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Communication

Evaluation of Morpho-Physiological Traits in Rice Genotypes for Adaptation under Irrigated and Water-Limited Environments

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Abstract: Drought is one of the major limitations to rice productivity worldwide. The present study compared variation in seventeen rice genotypes of Egyptian origin for morpho-physiological traits to identify the best genotypes with combination of adaptive traits under water-limited condition (DS). The DS reduced days to heading (DTH), plant height (PH), flag leaf angle (FLA), flag leaf area (FLAR), chlorophyll content (CHC), relative water content (RWC), grain yield (GY), and its components. Among genotypes, Hybrid 2 expressed the highest GY, panicle length (PL), number of tillers (NT), panicles per plant (NPP), and harvest index (HI) with maximum spikelet sterility (SS) under non-stress condition (NS), while the same genotype expressed ≈ 41% yield reduction under DS. The genotype Giza 179 had earlier DTH, higher and stable GY, FLAR, and yield component traits such as NPP, PW, and HI across the water regimes with least yield reduction (30.5%) under DS. The GY and FLAR, RWC, PL, NT, NPP, PW, and HI were positively correlated under DS. The cluster analysis showed a similarity index of 25% among genotypes. The high yielding genotypes Giza 179, IET 1444, and IRAT 170 had also increased yield components (PL, NT, NPP, PW, TGW and HI) under DS that were attributed to highest FLAR, RWC, and PH, while having reduced LR, FLA, TR, and SS; therefore, these genotypes were categorized as drought-tolerant. The Hybrid 2 and Giza 179 genotypes can perform well under NS; however, the cultivation of Giza 179, Sakha 107, IET 1444, and IRAT 170 would give an advantage in DS-prone areas, hence, these can be used as a donor parental line in future rice breeding programs.

Keywords: grain yield; principal component analysis; flag leaf area; adaptability; yield components

1. Introduction

Drought stress exerts several negative effects on growth and productivity of crops [1–3], and high drought risk often occurs with huge economic losses [4–6]. Even in the most productive agricultural regions, exposure to short periods of drought showed great yield losses. Growing world population and decline of water resources for crop production prioritize the development of high-yielding drought-tolerant cultivars with better adaptability to water-limited condition [7]. Drought is one of the major limitations to rice production, causing huge economic losses and having large effects on rice yield and its components, particularly during the reproductive stage [8]. If drought period matches with panicles initiation stage in rice, the number of spikelets and grains per panicle, including grain yield, are reduced [9,10]. Drought also delays the panicle emergence and flowering stages in rice. Nonetheless, drought affects morphological, physiological, biochemical, and molecular responses in rice plant [11–13]. Therefore, varietal adaptability for better crop performance and yield stability are required to reduce the yield gaps and sustain rice productivity under water-limited conditions [14].

Nonetheless, rice plant adapts several mechanisms to water-limited conditions through drought escape, avoidance, and tolerance [15]. Escape strategies rely on successful reproduction before the onset of severe stress, by shortened lifecycle associated with early flowering and maturity, a higher growth and photosynthesis rate, or the efficient storage and remobilization of reserves for seed production. Dehydration avoidance mechanisms in rice involve the maintenance of a tissue water status associated with minimized water loss caused by stomata closure, leaf rolling, stay green, deep roots, and high transpiration efficiency for maximized water uptake [15,16]. Nevertheless, developing rice for tolerance to drought stress through breeding is a sustainable and cost-effective approach in improving its productivity [17]. Several efforts have been made to improve drought tolerance by identifying donor genotypes, but success rate for their translation into drought-tolerant varieties is very low [18]. For example, screening a large set of genotypes at International Rice Research Institutes (IRRI) of different origins showed that most of the drought-tolerant accessions identified were of *aus* and indica types that belong to India, Bangladesh, and Sri Lanka [19,20]. Further, earlier genotypes being grown under drought-prone areas have been bred for irrigated environments rather than selected for drought tolerance [21].

As morphological, physiological, and genetic responses in rice to drought are of complex nature [11–13], characterizing genotypes based on these bases for drought tolerance is of prime importance for using them in future breeding programs. Nevertheless, identification of genotypes directly based on grain yield or development of cultivars with combination of putative traits which resist and produce economical yield under target environment is the effective strategy for improving drought tolerance in rice [21,22]. Moreover, identifying new donors' genotypes for drought tolerance may be helpful to overcome yield constraints under water-limited conditions. For example, evaluation of rice germplasm under irrigated and water-limited conditions may be useful to identify rice types with wide adaptability simultaneously under drought in some years and sufficient rainfall in others [21]. The stable cultivars usually express better yields and have high adaptability across a wide range of environments. Therefore, evaluating different genotypes across different environments or growing seasons helps to identify donor germplasm with adaptive traits for drought resistance, high yields, and grain quality in target environments [23–25]. No such comprehensive studies have been carried out to identify donor genotypes with adaptive traits in both irrigated and drought environments in cultivars of Egyptian origin [26]. The present study therefore evaluated the genotypic variation for morphological and physiological characteristics of drought tolerance, and to determine the most desirable ideotype with combination of traits, cluster analysis was performed. The genotypes identified may be used in future breeding programs of rice for both environments in particular drought.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted at Sakha Research Station of Rice Research Department, Field Crops Research Institute, Agriculture Research Center, Egypt, during 2019 and 2020 growing seasons. The experimental soil was clay type with 13.5 g kg^{-1} organic matter contents, 43.8 mg kg^{-1} of available N, 11.4 mg kg^{-1} of available P, and 8.5 soil pH. Average soil moisture contents of the experimental site for both years are given in Table 1.

