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Unveiling water stress responses in rice: Identifying traits for enhanced water-use efficiency

Irum Aziz[1 *], Zahid Aslam[1], Atif Kamran[1], Muhammad Amjad Bashir[1], Mubashir Ali[2] and Zahid Hussain[3]

[1]Department of Plant Breeding and Genetics, Ghazi University, Dera Ghazi Khan, 32200, Punjab, Pakistan
[2]Institute of Plant Breeding and Biotechnology, MNS University of Agriculture Multan, Pakistan
[3]Center for Biotechnology and Microbiology, University of Swat, Pakistan

*****Corresponding author: Irum Aziz (aziz.irum@gmail.com)

Abstract

Rice (*Oryza sativa* L.) is a primary source of nutrition for more than half of the world's population. Rice in the reproductive stages is highly susceptible to water stress, and deficit irrigation leads to a significant decrease in the grain yield. Under such conditions, it is imperative for plant breeders to explore the genetic potential of rice for better yield and quality under limiting watering conditions. Four rice varieties, viz. Super-Basmati (V1), Super Kinat (V2), V-385 (V3) and V-386 (V4) are sown under split-plot design in field conditions. For this, we evaluated the four rice varieties for stage-specific watering thresholds under two distinct water conditions, including normal water conditions (T1) and water deficit conditions (T2), throughout the growth period. The nursery was transplanted in the field after 30-40 days after sowing. The field capacity was measured by estimating the soil water content at 50% and was maintained throughout the growing season. After the harvest, data was recorded for the following traits i.e., plant height (PH), Number of fertile tillers per plant (NFT), Number of fertile tillers per plant (NTP), number of seeds per spike (SPS), days to maturity (DM), number of grains per plant (GPP), 1000 seed weight (TSW), seed length (SL), and seed weight (SW). ANOVA results represent that all these traits are significant except seed length (SL). All four varieties show different responses under normal and drought conditions. Under normal conditions, V4 had significantly lower seed weight than other genotypes, whereas, under water stress conditions, V3 and V4 outperformed V1 and V2 with significantly higher seed weight. Notably V-386, adapt to water stress with increased plant height and improved seed production per spike. However, this resilience comes at a cost, as V-386 exhibits delayed maturity under drought conditions compared to normal circumstances. The association among all morphological traits was studied using Pearson correlation analysis. The results of the correlation study under water deficit conditions showed a completely different trend as compared to normal water application. Principal component analysis was performed to visualize the relationships among the traits among all four varieties. This research suggests that the recorded traits can serve as a selection tool for predicting water-use-efficient genotypes in rice.

Keywords: Evaluation, Genotypes, Rice, Water stress

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Introduction

Rice is the largest irrigated crop, representing around 30% of the global irrigated land area, and meets the food requirements of nearly half of the world's population (Portmann et al., 2010; Almanac, 2013; Ibrahim et al., 2016; Ali et al., 2019; Champness et al., 2023). It contributes 1.9 percent of value added in agriculture and 0.4 percent in GDP (Pakistan Economic Survey, 2022-23). During the 2022-23 period, the crop was cultivated on 2,976 thousand hectares, yielding 2460 kg/hectare (Pakistan Economic Survey, 2022-23). As the global population continues to grow and the demand for rice increases, it becomes increasingly important to improve the yield of this crop (Saddique et al., 2018). Moreover, different strains of rice can contain significant amounts of Fiber, protein, vitamin B, iron, and manganese. This nutritional profile makes rice a valuable resource in combating malnutrition (Zibaee, 2013; Rathna Priya et al., 2019). However, the demand for water from urban and industrial users, along with various environmental factors such as silting of reservoirs, chemical pollution, declining groundwater tables, salinization, livestock production, and social pressures, is contributing to the escalating issue of global water scarcity (Change, 2022). Due to the limited availability of water for irrigation and the rising costs associated with it, rice farmers are compelled to improve water productivity. Their goal is to maximize rice production while using the least amount of water possible (Dawe, 2005; Ishfaq et al., 2020). Hence, the exploration of rice germplasm plays a crucial role in identifying genetic traits associated with deficit irrigation. This aids in the development of high-yielding rice varieties that are resilient to water stress (Sahebi et al., 2018).

Abiotic stresses, such as water stress, salinity, heat stress, and metal stress, are significant factors that limit crop productivity (Khalid et al., 2019; Yadav et al., 2020). Among these stresses, water stress, exacerbated by climate change, poses a major threat to sustainable rice production

(Subramanian, 2008; Mallareddy et al., 2023). Certain rice varieties, such as IR-64 and Super Basmati, are particularly susceptible to abiotic stresses, especially water stress, leading to reduced yields (Kumar et al., 2014; Sabar et al., 2019). Furthermore, aerobic or upland rice often exhibits low yields (Zhao et al., 2010). The interaction of various biotic and abiotic factors driven by climatic variability has intensified the challenges associated with global food security (Hussain et al., 2016). Water scarcity is globally recognized as the most critical factor, posing a serious threat to food security due to the shortage of water resources (Besada & Werner, 2015; Hamdy et al., 2003). Water stress has become an increasingly severe problem in crop production, exacerbated by population growth and climate change (Jian-Chang et al., 2008; Keller & Seckler, 2005). These unfavourable changes contribute to the occurrence of extreme events such as floods and droughts (Ebi & Bowen, 2016; Konisky et al., 2016). Water stress typically reduces the plant's life cycle, decreases photosynthesis, and accelerates the senescence process (Chaves et al., 2002; Reddy et al., 2004). Hence, tillering, flowering and grain filling stages are the most critical in enhancing rice yield and grain quality. Studying water stress conditions at the flowering stage in rice is crucial for understanding its impact on physiological traits, grain yield, contributing factors, and quality (Chen & Murata, 2002).

