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Effect of water stress on yield stability, water productivity, and canopy temperature of rice genotypes

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A b s t r a c t. A field experiment was conducted to evaluate the performance and water productivity of 15 rice genotypes under non-stress and drought-stress conditions in a warm-temperate climate. This study was laid out with a randomized complete block design at two research stations (Abbasabad and Katalom, Iran). Water deficit decreased the grain yield and increased the canopy temperature in all genotypes, but the response of water productivity to drought stress was not the same for the different genotypes. The maximum water productivity in non-stress and stress conditions (0.50 and 0.53 kg m^{-3}, respectively) were found in landraces. The canopy temperature was a reliable indicator for identifying drought-tolerant genotypes of rice. With each degree increase in canopy temperature, the grain yield decreased by 1 942 kg ha^{-1}. The biplot analysis demonstrated that landraces were the most suitable genotypes for cultivation under drought-stress and no-stress conditions. A principal component analysis based on stress tolerance indices showed that Shastak and Sahel were the most tolerant genotypes to drought stress. Overall, Shastak with a maximum grain yield (4 595 kg ha^{-1}), the highest water productivity, and savings of irrigation water by as much as 54% under conditions of drought stress may be introduced as a superior genotype for cultivation under water scarcity conditions and used in future breeding programmes.

K e y w o r d s: cultivar, irrigation cut-off, stress tolerance indices, grain yield, water use efficiency

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important cereals produced on a global basis, and meets the needs of more than half of the world's population as their main food source, especially in Asian countries (Samal *et al*., 2018). Rice is one of the most important food sources globally and is the second most-consumed crop in Iran. The area under cultivation for this crop globally is about 164 million ha, of which 0.26% is produced by Iran (FAOSTAT, 2020). In recent years, climate change and the subsequent increase in the incidents and duration of drought have threatened crop production and food security (Balazadeh *et al*., 2021; Farhadi *et al*., 2022). Drought stress is one of the most significant factors limiting crop yield, it has different effects at different stages of plant development and profoundly affects agricultural systems and food production (Golzardi *et al*., 2017; Ashoori *et al*., 2021; Baghdadi *et al*., 2021). However, rice requires a large amount of water for its growth and development (Sabouri *et al*., 2022), and drought is the most critical limiting factor for rice growth and production (Pandey and Shukla, 2015). A meta-analysis of recent studies shows that rice yield has decreased due to limited water resources so future droughts may lead to an even further decline in rice yield (Zhang *et al*., 2018). Therefore, it is necessary to develop drought-tolerant cultivars to improve rice yield stability and productivity in different environmental conditions (Pandey and Shukla, 2015). In order to produce superior cultivars, it is necessary to identify the existing genetic diversity (especially landraces) and determine their production potential in different environments (Mishra *et al*., 2018). Therefore, the identification and development of drought-tolerant genotypes of rice is one of the main goals of breeders in response to climate change (Monkham *et al*., 2018; Sabouri *et al*., 2022).

The response of rice to drought stress is very complex and involves several physiological, biochemical, and molecular changes. Since rice shows different reactions

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based on the intensity and duration of stress, it is necessary to compare the yield stability of genotypes in different environments to select the best genotypes with more confidence (Panda *et al*., 2021). A GGE biplot analysis is a graphical method used to analyse the yield stability of different genotypes in various environments (Pour-Aboughadareh *et al*., 2022). This method has been used to identify the tolerance and susceptibility levels of rice genotypes to drought stress (Poli *et al*., 2018; Sabouri *et al*., 2022). Another method of identifying drought-tolerant genotypes is to use stress tolerance indices (such as TOL, STI, SSI, MP, GMP, HM, RSI, YI, and YSI) and to rank the genotypes based on them (Krishnamurthy *et al*., 2016; Mariey and Khedr, 2017). In addition, it is possible to identify drought-tolerant genotypes by evaluating their water productivity and canopy temperature (Khorsand *et al*., 2020; Teymoori *et al*., 2020).

In order to select stable and high-yield genotypes in different regions and humidity conditions, using one analysis method alone is not sufficient and may not lead to desirable results. However, the evaluation of genotypes using different yield stability analysis methods and ranking them based on different drought tolerance indices and physiological characteristics may increase the likelihood of identifying desirable genotypes (Pour-Aboughadareh *et al*., 2022; Sabouri *et al*., 2022). Water scarcity and the increase in the incidents and duration of drought in recent years demand the identification of drought-tolerant genotypes with stable and desirable yields; however, despite the high potential of rice landraces in the last decade, thus far, the introduction of new drought-tolerant cultivars to market has not been adequate. This study compared rice cultivar yield stability, drought tolerance, and physiological characteristics using Iranian landraces. We intended to identify drought-resistant genotypes with a suitable yield and stability for cultivation in water-limited conditions and use them in future rice breeding programmes. Another aim of this study was to investigate the response of grain yield, canopy temperature, and the water productivity of rice genotypes to water deficit stress.