Table 1. Soil moisture contents of the experimental site on average in the 2019 and 2020 rice-growing season.

Soil Depth (cm)	Field Capacity (F.C.) (%)	Permanent Wilting Point (PWP) (%)	Available Water (AW) (cm)	Bulk Density (g/cm^3)
0–20	41.14	25.43	16.49	1.24
20–40	35.47	23.27	12.64	1.37
40–60	26.54	21.29	15.43	1.24

2.2. Experimental Design and Treatments

The 17 rice genotypes used for experimental material with pedigree and origin are presented in Table 2.

Table 2. The pedigree and characteristics of rice genotypes.

Genotypes	Pedigree	Origin
Giza 177	Giza 171/Yomji No. 1//Pi No. 4	Japonica
Giza 178	Giza 175/Milyang 49	Indica/Japonica
Giza 179	GZ 6296/GZ 1368	Indica/Japonica
Giza 182	Giza 181/IR 39422-161-1-3-1/Giza 181	Indica
Sakha 101	Giza 176/Milyang	Japonica
Sakha 102	GZ 4096-7-1/GZ 4120-2-5-2 (Giza 177)	Japonica
Sakha 103	Giza 177/Suweon 349	Japonica
Sakha 104	GZ 4096-8-1/GZ 4100-9-1	Japonica
Sakha 105	GZ 5581-46-3/GZ 4316-7-1-1	Japonica
Sakha 106	Giza 176/Milyang 79	Japonica
Sakha 107	Giza 177/BLI	Japonica
Sakha 108	Sakha 101/HR 1315824	Japonica
Hybrid 2	IR 6962SA/Giza 179	Indica
Egyptian Yasmine	Introduction	Indica
GZ 1368-S-5-4	IR 1615-31/BG 94-2349	Indica
IET 1444	TN 1/CO 29	Indica
IRAT 170	IRAT 13/Palawan	Indica

These rice genotypes were grown under well-irrigated conditions with continuous submergence (NS), and water stress (DS) conditions exposed to irrigation with twelve days interval started fifteen days after transplanting of nursery seedlings. The experimental design used was a split arrangement with irrigation in main plots and rice genotypes randomized in sub-plots using three replications. The average weather conditions for both growing seasons are given in Table 3. The rice nursery seedlings raised on 28 and 29 April during 2019 and 2020, respectively, were transplanted after 30 days in both seasons. The nursery seedlings of each genotype were transplanted in 20 cm apart rows and at similar distance between the hills with a net plot area of 6 m^2.

2.3. Crop Husbandry Practices

Whole phosphatic and 50% nitrogen fertilizers were applied at 36 kg P_2O_5 ha^{-1} and 144 kg N ha^{-1} using superphosphate (15.5% P_2O_5) and urea (46% N) as base during soil preparation. Remaining nitrogen was applied in two splits with 30% at initial tillering and 20% at panicle initiation stages.

Table 3. Average weather conditions for experimental period during growing seasons.

Growing Year	Month	Air Temperature (°C)			Relative Humidity (%)			Wind Speed (km/d)	Solar Radiation (Mj/m^2)	Pan Evaporation (mm)
		Max.	Min.	Mean	Max.	Min.	Mean			
2019	May	29.65	13.07	21.41	76.78	38.79	57.79	111.56	22.71	6.83
	June	31.86	17.79	24.82	82.61	47.24	64.92	109.55	28.24	7.84
	July	32.36	19.10	25.73	88.14	52.86	70.55	89.95	23.52	7.34
	August	32.56	19.50	26.03	88.84	53.27	71.05	77.39	21.31	6.83
	September	31.26	17.79	24.52	87.84	53.77	70.85	78.59	17.89	6.43
	October	29.25	13.47	21.41	76.58	52.36	64.52	91.96	12.06	4.62
2020	May	28.64	11.66	20.20	79.70	45.23	62.51	111.56	22.91	7.34
	June	31.86	17.09	24.52	81.81	47.24	64.52	117.59	23.12	8.34
	July	31.46	17.59	24.52	85.53	58.29	71.96	78.39	20.50	7.14
	August	33.17	18.69	25.93	92.06	59.30	75.68	65.33	22.41	6.53
	September	33.17	16.88	25.02	89.45	52.26	70.85	76.38	20.40	5.93
	October	29.15	13.47	21.31	76.38	49.75	63.11	70.35	15.28	4.72

