effects of genotype (G) and G × E interaction for grain yield ($P \leq 0.01$), whereas the environment (E) effect, tested against Error (a), was not significant for grain yield. Genotype, environment and G × E effects were significant for most of the other traits, the exceptions being thousand-grain weight (no significant effect) and productive tiller number (non-significant G × E interaction) (Table 4). For grain yield, genotype and G × E interaction explained 22.0% and 24.6% of the total variation (R^2), respectively, compared with 7.0% for environment (Table 4).

Mean grain yield (over genotypes) was 2088.1 kg ha^{-1} at E3 and 5016.3 kg ha^{-1} at E4 (Supplementary Table S1). Among the breeding lines, C1-26, C1-21, and C1-1 had the highest yields at E3 (aerobic Amol; 2890, 2560, and 2460 kg ha^{-1}, respectively, versus 1140 kg ha^{-1} for Vandana), and C2-4, C2-14, and C1-9 at E4 (aerobic Gorgan; 7733, 7133, and 7067 kg ha^{-1}, respectively, versus 6967 kg ha^{-1} for Vandana). These results indicate that several breeding lines

showed promising grain-yield performance under aerobic cultivation, although their relative performance varied among environments.

Genotype × environment interaction was evident among the top-performing lines, indicating that relative performance varied across environments. Analysis of variance for yield components (Table 4) showed significant genotype × environment interaction for filled grains per panicle and number of unfilled (sterile) spikelet per panicle ($P \leq 0.01$) and for panicle length ($P \leq 0.01$), whereas productive tiller number and thousand-grain weight did not show significant genotype × environment interaction. Panicle length also differed significantly among genotypes and environments (Table 4), and its means were similar in E1 and E2 (26.6 and 26.3 cm, respectively; Supplementary Table S1).

Days to flowering (FLR) differed significantly among environments (Table 4). Overall, the combined analysis revealed substantial genotype × environment interaction, indicating that genotype performance varied across environments. Because Bartlett's test indicated heterogeneous error variances, genotype stability was evaluated using the rank-based non-parametric analysis described below.

Yield Stability Analysis across Environments

Bartlett's test for homogeneity of variances revealed significant heterogeneity among the environments ($\chi^2 = 14.55$, $P = 0.0022$), indicating that the assumption of homogeneous variances required for conventional parametric stability models was not satisfied. Consequently, non-parametric stability statistics were employed to characterize consistency of genotype ranking across the environments. Thennarasu's non-parametric stability statistics NP(1), NP(2), NP(3), and NP(4) revealed considerable variation among breeding lines in their response to environmental variation (Table 5). Lower NP values indicated greater stability in terms of rank consistency, whereas Kang's rank-sum analysis identified genotypes combining superior grain yield with favorable stability rankings. Importantly, the NP statistics measure the consistency of genotype rankings across environments rather than grain-yield level itself. Thus, a high-yielding genotype such as C2-4 or C2-14 may be considered a promising aerobic candidate without necessarily being the most rank-stable genotype. Conversely, a genotype with a low NP value may show high rank stability while having a relatively lower mean grain yield. Based on the combined evaluation of mean grain yield, Thennarasu's stability parameters, and Kang's rank-sum values, the breeding

lines were therefore interpreted as high-yielding candidates, rank-stable candidates, or candidates combining both desirable attributes, rather than being broadly classified as stable or widely adapted solely on the basis of rank stability.

Grain Quality Traits, Disease and Pest Performance

Grain quality characteristics of the evaluated genotypes, including amylose content, grain dimensions, cooking quality parameters and disease / pest performance are summarized in Table 6. Grain quality evaluation revealed considerable variation among breeding lines for physicochemical and appearance-related traits. Amylose content ranged from 18.7% to 23.0% across lines and trials (line means 19.7–21.9%), with most advanced lines falling within the intermediate range preferred by Iranian consumers. The local check 'Tarom-Mazand' (20.0–22.0%) and the aerobic check 'Vandana' (19.5–22.0%) fell within the range of the breeding lines. Alkali spreading value indicated predominantly intermediate gelatinization temperature among selected lines, suggesting acceptable cooking behavior. Grain length before cooking varied from 6.1 to 7.4 mm among the breeding lines (genotype means over the three trials), and length-to-width ratio ranged from 3.0 to 3.5, classifying most lines as long and slender. Grain elongation after cooking was comparable to that of high-quality local cultivars, an important attribute for market acceptance. Chalkiness was generally low in advanced lines, although a few genotypes showed increased chalkiness under aerobic conditions, likely due to higher temperature during grain filling.

Evaluation of performance of test materials against key disease and pest indicated moderate resistance to leaf and neck blast in most breeding lines, with disease severity scores lower than those of susceptible checks. Stem borer incidence was generally low and did not differ significantly among genotypes. Taken together, the results demonstrated that several advanced aerobic rice breeding lines combined favorable yield performance and desirable grain quality traits, while rank stability varied among environments.

Discussion

The present study revealed substantial genetic variation among advanced aerobic rice breeding lines for yield, yield components, and grain quality under contrasting water regimes, confirming earlier reports on the existence of exploitable variability for drought tolerance and aerobic

adaptation in rice (Moumeni et al., 2021; Kumar et al., 2014). The lower mean grain yield under reproductive-stage drought stress (3417 vs. 4420 kg ha^{-1} in E2 and E1, respectively; Table 3) is consistent with previous studies identifying this growth stage as particularly sensitive to water deficit (Lafitte et al., 2007; Serraj et al., 2011). The genotype-specific responses were particularly important: C1-21 increased grain yield by 2.2% under reproductive-stage drought stress and was the highest-yielding breeding line under E2, whereas C1-26 and Vandana declined by 45.7% and 46.5%, respectively.

Reproductive-stage drought is known to reduce grain set mainly by impairing anther dehiscence and pollen germination (Zhang and Davies, 1990; Serraj et al., 2011), which is consistent with the lower number of filled grains and higher number of unfilled spikelets per panicle observed under drought stress in this study (Table 3). Because physiological traits (e.g., root characteristics, leaf water status, photosynthetic activity) were not measured, these mechanisms should be regarded as possible explanations rather than direct evidence from this experiment.

Under aerobic cultivation, the common local cultivar Tarom-Mazand exhibited poor adaptation, showing a severe yield penalty (1400 kg ha^{-1} at E3 vs. 3913 kg ha^{-1} under flooded conditions at E1; Supplementary Table S1). Similar responses of lowland rice cultivars under aerobic conditions have been widely reported and are often attributed to shallow root systems, poor nutrient uptake, and susceptibility to weed competition (Bouman et al., 2005; Peng et al., 2006). In the present study, however, the response of the breeding material was strongly environment-dependent. C1-26, C1-21, and C1-1 were the highest-yielding breeding lines at E3 (aerobic Amol), whereas C2-4, C2-14, and C1-9 were the highest-yielding breeding lines at E4 (aerobic Gorgan). These results indicate that several breeding lines have promising yield performance under aerobic cultivation, but that their relative performance varied among environments. Therefore, selection of aerobic rice breeding material should consider the target production environment rather than assuming that a single genotype will necessarily perform best across all aerobic environments.

The characterization of soil water dynamics during the stress period confirmed that the imposed treatment successfully generated a progressive reproductive-stage water deficit, which is a critical growth phase determining grain formation and final yield in rice. The decline in water table depth and the increase in soil water tension indicated a gradual reduction in soil water availability, allowing the evaluation of genotypic responses under realistic drought conditions rather than short-term dehydration stress. Reproductive-stage drought stress is known to reduce spikelet fertility,

grain filling, and yield through reduced leaf water status, impaired photosynthetic activity, and accelerated senescence; therefore, maintaining yield under this condition is considered an important criterion for drought-adapted rice breeding (Bouman and Tuong, 2001; Pantuwan et al., 2002). The observed reduction in irrigation water requirement under aerobic cultivation compared with flooded conditions further demonstrates the potential of aerobic rice systems to reduce water inputs in water-limited environments. Nevertheless, the present experiments were designed primarily to evaluate agronomic performance and did not directly quantify root traits or physiological mechanisms underlying water uptake. Therefore, the superior performance of particular breeding lines should be interpreted as evidence of phenotypic adaptation rather than proof of a specific physiological mechanism. The identification of breeding lines that combine high yield performance with favorable performance or rank stability across contrasting aerobic environments represents an important step toward developing climate-resilient rice cultivars for regions facing increasing water scarcity.