MATERIALS AND METHODS

Fifteen rice genotypes, including seven cultivars (Fajr, Neda, Shirodi, Khazar, Nemat, Sahel, and Pouya) along with eight Iranian landraces (Hashemi, Alikazemi, Shastak, Binam, Tarom, Deylamani, Haj Heidari, and Sangtarom) were evaluated under non-stress and drought-stress conditions at two research stations during the 2019 cropping season in a warm-temperate climate (hot-summer Mediterranean climate). The experiment was conducted in a randomized complete block design with three replications. The research stations belonged to the Islamic Azad University and were located in Abbasabad (36°41'N 51°03'E, 137 m a.s.l.) and Katalom (36°52'N 50°42'E, 16 m a.s.l.) in Iran. The characteristics of the studied genotypes are presented in Table 1. The studied environments included non-stress conditions in Abbasabad (E1), non-stress conditions in Katalom (E2), drought-stress conditions in Abbasabad (E3), and drought-stress conditions in Katalom (E4). The physicochemical properties of the soil of the research stations are presented in Table 2. The meteorological data of the experiment sites, including precipitation and temperature during spring and summer 2019, are provided in Table 3.

Table 1. Name, pedigree, and origin of the investigated rice genotypes

Genotype name	Pedigree	Origin
Fajr	Cultivar, IR62871-175-1-10	IRRI, Philippines
Neda	Cultivar, Sangtarom × HassanSaraei × Amol3	Mazandran, Iran
Hashemi	Iranian landrace	Guilan, Iran
Shirodi	Cultivar, Khazar × Deilmani	Mazandran, Iran
Khazar	Cultivar, IR2071-625-1-52 × TNAU 7456	Guilan, Iran
Alikazemi	Iranian landrace	Guilan, Iran
Nemat	Cultivar, D2-12-28, Amol3 × Sangtarom	Mazandran, Iran
Shastak	Iranian landrace	Mazandran, Iran
Binam	Iranian landrace	Guilan, Iran
Sahel	Cultivar, IR62871-264-3-4	IRRI, Philippines
Tarom	Iranian landrace	Mazandran, Iran
Deylamani	Iranian landrace	Guilan, Iran
Hajheydari	Iranian landrace	Mazandran, Iran
Sangtarom	Iranian landrace	Mazandran, Iran
Pouya	Cultivar, mutant cultivar of Mousa Tarom	Mazandran, Iran

IRRI – International Rice Research Institute.

Table 2. Physicochemical properties of soil at the research stations

Location	Texture	pH	EC ($ds\ m^{-1}$)	Organic matter (%)	Total N (%)	Available P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)
Abbasabad	Clay	6.6	0.63	1.57	0.12	24.3	130
Katalom	Clay loam	6.4	0.78	1.94	0.18	12.6	220

EC – Electrical conductivity.

Table 3. The meteorological data of the experiment sites during the 2019 cropping season

Month	Rainfall (mm)		Temperature (°C)					
			Average		Maximum		Minimum	
	Abbasabad	Katalom	Abbasabad	Katalom	Abbasabad	Katalom	Abbasabad	Katalom
April	0.4	1.5	20.6	17.7	25.7	22.3	15.5	13.1
May	0.5	0.1	24.3	24.4	28.7	29.7	19.8	19.2
June	0.5	2.6	26.4	26.8	30.7	31.6	22.0	22.1
July	0.1	0.4	27.2	27.4	33.6	33.1	20.9	21.6
August	1.4	4.0	26.0	24.1	30.9	28.5	21.1	19.6

In order to prepare seedlings, the seeds were sown in the nursery on April 21. Prior to transplantation, ploughing, levelling, and plot preparation operations were performed. The required fertilizers were determined based on soil test results and the nutritional needs of the rice plants. Accordingly, at the time of planting, urea, triple superphosphate, and potassium sulphate were added to the soil at the rates of 75, 200, and 100 kg ha^{-1}, respectively. Again, at the beginning of the tillering stage, 75 kg of urea ha^{-1} was applied (Poli *et al*., 2018). About 30 days after sowing the seeds in the nursery (on May 20), the seedlings were transferred to the main field. Manual transplanting was performed at an interval of 25×25 cm (Sabouri *et al*., 2022). The size of each experimental plot was assumed to be 6 m^2, which included eight planting rows (Yang *et al*., 2019). Under non-stress conditions, irrigation continued throughout the growth period. Flood irrigation was performed with well water. The electrical conductivity (EC) of the irrigation water was equivalent to 0.038 S m^{-1}. Under drought stress conditions, the plants were irrigated up to the tillering stage, similar to the treatment applied under non-stress conditions, and to apply drought stress treatment, irrigation was stopped from the tillering stage to the end of the growing season. In order to determine the grain yield, six middle rows of each plot were harvested on September 1. The canopy temperature was measured using an infrared thermal imaging camera (IVN 770-P). Water productivity was calculated using Eq. (1) (Fawibe *et al*., 2020):

