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ASSESSING PRODUCTIVITY AND QUALITY POTENTIAL OF PROMISING NEWLY DEVELOPED RICE LINES UNDER WATER DEFICIT AND WELL-WATERED CONDITIONS

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Abstract

Water defecit is a crucial environmental stress that destructively limits rice growth and productivity, particularly under the current climate change. Consequently, developing drought-tolerant and high-yielding rice genotypes is essential to sustain rice production. This study aimed to investigate the genetic diversity of agronomic and qualitative characteristics among newly developed rice lines, comparing them to commercial checks under both water deficit and well-watered conditions. Thirteen newly advanced lines were collected from the F8 generation in the breeding program following a pedigree scheme. The studied advanced lines and five commercial cultivars were assessed under two water regimes: full irrigated (13000 m^3/ha) and water stress (8500 m^3/ha) conditions. The obtained results indicated highly significant variation among the evaluated genotypes in all studied agronomic and quality characters. Water deficit significantly reduced number of panicles per plant, 1000-grain weight, grain yield, hulling percentage, milling percentage, grain width, grain length, grain thickness, grain shape, hardness, elongation percentage, gel consistency, and gelatinization temperature (spreading and clearing), while broken and sterility percentage were significantly increased. Drought stress caused hindrance in panicle development and growth and hence reduced grain size and grain number as well as all quality characters. Cluster analysis, PC-biplot, and hierarchical clustering efficiently classified the evaluated genotypes based on the studied grain yield, yield components and quality traits. The evaluated genotypes were classified into distinct groups varying from drought-tolerant to moderately sensitive genotypes based on their agronomic performance and quality under drought stress. The advanced lines L5, L6, L7, L8, L10, L11, L12, and L13 displayed good agronomic and quality performance under drought stress. Moreover, lines L5, L6, L7, and L8 exhibited high-quality performance under drought stress. Generally, the genotypes L4, L5, L6, L7, L8, and L13 were identified as promising for improving yield traits and quality parameters under water deficit conditions. Subsequently, these identified genotypes could also be recommended for commercial cultivation under water deficit conditions. Furthermore, these genotypes could be exploited effectively to further improve of drought tolerance in rice through breeding programs to reinforce grain yield and quality under water shortage conditions, particularly under current climate change.

Key words: Rice, Drought stress, Yield traits, Quality traits, Cluster analysis, PC-biplot.

Introduction

Rice (*Oryza sativa*) is a staple food of a large proportion of the world population due to its valuable nutritional benefits (Khan *et al.*, 2022). It contains high content of carbohydrates, calories, minerals, vitamins, and protein (Kraithong *et al.*, 2018). Its total acreage is about 165×10^6 hectares producing almost 787×10^6 tons yearly (FAOSTAT, 2023). However, its production requires increasing due to the rapidly growing global population and current global climate change (Khush, 2005). Water supply is limited, and future food demand is likely to further escalate the influences of drought, particularly under current climate change (Cramer *et al.*, 2018). Drought severity is irregular and depends on various factors such as rainfall distribution, moisture-storing capacity of soils, and evaporative demands (Farooq *et al.*, 2009a; Bodner *et al.*, 2015). Drought is a crucial environmental stress that threats world food security (Khan *et al.*, 2021a). It is a more complex phenomenon than the other abiotic stresses as it can occur at any stage during plant growth (Ali *et al.*, 2021). It is becoming a steadily severe problem in several regions worldwide and is considered a catalyst of the great famines (Kaniewski *et al.*, 2015). It destructively impacts plant development, lowers grain yield, and greatly affects grain quality (Yang *et al.*, 2019; Ostmeyer *et al.*, 2020; Dietz *et al.*, 2021). The productivity of rice under water stress conditions varies according to the specific growth stage of the plant. Flowering is considered the most sensitive stage followed by the booting and grain-filling stage (Mukamuhirwa *et al.*, 2020). Water deficit promotes the remobilization of stored carbon preserves and boosts plant senescence. Moreover, drought stress during reproduction stage accelerates grain-filling and constraints rice productivity and quality (Prathap *et al.*, 2019). Consequently, breeding of drought-tolerant and high-yielding genotypes has become irreplaceable to sustain agricultural production (Kumar *et al.*, 2012; Pandey *et al.*, 2022; Hussain *et al.*, 2023). Rice exhibits a wide range of genotypes, characterized by considerable genetic diversity cultivated across a variety of eco-ecological conditions. This involves thousands of beneficial allelic variations of traits of economic significance that remain unutilized (Ismail *et al.*, 2007). Addressing current threats begins with an exploration of the genetic diversity present in available plant materials. This crucial first step aims to assess the extent of genetic variability and identify desirable heritable traits for future cultivation and breeding efforts (Ravi *et al.*, 2003). The diverse rice genotypes with distinct genetic structures are a valuable potential for future rice improvement. Consequently, evaluating rice genotypes under different treatments is decisive for assessing their performances and recognizing drought-tolerant genotypes. Evaluating rice genotypes under drought stress provides insights for breeding programs to develop drought-tolerant and high-yielding varieties.

Alongside developing high-yielding genotypes, high-quality rice grains are required. Grain quality traits of rice are vital to cater to the demand of millers and consumers. Therefore, it receives increasing attention (Bouman *et al.*, 2007). Consequently, the recent attempt in rice breeding includes improving both grain yield and quality. Grain physical attributes, hulling, milling recovery, and cooking quality are very important for millers and consumers (Saha *et al.*, 2007). The quality characteristics based on grain appearance, size, shape, taste, tenderness, and flavor have become important criteria in developing rice genotypes for cultivation and consumption (Rao *et al.*, 2013). The present study aimed to assess the genetic diversity related to productivity and quality traits in diverse advanced rice lines and commercial cultivars to estimate the negative impact of water deficit on grain yield and quality traits, and determine the relationship among the evaluated traits under normal and water regime conditions.