The significant genotype × environment interaction detected in the multi-environment evaluation highlights the importance of multi-location testing in aerobic rice breeding (Atlin et al., 2006). Because Bartlett's test detected significant heterogeneity of environmental variances, non-parametric stability statistics were considered more appropriate for evaluating consistency of genotype rankings than variance-based parametric methods under the conditions of the present dataset. Non-parametric approaches are particularly useful when the objective is to assess the consistency of genotype ranking across contrasting environments, because the statistics are based on genotype ranks rather than the magnitude of yield deviations and therefore do not directly measure yield level itself. Accordingly, the Thennarasu NP(1)–NP(4) statistics in this study were interpreted as measures of rank stability, not as measures of high yield. The results should therefore not be interpreted as showing that the same lines were simultaneously the highest yielding and the most stable in every environment. Rather, C1-26, C1-21, and C1-1 were identified primarily through their high grain-yield performance at E3, and C2-4, C2-14, and C1-9 through their high grain-yield performance at E4, and the Thennarasu statistics through consistency of genotype ranks across the environments included in the stability analysis (Thennarasu, 1995). Kang's rank-sum analysis provided an additional criterion for identifying genotypes that combined favorable yield performance and stability ranking (Kang, 1988). Thus, the most useful breeding candidates were those that combined relatively high grain yield with favorable stability statistics, rather than those

selected solely for either yield or rank stability. The use of rank-based analysis is consistent with previous applications of non-parametric stability methods, whereas AMMI/biplot analyses have been used in fully replicated multi-environment datasets to visualize G × E patterns (Aryana and Wangiyana, 2016). In the present study, AMMI was not used as the primary stability procedure because significant heterogeneity of residual variances was detected by Bartlett's test, while E5 had only one replication and consequently could not provide an independent error estimate for an inferential multi-environment AMMI analysis.

Grain quality remains a critical determinant of adoption for new rice cultivars in Iran. One of the major limitations of previously released aerobic rice varieties has been their inferior grain quality compared with traditional cultivars (Moumeni, 2014). In the present study, most advanced lines exhibited intermediate amylose content, long slender grains, and desirable cooking characteristics comparable to popular Iranian cultivars. This combination is particularly relevant for breeding programs targeting Iranian rice-growing regions, where consumer and market preferences strongly influence cultivar adoption. The observed variation in grain-quality traits also indicates that selection for aerobic adaptation and drought response can be conducted together with quality traits, rather than treating grain quality as a separate breeding objective. These findings demonstrate that improved adaptation to aerobic and drought-stress conditions may be achieved without necessarily compromising grain quality, when appropriate parental combinations and selection strategies are employed.

Moderate resistance to blast disease observed in several advanced lines is particularly advantageous, as aerobic systems can sometimes favor disease development due to fluctuating soil moisture and canopy microclimate (Serraj et al., 2011). Continued evaluation under disease hotspot environments will be necessary to confirm the stability of resistance. Because disease resistance was not the primary objective of the present experiments, these observations should be considered preliminary and require confirmation under dedicated disease-screening conditions.

Overall, the results support the feasibility of breeding rice cultivars combining aerobic adaptation, reproductive-stage drought tolerance, yield performance, and acceptable grain quality. The study also demonstrates that these attributes should not be considered synonymous: high grain yield, reproductive-stage drought response, and rank stability represent different aspects of adaptation. The identified breeding lines therefore provide valuable genetic resources for future breeding programs aimed at improving adaptation to water-limited rice production and enhancing climate

resilience. In particular, lines showing both relatively high grain yield and favorable rank stability warrant further multi-location evaluation before advancement as broadly adapted aerobic rice candidates.

Conclusions

Substantial variation was observed among the evaluated breeding lines for grain yield, reproductive-stage drought response, grain quality, and adaptation to water-limited environments. C1-21 was the highest-yielding breeding line under reproductive-stage drought stress at Amol (E2; 3967 kg ha^{-1}; +2.2% relative to flooded conditions), unlike C1-26 (−45.7%) and Vandana (−46.5%), whereas C1-26, C1-21, and C1-1 (E3) and C2-4, C2-14, and C1-9 (E4) were the highest-yielding breeding lines under aerobic cultivation. These results demonstrate clear environment-specific differences in the performance of the breeding lines and identify several lines with specific promise for aerobic cultivation. Thennarasu's NP statistics and Kang's rank-sum method were used to assess rank consistency and the combined yield–stability criterion, respectively, rather than to equate stability with high yield. Overall, the study identified both environment-specific high-yielding breeding lines and lines with comparatively consistent rankings, providing a basis for targeted selection and further multi-location evaluation of promising materials for aerobic rice production.

Acknowledgments

The authors acknowledge the Rice Research Institute of Iran and regional research stations for field support and technical assistance. Funding support from national agricultural research programs is gratefully acknowledged.

References

1. Aryana, I.G.P.M. and Wangiyana, W. 2016. Yield performance and adaptation of promising amphibious red rice lines on six growing environments in Lombok, Indonesia. AGRIVITA, *Journal of Agricultural Science*, 38(1): 40–46. doi:10.17503/agrivita.v38i1.494.

2. Atlin, G.N., Lafitte, H.R., Tao, D., Laza, M., Amante, M., and Courtois, B. 2006. Developing rice cultivars for high-fertility upland systems in the tropics. *Field Crops Research*, 97: 43–52.

3. Bouman, B. A. M., Lampayan, R. M. and Tuong, T. P. 2007a. Water management in irrigated rice: coping with water scarcity. International Rice Research Institute, Los Baños, Philippines, 54 P.

4. Bouman, B.A.M., and Tuong, T.P. 2001. Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, 49:11–30.

5. Bouman, B.A.M., Humphreys, E., Tuong, T.P., and Barker, R. 2007b. Rice and water. *Advances in Agronomy*, 92: 187–237.

6. Bouman, B.A.M., Peng, S., Castañeda, A.R., and Visperas, R.M. 2005. Yield and water use of irrigated tropical aerobic rice systems. *Agricultural Water Management*, 74: 87–105.

7. FAO. 2021. FAOSTAT statistical database. Food and Agriculture Organization of the United Nations, Rome, Italy.

8. IRRI. 2013. Standard Evaluation System for Rice. International Rice Research Institute, Manila, Philippines.

9. Juliano, B. O. 1971. Simplified Assay for Milled-Rice Amylose. Cereal Sci. Today, 16: 334-338.

10. Kang, M.S. 1988. A rank-sum method for selecting high-yielding, stable corn genotypes. *Cereal Research Communications*, 16:113–115.

11. Kumar, A., Dixit, S., Ram, T., Yadaw, R.B., Mishra, K.K., and Mandal, N.P. 2014. Breeding high-yielding drought-tolerant rice: Genetic variations and conventional breeding strategies. *Advances in Agronomy*, 125: 71–144.

12. Lafitte, H.R., Yongsheng, G., Yan, S., and Li, Z.K. 2007. Whole plant responses, key processes, and adaptation to drought stress: The case of rice. *Journal of Experimental Botany*, 58: 169–175.

13. Little, R. R., Hilder, G. B. and Dawson, E. H. 1958. Differential effect of dilute alkali on 25 varieties of milled white rice. *Cereal Chemistry*, 35(2): 111-126.