$$WP = \frac{Y}{TW} \ , \tag{1}$$

where: WP – water productivity (kg m^{-3}), Y – marketable yield (kg ha^{-1}), TW – total applied irrigation water ($m^3\ ha^{-1}$). In order to evaluate the drought tolerance of rice genotypes, indices including tolerance index (TOL), stress tolerance index (STI), stress sensitivity index (SSI), mean productivity (MP), geometric mean productivity (GMP), harmonic mean (HM), relative stress index (RSI), yield index (YI), and yield stability index (YSI) were calculated (Sabouri *et al*., 2022). The aforementioned indices were calculated based on the yield of genotypes under non-stress (Yp) and drought stress (Ys) conditions. A principal component analysis (PCA) based on Yp, Ys, stress tolerance indices, and physiological characteristics was applied using the XLSTAT software. All biplots were generated using the software GGE biplot package in this research.

A Bartlett test was used to evaluate the homogeneity of experimental error variance in the studied environments. A combined analysis of variance was performed using the SAS9.1 software. The environment and block were assumed to be random effects. In order to obtain a mean comparison, the least significant difference (LSD) test at the level of 5% probability was used. A cluster analysis was performed based on Euclidean distance and after standardizing the data using Heatmapper software. The GGE biplot analysis evaluated the yield stability of genotypes in different environments (no-stress and drought stress conditions) (Sabouri *et al*., 2022). GGE biplot software was used to investigate the main effect of the genotype (G) and the interaction of the genotype × environment (GE). This software applies Eq. (2) to draw biplots (Pour-Aboughadareh *et al*., 2022):

$$Y_{ij} - \mu - \beta_j = \lambda_1 \zeta_{i1} \eta_{j1} + \lambda_2 \zeta_{i2} \eta_{j2} + \varepsilon_{ij} \ , \tag{2}$$

where: Y_{ij} – the response of ith genotype at the jth environment, μ – total mean, β_j – the effect of the environment, λ_1 and λ_2 – the single values of the first two principal components (PC_1 and PC_2), ξ_{i1} and ξ_{i2} – the eigenvectors of the ith

Table 4. The combined ANOVA for the grain yield of rice genotypes across four environments

Source	d.f.	S.S.	M.S.	T.S.S. (%)
Environment (E)	3	666 436 768	222 145 589*	65.96
Block × E	8	2 953 202	3 69 150	0.29
Genotype (G)	14	153 563 886	10 968 849*	15.20
G × E	42	137 576 538	3 275 632*	13.62
Error	112	49 823 665	444 854	4.93

d.f. – degrees of freedom, S.S. – sum of squares, M.S. – mean squares, T.S.S. – total sum of squares, * – significant ($p \leq 0.01$).

Table 5. Mean grain yield of 15 rice genotypes across four environments

Genotype name	Genotype No.	E1	E2	E3	E4	Mean
Fajr	G1	5 282 ^{gh}	5 238 $^{e-g}$	2 429 ^{cd}	1 655 ^{f}	3 651 ^{e}
Neda	G2	6 899 $^{c-e}$	6 648 ^{cd}	3 993 ^{a}	3 681 $^{a-c}$	5 305 $^{b-d}$
Hashemi	G3	5 790 $^{e-g}$	4 698 ^{fg}	1 512 ^{e}	3 372 ^{bc}	3 843 ^{de}
Shirodi	G4	5 535 ^{fg}	5 940 $^{d-f}$	3 015 ^{bc}	3 821 ^{ab}	4 578 $^{c-e}$
Khazar	G5	4 208 ^{h}	4 592 ^{g}	3 012 ^{bc}	2 985 $^{b-e}$	3 699 ^{e}
Alikazemi	G6	9 327 ^{a}	9 432 ^{a}	3 015 ^{bc}	2 784 $^{c-e}$	6 140 ^{ab}
Nemat	G7	7 388 $^{b-d}$	6 822 $^{b-d}$	3 042 ^{bc}	3 204 ^{bc}	5 114 $^{b-e}$
Shastak	G8	8 521 ^{ab}	9 720 ^{a}	4 676 ^{a}	4 515 ^{a}	6 858 ^{a}
Binam	G9	6 791 $^{d-f}$	7 481 ^{bc}	3 816 ^{ab}	2 952 $^{b-e}$	5 260 $^{b-d}$
Sahel	G10	8 319 ^{ab}	8 108 ^{b}	3 954 ^{a}	3 105 $^{b-d}$	5 871 $^{a-c}$
Tarom	G11	8 162 $^{a-c}$	5 874 $^{d-g}$	3 062 ^{bc}	2 994 $^{b-e}$	5 023 $^{b-e}$
Deylamani	G12	6 924 $^{c-e}$	5 346 $^{e-g}$	3 882 ^{ab}	3 129 ^{bc}	4 820 $^{b-e}$
Hajheydari	G13	5 504 $^{f-h}$	6 236 $^{c-e}$	3 032 ^{bc}	1 680 ^{f}	4 113 ^{de}
Sangtarom	G14	9 121 ^{a}	10 219 ^{a}	1 830 ^{de}	2 192 ^{ef}	5 840 $^{a-c}$
Pouya	G15	5 970 $^{e-g}$	6 302 $^{c-e}$	2 445 ^{cd}	2 220 $^{d-f}$	4 234 ^{de}