Material and Methods

Experimental site and plant materials: The field experiment was conducted at the farm of Sakha Research Station, Agricultural Research Center, Egypt (31° 09' N, 30° 09' E) during the summer seasons of 2021 and 2022. This experimental site is characterized by a hot climate and minimal rainfall throughout the rice-growing seasons (Table S1). The soil analysis revealed that the soil was clay throughout the profile (21.33% sand, 29.44% silt, and 49.24% clay) (Table S2). Thirteen newly developed advanced rice genotypes alongside 5 commercial checks (Table 1) were evaluated under water deficit and well-watered conditions in the 2021 and 2022 rice growing seasons. The used advanced lines were collected from F8 generation in the Sakha Research Station breeding program following a pedigree scheme based on agronomic performance.

Experimental design and agronomic practices: The applied experimental design was a split-plot arrangement with 3 replicates. Irrigation treatments were assigned to the main plots, and the evaluated genotypes were assigned to the sub-plots. The seeds of each genotype were sown in the nursery on the 5th of May in both seasons and then transplanted to the field after 30 days. The seedlings of each genotype were individually transplanted in six 5-m long rows with 20 cm space between rows and 20 cm space between hills.

The Department of Water Requirement and Field Irrigation, Center of Agricultural Research under the Egyptian Ministry of Agriculture and Land Reclamation, determines the irrigation practices recommends for flooded rice in the study region. The optimal irrigation amount was identified at approximately 12860 m^3/ha based on climatic variables and soil type. Accordingly, the full irrigation treatment was conducted using constant flooding every 4 days with a sufficient submersion depth, providing 13000 m^3/ha throughout the growing season. Conversely, the drought treatment was conducted using irrigation every 12 days without standing water, providing 8500 m^3/ha, representing about 65% of the recommended amount to induce water deficit conditions. The stress condition was given after 15 days from the transplantation date until maturity. The applied irrigation amounts for applied irrigation treatments were determined utilizing a flow meter. . Nitrogen fertilizer was added in three splits, while phosphorus and potassium were added in full doses at the time of sowing. Nitrogen fertilizer at a rate of 166 kg N/ha was added in the form of urea (46.0% N). Phosphorous was applied at a rate of 75 kg P_2O_5/ha as super-phosphate (15% P_2O_5), and potassium at a rate of 90 kg K_2O /ha as potassium sulfate (48% K_2O).

Measured traits: Number of panicles per plant was recorded at harvest by recording the number of panicles per plant of 10 randomly collected plants from each plot. Thousand-grain weight was recorded based on the weight of 1000 grains collected for each plot. The sterility percentage was determined by dividing the number of unfilled grains by the total grains from 10 panicles per plot. Grain yield was determined by harvesting the 4 central rows from each plot and converted to kg/ha based on the harvested area. Grain quality traits were determined at Grain Quality Lab, Rice Technology Training Center (RTTC), Alexandria, Egypt. The determined grain quality traits were milling percentage, hulling percentage, broken percentage, grain width, grain length, grain shape, grain thickness, hardness, gel consistency, elongation percentage, and gelatinization temperature (spreading and clearing). The paddy rice samples were prepared using Dockage Tester Machine (Carter Day CO, style number XT3, USA) to automatically clean the mud balls, dust foreign matter, and immature green. Rice samples comprising 200 g for each were collected randomly, dehulled with an experimental Satake huller machine, and polished in a Satake miller. Moisture content was adjusted at 14 % by drying with hot air utilizing a rotary dryer. The length and width of milled rice kernel were determined utilizing a micrometer, and size and shape were categorized as outlined by Khush *et al*., (1978). Gel consistency was determined following the procedure described by Cagampang *et al*., (1973) and the gelatinization temperature was determined as outlined by Little (1958).

Table S1. Meteorological data for the two growing seasons 2021 and 2022.

Season	Month	Air temperature (°C)			Relative humidity			wide speed (km/day)	Solar radiation Mj/m^2
		Max	Min	Mean	Max	Min	Mean		
2021	May	29.71	13.10	21.45	76.93	38.87	57.91	111.78	22.76
	June	31.92	17.83	24.87	82.78	47.33	65.05	109.77	28.30
	July	32.42	19.14	25.78	88.32	52.97	70.69	90.13	23.57
	August	32.63	19.54	26.08	89.02	53.38	71.19	77.54	21.35
	September	31.32	17.83	24.57	88.02	53.88	70.99	78.75	17.93
	October	29.31	13.50	21.45	76.73	52.46	64.65	92.14	12.08
2022	May	28.70	11.68	20.24	79.86	45.32	62.64	111.78	22.96
	June	31.92	17.12	24.57	81.97	47.33	64.65	117.83	23.17
	July	31.52	17.63	24.57	85.70	58.41	72.10	78.55	20.54
	August	33.24	18.73	25.98	92.24	59.42	75.83	65.46	22.45
	September	33.24	16.91	25.07	89.63	52.36	70.99	76.53	20.44
	October	29.21	13.50	21.35	76.53	49.85	63.24	70.49	15.31

Table S2. Some physical and chemical soil properties of the experimental sites during 2021 and 2022 growing seasons.

Properties	2021		2022	
	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Soil texture	Clay	Clay	Clay	Clay
Sand (%)	21.42	21.25	21.4	21.23
Silt (%)	29.42	29.55	29.43	29.36
Clay (%)	49.16	49.2	49.17	49.41
Electric conductivity (ds/m)	2.02	2.12	2.02	2.21
PH	8.21	8.31	8.01	8.12
Organic matter (%)	1.31	1.32	1.21	1.22
$CaCo_3$ (%)	3.7	3.13	3.86	3.21
Soluble ions (meq/L)				
Ca^{++}	5.12	4.8	5.42	5.22
Mg^{++}	2.12	2	2.43	2.31
Na^{+}	12	13.11	11.81	12.33
K^{+}	0.42	0.54	0.62	0.51
Co_3^{--}	-	-	-	-
Hco_3^{-}	3.51	3.81	3.71	4.22
Cl^{-}	14.8	14.91	15.22	15.91
So_4^{--}	1.31	1.75	1.24	1.92
Available p (ppm)	12.62	12.01	14.21	14.33
Available Zn (ppm)	0.71	0.72	0.82	0.82
Available Fe (ppm)	5.22	5.12	6.11	6.02
Available Mn (ppm)	2.13	2.33	2.51	2.12

Table 1. Code, name, and parentage of the evaluated rice genotypes.