2.4. Measurements of Morpho-Physiological and Agronomic Traits

Data on agronomical traits were recorded from ten randomly selected plants for each genotype of each replicate. Among morphological traits, days to heading (DTH) was determined from sowing to date for first panicle exertion, plant height (PH) from the soil surface to the tip of the main panicle of each plant, and leaf rolling (LR) recorded by a visual estimation [27]. The flag leaf angle (FLA) and its area (FLAR) were measured at heading stage following Yoshida et al. (1976):

$$\text{Flag leaf area}\ (\text{cm}^2) = K \times \text{leaf length(cm)} \times \text{maximum width(cm)}$$

where K (0.75) is a rectification factor used for the whole growth period, except for the seedling and maturity periods. The leaf temperature (LT) was calculated by the thermocouple of the steady-state porometer pressed against the adaxial and abaxial surfaces of the leaf, and the leaf-to-air temperature gradient (TL–TA) was measured by using the atmospheric temperature [28]. The chlorophyll content (CC) was determined using SPAD chlorophyll meter (Minnolta, Japan). Relative water content (RWC) of flag leaf was calculated using the following formula:

$$\text{RWC} = ((\text{FW}) - (\text{DW}) / (\text{TW} - \text{DW})) \times 100$$

where FW is flag leaf fresh weight, DW is flag leaf dry weight, and TW is flag leaf turgid weight.

A portable steady-state porometer, LICOR, (LI-1600, Lincoln, NE, USA) was used for assessing the steady-state CO_2 and H_2O exchange degrees of leaves. Stomatal conductance (SC) and transpiration rate (TR) were measured in the fully expanded flag leaf.

At harvesting, ten panicles were selected randomly from each replicate to measure panicle length (PL) and weight (PW), number of tillers (NTP) and panicles per plant (NPP), 1000-grain weight (TGW), and spikelet sterility (SS). Spikelet sterility was determined by dividing the unfilled spikelets from a panicle to the total spikelets. The rice grain yield (GY) was estimated from unit area and adjusted to 14% moisture content and converted to t ha^{-1}. Harvest index (HI) was calculated by dividing grain yield by biological yield and expressing into percentage.

2.5. Statistical Analysis

Analysis of variance was conducted for all the traits using combined analysis according to Steel et al. [29]. Year was also considered as a factor, and where it was found to be nonsignificant, the data were pooled. The analysis of covariance analysis (ANCOVA), mean comparisons, correlation, and cluster analysis were performed using Minitab version 17. Days to heading was taken as covariable for all data analysis, and then adjusted means were used for further statistical analysis.

3. Results

3.1. Effect of Studied Factor on Morpho-Physiological Traits

The analysis of covariance showed that year (Y) effect was nonsignificant for all morpho-physiological traits except for LT, SC, and TR. The irrigation (I) and genotypic (G) difference were highly significant for all traits, while, only I × G interaction was significant for all traits except LT (Table 4).

Table 4. Analysis of covariance for different morpho-physiological traits.

Source	DF	PH	LR	FLA	FLAR	LT	CHC	RWC	SC	TR
Model	70	618.25 **	8.62 **	578.71 **	137.92 **	3.75 **	42.91 **	156.39 **	0.000341 **	435.17 **
Covariates	1	9.36	0.51	19.28	0.19	0.03	7.86	1.09	0.000001	0.03
DTH	1	9.36	0.51	19.28	0.19	0.03	7.86	1.09	0.000001	0.03
Blocks	2	6.22	0.53	31.95	5.44	0.76	1.26	2.86	0.000063 **	1.14
Linear	18	2060.52 **	26.09 **	1971.88 **	348.45 **	13.52 **	116.90 **	550.73 **	0.000837 **	986.03 **
Y	1	0.04	0.28	1.48	0.04	13.08 **	1.05	0.02	0.000084 **	42.33 **
I	1	2673.96 **	69.72 **	39.76 *	636.31 **	14.70 **	142.75 **	695.90 **	0.000814 **	621.36 **
G	16	1234.47 **	5.93 **	2061.63 **	187.51 **	6.76 **	51.69 **	276.08 **	0.000649 **	787.82 **
2-Way Interactions	33	37.94 **	2.01 **	76.14 **	32.55 **	0.42	17.10 **	23.24 **	0.000189 **	378.13 **
Y × I	1	3.82	0.67	0.53	2.49	0.01	0.23	1.11	0.000001	0.45
Y × G	16	3.70	0.16	4.37	2.99	0.00	1.69	2.08	0.000000	0.08
I × G	16	74.35 **	3.88 **	153.1 **	60.86 **	0.85	33.76 **	45.76 **	0.000388 **	777.98 **
3-Way Interactions	16	3.93	0.18	1.96	2.79	0.00	3.11	2.23	0.000000	0.08
Y × I × G	16	3.93	0.18	1.96	2.79	0.00	3.11	2.23	0.000000	0.08
Error	133	2.69	0.69	7.13	2.19	0.53	2.43	1.83	0.000011	0.83
Total	203									

* = Significant at 0.05; ** = significant at 0.01 level of probability; DTH = days to heading; PH = plant height; LR = leaf rolling; FLA = flag leaf angle; FLAR = flag leaf area; LT = leaf temperature; CHC = chlorophyll content; RWC = relative water content; SC = stomatal conductance; TR = transpiration rate.