14. Moumeni, A. 2014. Study on possibility of changing rice cultivation system from irrigation to aerobic condition in Mazandaran province. *Journal of Crop Production*, 6(4): 215-228 (In Persian, Abstract in English).

15. Moumeni, A., Arazi, V., Rostami, M. and Fathi, N. 2021. Assessment of genotype × environment interaction and grain yield stability of selected aerobic rice (*Oryza sativa* L.)

459 genotypes in northern region of Iran. *Iranian Journal of Crop Sciences*, 22(4): 305-320 (In Persian,
460 Abstract in English).
461 16. Pantuwan, G., Fukai, S., Cooper, M., Rajatasereekul, S., and O'Toole, J.C. 2002. Yield
462 response of rice (Oryza sativa L.) genotypes to drought under rainfed lowlands: 3. Plant factors
463 contributing to drought resistance. *Field Crops Research*, 73:181–200.
464 17. Peng, S., Bouman, B.A.M., Visperas, R.M., Castañeda, A., Nie, L., and Park, H.K. 2006.
465 Comparison between aerobic and flooded rice in the tropics: Agronomic performance in an eight-
466 season experiment. *Field Crops Research*, 96: 252–259.
467 18. SAS Institute Inc. 2013. Statistical Analysis Software. User's Guide: Statistics. Version
468 9.4. SAS Institute Inc., Cary, NC, USA.
469 19. Serraj, R., Kumar, A., McNally, K.L., Slamet-Loedin, I., Bruskiewich, R., Mauleon, R.,
470 Cairns, J., and Hijmans, R.J. 2011. Improvement of drought resistance in rice. *Advances in*
471 *Agronomy*, 103: 41–99.
472 20. Thennarasu, K. 1995. On certain non-parametric procedures for studying genotype-
473 environment interactions and yield stability. PhD Dissertation, PJ School, IARI, New Delhi, India.
474 21. Torres, R.O. and Henry, A. 2018. Yield stability of selected rice breeding lines and donors
475 across conditions of mild to moderately severe drought stress. *Field Crops Research*, 220: 37–45.
476 doi: 10.1016/j.fcr.2016.09.011.
477 22. Tuong, T.P., and Bouman, B.A.M. 2003. Rice production in water-scarce environments.
478 In: *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CABI
479 Publishing, Wallingford, UK. pp. 53–67.
480 23. van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic
481 conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44:892–898.
482 24. Yeh, W. H. and Bonman, J. M. 1986. Assessment of partial resistance to *Pyricularia oryzae*
483 in six rice cultivars. *Plant Pathology*, 35: 319-323.
484 25. Zhang, J., and Davies, W.J. 1990. Changes in the concentration of ABA in xylem sap as a
485 function of changing soil water status can account for changes in leaf conductance and growth.
486 *Plant, Cell and Environment*, 13: 277–285.
487
488
489

Table 1. list and pedigree of evaluated aerobic rice breeding lines and check cultivars.

No.	Code	Genotype	Pedigree
1	G01	C1-1	Tarom mahalli/ Vandana
2	G02	C1-12	Tarom mahalli/ Vandana
3	G03	C1-14	Tarom mahalli/ Vandana
4	G04	C1-15	Tarom mahalli/ Vandana
5	G05	C1-16	Tarom mahalli/ Vandana
6	G06	C1-21	Tarom mahalli/ Vandana
7	G07	C1-22	Tarom mahalli/ Vandana
8	G08	C1-26	Tarom mahalli/ Vandana
9	G09	C1-41	Tarom mahalli/ Vandana
10	G10	C1-45	Tarom mahalli/ Vandana
11	G11	C1-6	Tarom mahalli/ Vandana
12	G12	C1-7	Tarom mahalli/ Vandana
13	G13	C1-9	Tarom mahalli/ Vandana
14	G14	C2-1	Tarom-Mazand/Vandana
15	G15	C2-10	Tarom-Mazand/Vandana
16	G16	C2-13	Tarom-Mazand/Vandana
17	G17	C2-14	Tarom-Mazand/Vandana
18	G18	C2-18	Tarom-Mazand/Vandana
19	G19	C2-3	Tarom-Mazand/Vandana
20	G20	C2-4	Tarom-Mazand/Vandana
21	G21	C2-5	Tarom-Mazand/Vandana
22	G22	C3-3	Tarom-Mazand/IR78908-193-B-3-B
23	G23	C3-5	Tarom-Mazand/IR78908-193-B-3-B
24	G24	Tarom-Mazand	Check variety 1
25	G25	Neda	Check variety 2
26	G26	Shiroudi	Check variety 3
27	G27	Vandana	Check variety 4

Table 2. Monthly climatic data and soil physicochemical properties of the experimental sites (Amol, Gorgan, and Yasuj) during the 2022–2023 growing seasons.

Climate parameters										
Location	Parameters	March	April	May	June	July	August	September		
Amol	temperature (oC)	15.5	19.5	24.6	26.9	27.7	26.2	23.2		
Gorgan		14.4	18.9	25.7	29.6	30.8	29.7	26.1		
Yasuj		10.3	14.7	19.0	25.2	27.5	25.9	22.9		
Amol	rainfall (mm)	15.6	46.1	2.0	0.9	20.1	8.6	79.6		
Gorgan		24.0	42.6	1.2	14.2	0.0	0.0	69.4		
Yasuj		87.0	20.5	8.5	0.0	6.5	8.5	0.1		
Soil Characteristics										
	soil texture	clay (%)	sand (%)	silt (%)	Total N (%)	K^+ (ppm)	P^+ (ppm)	pH	O.C (%)	EC ($ds.m^{-1}$)
Amol	Loam	21	44	35	0.20	267	29.0	7.9	1.67	0.9
Gorgan	Clay-Loam	20	14	66	0.13	496	13.7	7.7	1.30	1.1
Yasuj	Silt-Clay-Loam	34	54	12	0.20	367	18.0	7.8	1.83	0.6

Mean monthly air temperature (°C) and total monthly rainfall (mm) were recorded from March to September. Soil properties include texture (% clay, sand, silt), total nitrogen (%), available potassium (K^+, ppm), available phosphorus (P^+, ppm), pH, organic carbon (O.C, %), and electrical conductivity (EC, dS m^{-1}). Data represent the average of three replications per location.

Table 3. Analysis of variance (mean squares) for agronomic traits under different cultivation systems.

a) E1 – Conventional flooded, Amol

SOV	df	Mean squares (E1)									
		FLR	PLH	TLR	PL	FG	NFG	BGL	BGW	TGW	YLD
Rep	2	7.49	77.14	2.56	2.44	290.0	160.3	0.02	0.23	4.24	1832281*
Genotypes	26	75.10**	714.22**	4.81	7.58**	454.5**	375.9**	0.94**	0.20	18.67**	1662823**
Error	52	3.56	37.26	2.97	2.11	190.3	62.9	0.09	0.18	1.60	365364
CV		1.97	4.06	13.38	5.47	14.51	38.5	3.06	16.1	5.40	13.7
Mean		95.6	150.3	12.8	26.5	95.1	20.6	9.70	2.70	23.6	4420
R^2		0.91	0.91	0.46	0.65	0.56	0.76	0.84	0.38	0.86	0.71

b) E2 – Reproductive-stage drought stress, Amol

SOV (b)	df	Mean squares (E2)									
		FLR	PLH	TLR	PL	FG	NFG	BGL	BGW	TGW	YLD
Rep	2	2.09	211.5**	3.70	0.50	262.7	48.4	0.16	0.24	46.3**	221756
Genotypes	26	52.03**	1106.3**	3.94*	12.20**	1174.2**	282.1**	0.99**	0.29	17.7**	445865*
Error	52	24.24	36.88	2.21	1.70	259.1	104.3	0.13	0.21	3.1	227269
CV		5.09	4.52	12.70	5.01	17.6	37.5	3.86	18.8	8.2	13.9
Mean		96.6	134.2	11.7	26.3	91.4	27.2	9.3	2.5	21.6	3417
R^2		0.52	0.93	0.49	0.78	0.70	0.58	0.80	0.42	0.77	0.51