Code	Genotypes	Pedigree
	Advanced lines	
L1	GZ - 8452-6-1-3-2	GZ - 5603 -3- 2 -2-1 / Yun Len 4
L2	GZ – 8714 - 7-1-1-2	Giza-177 /Aniung Byeo
L3	GZ – 9730 - 1-1-1-1	Giza-159 / Milyang 23
L4	GZ - 9781-3-2-2-6	GZ-6910-28-1-3-1Nanjing-15
L5	GZ-9792-13-1-1-2	GZ – 6522 - 15-1-1-13 / BL -1
L6	GZ-10487-2-2-7-4	IRAT-112 / Giza177
L7	GZ-10739-1-3-2-1	Giza-177 / KEHWA 4
L8	GZ-10739-1-3-2-3	Giza-177 / KEHWA 4
L9	GZ-11042-5-8-2-2	Sakha-101 / IR60080-46 A
L10	GZ-11075-7-1-2-1-2	Giza-178 / ZX 788
L11	GZ-106170-2-2-1-2-1	IRAT-170 x Sakha106
L12	GZ-106170-2-3-2-4-1	IRAT-170 x Sakha106
L13	GZ-106891-9-1-5-1-5	WAB-891 x Sakha106
	Commercial cultivars	
C1	Giza -177	Giza-171/Yamji No.1//Pi-No.4
C2	Giza -178	Giza -175/ Milyang49
C3	Giza -179	GZ-6296 / GZ1368
C4	Sakha-107	Giza-177 / BL -1
C5	Sakha-108	Sakha-101 / HR 1315824

Statistical analysis

The obtained data for all measured traits were subjected to analysis of variance (ANOVA) employing R statistical software version 4.1.1. Normality distribution of the residuals and homogeneity of variances were applied before the analysis of variance by Shapiro–Wilk and Bartlett's tests (Bartlett, 1937; Shapiro & Wilk, 1965). The least significant difference test separated differences among the growing season, irrigation regime, genotype, and their interaction ($p<0.05$).

Results

Analysis of variance and mean performance: The analysis of variance displayed that the mean squares due to genotype, irrigation treatment, and their interaction were highly significant for all evaluated traits. However, the mean squares due to year and its interaction with genotypes and irrigation treatment were non-significant for most studied traits (Table 2). Drought stress negatively impacted all evaluated traits. The evaluated genotypes displayed significant variations in the performance of studied traits under both irrigation treatments (Tables 3 and 4). The genotypes L12, L6, L13, L11, L10, L8, L5, and L7 exhibited superior values for number of panicles/plants under well-watered conditions. Moreover, L12, L13, L2, L3, L8, and L7 produced the highest number of panicles/plants under water deficit conditions (Table 3). While Sakha-108, Giza-178, L9, Giza-177, and L3 possessed the minimal values for such trait. L8, L10, L2, Giza-178, L12, L7, L5, and Sakha-108 obtained the lowest values for sterility percentage. Otherwise, the maximum values for sterility percentage were presented by L9, L11, L4, L1, and L6. The genotypes L6, L11, L13, L7, L10, L5, and L8 produced the uppermost 1000-grain weight, while the lowest values were assigned for Giza-179, L9, L3, L4, Sakha-108, and Giza-177. The genotypes L6, L8, L13, L7, L11, L12, L5, L10, and L2 exhibited maximum values for grain yield while L4, Giza-178, L3, Sakha-108, and Giza-177 produced the lowermost grain yield (Table 3). Sakha-108, L10, L4, L6, L3, L5, and L11 showed the highest values for grain length trait, while L7, L2, Giza-177, L8, L9, Giza-178, and L13 noticed the lowest values. L6, L4, L7, L8, L5, L9, and L3 had the maximum values for grain width while L13, Sakha-108, L2, Sakha-107, and Giza-178 produced the lowest values. L4, L6, L2, L3, L7, L9, L5, and L8 produced superior values for grain thickness, while L13, L1, L10, Giza-178, L11 displayed lowest values (Table 3). The genotypes L10, Sakha-108, Giza-178, Giza-179, L11, and L12 exhibited superior values for grain shape, while the lowest values were determined to L9, Sakha-107, L8, L6, and L7. Giza-177, Giza-178, L4, L13 and L5 recorded the lowest broken percentage while L3, Sakha-107, L11, Sakha-108, and Giza-179 displayed higher values.

Table 2. Analysis of variance for evaluated traits of the assessed rice genotypes under well-watered and drought stress over two seasons of 2021 and 2022.

Source of variance	df	No. of panicles/ plant	Sterility (%)	1000-grain weight (g)	Grain yield (t/ha)	Grain length (mm)	Grain width (mm)	Grain shape	Grain thickness (mm)
Years (Y)	1	6.10*	3.70^{ns}	0.31^{ns}	1.11^{ns}	0.8^{ns}	0.20*	0.20^{ns}	0.20^{ns}
Irrigation (I)	1	53668**	239540**	296.6**	22395**	682.7**	293.1**	106.4**	80.9**
Y×I	1	0.05^{ns}	0.40^{ns}	0.004^{ns}	0.012^{ns}	0.004^{ns}	0.003^{ns}	0.002^{ns}	0.002^{ns}
Genotype (G)	17	8048**	13409**	51.91**	1242**	100.0**	67.8**	34**	24.3**
GxY	17	0.02^{ns}	0.03^{ns}	0.003^{ns}	0.004^{ns}	0.003^{ns}	0.002^{ns}	0.002^{ns}	0.002^{ns}
G×I	17	168.7**	7870**	15.4**	15.2**	22.1**	8.91**	9.5**	2.3**
G×Y×I	17	0.01^{ns}	0.02^{ns}	0.004^{ns}	0.005^{ns}	0.005^{ns}	0.001^{ns}	0.004^{ns}	0.001^{ns}
Error	136	0.61	0.41	0.017	0.23	0.13	0.02	0.0117	0.009