E1 – non-stress conditions in Abbasabad, E2 – non-stress conditions in Katalom, E3 – drought stress conditions in Abbasabad, E4 – drought stress conditions in Katalom. Means in the same column followed by different letters differ significantly at $p<0.05$.

genotype for PC_1 and PC_2, η_{j1} and η_{j2} – the eigenvectors of the jth environment for PC_1 and PC_2, and ε_{ij} – the general residue associated with genotype i and environment j.

RESULTS AND DISCUSSION

The combined analysis of variance showed that the effects of the environment, genotype, and genotype × environment interaction on grain yield (GY) were significant ($p \leq 0.01$) (Table 4). Of the total variation in GY, 65.96, 15.20, and 13.62% were attributable to the environment, genotype, and genotype × environment interaction, respectively (Table 4). Means comparisons in all of the studied environments showed that genotype G8 had the highest GY (6 858 kg ha^{-1}), followed by genotypes G6, G10, and G14 (6 140, 5 871, and 5 840 kg ha^{-1}, respectively) (Table 5). Drought-stress reduced the yield of all genotypes, although the reduction rate was not the same in all of them, and drought-tolerant genotypes were less affected by water restriction. The results of previous studies have shown that the response of rice plants to drought stress is very complex and involves several physiological, biochemical, and molecular changes (Gupta *et al*., 2020; Melandri *et al*., 2020). Kim *et al*. (2020) have shown that rice genotypes with deep and extensive root systems and high root/shoot ratios have a higher drought tolerance. Deficit irrigation in drought-sensitive rice genotypes reduces leaf photosynthetic capacity and relative water content (RWC) and ultimately reduces GY (Zhu *et al*., 2020). Similar to this study, Panda *et al*. (2021) stated that many drought-tolerant genotypes among rice landraces can be used in breeding programmes to develop drought-resistant rice cultivars. In the present study, the genotype G8 had a high yield potential under drought stress conditions and showed the least yield reduction in response to water shortage.

The heat map showed that no genotype could produce maximum GY in all environments (Fig. 1). The average GY of the genotypes in different environments ranged from 1 512 kg ha^{-1} (genotype G3 in environment E3) to

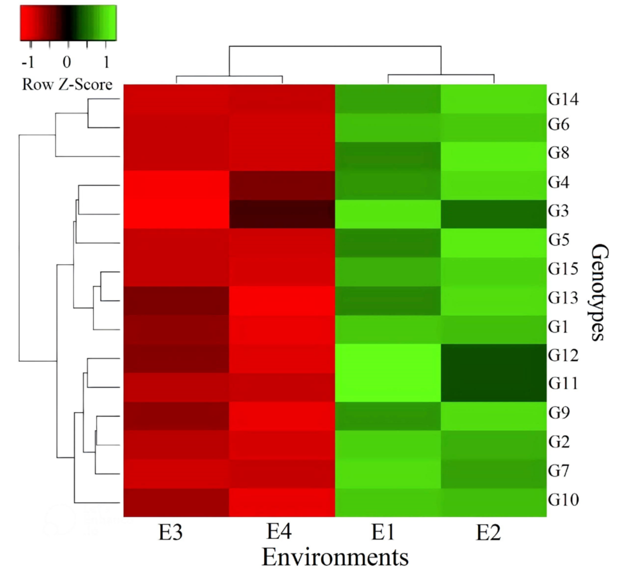

Fig. 1. Cluster analysis of rice genotypes based on grain yield in four experimental environments. The light green and light red areas indicate the maximum and minimum yields, respectively, whereas the black areas show moderate yield. Explanation as in Table 5.