c) E3 – Aerobic, Amol

SOV (c)	df	Mean squares (E3)									
		FLR	PLH	TLR	PL	FG	NFG	BGL	BGW	TGW	YLD
Rep	2	6.82	393.3	-	8.87	1495.6*	113.9	0.04	0.08	522.9	4283568**
Genotypes	26	123.6**	191.9	-	6.79*	821.3**	336.6*	0.89**	0.08**	380.8	1376073**
Error†	50	36.3	132.6	-	3.41	347.4	172.5	0.39	0.02	428.1	520763
CV		5.22	12.3	-	8.47	30.2	61.9	6.91	5.92	83.1	34.9
Mean		115.2	93.3	-	21.8	61.6	21.2	9.1	2.54	24.9	2065
R^2		0.64	0.48	-	0.53	0.58	0.51	0.54	0.66	0.34	0.70

d) E4 – Aerobic, Gorgan

SOV (d)	df	Mean squares (E4)									
		FLR	PLH	TLR	PL	FG	NFG	BGL	BGW	TGW	YLD
Rep	2	2.01	0.36	0.03	0.06	31.6	7.88	-	-	9.5	8528780
Genotypes	26	2.64	63.7	5.45	0.98	84.9*	29.1	-	-	23.8**	5783716*
Error†	50	2.93	108.7	3.89	0.64	46.4	35.6	-	-	5.8	2771980
CV		1.70	9.2	26.8	3.9	9.1	23.9	-	-	11.8	32.7
Mean		99.1	113.6	7.4	20.7	75.6	24.9	-	-	20.3	5084
R^2		0.32	0.23	0.41	0.43	0.49	0.30	-	-	0.69	0.55

Where: a): Conventional flooded cultivation (E1: Amol);b): Reproductive-stage drought stress (E2: Amol); c): Aerobic cultivation system (E3: Amol); d): Aerobic cultivation system (E4: Gorgan); Units indicated for each trait: FLR (days), PLH (cm), TLR (no. plant^{-1}), PL (cm), FG (no. panicle^{-1}), NFG (no. panicle^{-1}), BGL (mm), BGW (mm), TGW (g), YLD (kg ha^{-1}). †: Missing observations in a limited number of experimental units resulted in slight differences among residual degrees of freedom across environments. Individual-environment ANOVA was not performed for E5 (Yasuj) because replicate-level observations required for estimation of the experimental error term were unavailable. Degrees of freedom were adjusted accordingly during analysis. R^2: coefficient of determination of the model. * and **: significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; -: not available. Trait abbreviations are defined in the footnote of Table 4.

519 **Table 4.** Combined analysis of variance for different traits on advance breeding rice genotypes
520 across four environments (trials).

SOV	df	Mean square							
		FLR	PLH	TLR	PL	FG	NFG	TGW	GYLD
Replication	2	1.84	65.1	0.9	3.6	629.5	24.8	89.4	3243927*
Environment	3	6750**	48803.3**	660.9**	729.3**	18591**	766.7*	312.7	11723029
Error (a)	6	4.86	207.9	2.7	2.8	481.8	102.6	164.8	3950047
Genotype	26	145.7**	1248.5**	6.4**	10.8**	694.5**	407.6**	104.7	4224686**
Genotype×Environment	77	36.6**	277.9**	3.9	5.7**	624.3**	207.9**	113.4	1597221**
Error (b)	204	16.7	78.1	3.02	1.9	211.1	93.6	107.5	987952
CV %		4.02	7.17	16.2	5.9	17.9	41.2	45.9	26.1
mean		101.6	123.1	10.7	23.9	81.1	23.5	22.6	3816.1
R^2 Environment (%)		66.8	2.0	64.3	65.9	33.0	4.7	2.6	7.0
R^2 Genotype (%)		12.5	44.7	5.4	8.5	10.7	21.8	7.7	22.0
R^2 G×E (%)		9.3	29.5	9.7	13.2	28.4	32.9	24.6	24.6

521 Where: FLR: Number of days to 50% flowering (days), PLH: Plant height (cm), TLR: Number of productive tillers per plant (no.
522 plant^{-1}), PL: Panicle length (cm), FG: Number of filled grains per panicle (no. panicle^{-1}), NFG: Number of unfilled (sterile) spikelet
523 per panicle (no. panicle^{-1}), BGL: Brown grain length (mm), BGW: Brown grain width (mm), TGW: Thousand grain weight (g),
524 GYLD: Grain yield (kg ha^{-1}).
525 The main effects of replication and environment were tested with the first error, while genotype and the genotype × environment
526 interaction were tested with the second error. E1 = conventional flooded cultivation at Amol; E2 = reproductive-stage drought stress
527 at Amol; E3 = aerobic cultivation at Amol; E4 = aerobic cultivation at Gorgan; E5 = aerobic cultivation at Yasuj. E5 (aerobic
528 cultivation at Yasuj) was excluded from the combined ANOVA because only one replication was available. * and **: significant at
529 $P \leq 0.05$ and $P \leq 0.01$, respectively. R^2 (%) = sum of squares of the source (mean square × df) / total sum of squares × 100, calculated
530 for each trait.

Table 5. Grain yield performance and stability ranking of advanced aerobic rice breeding lines based on Thennarasu's non-parametric statistics and Kang's rank-sum method across environments.

Genotype	YLD	NP1	NP2	NP3	NP4	Rank (YLD)	Rank (Stability)	Kang Rank Sum	Group	Interpretation
C2-14	4345.8	1.38	0.68	1.52	0.19	6	2	8	High-yielding and rank-stable	High mean yield with favorable rank stability
C2-1	4065.8	3.00	1.33	3.16	0.35	9	12	21	High-yielding and rank-stable	High mean yield with favorable rank stability
C1-22	3366.7	2.81	0.60	3.38	0.18	23	1	24	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C2-5	3790.8	3.75	1.11	4.72	0.35	13	11	24	High-yielding and rank-stable	Relatively high mean yield with favorable rank stability
C1-9	4492.5	4.25	2.34	4.44	0.61	5	20	25	High-yielding	High mean yield, but comparatively less consistent ranking
C1-26	4524.2	4.25	2.19	5.21	0.67	4	22	26	High-yielding	High mean yield, but comparatively less consistent ranking
C1-41	3379.2	4.50	0.88	4.56	0.22	21	5	26	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C1-12	3301.7	3.25	0.71	3.90	0.21	24	3	27	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C1-6	3486.7	4.50	1.09	5.72	0.35	18	10	28	Rank-stable	Favorable rank stability with moderate mean yield
C2-10	3997.5	3.50	1.40	4.64	0.46	10	18	28	High-yielding	Relatively high mean yield, but less consistent ranking
C1-15	3593.3	6.00	1.60	6.00	0.40	15	15	30	Intermediate	Intermediate yield and rank stability
C1-21	3951.7	5.00	1.67	5.61	0.47	11	19	30	High-yielding	Relatively high mean yield, but less consistent ranking
C3-5	3504.2	5.00	1.18	6.75	0.40	17	14	31	Rank-stable	Favorable rank stability with moderate mean yield
C1-1	3532.1	5.50	1.52	6.26	0.43	16	16	32	Intermediate	Intermediate yield and rank stability
C1-16	2994.2	3.88	0.71	4.71	0.22	29	4	33	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C2-13	3250.0	5.25	1.06	5.45	0.28	26	7	33	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C2-4	4297.5	10.50	3.23	10.56	0.81	7	26	33	High-yielding	High mean yield, but comparatively less consistent ranking
C1-7	3141.7	4.25	0.80	4.87	0.23	28	6	34	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C2-18	3846.7	7.25	2.47	8.41	0.72	12	23	35	High-yielding	Relatively high mean yield, but less consistent ranking
C1-45	3233.8	4.00	0.84	5.34	0.28	27	9	36	Rank-stable	Consistent genotype ranking, but relatively lower mean yield
C1-14	3419.2	5.25	1.29	7.08	0.44	20	17	37	Intermediate	Intermediate yield and rank stability
C2-3	3250.8	5.38	1.09	7.12	0.36	25	13	38	Rank-stable	Favorable rank stability with relatively lower mean yield
C3-3	3371.7	-	-	-	-	22	-	-	Yield only	Stability statistics unavailable; yield performance only
C3-4	3700.0	-	-	-	-	14	-	-	Yield only	Stability statistics unavailable; yield performance only