Source of Variance	df	Broken (%)	Hardness	Hulling (%)	Milling (%)	Elongation (%)	Gel Consistency	Gel temp. spreading	Gel temp. clearing
Years (Y)	1	3.90^{ns}	0.90^{ns}	170.8^{ns}	137.1^{ns}	101.3^{ns}	231.5^{ns}	0.50*	0.51*
Irrigation (I)	1	7961.9**	2488.1**	2623**	2207.4**	279324**	76893**	4376**	3036**
Y×I	1	0.062^{ns}	0.005^{ns}	0.31^{ns}	0.31^{ns}	0.01^{ns}	0.20^{ns}	0.0001^{ns}	0.0002^{ns}
Genotype (G)	17	1871.9**	90.41**	1709**	1663**	12999**	7576**	836.6**	706.7**
GxY	17	0.007^{ns}	0.004^{ns}	0.04^{ns}	0.001^{ns}	0.03^{ns}	0.03^{ns}	0.002^{ns}	0.002^{ns}
G×I	17	421.6**	37.50**	105 **	56.20**	5374**	1356**	182.8**	88.51**
G×Y×I	17	0.007^{ns}	0.004^{ns}	0.2^{ns}	0.11^{ns}	0.10^{ns}	0.20^{ns}	0.002^{ns}	0.002^{ns}
Error	136	0.4	0.10	16.10	12.80	9.21	21.70	0.10	0.13

ns, *, ** indicate nonsignificant, $p<0.05$, and $p<0.01$

Table 3. Agronomic performance and grain shape of the evaluated advanced lines and commercial rice cultivars under normal irrigation (N-I) and drought stress (D-S) conditions over two seasons of 2021 and 2022.

Genotype	Number of panicles /plant		Sterility (%)		1000 grain weight (g)		Grain yield (t/ha)		Grain length (mm)		Grain width (mm)		Grain thickness (mm)		Grain shape	
	N-I	**D-S**	**N-I**	**D-S**	**N-I**	**D-S**	**N-I**	**D-S**	**N-I**	**D-S**	**N-I**	**D-S**	**N-I**	**D-S**	**N-I**	**D-S**
L1	17.50	13.30	7.20	19.15	23.17	22.23	10.30	7.83	5.13	5.09	2.64	2.63	1.98	1.78	1.95	1.92
L2	19.30	13.20	8.02	10.54	25.43	23.45	10.00	8.03	5.12	4.94	2.78	2.41	2.20	2.06	2.12	1.77
L3	18.87	8.97	6.40	17.39	24.47	21.13	9.68	6.99	5.57	5.55	3.09	2.79	2.14	2.04	1.99	1.80
L4	16.62	13.30	8.08	20.30	23.75	20.02	9.50	7.32	5.89	5.57	3.15	3.02	2.15	2.13	1.95	1.76
L5	17.20	14.40	7.65	8.18	25.18	24.42	10.90	8.80	5.89	5.48	3.07	2.83	2.03	1.98	1.95	1.92
L6	16.20	15.82	7.48	19.03	28.25	27.57	11.75	9.60	5.66	5.57	3.38	3.15	2.25	2.12	1.77	1.67
L7	20.04	14.20	4.63	8.24	25.93	24.60	11.58	9.30	5.15	4.96	3.05	2.97	2.03	2.02	1.69	1.67
L8	18.49	15.02	8.25	11.61	26.95	24.03	11.78	9.36	5.22	4.89	3.06	2.94	2.22	1.95	1.70	1.68
L9	11.66	9.33	4.88	23.61	23.02	21.87	9.72	7.78	5.78	4.81	3.16	2.80	2.05	2.01	1.81	1.71
L10	16.14	15.10	5.61	10.66	24.87	24. 43	10.28	8.32	5.90	5.69	2.63	2.59	1.80	1.76	2.23	2.18
L11	16.21	15.20	6.57	20.51	28.73	26.78	11.36	9.10	5.80	5.33	2.82	2.51	1.78	1.62	2.11	2.04
L12	20.33	19.04	4.52	8.50	28.15	23.05	11.08	8.92	5.63	5.08	2.67	2.52	1.91	1.86	2.09	2.01
L13	19.73	15.62	4.29	15.24	28.68	25.37	11.60	9.33	5.43	4.59	2.68	2.47	1.97	1.79	2.01	1.84
Giza-177	16.46	9.20	5.60	17.53	22.42	17.83	10.23	6.50	5.41	4.94	2.96	2.58	2.23	1.91	1.91	1.83
Giza-178	18.17	10.12	7.37	9.67	24.75	23.12	10.66	7.03	5.27	4.71	2.52	2.21	1.83	1.70	2.13	2.09
Giza-179	17.34	12.90	7.70	15.97	26.43	21.93	10.78	7.61	5.49	5.33	2.60	2.57	1.90	1.81	2.11	2.08
Sakha-107	15.07	13.32	6.20	18.39	23.93	22.97	10.40	7.80	5.70	5.18	3.03	2.29	2.03	1.82	2.46	1.69
Sakha-108	14.66	10.80	6.90	7.38	23.75	19.13	10.70	6.88	5.79	5.75	2.66	2.46	1.89	1.85	2.33	2.14
Mean	**17.22**	**13.27**	**6.52**	**14.55**	**25.44**	**22.91**	**10.68**	**8.14**	**5.55**	**5.19**	**2.89**	**2.65**	**2.02**	**1.90**	**2.02**	**1.88**
LSD I $_{0.05}$	1.53		1.26		1.09		1.09		0.21		0.11		0.07		0.09	
LSD G $_{0.05}$	1.65		2.38		1.17		1.35		0.27		0.18		0.19		0.19	
LSD IxG $_{0.05}$	1.92		3.52		1.16		2.56		0.39		0.29		0.14		0.17	

Table 4. Quality traits of the evaluated advanced lines and commercial rice cultivars under normal irrigation (N-I) and drought stress (D-S) conditions over two seasons of 2021 and 2022.