3.2. Morpho-Physiological Variation among Genotypes

The drought stress (DS) reduced the morpho-physiological traits compared to NS, except for LT, while leaf rolling score (LR) significantly increased under DS. Among genotypes, Giza 177, Giza 177, and Sakha 103 observed earlier heading under both NS and DS condition, respectively. Egyptian Yasmine was the latest heading genotype under both NS (120.50 days) and DS (110.50 days). The Sakha 101 and Sakha 108 genotypes were shortest, while IRAT I70 had the tallest plants under both NS and DS. Among genotypes, IET 1444 and IRAT 170 had minimum, while Sakha 103 had the maximum LR score under both NS and DS conditions. Maximum FLA was obtained for Sakha 105 and Sakha 106 genotypes while the lowest was obtained for GZ 1368-S-5-4 under both NS and DS (Table 5). Nonetheless, maximum FLAR was expressed by Egyptian Yasmine and Giza 179 genotypes while minimum values in Giza-103 under both NS and DS, respectively. Maximum CHC was observed for Sakha 102 and minimum for Egyptian Yasmine, while highest RWC was for IET 1444 under both NS and DS (Table 2). Maximum SC was found in IRAT 170 and Sakha-103 under irrigated, while it was similar in IET 1444, Egyptian Yasmine, and Giza 177 under both NS and DS conditions. Minimum TR was found in IET 1444 under both NS and DS, while maximum was found in Giza 179 under NS condition (Table 5).

Table 5. Morpho-physiological traits performance of rice genotypes under water-deficit (DS) conditions.

Genotypes	DTH		PH (cm)		LR		FLA		FLAR (cm^2)		LT (°C)		CHC		RWC (%)		SC		TR	
	NS	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**
Giza 177	91.83	84.33	101.66	82.64	2.69	6.15	49.68	53.72	29.09	16.75	26.81	27.86	42.04	36.65	83.16	66.44	0.07	0.07	44.88	43.47
Giza 178	98.17	98.00	98.18	74.60	2.61	3.79	26.99	27.58	30.14	29.67	25.85	28.09	41.07	33.58	88.08	80.74	0.07	0.05	51.91	46.93
Giza 179	88.50	82.50	95.71	77.97	2.82	4.89	32.08	28.66	35.20	30.11	24.74	26.84	42.42	41.00	88.36	82.94	0.06	0.05	91.50	41.07
Giza 182	99.50	89.17	93.60	82.28	1.39	5.30	28.62	25.98	30.42	20.27	24.85	25.79	43.08	41.19	81.88	67.53	0.07	0.06	46.98	43.62
Sakha 101	111.17	105.5	89.37	69.56	2.27	5.66	45.92	39.12	29.04	20.43	25.96	26.99	45.46	36.91	83.62	72.95	0.07	0.06	45.95	41.45
Sakha 102	92.50	87.83	108.83	84.04	2.33	6.02	52.33	51.38	25.61	17.83	25.75	26.79	46.56	42.19	81.19	70.53	0.05	0.05	44.02	39.18
Sakha 103	91.50	85.17	97.95	76.83	2.37	8.12	54.73	43.02	25.49	14.91	26.19	27.23	40.39	35.08	83.08	65.54	0.10	0.05	44.95	40.63
Sakha 104	103.50	97.83	104.78	93.18	1.90	5.13	42.84	27.62	35.01	28.48	26.24	27.28	40.14	34.94	85.09	73.80	0.07	0.05	46.77	41.12
Sakha 105	97.33	89.00	103.70	75.63	1.31	5.30	60.90	71.36	33.08	15.22	24.63	25.58	39.21	37.94	78.58	69.71	0.06	0.05	46.32	43.04
Sakha 106	92.17	85.33	106.30	83.73	1.68	6.28	62.18	56.44	27.23	14.30	24.88	25.85	48.86	34.67	78.72	71.01	0.07	0.06	43.01	41.04
Sakha 107	92.83	86.33	103.32	91.79	1.57	3.91	62.25	46.01	28.98	21.90	23.83	25.86	43.74	40.47	89.25	78.52	0.07	0.06	49.77	40.99
Sakha 108	108.83	100.50	87.69	70.96	1.36	5.36	50.41	53.80	25.62	18.74	25.84	26.83	43.65	37.95	82.04	71.74	0.06	0.05	45.97	44.15
Hybrid 2	106.50	97.17	101.21	79.75	1.45	4.82	28.45	25.55	35.56	23.13	25.27	27.38	42.96	37.92	78.54	69.65	0.06	0.06	45.72	42.35
Egyptian Yasmine	120.50	110.50	105.05	79.27	1.24	4.80	19.15	27.18	40.39	17.58	26.69	27.70	37.75	33.76	70.95	65.02	0.07	0.07	43.24	39.37
GZ 1368-S-5-4	101.50	96.50	108.19	86.01	1.82	4.18	21.06	18.88	27.79	18.25	25.60	27.77	38.05	37.07	88.44	74.86	0.06	0.05	95.55	41.27
IET 1444	101.00	95.50	103.16	82.36	1.67	2.55	22.98	20.84	32.61	27.07	24.23	26.28	40.67	38.28	90.28	82.66	0.07	0.07	38.85	35.24
IRAT 170	105.00	98.67	133.21	117.05	1.18	3.43	30.08	32.71	34.64	28.22	24.24	26.28	37.59	36.80	78.29	75.38	0.08	0.06	44.24	43.59
Mean	100.02	93.52	102.47	82.80	1.86	5.04	40.62	38.23	30.94	21.34	25.38	26.85	41.98	37.44	82.91	72.88	0.07	0.06	51.15	41.68

NS = non-stress treatment; DS = water-deficit treatment; DTH = days to heading; PH = plant height; LR = leaf rolling; FLA = flag leaf angle; FLAR = flag leaf area; LT = leaf temperature; CHC = chlorophyll content; RWC = relative water content; SC = stomatal conductance; TR = transpiration rate.