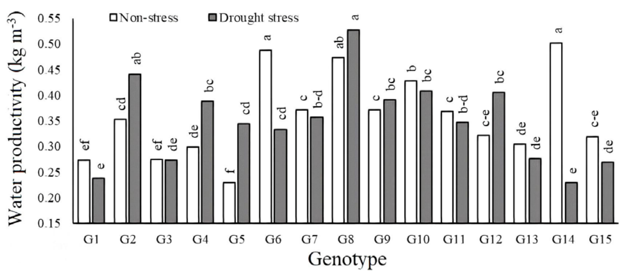

Fig. 2. Water productivity (kg m^{-3}) of rice genotypes under non-stress and drought stress conditions. For each stress level, means followed by similar letters do not differ significantly at $p<0.05$. G1 – Fajr, G2 – Neda, G3 – Hashemi, G4 – Shirodi, G5 – Khazar, G6 – Alikazemi, G7 – Nemat, G8 – Shastak, G9 – Binam, G10 – Sahel, G11 – Tarom, G12 – Deylamani, G13 – Hajheydari, G14 – Sangtarom, G15 – Pouya.

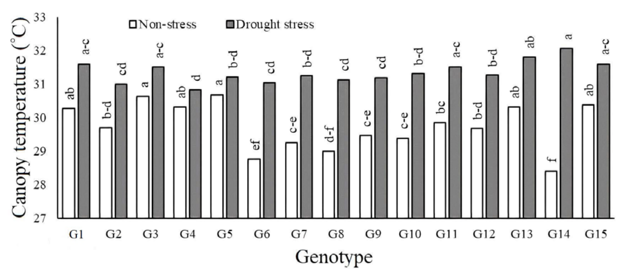

Fig. 3. Canopy temperature (°C) of rice genotypes under non-stress and drought stress conditions. Explanation as in Fig. 2.

10219 kg ha^{-1} (genotype G14 in environment E2) and showed considerable variation in experimental environments (Fig. 1 and Table 5). A cluster analysis based on GY divided the studied genotypes into three general groups (Fig. 1). The first group consisted of the G14, G6, and G8 genotypes, which produced the highest yields in the studied environments. The second group included genotypes G4, G3, G5, G15, G13, and G1 which all produced low yields in the experimental environments. The third group also included G12, G11, G9, G2, G7, and G10 which had moderate yields (Fig. 1). Also, the environments were divided into two groups with high yields (E1 and E2) and low yields (E3 and E4) (Fig. 1). The heat map also showed that drought stress reduced GY in all genotypes. Drought stress reduces rice GY by negatively affecting the net photosynthesis rate, stomatal conductance (internal CO_2 concentration), transpiration rate, PSII photosystem activity, RWC, and membrane stability (Dash *et al*., 2018, Mishra *et al*., 2018, Zhu *et al*., 2020).

The effect of drought stress on water productivity (WP) differed between the various genotypes studied (Fig. 2). Similar results have been reported by Yang *et al.* (2019). Water deficit decreased WP in genotypes G1, G6, G7, G10, G11, G13, G14, and G15 and increased WP in genotypes G2, G4, G5, G8, G9, and G12 (Fig. 2). The maximum WP in non-stress and stress conditions (0.50 and 0.53 kg m^{-3}, respectively) were found in genotypes G14 and G8, respectively. Genotype G8 had high WP in stress and non-stress conditions, while genotypes G1 and G3 showed low WP in all environments. The most significant reduction in WP under drought stress was recorded in genotype G14, which indicates its high sensitivity to water scarcity (Fig. 2). Genotypes with a higher WP under water deficit conditions show more drought tolerance, whereas drought-sensitive genotypes have a lower WP (Tshikunde *et al*., 2018). The cultivation of a drought-resistant genotype along with irrigation management which includes changing the amount of water consumed in the vegetative and reproductive stages may serve to minimize evapotranspiration and increase water productivity (Balazadeh *et al*., 2021; Farhadi *et al*., 2022).

Drought stress increased the canopy temperature (CT) in all genotypes, but the rate of change was different (Fig. 3). The maximum CT under stress conditions was recorded in genotype G14, followed by G13, G15, G1, G11, and G3. The greatest change in CT due to water deficit was recorded in drought-sensitive genotype G14, this value increased from 28.4°C under non-stress conditions to 32.1°C under stress conditions. Genotypes G8, G6, G7, G9, and G10, had low CT values in stress and non-stress conditions, indicating their drought tolerance (Fig. 3). A regression analysis showed that the GY of rice genotypes decreased linearly with increasing CT. Accordingly, with each degree increase in CT, the average GY decreased by 1942 kg ha^{-1} (Fig. 4). Since the CT depends on the transpiration rate, water absorption capacity, and water productivity, a low CT indirectly indicates the high ability of roots to absorb (Yan *et al*., 2012). Also, since CT is correlated with crop RWC and yield, genotypes with a lower CT show an improved water potential and will have more tolerance to drought stress (Khorsand *et al*., 2020; Teymoori *et al*., 2020).