Genotype	Broken %		Hardness		Hulling (%)		Milling %		Elongation (%)		Gel Consistency		Gel temperature spreading		Gel temperature clearing	
	N-I	D-S	N-I	D-S	N-I	D-S	N-I	D-S	N-I	D-S	N-I	D-S	N-I	D-S	N-I	D-S
L1	12.29	12.83	5.64	5.17	79.72	79.54	70.92	70.01	58.03	51.33	91.33	85.52	3.20	3.20	3.55	3.55
L2	10.09	12.92	6.05	5.07	81.32	80.49	72.44	72.25	65.6	57.49	96.30	92.19	3.56	3.50	3.88	3.86
L3	12.65	13.48	6.25	5.96	80.56	79.63	71.73	71.67	61.49	60.13	93.67	93.10	4.62	3.85	4.34	4.22
L4	10.80	11.08	5.72	5.29	81.5	80.49	72.02	71.25	66.09	60.65	95.05	91.98	5.55	5.09	5.36	5.10
L5	10.16	10.28	6.41	5.92	80.73	79.40	71.50	71.12	69.40	63.41	98.55	94.83	5.72	4.18	5.24	4.59
L6	11.07	12.16	5.97	5.06	80.32	80.09	71.31	70.53	66.35	65.94	97.55	94.94	4.64	4.86	4.34	4.67
L7	12.67	12.88	5.94	5.24	81.16	81.01	72.94	72.24	63.28	60.18	92.59	91.83	5.81	5.21	5.64	5.42
L8	11.24	12.41	5.97	5.47	81.18	79.81	73.20	72.94	62.51	62.42	93.32	91.06	6.14	5.54	6.38	5.69
L9	9.84	12.10	6.13	5.33	79.40	78.85	71.17	71.00	65.02	54.08	93.28	88.62	3.85	3.09	4.28	3.44
L10	12.48	12.91	6.25	5.54	79.64	79.55	71.77	70.59	63.30	57.70	92.06	90.07	3.76	3.53	4.08	3.24
L11	13.39	13.42	5.74	4.35	78.33	78.08	69.86	69.06	68.39	58.93	96.35	91.03	3.59	2.85	3.65	3.41
L12	11.56	13.16	5.98	5.84	78.35	78.31	70.02	68.88	67.40	62.14	95.10	92.89	3.80	3.72	3.94	3.94
L13	10.01	10.88	5.71	5.68	78.31	77.67	69.98	69.47	64.38	54.01	93.50	88.89	4.10	3.61	4.37	3.38
Giza-177	7.94	11.71	6.02	5.37	80.83	78.89	71.42	69.96	68.42	53.27	96.93	88.8	3.85	3.28	4.16	3.53
Giza-178	7.72	11.31	6.54	5.46	78.68	78.64	70.55	70.10	63.46	53.73	92.33	89.85	5.56	3.13	5.23	3.36
Giza-179	13.18	13.34	6.46	5.34	78.08	77.45	70.15	69.72	66.79	55.10	96.30	92.00	5.84	3.41	5.37	3.20
Sakha-107	12.07	13.47	6.05	5.45	77.95	77.36	69.33	69.28	62.52	50.24	91.65	83.58	6.05	3.38	5.84	3.68
Sakha-108	12.76	13.41	5.91	4.99	78.65	76.90	69.80	68.51	59.79	52.03	90.12	86.87	5.21	3.23	5.58	3.52
Mean	**11.22**	**12.43**	**6.04**	**5.36**	**79.71**	**79.01**	**71.12**	**70.48**	**64.57**	**57.38**	**94.22**	**90.45**	**4.71**	**3.81**	**4.74**	**3.99**
LSD I $_{0.05}$	0.47		0.23		1.16		1.67		1.45		1.61		0.26		0.21	
LSD G $_{0.05}$	0.59		0.29		1.93		2.14		2.08		2.59		0.29		0.28	
LSD IxG $_{0.05}$	0.84		0.42		2.19		2.84		2.39		3.50		0.41		0.39	

The highest grain hardness was recorded by L3, L5, L12, L13, L10, and L8 while the lowest values were assigned for L1, L2, L6, Sakha-108, and L11 (Table 4). The highest values of hulling percentage were assigned for L7, L2, L4, L6, L8, L3, L10, L1, and L5 while the lowest values were obtained by L13, Giza-179, Sakha-107, Sakha-108. The genotypes L8, L2, L7, L3, L4, L5, and L9 possessed the highest values for milling while L13, Sakha-107, L11, L12, Sakha-108 had reduced values. The genotypes L6, L5, L8, L12, L4, L7, L3, L11 displayed the uppermost values for elongation while Giza-178, Giza-177, Sakha-108, L1, Sakha-107 gave the lowest values. The highest values for gel consistency were exhibited by L6, L5, L3, L12, L2, Giza-179, L4, and L7 while the lowest values were recorded by L1, L10, Sakha-107, and Sakha-108. L8, L7, L4, L6, and L5 displayed superior values for gelatinization temperature (spreading) while Giza-177, Sakha-108, L1, Giza-178, L9, and L11 recorded the minimum values. The highest values of gelatinization temperature (clearing) were assigned for L8, L7, L4, L6, L5, and L3, while L9, L11, L13, Giza-178, L10, and Giza-179 recorded the lowest values (Table 4).