3.3. Agronomic Performance of Rice Genotypes

The analysis of covariance showed that year (Y) effect was nonsignificant for all agronomic traits except for NPP and PW. The irrigation (I) and genotypic (G) difference were highly significant for all traits, while among interactions, Y × I and Y × G interaction was only significant for NPP and NT, and NPP and TGW, respectively. Likely, I × G interaction was significant for all studied traits. Interestingly, Y × I × G interaction was significant only for PL, NPP, and TGW traits (Table 6).

Table 6. Analysis of covariance for agronomical traits.

Source	DF	PL	NT	NPP	PW	TGW	SP	GY	HI
Model	70	26.58 **	76.09 **	79.28 **	1.99 **	0.50 **	170.60 **	18.39 **	313.89 **
Covariates	1	0.46	0.29	0.28	0.27 *	0.01	1.12	0.32	3.29
DTH	1	0.46	0.29	0.28	0.27 *	0.01	1.12	0.32	3.29
Blocks	2	1.88	0.31	0.32	0.04	0.01	8.80 **	0.05	0.73
Linear	18	55.68 **	230.57 **	244.57 **	7.27 **	1.21 **	556.89 **	58.53 **	1037.00 **
Y	1	0.44	1.62	12.11 **	0.25 *	0.06	0.04	0.05	0.05
I	1	127.80 **	497.80 **	511.42 **	3.80 **	2.35 **	1328.94 **	116.45 **	2008.65 **
G	16	19.66 **	61.91 **	66.58 **	4.85 **	0.60 **	78.65 **	13.08 **	244.77 **
2-Way Interactions	33	9.45 **	13.56 **	14.84 **	0.16 **	0.19 **	31.43 **	3.40 **	51.62 **
Y × I	1	0.02	2.16	22.29 **	0.19	0.04	0.27	0.20	0.21
Y × G	16	2.24	2.30 **	4.37 **	0.09	0.12 **	0.83	0.17	2.17
I × G	16	16.83 **	25.53 **	24.42 **	0.24 **	0.27 **	62.29 **	6.70 **	101.04 **
3-Way Interactions	16	2.68 *	2.21 **	2.39 **	0.08	0.16 **	0.89	0.19	1.35
Y × I × G	16	2.68 *	2.21	2.39 **	0.08	0.16 **	0.89	0.19	1.35
Error	133	1.42	1.06	1.06	0.06	0.02	0.76	0.16	3.01
Total	203								

* = Significant at 0.05; ** = significant at 0.01 level of probability; PL = panicle length; NT = number of tillers; NPP = number of panicles per plants; PW = panicle weight; TGW = 1000-grain weight; SP = spikelet sterility; GY = grain yield; HI = harvest index.

3.4. Agronomic Performance of Rice Genotypes

The DS significantly reduced the yield traits compared to NS except spikelet sterility, which increased under DS. Among genotypes, maximum PL was recorded in Egyptian Yasmine, Hybrid 2, and IRAT 170 under NS, while genotypes IRAT 170, IET 1444, including Sakha 107, Sakha 101, and Giza 179, had maximum PL under DS. Minimum PL was found in Sakha 103. Highest GY, NT, NPP, PW, and HI were observed in Hybrid 2 and Giza 179 under NS, followed by Giza 178 and IET 1444. Under DS, genotypes Giza 179 and Sakha 107 expressed higher GY and HI, as well as NT, NPP, PW, and reduced SS. These genotypes both also produced GY > 8.0 t ha^{-1} under DS (Table 7).

3.5. Cluster Analysis and Pearson Correlation

Seventeen rice genotypes were clustered into four clusters with a similarity index of 25% (Figure 1).

Both cluster I and IV shared the same number of members (three) and were the smallest groups. Cluster III was the biggest group with six members, while cluster II was represented by five members. Cluster IV consisted of genotypes Giza 179, IET 1444, and IRAT 170. This cluster showed the highest values of GY and all of its components (PL, NT, NPP, PW, TGW, and HI) under DS. This cluster also showed highest values of FLAR, RWC, and PH, but lowest values of LR, FLA, TR, and SS. Therefore, the members of this group can be categorized as drought-tolerant rice genotypes. Meanwhile, the lowest values of most of the agronomical traits (GY, PL, NT, NPP, TGW, and HI) under DS were observed in cluster I. Cluster I also recorded the lowest values of FLAR, CHC, and RWC, but highest values of SS, LR, and LT. Under DS, high positive correlations were observed between GY and FLAR, RWC, PL, NT, NPP, PW, and HI. Though positive correlations were also observed between GY and PH, CHC, TR, and TGW, the results were not significant. Meanwhile, SS showed high negative correlation with GY (Table 8).

Table 7. Agronomic and yield traits of rice genotypes under water-deficit (DS) treatments.