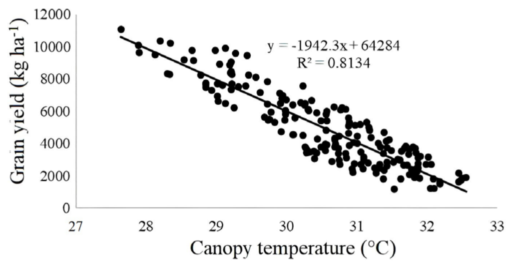

Fig. 4. Relationship between the canopy temperature (°C) and grain yield (kg ha^{-1}) of rice genotypes across four environments.

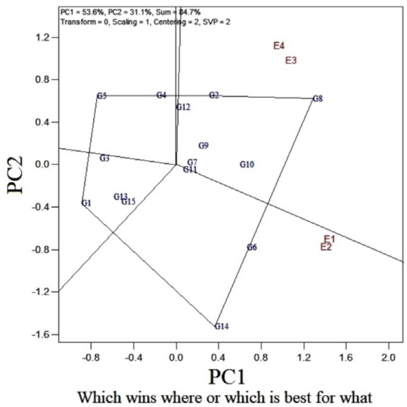

Fig. 5. The polygon-view of the GGE biplot to display the which-won-where pattern. Explanation as in Table 5 and in Fig. 2.

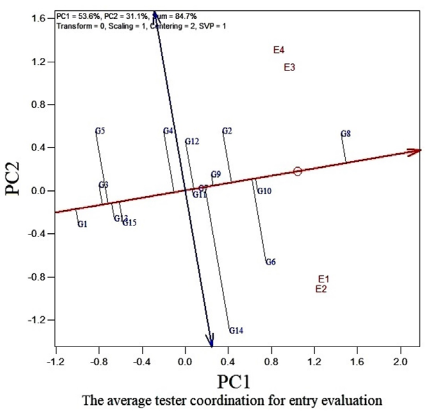

Fig. 6. Biplot of the average-environment coordination (AEC) for the simultaneous selection of grain yield and stability of rice genotypes.

One of the major challenges in rice breeding programmes is the identification of drought-tolerant genotypes with a good yield and a high degree of stability in different environments (Monkham *et al*., 2018). Therefore, it is necessary to evaluate the genotypes in different environments and analyse the genotype × environment interaction (GEI) by applying methods like the GGE biplot (Sánchez-Martín *et al*., 2017). The GGE biplot graphical analysis showed that the first two principal components explained 84.7% of the total GEI variance (PC1: 53.6% and PC2: 31.1%) (Fig. 5). The polygon-view of the GGE biplot revealed that genotype G14 in environments E1 and E2 (no-stress conditions) and genotype G8 in environments E3 and E4 (drought stress conditions) had the highest GY (Fig. 5). Genotypes G10, G2, and G9 were very similar to genotype G8 and showed a high degree of adaptability to drought stress conditions. Similarly, genotypes G14 and G6 were suitable for cultivation under no-stress conditions (Fig. 5). Genotypes G1, G5, G3, G13, G15, and G4 were the most undesirable genotypes in all of the environments studied. Genotypes G7 and G11 had minimal GEI and showed a high degree of general compatibility, although their GYs were not high (Fig. 5). Similar to the present study, Poli *et al*. (2018) used the polygon-view of the GGE biplot to identify superior rice genotypes in different environments and introduced stable genotypes for cultivation under no-stress and drought stress conditions. The biplot of the average-environment coordination (AEC) is used to evaluate the yield and stability of the genotypes (Pour-Aboughadareh *et al*., 2022). Accordingly, genotypes G7, G11, G9, G13, G15, G3, and G1 did not produce acceptable yields despite their high degree of stability (Fig. 6). Genotypes G14, G6, G5, and G4 also demonstrated a low yield stability. However, genotype G8, which had maximum GY and a favourable yield stability, is identified as the most suitable genotype in terms of yield and stability. Genotype G10 was also the second most superior genotype with a lower yield and higher stability (Fig. 6). Naroui Rad and Bakhshi (2021) also used the biplot of AEC to evaluate genotypes under no-stress and drought stress conditions and introduced superior genotypes by considering both yield and stability.