Genotypic classification under drought stress: The hierarchical cluster grouped the assessed eighteen rice genotypes into 3 groups based on yield traits under drought stress conditions (Fig. 1A). Group (a) included 8 genotypes (L12, 6, L11, 13, L7, L8, L10, and L5) that possessed the highest yield traits; hence, they were considered drought-tolerant genotypes. Group (b) comprised 5 genotypes (L2, L1, Sakha-107, L4, and Giza-179) with intermediate values; hence, they were moderately drought-tolerant. While group (c) consisted of 5 (Giza-177, Sakha-108, Giza-178, L9, and L3) low-vary genotypes; therefore, they were classified as moderately sensitive. Similarly, the evaluated genotypes were divided into 3 groups based on quality parameters (Fig. 1B). Group (a) comprised of 4 genotypes (L4, L6, L7, L7, and L8) that exhibited the highest quality parameters. Group (b) comprised 5 genotypes (Giza-179, Sakha-107, L2, L3, and L5) with intermediate values. Meanwhile, group (c) included 9 genotypes (L9, Giza-177, Giza-178, L11, L12, Sakha-108, L1, L10, and L13) with low values.

Relationships among evaluated genotypes and studied traits: The principal component analysis implied that PC1 and PC2 described 46.74 and 16.33% of the total variation, respectively (Fig. 2). The PC1 described higher variation and appeared to correspond with the evaluated genotypes. PC1 divided the genotypes into 2 groups on the positive and negative sides of PC1. Most of the studied yield and quality traits were correlated with the genotypes on the positive side of PC1 indicating that the genotypes situated on the positive side of PC1 (L8, L7, L4, L5, L2, L3, L5, and L6) exhibited high performance of most yield and quality traits under drought stress. On the contrary, the remaining genotypes are on the opposite side of PC1 presenting lower yield and quality traits. The traits displayed adjacent vectors had strong positive inter-association versus those that had vectors with larger angles. Most of the studied traits exhibited positive associations except broken percentage, grain shape, and sterility percentage displayed negative associations with the remaining traits. Likewise, the heatmap and hierarchical clustering based on the yield and quality traits divided the assessed genotypes into different clusters (Fig. 3). The genotypes L3, L4, L5, L6, L7, L8, and L13 displayed the highest values for most yield and quality traits (depicted in red). On the contrary, the remaining genotypes had low values (blue values).

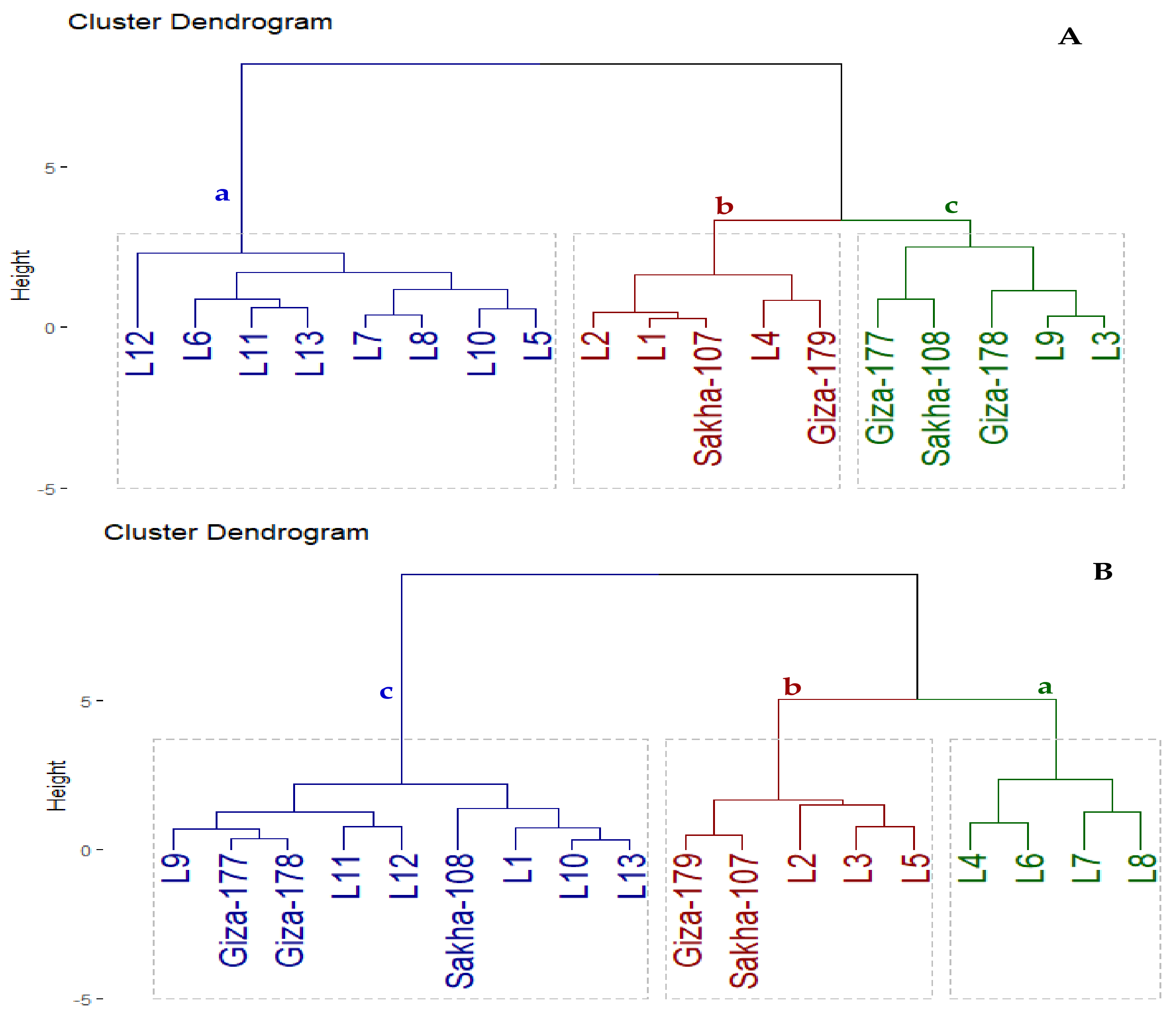

Fig. 1. Dendrogram of the evaluated rice genotypes based on yield traits (A) and quality traits (B) over two seasons of 2021 and 2022.