Values of NP(1), NP(2), NP(3), and NP(4) were calculated based on genotype ranks across environments. Genotypes were interpreted according to their mean grain yield and rank stability. High yield and stability were considered distinct criteria; therefore, a genotype could be classified as high-yielding, rank-stable, or both, depending on its relative yield performance and consistency of ranking across aerobic environments. YLD, mean grain yield across environments; NP, Thennarasu's non-parametric stability parameter. Data of E5 (Yasuj), which had no replication, were used only for ranking the genotypes.

543 **Table 6.** Grain quality traits (amylose content %, grain length mm, L/W ratio, elongation, alkali spreading value, blast score 0–9).

Genotype	Mean of various traits in different environments																
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3		
	GL(BC)	GL(BC)	GL(BC)	GL(AC)	GL(AC)	GL(AC)	Elong.	Elong.	Elong.	GT	GT	GT	AC (%)	AC (%)	AC (%)	STBR	BLAST
C1-1	7.29	7.31	6.06	14.44	13.14	11.60	1.98	1.79	1.91	4.80	3.00	4.50	19.50	22.50	21.20	3	3
C1-12	7.35	5.69	6.04	11.56	12.95	10.40	1.57	2.00	1.70	4.50	3.00	5.00	20.70	21.30	22.90	3	1
C1-14	7.36	6.08	7.08	13.41	10.06	10.55	1.82	1.65	1.49	4.80	4.80	3.50	23.00	21.50	21.10	3	0
C1-15	7.32	7.23	7.51	11.30	13.60	13.31	1.54	1.88	1.77	4.80	3.50	3.80	20.00	20.00	21.30	3	0
C1-16	7.86	6.20	6.40	12.44	13.20	11.20	1.58	2.00	1.75	5.50	5.50	5.00	19.80	23.00	18.70	5	1
C1-21	6.94	6.51	6.42	12.30	11.97	12.20	1.77	1.83	1.90	3.90	3.80	4.50	22.00	19.90	20.10	3	5
C1-22	7.27	6.12	6.26	12.47	12.77	11.25	1.71	2.00	1.79	4.00	5.50	3.00	20.50	21.60	22.40	3	1
C1-26	6.61	5.75	6.32	10.85	11.90	10.30	1.64	2.00	1.62	4.80	3.50	3.50	21.50	21.20	21.20	1	1
C1-41	6.56	6.86	5.53	11.85	11.10	10.15	1.80	1.60	1.89	4.00	4.50	3.50	19.00	21.60	19.20	3	1
C1-45	6.75	5.85	6.17	10.37	11.70	11.20	1.58	2.00	1.81	3.70	3.50	4.00	19.60	20.00	21.20	3	1
C1-6	7.26	6.78	6.01	12.40	12.71	11.40	1.70	1.87	1.89	3.80	3.50	4.00	21.80	22.00	21.20	3	1
C1-7	7.32	6.30	7.36	13.42	11.67	11.85	1.83	1.85	1.61	4.80	4.20	4.00	21.50	20.50	22.50	1	0
C1-9	7.34	7.15	7.05	13.59	13.38	11.55	1.85	1.87	1.63	7.00	3.80	5.00	20.70	21.80	20.40	3	0
C2-1	7.16	6.63	6.15	13.46	11.35	12.72	1.87	1.71	2.00	4.50	3.70	4.00	19.70	22.00	20.40	1	0
C2-10	6.39	6.70	5.46	10.90	11.77	11.15	1.70	1.75	2.00	4.90	4.00	4.50	19.80	20.00	19.30	1	0
C2-13	7.37	6.55	6.79	12.83	12.88	11.50	1.74	1.96	1.69	3.80	3.50	4.00	19.50	23.00	18.80	1	3
C2-14	6.92	6.10	7.87	12.04	13.68	11.15	1.73	2.00	1.41	4.30	4.80	4.50	19.90	20.50	20.20	3	3
C2-18	6.16	6.52	7.42	13.53	13.14	12.45	2.00	2.00	1.67	3.50	3.80	3.50	21.00	21.40	22.50	3	1
C2-3	6.87	7.81	6.60	12.72	11.25	11.75	1.85	1.44	1.78	4.80	4.50	4.50	20.00	20.20	21.60	1	0
C2-4	6.71	5.50	6.22	11.58	13.23	11.60	1.72	2.40	1.86	4.80	4.00	3.00	21.80	21.70	19.60	3	1
C2-5	7.84	6.59	6.26	11.85	12.84	12.29	1.51	1.94	1.96	5.50	5.50	4.50	20.80	19.80	20.50	1	1
C3-3	6.47	6.40	6.68	13.65	12.74	12.30	2.00	1.99	1.84	4.50	3.70	4.00	19.00	21.10	22.80	3	0
C3-5	7.38	7.36	6.52	11.97	10.80	12.89	1.62	1.41	1.97	3.00	3.50	4.50	20.50	21.40	20.60	1	1
T.Mazand	6.63	6.69	6.40	13.71	12.10	11.65	2.00	1.80	1.82	3.60	4.00	4.50	20.00	20.50	22.00	1	0
NEDA	7.71	6.68	7.29	13.80	12.15	13.07	1.78	1.81	1.79	3.00	3.00	4.00	19.00	22.00	21.40	5	5
SHIROUDI	7.78	6.98	6.86	14.18	12.79	13.70	1.82	1.83	1.99	3.90	3.50	3.80	22.00	20.20	20.40	3	0
VANDANA	6.49	6.45	5.58	11.95	11.04	10.05	1.84	1.76	1.80	5.50	3.00	4.00	20.80	22.00	19.50	5	5

544 Where: GL(BC): Grain length of milled rice before cooking (mm), GL(AC): Grain length of milled rice after cooking (mm), Elong.: Elongation ratio, AC: Amylose content (%), GT: Alkali digestion
545 value, STBR: Stem borer tolerance, BLAST: Blast disease resistance, Numbers 1 to 3 represent the trial numbers, respectively: conventional flooded conditions, reproductive-stage drought stress, and
546 aerobic cultivation method (Amol region).