Due to climate change in recent years and the significant yield reduction due to drought stress, it is necessary to identify drought-resistant genotypes (Baghdadi *et al*., 2021). A comparison between drought tolerance indices and physiological characteristics showed that genotype G8 had the highest Ys, WP, MP, GMP, HM, STI, and YI, and low CT, so it was identified as the most drought-tolerant genotype (Table 6). The WP, CT, GMP, STI, MP, and HM significantly correlated with Yp and Ys and were the most desirable indices for comparing the drought tolerance of genotypes in this study (Table 7). Sabouri *et al*. (2022) also introduced MP, GMP, HM, and STI as the most appropriate indices for identifying drought-tolerant rice genotypes. Krishnamurthy *et al*. (2016) and also Mariey and Khedr (2017) also reported similar results. Based on the aforementioned desirable indices, the highest drought tolerance was found in genotype G8, followed by G10 (Table 6). Furthermore, the canopy temperature under no-stress (CTp) and drought stress conditions (CTs) showed a significant negative correlation with Yp and Ys, respectively (Table 7). Therefore, it is possible to identify drought-tolerant genotypes by measuring the CT in the reproductive stage. In order to identify drought-tolerant genotypes in plant breeding programmes, it is necessary to use a combination of stress tolerance indices and physiological characteristics using a principal component analysis (PCA) or GT-biplot (Thiry *et al*., 2016). TOL, MP, GMP, STI, SSI, and HAR are the most suitable

Table 6. Drought tolerance indices and physiological characteristics of rice genotypes

Genotype	Yp	Ys	WP	CT	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
G1	5260	2042	0.26	30.94	3218	3651	3277	2941	1.09	0.23	0.67	0.39	0.88
G2	6773	3837	0.40	30.36	2936	5305	5098	4899	0.78	0.55	1.26	0.57	1.28
G3	5244	2442	0.27	31.07	2802	3843	3579	3332	0.96	0.27	0.81	0.47	1.06
G4	5738	3418	0.34	30.57	2320	4578	4428	4284	0.72	0.41	1.13	0.60	1.35
G5	4400	2999	0.29	30.95	1401	3699	3632	3566	0.57	0.28	0.99	0.68	1.55
G6	9380	2900	0.41	29.90	6480	6140	5215	4430	1.24	0.57	0.96	0.31	0.70
G7	7105	3123	0.36	30.26	3982	5114	4710	4339	1.00	0.47	1.03	0.44	1.00
G8	9120	4595	0.50	30.06	4525	6858	6474	6111	0.89	0.89	1.51	0.50	1.14
G9	7136	3384	0.38	30.33	3752	5260	4914	4591	0.94	0.51	1.12	0.47	1.08
G10	8213	3530	0.42	30.35	4684	5871	5384	4937	1.02	0.61	1.16	0.43	0.97
G11	7018	3028	0.36	30.68	3990	5023	4610	4230	1.02	0.45	1.00	0.43	0.98
G12	6135	3506	0.36	30.48	2630	4820	4637	4462	0.77	0.45	1.16	0.57	1.30
G13	5870	2356	0.29	31.06	3514	4113	3718	3362	1.07	0.29	0.78	0.40	0.91
G14	9670	2011	0.37	30.23	7659	5840	4409	3329	1.42	0.41	0.66	0.21	0.47
G15	6136	2333	0.29	30.99	3803	4234	3783	3380	1.11	0.30	0.77	0.38	0.86

Yp – grain yield under non-stress conditions (kg ha^{-1}), Ys – grain yield under drought stress conditions (kg ha^{-1}), WP – water productivity (kg m^{-3}), CT – canopy temperature (°C), TOL – tolerance index (kg ha^{-1}), MP – mean productivity, GMP – geometric mean productivity, HM – harmonic mean, SSI – stress susceptibility index, STI – stress tolerance index, YI – yield index, YSI – yield stability index, RSI – relative stress index. More explanations as in Fig. 2.

Table 7. Correlation coefficients between grain yields under non-stress (Yp) and drought stress conditions (Ys) with physiological characteristics and drought tolerance indices

Traits	WP	CT	CTp	CTs	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Yp	0.79^{**}	-0.85^{**}	-0.95^{**}	0.05^{ns}	0.90^{**}	0.93^{**}	0.75^{**}	0.52^{*}	0.60^{*}	0.73^{**}	0.25^{ns}	-0.60^{*}	-0.60^{*}
Ys	-0.78^{**}	-0.55^{*}	-0.25^{ns}	-0.75^{**}	-0.20^{ns}	0.59^{*}	0.83^{**}	0.95^{**}	-0.57^{*}	0.83^{**}	0.99^{**}	0.57^{*}	0.57^{*}

CTp – canopy temperature under non-stress conditions, CTs – canopy temperature under drought stress conditions. ** – significant ($p \le 0.01$), * – significant ($p \le 0.05$), ns – non-significant. More explanations as in Fig. 2.