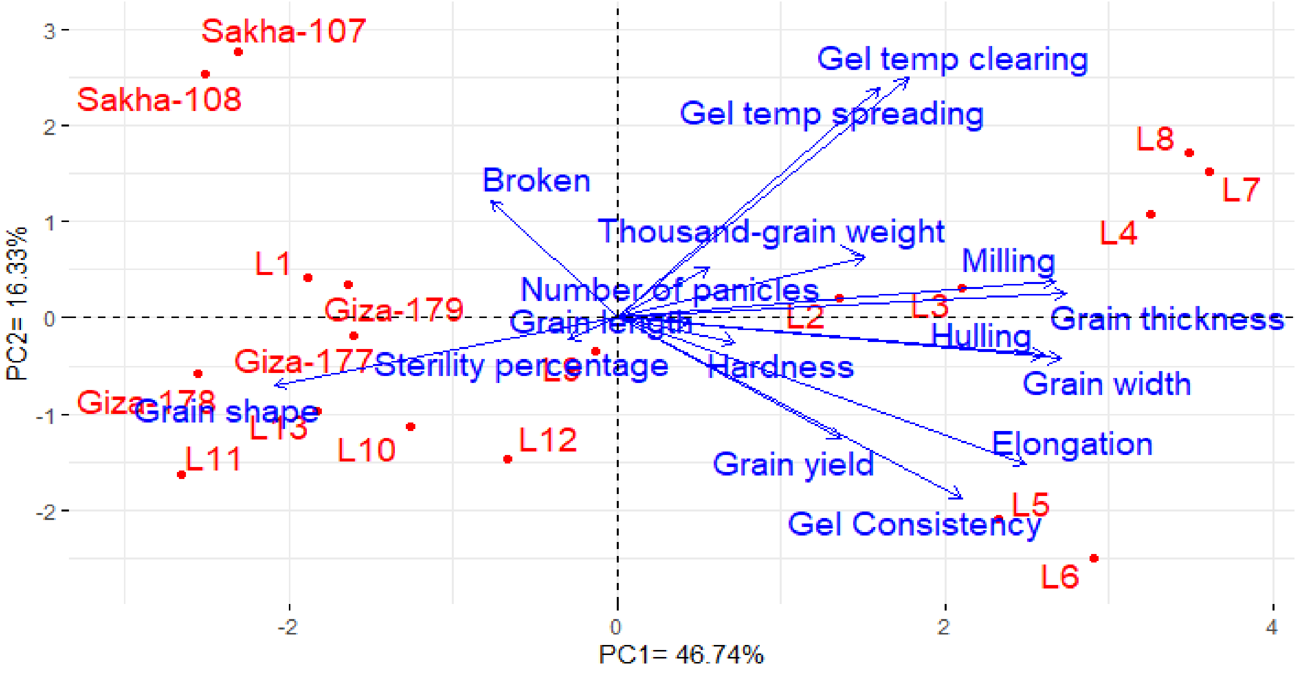

Fig. 2. PC-biplot for the evaluated traits of rice genotypes under drought stress conditions over two growing seasons.

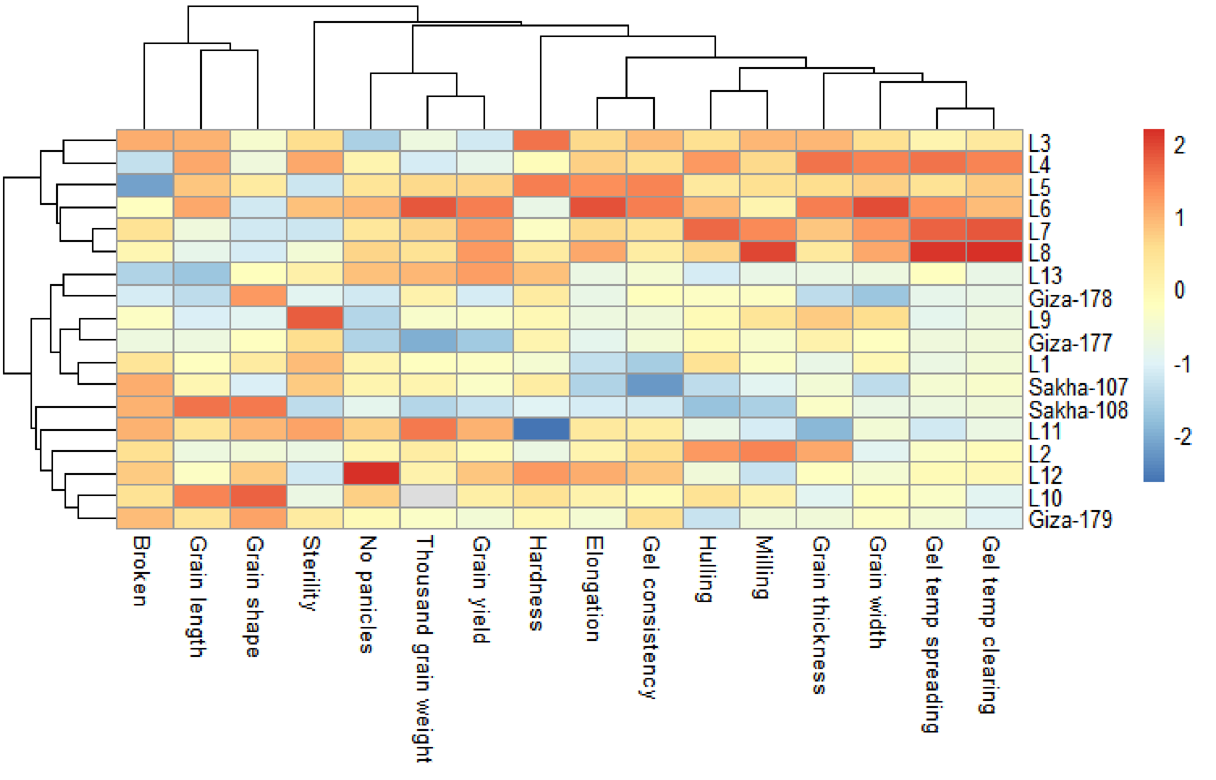

Fig. 3. Heatmap clustering for the evaluated traits of rice genotypes under drought stress conditions over two growing seasons.