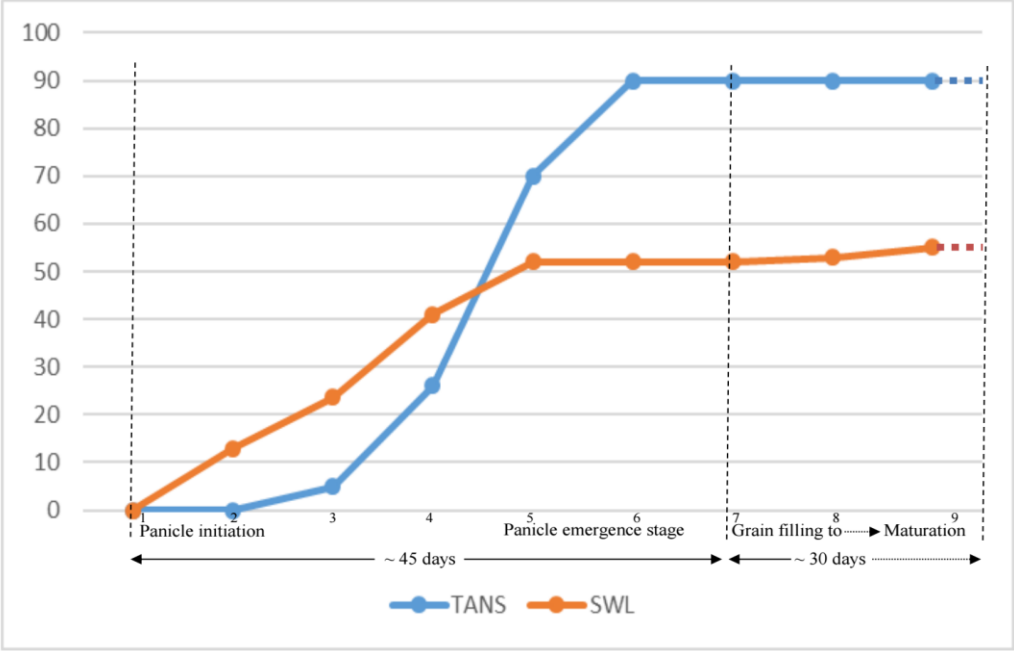


Figure 1. Changes in tensiometer readings and soil water table depth from panicle initiation to maturity under reproductive-stage drought stress. TANS: tensiometer reading (cmHg); SWL: soil water table depth relative to the soil surface (cm). Numbers 1–9 indicate successive measurements taken at weekly intervals. The approximate periods of panicle initiation, panicle emergence, grain filling, and maturity are indicated.

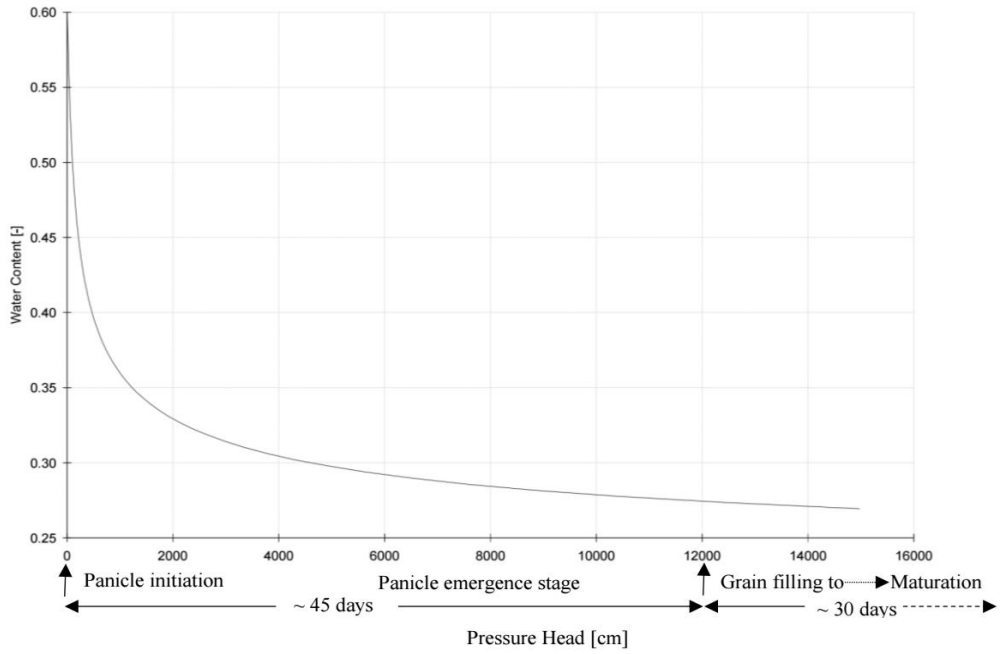


Figure 2. Soil water content as a function of pressure head, calculated weekly from the measurements, during reproductive-stage drought stress, with the approximate timing of panicle initiation, panicle emergence, grain filling, and maturity indicated.

Supplementary Table S1 - Mean performance of genotypes across five environments (three aerobic + two stress conditions).

Genotype	FLR					PLH					TLR					PL					FG				
	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5
C1-1	90.67	91.00	110.00	99.67	107.00	155.13	145.87	91.87	115.07	71.00	12.87	9.80	.	7.07	5.00	26.81	29.35	19.09	20.03	14.00	78.20	108.27	43.20	89.57	73.00
C1-12	90.00	90.67	110.00	99.33	109.00	151.73	142.13	85.40	104.40	78.00	10.80	11.13	.	8.20	6.00	27.50	27.44	20.53	20.20	15.00	82.60	98.27	50.47	77.33	79.00
C1-14	95.67	94.67	112.33	99.00	110.00	144.80	131.73	92.27	104.73	75.00	12.80	13.13	.	10.67	6.00	24.66	24.77	21.47	20.93	16.00	89.67	66.20	73.27	75.57	83.00
C1-15	90.67	92.00	109.33	98.33	109.00	148.00	139.27	92.80	113.90	73.00	10.93	11.13	.	6.57	4.00	29.19	28.61	23.68	20.60	16.00	96.67	93.07	50.67	77.60	74.00
C1-16	95.00	98.67	111.67	99.00	107.00	157.40	132.67	101.60	114.40	72.00	13.00	13.20	.	7.20	4.00	26.29	24.65	21.22	20.37	15.00	91.93	64.00	53.47	76.93	72.00
C1-21	91.33	93.33	115.67	99.00	107.00	132.60	108.67	91.93	115.57	70.00	13.00	13.60	.	5.77	6.00	25.58	26.05	22.67	20.57	16.00	97.13	77.47	76.47	74.77	73.00
C1-22	95.67	96.67	114.33	99.33	107.00	143.13	121.00	101.13	118.37	71.00	13.60	11.80	.	8.70	5.00	25.65	23.99	23.27	20.87	17.00	89.53	55.40	59.20	71.33	75.00
C1-26	101.00	104.00	121.67	101.67	106.00	132.93	117.27	96.00	117.63	69.00	14.60	13.93	.	8.03	6.00	26.73	24.67	23.27	20.97	15.00	95.93	81.27	72.13	74.57	81.00
C1-41	99.00	97.33	120.33	100.33	107.00	152.53	128.20	91.45	111.10	70.00	12.60	11.67	.	7.07	5.00	25.07	25.13	20.44	20.87	16.00	85.00	88.00	48.00	76.07	77.00
C1-45	93.33	95.67	112.67	99.00	108.00	159.33	141.73	94.80	112.87	73.00	12.67	11.33	.	4.93	7.00	22.93	24.45	19.17	19.87	14.00	75.60	75.67	48.40	81.70	76.00
C1-6	92.67	95.00	109.67	98.67	108.00	158.13	146.93	91.20	116.03	74.00	13.20	10.80	.	5.07	6.00	25.95	27.21	21.90	20.03	16.00	85.93	91.47	57.33	75.97	69.00
C1-7	94.33	93.00	111.67	99.33	107.00	163.27	145.60	83.33	117.20	74.00	11.67	10.53	.	6.10	5.00	27.77	27.68	22.54	20.57	15.00	103.13	117.27	54.53	83.93	75.00
C1-9	93.67	94.33	116.67	98.33	111.00	145.07	121.40	97.27	114.23	79.00	13.73	11.13	.	6.97	8.00	28.31	27.50	23.59	19.87	15.00	81.73	93.87	92.60	75.93	81.00
C2-1	91.33	95.33	108.33	98.67	107.00	159.20	150.00	105.07	115.60	72.00	11.67	11.73	.	6.97	5.00	27.36	27.92	22.37	20.17	15.00	93.07	82.40	48.80	78.73	68.00
C2-10	98.33	98.67	112.33	98.67	107.00	168.13	147.60	96.07	116.23	71.00	11.53	11.93	.	5.20	5.00	25.05	25.75	21.34	20.80	15.00	101.13	121.33	67.20	76.73	79.00
C2-13	88.67	91.67	108.33	99.67	107.00	142.93	132.93	91.40	116.10	69.00	14.33	10.87	.	7.47	6.00	27.92	29.05	22.39	20.80	16.00	101.80	117.80	51.55	76.00	78.00
C2-14	97.00	98.33	114.00	98.33	107.00	164.93	147.73	102.00	118.20	71.00	13.27	12.13	.	9.63	5.00	25.47	26.77	21.15	22.07	17.00	106.33	111.47	62.33	69.13	71.00
C2-18	93.67	95.33	118.33	98.67	105.00	158.00	150.00	90.07	110.60	68.00	11.33	11.47	.	8.30	8.00	27.20	27.89	19.77	20.67	16.00	99.73	95.00	41.33	75.77	82.00
C2-3	96.00	99.00	114.00	97.67	109.00	162.00	147.80	101.80	115.77	74.00	12.67	13.27	.	7.40	4.00	25.57	26.95	20.82	20.83	15.00	94.40	110.67	59.87	62.77	65.00
C2-4	97.67	99.33	113.00	101.00	107.00	162.73	148.93	95.80	116.20	71.00	12.33	11.80	.	8.70	6.00	26.30	26.67	19.49	21.57	16.00	98.20	117.93	58.87	66.53	80.00
C2-5	99.33	98.67	112.33	99.67	108.00	161.00	142.67	97.33	115.10	69.00	12.33	11.93	.	8.80	4.00	27.05	25.86	19.94	20.37	16.00	110.73	112.40	57.60	74.03	67.00
C3-3	92.67	96.33	122.00	99.50	107.00	158.73	150.00	74.40	114.45	71.00	13.13	11.73	.	5.95	5.00	27.67	28.34	22.23	20.60	16.00	91.67	94.07	51.50	67.80	70.00
C3-5	90.33	95.00	121.50	98.00	106.00	157.13	149.87	99.60	116.20	69.00	13.93	10.67	.	9.90	4.00	26.95	26.80	23.71	20.70	13.00	92.73	85.80	98.10	72.60	66.00
T-Mazand	96.00	95.33	109.00	98.33	113.00	161.33	148.67	100.67	111.23	91.00	12.33	9.40	.	6.97	4.00	27.14	28.63	22.15	21.53	16.00	88.60	100.87	44.40	80.37	67.00
Neda	107.33	95.33	132.33	97.67	108.00	101.67	74.40	76.00	101.43	69.00	15.07	13.67	.	7.37	6.00	25.23	20.79	22.38	19.73	15.00	95.13	60.33	63.60	73.17	79.00
Shiroudi	109.00	107.00	131.67	99.00	110.00	114.67	91.40	78.67	107.60	86.00	16.40	11.33	.	7.10	5.00	30.77	25.45	24.64	20.97	15.00	99.13	56.33	75.67	77.30	69.00
Vandana	102.00	106.67	122.33	97.67	105.00	142.33	118.60	101.00	120.13	68.00	12.20	11.00		7.87	5.00	24.86	22.75	23.41	21.43	14.00	140.33	91.27	111.53	73.50	80.00
Mean	95.6	96.6	115.4	99.0	107.7	150.3	134.2	93.4	113.7	72.9	12.9	11.7	.	7.4	5.4	26.6	26.3	21.8	20.7	15.4	95.0	91.4	61.9	75.4	74.4
LSD 5%	3.09	8.07	.	2.80	.	10.01	9.95	.	17.10	.	2.83	2.44	.	3.20	.	2.38	2.16		1.30	.	22.60	26.40		11.20	.
CDt 5%			2.01					2.01										2.01					2.01		