Genotypes	PL (cm)		NT		NPP		PW (g)		TGW (g)		SP (%)		GY (t ha^{-1})		HI (%)	
	NS	DS	NS	DS	NS	DS	NS	DS	NS	DS	NS	DS	NS	DS	NS	DS
Giza 177	24.68	16.61	22.04	10.01	20.51	8.94	4.63	3.59	27.00	17.15	5.48	21.82	9.89	6.69	47.78	25.02
Giza 178	23.28	18.76	26.78	14.66	25.24	14.40	4.71	4.32	22.84	14.70	7.23	11.16	11.79	7.98	41.82	33.66
Giza 179	21.98	19.64	23.03	16.25	24.19	14.94	5.46	4.86	23.56	20.74	6.26	18.79	13.02	9.05	49.81	39.46
Giza 182	20.55	16.08	22.84	11.97	21.52	10.48	3.54	2.79	26.51	21.52	7.35	25.39	11.57	6.12	42.51	20.67
Sakha 101	23.17	19.78	23.06	16.50	21.87	15.72	2.16	1.30	27.63	23.01	5.46	19.37	11.98	7.10	50.55	28.02
Sakha 102	21.12	18.46	24.85	13.84	24.12	12.89	3.56	2.56	26.42	21.38	5.92	22.52	10.59	6.49	43.50	25.07
Sakha 103	21.65	15.29	21.85	10.29	20.15	8.72	3.86	2.97	23.32	15.72	7.07	29.74	10.93	4.75	43.35	20.02
Sakha 104	21.55	17.86	22.80	17.05	21.86	16.27	3.29	2.26	26.81	19.54	6.32	20.63	10.91	7.27	46.37	26.93
Sakha 105	22.01	17.49	23.98	13.23	22.49	11.62	3.43	2.68	27.26	21.23	5.99	24.28	11.19	5.95	47.10	24.46
Sakha 106	20.02	19.47	23.19	13.83	21.61	11.91	4.46	3.13	27.28	21.58	7.72	20.47	11.92	6.85	47.17	28.54
Sakha 107	22.62	19.20	24.14	19.42	23.23	17.86	3.69	3.37	33.86	22.90	6.35	15.80	11.64	9.52	47.33	35.80
Sakha 108	21.20	16.85	25.04	15.56	23.42	13.30	3.37	2.45	27.50	22.20	6.66	22.48	11.62	6.39	49.50	26.99
Hybrid 2	25.84	17.74	28.02	16.82	25.91	14.80	4.34	3.74	24.87	20.85	9.35	25.84	13.16	7.70	52.09	28.80
Egyptian Yasmine	25.66	16.29	18.62	12.55	16.90	11.14	3.30	2.38	31.98	21.55	7.60	28.31	10.25	4.10	35.60	20.98
GZ 1368-S-5-4	22.77	18.68	24.02	16.19	22.16	13.73	3.41	2.91	23.25	22.89	6.58	17.32	9.38	6.49	36.90	20.49
IET 1444	20.88	20.30	25.56	20.66	24.42	19.52	3.56	3.16	24.19	23.06	8.00	15.27	8.86	7.26	34.21	26.39
IRAT 170	25.35	22.75	18.01	14.78	16.55	13.76	2.97	2.65	28.41	23.50	8.85	14.63	7.97	7.18	32.40	26.98
Mean	22.61	18.31	23.40	14.92	22.13	13.53	3.75	3.01	26.63	20.80	6.95	20.81	10.98	6.88	44.00	26.96

NS = non-stress treatment; DS = water-deficit treatment; PL = panicle length; NT = number of tillers; NPP = number of panicles; PW = panicle weight; TGW = 1000-grain weight; SP = spikelet sterility; GY = grain yield; HI = harvest index.

Table 8. Pearson correlations showing the strength of relationships of all observed parameters under water-deficit treatment (DS).

	DTH	PH	LR	FLA	FLAR	LT	CHC	RWC	SC	TR	PL	NT	NPP	PW	TGW	SP	GY
PH	−0.042																
LR	−0.365	−0.375															
FLA	−0.403	−0.190	0.510 *														
FLAR	0.177	0.332	−0.663 **	-0.617 **													
LT	0.367	−0.223	0.080	-0.402	0.137												
CC	−0.449	0.037	−0.099	0.086	0.057	−0.485 *											
RWC	−0.054	0.152	−0.702 **	-0.363	0.767 **	−0.092	0.200										
SC	0.207	0.142	−0.258	-0.158	−0.076	−0.034	−0.120	−0.161									
TR	0.011	−0.031	0.096	0.188	0.075	0.183	−0.194	−0.115	−0.349								
PL	0.092	0.557 *	−0.622 **	-0.183	0.550 *	−0.267	0.108	0.699 **	0.075	−0.126							
NT	0.229	0.137	−0.709 **	-0.374	0.564 *	−0.191	0.236	0.763 **	0.021	−0.384	0.587 *						
NP	0.245	0.157	−0.726 **	-0.392	0.655 **	−0.150	0.203	0.804 **	0.038	−0.360	0.627 **	0.981 **					
PW	−0.523 *	−0.038	−0.193	-0.178	0.389	0.163	0.126	0.444	−0.083	0.195	0.062	0.043	0.046				
TGW	0.262	0.298	−0.428	-0.061	−0.018	−0.540 *	0.436	0.171	0.229	−0.407	0.483 *	0.529 *	0.444	−0.426			
SP	−0.039	−0.342	0.710 **	0.243	−0.636 **	0.009	−0.007	−0.848 **	0.041	−0.138	−0.777 **	−0.581 *	−0.645 **	−0.279	−0.125		
GY	−0.296	0.202	−0.473	-0.138	0.634 **	−0.159	0.380	0.777 **	−0.118	0.122	0.581 *	0.656 **	0.683 **	0.512 *	0.129	−0.702 **	
HI	−0.232	0.008	−0.337	-0.006	0.601 *	−0.093	0.219	0.728 **	−0.149	0.159	0.493 *	0.512 *	0.557 *	0.581 *	−0.013	−0.576 *	0.884 **