Discussion

Limited water availability induced by abrupt climate change would put rice productivity at risk in the Mediterranean region and threaten food security (Korres *et al.*, 2017; Acharjee *et al.*, 2019). Hence, breeding drought-tolerant and high-yielding rice genotypes has become increasingly crucial to sustain rice production in the face of the current climate change and population growth (Lone *et al.*, 2019; Hussain *et al.*, 2021; Baldoni, 2022). The present study evaluated 13 newly developed advanced rice lines and 5 commercial cultivars under drought stress versus well-watered conditions. The analysis of variance indicated highly significant variation among the assessed genotypes in all evaluated yield and quality traits. The significant difference revealed considerable genetic variability in the evaluated materials and provided an excellent potential for improving rice grain yield and quality (Nirmaladevi *et al.*, 2015; Asante *et al.*, 2019). Grain yield and quality traits exhibited stable performance across growing seasons with significant interaction with irrigation treatments. This indicated their different response to water stress conditions in the productivity and quality traits.

Water scarcity adversely impacted all studied number of panicles per plant, 1000-grain weight, and grain. Water shortage during flowering and grain filling of rice could interrupt floret initiation and increase sterility percentage or abortion of immature embryos (Kamoshita *et al.*, 2004; Acuña *et al.*, 2008). Drought stress causes retardation of panicle development and growth which decreases grain size and grain number (Quinones *et al.*, 2017). The considerable declines in yield traits under drought stress were caused due to a deprivation of absorbed water and accordingly inhibition of cell elongation and division (Farooq *et al.*, 2009b). Moreover, water shortage generates reactive oxygen species in plant cells and damages nucleic acids, photosynthetic pigments, membrane lipids, and enzyme activity (Desoky *et al.*, 2021).

Additionally, water shortage negatively affects starch formation and storage, resulting in the loose packing of starch granules, accordingly increasing chalky grain formation (Rosa *et al.*, 2009). Grain dimensions of brown rice that included grain width, grain length, grain shape and grain thickness were reduced under drought conditions. This could be due to insufficient assimilates to complete endosperm development during grain filling (Mostajeran and Rahimi-Eichi, 2009; Wang *et al.*, 2022). Endosperm development in rice is highly associated with the accumulated carbohydrates during photosynthesis, which are assimilated to the grains during grain filling (Ghorbani Javid *et al.*, 2011). Under water deficit, the vegetative phase of the rice plants is accelerated, resulting in a short period of photosynthesis. This restricts the accumulation of carbohydrates required for assimilation during grain filling and reduced grain dimensions (Vijayaraghavareddy *et al.*, 2021). Moreover, water deficit led to reduced milling recovery, poor grain palatability, and appearance due to chalkiness in rice grains (Jabran *et al.*, 2017; Yang *et al.*, 2019). The increase in broken percentage is related to rice genotypes. When exposed to water shortage, the number of chalky grains rose, consequently making grains more prone to breakage. Chalky areas are portions of grain where starch granules are less densely packed than translucent areas (Nevame *et al.*, 2018). The hull percentage was better under normal irrigation than under water deficit conditions. This enhancement in hull percentage could be attributed to a decrease in brown rice which may be related to grain filling (Huang *et al.*, 2008). The milling percentage was reduced under drought conditions, which caused an increase in bran production (Emam *et al.*, 2014). Drought stress increases chalky grains that are considered less dense than transparent grains and accordingly, the hardness percentage is reduced (Zhang *et al.*, 2022). Significant reduction in elongation percentage due to the reduction in grain size and the amount of absorbance of water during cooking and accordingly, less expansion volume (Fahad *et al.*, 2019). Gelatinization temperature is the temperature range wherein most starch granules were permanently gelatinized and swelled in warm water. Gel consistency and gelatinization temperature influence cooked rice texture and grain expansion volume upon cooking (Krishnan *et al.*, 2011). Gelatinization temperature and gel consistency were reduced under drought stress, which could be due to a moisture shortage at the reproductive phase, especially during grain filling during the ripening period (Vidal *et al.*, 2007).

Cluster analysis, PC-biplot, and hierarchical clustering are effective statistical tools to classify the evaluated genotypes based on the studied grain yield and quality traits (Abaidoo *et al.*, 2017; Alam *et al.*, 2021; Morsi *et al.*, 2023). The results indicated that the genotypes L4, L5, L6, L7, L8, and L13 were identified as promising for improving yield traits and quality parameters under water deficit conditions. The promising genotypes adapted to adversities induced by water scarcity and enhanced plant development, productivity, and quality. Alterations in plant traits accompanied by mineral nutrient uptake and diminished water loss through transpiration are adaptation mechanisms undertaken by tolerant genotypes (Cabuslay *et al.*, 2002; Khan *et al.*, 2021b; Kumar *et al.*, 2023). Consequently, these identified genotypes could inherit favorable alleles to their progeny and enhance grain yield under drought stress conditions. In this context, Kumar *et al*., (2012), Lone *et al*., (2019), Ghazy *et al*., (2021), and Joshi *et al*., (2018) evaluated rice genotypes under drought stress and identified promising rice genotypes based on their agronomic performance under drought stress.

Conclusions

Drought stress adversely impacted number of panicles per plant, 1000-grain weight, grain yield, and grain dimensions. Besides, water shortage negatively affected rice grain quality comprising preferential standards, milling recovery, physical attributes, specifically head rice recovery, and physic-chemical properties. The evaluated genotypes exhibited highly significant variation in all evaluated yield and quality traits. The significant difference revealed considerable genetic variability in the evaluated materials and provided an excellent potential for improving rice grain yield and quality. The genotypes L4, L5, L6, L7, L8, and L13 were recognized as promising for improving yield traits and quality parameters under water deficit conditions. Consequently, these genotypes could inherit favorable alleles to their progeny and enhance grain yield under drought stress conditions.

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