Continued from Supplementary Table S1- Mean performance of genotypes across five environments (three aerobic + two stress conditions).

Genotype	NFG					BGL					BGW					TGW					GYLD				
	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5†
C1-1	6.67	14.73	22.07	23.50	17.00	9.93	9.24	9.73	.	.	2.75	2.55	2.55	.	.	27.77	24.07	19.53	19.33	23.00	3886.67	3840.00	2460.00	4100.00	2100.00
C1-12	27.33	18.53	10.87	30.40	17.00	9.13	9.24	8.63	.	.	2.83	2.74	2.85	.	.	26.53	25.60	25.20	20.67	26.00	3640.00	3653.33	2170.00	3233.33	3700.00
C1-14	19.00	44.93	23.87	22.73	14.00	9.76	9.52	9.02	.	.	2.64	2.38	2.53	.	.	24.13	23.03	22.77	17.33	27.00	3993.33	2743.33	2010.00	4300.00	3900.00
C1-15	20.87	19.13	25.73	23.90	15.00	10.32	10.34	9.17	.	.	2.59	2.44	2.56	.	.	26.27	25.77	24.97	23.33	21.00	4613.33	3713.33	1340.00	4066.67	2500.00
C1-16	27.13	43.33	28.73	20.53	22.00	9.96	9.61	9.13	.	.	2.76	2.61	2.67	.	.	23.33	22.93	24.57	18.67	21.00	3353.33	2870.00	2030.00	3633.33	2300.00
C1-21	24.00	47.47	21.67	27.33	17.00	9.65	9.13	9.17	.	.	2.61	2.44	2.42	.	.	23.60	20.63	20.97	22.00	22.00	3880.00	3966.67	2560.00	5400.00	2300.00
C1-22	26.33	37.33	33.67	30.50	16.00	9.50	8.89	8.70	.	.	2.75	2.58	2.77	.	.	26.33	21.87	23.03	21.00	23.00	4140.00	2516.67	1693.33	4766.67	2350.00
C1-26	37.73	27.60	29.27	24.10	13.00	9.00	8.67	8.31	.	.	2.91	2.70	2.70	.	.	24.40	21.23	23.50	22.00	26.00	6093.33	3310.00	2890.00	5833.33	2800.00
C1-41	33.53	37.07	32.00	24.80	14.00	9.48	8.97	9.06	.	.	2.66	2.46	2.58	.	.	23.47	19.83	20.85	22.00	19.00	3766.67	3066.67	1800.00	5000.00	1900.00
C1-45	18.33	30.00	22.07	28.07	20.00	9.60	8.80	8.75	.	.	2.62	2.35	2.51	.	.	22.50	21.37	21.93	18.33	22.00	4326.67	3180.00	1810.00	3633.33	1950.00
C1-6	14.93	26.47	21.53	27.53	23.00	9.80	9.33	9.51	.	.	2.62	2.31	2.44	.	.	22.07	19.83	22.00	22.00	21.00	4100.00	3700.00	1820.00	4300.00	1900.00
C1-7	30.67	29.00	13.73	26.67	18.00	10.04	9.78	9.50	.	.	2.53	2.25	2.59	.	.	22.90	21.53	25.17	20.33	26.00	4366.67	3100.00	1400.00	3433.33	2200.00
C1-9	18.60	12.87	29.27	27.50	13.00	10.27	9.78	9.25	.	.	2.76	2.52	2.87	.	.	26.93	25.47	26.00	21.33	28.00	4613.33	3330.00	2066.67	7066.67	4300.00
C2-1	12.67	26.93	12.33	25.73	15.00	9.93	9.85	9.44	.	.	2.53	2.39	2.44	.	.	24.73	21.10	22.97	20.00	19.00	4826.67	3433.33	2106.67	5966.67	1850.00
C2-10	8.47	18.53	19.87	22.83	21.00	9.10	8.47	8.16	.	.	2.52	2.30	2.42	.	.	20.10	17.30	19.17	16.67	23.00	4386.67	3500.00	2033.33	5866.67	2250.00
C2-13	11.80	16.53	8.38	23.73	16.00	10.59	9.81	9.52	.	.	2.51	2.32	2.48	.	.	22.63	22.77	24.93	21.33	26.00	3933.33	3433.33	1240.00	3966.67	2500.00
C2-14	12.60	25.87	8.60	21.83	22.00	8.92	8.67	8.99	.	.	2.49	2.30	2.43	.	.	19.37	19.53	20.70	16.33	21.00	4560.00	3616.67	1986.67	7133.33	1900.00
C2-18	9.73	22.47	10.53	24.33	14.00	10.02	9.46	9.49	.	.	2.49	2.29	2.49	.	.	23.37	22.13	23.20	20.67	24.00	4686.67	3906.67	1806.67	4500.00	2900.00
C2-3	14.00	36.60	8.00	25.07	25.00	8.84	8.44	8.31	.	.	2.50	2.30	2.40	.	.	20.93	16.50	80.30	16.33	17.00	3986.67	3500.00	2073.33	3583.33	1700.00
C2-4	14.07	18.80	11.00	29.13	18.00	9.07	8.67	8.67	.	.	3.76	2.36	2.42	.	.	19.07	20.17	19.67	16.33	23.00	3880.00	3756.67	1700.00	7733.33	2700.00
C2-5	15.47	16.47	8.33	24.17	24.00	8.91	8.49	8.67	.	.	2.53	2.25	2.45	.	.	19.57	18.47	19.13	17.33	22.00	4106.67	3380.00	2060.00	5473.33	1850.00
C3-3	12.80	36.60	37.30	19.10	26.00	9.82	9.72	9.26	.	.	2.53	2.27	2.54	.	.	23.90	21.47	22.50	21.50	22.00	4273.33	3480.00	2065.00	4150.00	1850.00
C3-5	9.07	31.20	26.80	31.90	27.00	10.14	9.32	7.93	.	.	2.51	2.22	2.61	.	.	22.73	18.73	22.30	19.00	18.00	4566.67	3176.67	2030.00	2800.00	1550.00
T-Mazand	12.67	24.20	22.07	20.47	26.00	9.80	9.47	9.34	.	.	2.47	2.28	2.36	.	.	23.47	22.60	22.43	21.33	23.00	3913.33	3680.00	1400.00	4900.00	2200.00
Neda	22.87	15.40	23.00	24.83	21.00	10.34	10.10	10.18	.	.	2.46	2.32	2.35	.	.	28.47	24.57	25.17	27.33	24.00	6680.00	4016.67	3986.67	5866.67	2350.00
Shiroudi	45.20	29.60	14.47	27.70	23.00	10.45	10.26	9.89	.	.	2.47	2.35	2.27	.	.	25.47	23.70	23.50	26.33	22.00	5533.33	3583.33	4700.00	7766.67	2300.00
Vandana	50.20	26.67	52.67	17.37	19.00	8.48	8.45	8.21	.	.	2.94	2.70	2.85	.	.	22.80	19.83	23.73	19.00	25.00	5253.33	2810.00	1140.00	6966.67	2250.00
Mean	20.6	27.2	21.4	25.0	19.1	9.7	9.3	9.0	.	.	2.7	2.4	2.5	.	.	23.6	21.6	24.8	20.3	22.7	4420.7	3417.2	2088.1	5016.3	2383.3
LSD 5%	12.90	16.70		9.80	.	0.48	0.59		.	.	0.70	0.17		.	.	2.07	2.89		3.90	.	990.70	781.00		2730.00	.
CDt 5%			2.01					2.01					2.01					2.01					2.01		