* = Significant at 0.05; ** = significant at 0.01 level of probability; DTH = days to heading; PH = plant height; LR= leaf rolling; FLA= flag leaf angle; FLAR = flag leaf area; LT = leaf temperature; CHC = chlorophyll content; RWC = relative water content; SC = stomatal conductance; TR = transpiration rate; PL = panicle length; NT = number of tillers; NPP = number of panicles; PW = panicle weight; TGW = 1000-grain weight; SS = spikelet sterility; GY = grain yield; HI = harvest index.

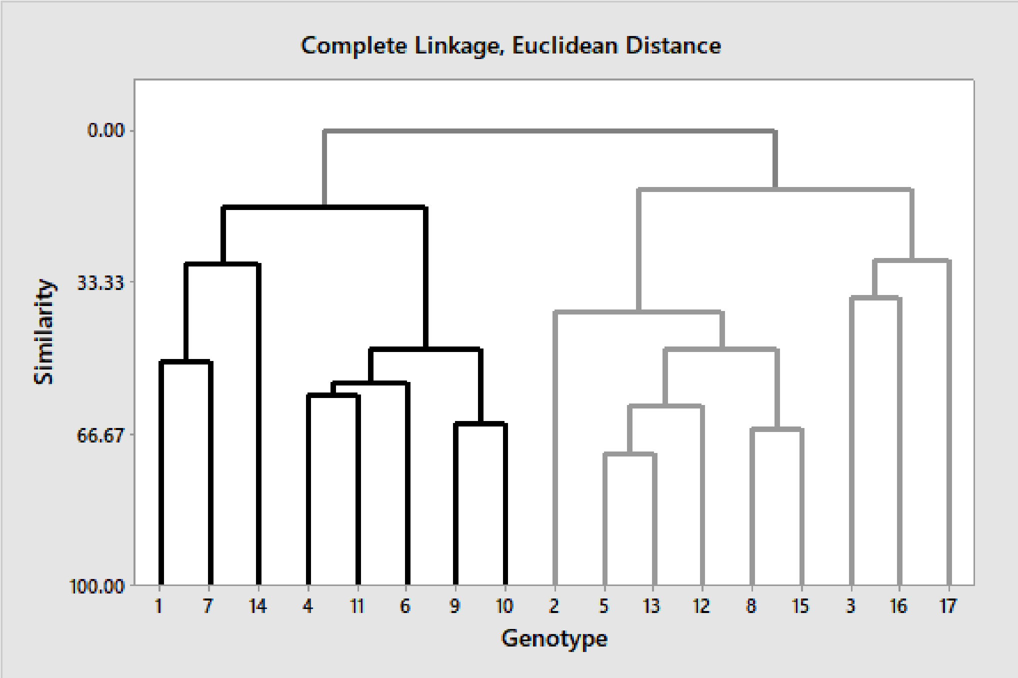

Figure 1. Clustering of 17 rice genotypes with response to water-deficit treatment (DS).

4. Discussion

The present study evaluated the morpho-physiological and agronomical responses of rice genotypes to identify the plant types with combination of traits adaptive to water-limited conditions. The significant differences observed for all studied traits among rice genotypes provide wide genetic variability and an opportunity for yield improvement under both NS and DS conditions (Tables 1 and 2). A little variation in environment may affect wide adaptability and potential of rice genotypes. The variation in GY and secondary traits in rice genotypes of the present study shows that genotypes with combinations of traits adaptive to drought can be identified and complexity of their mechanisms can be characterized [30]. High GY and its contributing traits, including reduced SS, was observed under NS condition with little reduction under DS. The genotypes Giza 179 and Sakha 107 produced >8.0 t ha^{-1} GY under DS with reduction of 30.49% and 18.21%, respectively, compared to NS. Several studies report GY as the most appropriate and direct criteria for selection of genotypes for drought tolerance due to moderate to high heritability of this trait under DS [31,32]. The DS reduced PH, as observed with genotypic variation in the present study and also reported earlier [33,34], and could be attributed to decrease in turgor to impair the cell elongation and expansion under DS. Among genotypes, Giza 179 and Sakha 107 observed earlier heading under both NS and DS, respectively, while Egyptian Yasmine had delayed heading under DS. Under DS, earlier heading or flowering is advantageous to escape drought [35–37], which often incurs at the cost of yield penalty. In the present study, earlier heading genotypes Giza 179 and Sakha 107 observed small reduction in yield that might be associated with mild DS observed in the present study (Table 6); however, another plausibility may be the stable and relatively drought-tolerant character of these genotypes [38,39]. These effects of drought also depend on crop stage, duration, and intensity. For instance, drought before reproductive stage shortens plant cycle and plants escape from prolonged effects of stress by earlier flowering at later developmental stages and produce better GY than delayed flowering genotypes [36,37,40,41]. However, reduced yield in delayed flowering genotype Egyptian Yasmine explains that this trait is genotype-dependent and shows combined effect of slow crop development and reduced panicle elongation rate [40]. Flag leaf angle (FLA) and FLAR reduced under DS; however, genotypes Sakha 105 and Sakha 106 expressed maximum, while GZ 1368-S-5-4 expressed lowest FLA under both NS and DS conditions. Nonetheless, genotypes Sakha 104 and Giza 179 expressed maximum FLAR under both NS and DS, respectively.