indicators for determining tdrought-tolerant hybrids for plant production under high-yield drought conditions based on PCA (Khatibi *et al*., 2022). The PCA is based on the correlation matrix between Yp, Ys, drought tolerance indices and physiological characteristics showed that the first two principal components explained 97.69% of the total variation (PC1: 58.56% and PC2: 39.13%) (Fig. 7). Based on the GT-biplot analysis, genotype G8 had the highest PC1 score among the studied genotypes and was identified as the most drought-tolerant genotype. Genotype G10 also had a high PC1 score and a near-to-zero PC2, thereby ranking second in drought tolerance. The GT-biplot analysis also showed that CT was negatively correlated with GMP, STI, MP, HM, WP, Yp, and Ys. Therefore, CT measurement should be introduced as a practical and immediate method to evaluate the drought tolerance of rice genotypes (Yan *et al*., 2012; Khorsand *et al*., 2020; Teymoori *et al*., 2020). Similar to the present study, Sharifi and Ebadi (2018) and Sabouri *et al*. (2022) also used a GT-biplot analysis to identify superior rice genotypes under drought stress conditions. They also revealed that using a combination of drought tolerance indices and GT-biplot are effective methods for screening superior genotypes with more accuracy.

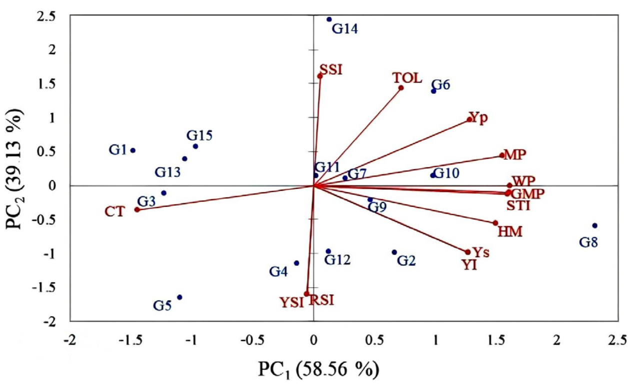

Fig. 7. Genotype × trait (GT)-biplot for grain yield under non-stress (Yp) and drought stress conditions (Ys), drought tolerance indices, and physiological characteristics of rice genotypes. Explanations as in Fig. 2 and in Table 6.

CONCLUSIONS

1. Drought stress increased the canopy temperature in all genotypes, but the water productivity response to drought stress was not the same in different genotypes. The maximum water productivity in non-stress and drought stress conditions were recorded in the landraces. The greatest increase in canopy temperature under water deficit conditions was observed in genotype Sangtarom, which increased from 28.4°C under non-stress conditions to 32.1°C under drought stress conditions. With each degree increase in canopy temperature, the average grain yield of the genotypes decreased by 1 942 kg ha^{-1}.

2. Biplot analysis showed that Shastak and Sangtarom were the most suitable genotypes for cultivation under drought-stress and no-stress conditions, respectively. Genotypes Sahel, Neda, and Binam were very similar to genotype Shastak and showed a high degree of adaptability to drought stress conditions. Genotypes Nemat and Tarom showed a high degree general compatibility, but their grain yield values were not high. However, Shastak and Sahel were the ideal genotypes in both yield and stability.

3. Canopy temperature was negatively correlated with geometric mean productivity, stress tolerance index, mean productivity, harmonic mean, water productivity, and yield under non-stress and drought stress conditions. Therefore, canopy temperature measurement should be introduced as a practical and immediate method to evaluate the drought tolerance of rice genotypes. Furthermore, the water productivity, canopy temperature, geometric mean productivity, stress tolerance index, mean productivity, and harmonic mean were significantly correlated with yield under non-stress and drought stress conditions and were found to be the most suitable indices for identifying drought-tolerant genotypes in the present study. The genotype–trait biplot analysis based on grain yield, drought tolerance indices, and physiological characteristics showed that Shastak and Sahel were the most drought-tolerant genotypes to drought stress.

4. Genotype Shastak produced the maximum grain yield (4 595 kg ha^{-1}) and water productivity (0.53 kg m^{-3}), and savings of irrigation water by 54% under drought stress, it had a low canopy temperature in different moisture conditions, the highest drought tolerance indices, and an acceptable level of yield stability in the studied environment therefore it should be introduced as a superior genotype for cultivation in water-limited areas. In addition, Sangtarom and Alikazemi are presented as suitable genotypes for cultivation in waterlogged areas where it is possible to meet the water needs of rice throughout the growing season.

5. Rice landraces had a higher yield potential than cultivars under drought stress and non-stress conditions. Therefore, these genotypes could be used to produce high-yielding and drought-resistant cultivars in future breeding programmes.

Conflict of interest: All authors declare no conflict of interest.

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