Where: Numbers E1 to E5 correspond to environments: E1 – Conventional transplanting/flooded (Amol), E2 – Reproductive-stage drought stress (Amol), E3 – Aerobic conditions (Amol), E4 – Aerobic conditions (Golestan), and E5 – Aerobic conditions (Kohgiluyeh and Boyer-Ahmad, †: E5 was used only in the rank-based analysis, because the available analysis file did not contain the replicate-level observations required to estimate an independent experimental error term for E5).

FLR: Number of days to 50% flowering (days), PLH: Plant height (cm), TLR: Number of productive tillers per plant (no. plant^{-1}), PL: Panicle length (cm), FG: Number of filled grains per panicle (no. panicle^{-1}), NFG: Number of unfilled (sterile) spikelet per panicle (no. panicle^{-1}), BGL: Brown grain length (mm), BGW: Brown grain width (mm), TGW: Thousand grain weight (g), GYLD: Grain yield (kg ha^{-1}).

LSD: Least significant difference, CDt: Critical difference for significance, * and ** indicate significance at the 5% and 1% probability levels, respectively, and "." indicates missing data.

Journal of Agricultural Science and Technology (JAST), 29(5)
In Press, Pre-Proof Version

ارزیابی لاین‌های به‌نژادی برنج هوازی: عملکرد در شرایط هوازی و تنش خشکی در مرحله زایشی

علی مومنی، هرداد عمواقلی طبري، ابوالفضل فرجی، مصطفی یوسفیان، وحید خسروی، و هادی مومنی هلالی

چکیده

کمبود آب و وقوع روزافزون خشکسالی‌ها، تولید برنج را تهدید می‌کنند و ضرورت به‌کارگیری سامانه‌های کشتِ صرفه‌جویِ آب را بیش از پیش نمایان می‌سازند. کشت برنج هوازی — (Aerobic rice) که در شرایط بدون غرقاب انجام می‌شود — با کاهش نیاز به آب و در عین حال حفظ سطح تولید، جایگزینی پایدار محسوب می‌گردد. در این پژوهش، ۲۳ لاین اصلاحی پیشرفته برنج هوازی (حاصل از تلاقی ارقام بومی ایران با ارقام اهداکننده صفات هوازی) به همراه چهار رقم شاهد، در سه سامانه کشت مورد ارزیابی قرار گرفتند: کشت نشایی غرقابی (متداول)، شرایط تنش خشکی در مرحله زایشی، و شرایط کاملاً هوازی. این ارزیابی‌ها در سه منطقه اصلی برنج‌کاری ایران که نماینده نواحی مختلف زراعی-اکولوژیکی هستند، انجام شد. صفات زراعی، اجزای عملکرد، عملکرد دانه و شاخص‌های کیفیت پخت در هر محیط به‌طور جداگانه و همچنین در قالب تحلیل واریانس مرکب اندازه‌گیری و تحلیل شدند. از آنجا که آزمون بارتلت (Bartlett's test) ناهمگونی واریانس‌های خطا را نشان داد، برای سنجش ثبات رتبه ژنوتیپ‌ها در محیط‌های مختلف هوازی، از آماره‌های ناپارامتریک مبتنی بر رتبه استفاده شد. نتایج نشان‌دهنده تفاوت‌های معنادار در عملکرد لاین‌ها تحت شرایط گوناگون بود. در شرایط تنش خشکی مرحله زایشی، لاین C1-21 بیشترین عملکرد دانه (۳۹۶۷ کیلوگرم در هکتار) را در میان لاین‌های اصلاحی به خود اختصاص داد. در شرایط کشت هوازی نیز لاین‌هایC1-26 ، C1-21وC1-1 (در منطقه آمل) و لاین‌هایC2-4 ، C2-14وC1-9 (در منطقه گرگان) بالاترین عملکرد را داشتند؛ این در حالی است که عملکرد رقم شاهدِ هوازی «واندانا (Vandana)» در این شرایط به ترتیب ۱۱۴۰ و ۶۹۶۷ کیلوگرم در هکتار بود. بررسی شاخص‌های کیفیت دانه نشان داد که اکثر لاین‌ها دارای محتوای آمیلوز متوسط (۱۹ تا ۲۲ درصد)، میزان افزایش طول دانه مطلوب هنگام پخت (۱.۶۵ تا ۱.۹۹) و شکل دانه‌ای مشابه ارقام محبوب ایرانی بودند. یافته‌های این پژوهش بیانگر آن است که هنگام گزینش لاین‌ها برای اصلاح برنج هوازی، باید «سازگاری اختصاصی» و «ثبات مبتنی بر رتبه» به‌طور جداگانه مد نظر قرار گیرند.