The FLAR, leaf area index (LAI), leaf relative water contents (LRWC), and chlorophyll pigments are putative traits used as evaluation criteria for drought tolerance [8,41,42]. Decrease in leaf area under DS might be attributed to less leaf growth owing to decrease in cell division and expansion concomitantly with decreases in turgor potential and water potential, as evident from decrease in RWC in the present study [17,42,43]. Likely, genotypic variation for leaf traits, such as increased LR score and LT, decrease in CHC under DS show the plasticity of these traits in rice varietal selection for drought resistance [44,45]. Further, leaf rolling (LR) is a desirable trait to reduce dehydration, particularly when drought occurs suddenly, to maintain water status, and genotypic variation exists with intensity of water stress experienced by the plant [17,46,47]. On the other hand, some studies report that low LR score contributes to higher GY; however, no such evidence was found in the present study. Similar findings were reported earlier by Kadioglu and Terzi [48]. In the present study, the genotypes Sakha 105, Sakha 108, and Egyptian Yasmine had minimum LR score under NS, and IET 1444 under DS, while Sakha 103 had the maximum LR score under DS. The minimum LR score, by IET 1444 under DS, reflecting independence of this trait in this genotype and response, was also reflected by maintenance of higher RWC, reduced LT, and higher grain-filling rate. Therefore, these genotypes comparatively performed better for yield than other genotypes, also evident from cluster analysis (Figure 1).

Grain yield (GY) is highly associated with the chlorophyll contents, the most important component in photosynthesis, and had positive association with GY in the present study. However, decrease in CHC under DS shows the obvious effect of disruption in synthesis and degradation of photosynthetic pigments that might be associated with lipid-peroxidation-induced damages to chloroplast membrane [49,50]. Nonetheless, drought, nutrient, and light directly or indirectly affect CHC, which results in disruption of other physiological processes [17]. The significance of leaf traits such as CHC, LT, FLAR, and LR, including RWC during grain-filling, is well recognized. As higher FLAR is required for synthesis and transport of assimilates that is also evident from a positive relationship of flag leaf traits with GY under water-limited condition of present study [51]. Positive relationship of CHC, TGW, NPP, RWC, PW, and FLAR indicates the contribution of these traits in improving GY of rice genotypes, while LR, SS, and LT are negatively correlated with GY (Table 5). All genotypes showed increased SS under DS, indicating its association with limit of GY by affecting spikelet sterility and grain-filling [52–56], as evident from the negative association of SS with GY (Table 5). Maximum reduction in grain yield was recorded in Sakha 103 and Egyptian Jasmine genotypes, which was attributed to increased SS under DS in these genotypes. When drought occurs during flowering and grain-filling stages, both the photosynthesis and translocation processes are greatly affected, which ultimately reduces yield [52–56].

However, these traits seem to be of less heritability, as compared to heading time, plant height, and leaf rolling showing moderate to high heritability, and are considered favorable in selection of drought-tolerant genotypes [56–59]. Therefore, physiological traits such as CHC, TWG, RWC, and FLAR that had positive association with GY are used in the selection of Sakha 107 and Giza 179 as drought-tolerant genotypes. Hybrid 2 is highly recommended for irrigated rice areas; however, the cultivation of Sakha 107 and Giza 179 (GY under DS =>8.0 t ha^{-1}) would give an advantage for water-stress-prone areas. Giza 179 can be considered as the most stable and promising rice genotype for both NS and DS areas (GY NS = 11.8 t ha^{-1}; GY DS = 8.3 t ha^{-1}). Nonetheless, the Sakha 107 and Giza 179, with the highest GY and its contributing traits under DS, can be utilized as donor parents in breeding programs for developing new high-yielding drought-tolerant rice genotypes.

5. Conclusions

Breeding for drought-tolerant rice is one of the most important approaches used to reduce detrimental effects of water stress. However, the selection of the parental lines is critical and must be emphasized to ensure the effectiveness of a breeding program. Rice subjected to water stress reduced DTH, PH, FLA, FLAR, CC, and RWC, and the effects were also reflected in yield and its components. The desirable mean values for NP, GW, ST, and GY were observed in Hybrid 2 and Giza 179. Giza 179, Sakha 107, IET 1444, and IRAT 170 also showed good performance under DS. The early heading exhibited by Giza 179 and Sakha 107 genotypes shows their drought escape strategy as an advantage under DS. The utilization of these genotypes as parental lines in a rice breeding program can help to develop promising breeding lines with earlier maturity, high yield, and drought characteristics.

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