Rice is highly susceptible to drought stress due to its semi-aquatic ancestry, resulting in significant impacts on its growth and grain production (Yue et al., 2006; Fahad et al., 2017). Water stress is a major contributor to yield reductions in rice-growing regions worldwide (Fahad et al., 2019). The effects of water stress on rice encompass various morphological, physiological, and molecular characteristics crucial for its growth and development (Farooq et al., 2009). Limited water availability during a water-deficit condition negatively affects rice in several ways. It hampers germination, reduces plant biomass, tiller numbers, and plant height, and alters root angle (Ji et al., 2012; Akram et al., 2013; Sokoto, 2014). Furthermore, water stress leads to decreased transpiration, stomatal conductance, water use efficiency, relative water content, chlorophyll content, photosynthesis, and photosystem II activity. It also affects membrane stability and alters abscisic acid content (Ding et al., 2014; Yang et al., 2014). In response to water stress, rice triggers the accumulation of Osmo protectants such as proline, sugars, polyamines, and antioxidants to mitigate its detrimental effects (Li et al., 2011; Fahramand et al., 2014). Additionally, water stress also induces changes in gene expression, including those encoding transcription factors and defense-related proteins (Nakashima et al., 2014). These molecular responses play a vital role in enhancing rice's tolerance to drought stress. Overall, the susceptibility of rice to stress and its subsequent impacts on various aspects of growth, physiology, and gene expression highlight the need for further research to develop strategies for improving drought tolerance in rice cultivation.

Plant breeders could play a vital role in producing and identifying the rice genotypes that could exhibit tolerance to water-deficit conditions. They recognize the value of screening and selecting genotypes based on their potential for water tolerance. Hence, the selected rice genotypes are particularly valuable for cultivation in regions facing water-deficit conditions. Hence, the aim of this study was to assess the performance of water-deficit rice genotypes using effective screening techniques under water stress and normal conditions. The findings of this study will contribute to the selection of rice genotypes with improved performance under different levels of water stress. The present study utilized four rice varieties to investigate their genetic diversity and identify suitable genotypes for the development of new rice varieties with enhanced genetic potential. The data generated from this study will be of great value to rice breeders in their efforts to produce high-yielding hybrids and varieties specifically adapted to water-stressed fields.

Materials and Methods

Varieties and their characters

Super basmati (V1): celebrated for its long grains, aromatic fragrance, and distinctive flavor, generally requires a moderate amount of water, making it adaptable to various agricultural conditions and contributing to its widespread cultivation. Super Kinat (V2): known for its extra-long grains and exceptional cooking qualities, typically requires moderate water levels, making it adaptable to cultivation in diverse Agro-climatic conditions. V-385 (V3): distinguished by its medium-grain size, excellent cooking properties, and a well-balanced aroma and taste, exhibits moderate water needs, making it suitable for cultivation in regions with varying water availability. V-386 (V4): characterized by its specific traits such as medium-grain size and a harmonious blend of aroma and taste, typically demonstrates a moderate water requirement, rendering it well-suited for cultivation in regions with diverse water availability.

Experimental design, nursery preparation and transplantation

A field experiment was conducted at Fazil Pur district Rajan Pur during the rice-growing season 2021. The experimental material including four rice genotypes, i.e., Super-Basmati (V1), Super Kinat (V2), V-385 (V3) and V-386 (V4) were utilized in this experiment. Two water treatments were planned in a split-plot design with three replicates. Two water treatments included normal and water deficit throughout the growth period at the tillering, flowering and grain filling stage (Fig. 1). The water stress was employed by watering the field with half the amount of the water compared to normal. The field capacity was measured by estimating the soil water content at 50% and was maintained throughout the growing season. All Rice cultivars have similar growth periods. Seeds of all genotypes were treated to Fungicides before sowing, at a dose of 2g Benlate ($C_{14}H_{18}N_4O_3$) per 1 kg of rice seed. All of the seeds were soaked in water for two days. Rice seedlings were also planted in the soils that had been prepared. Seeds of each genotype were sown in various blocks using the broadcasting method. The rice nursery was ready for transplantation 30 to 40 days after seeding. The prepared nursery of each rice genotype was transplanted into a separate field using a Randomized Complete Block Design (RCBD) with three replications. The rice plants were spaced 30 cm R x R and 22 cm P x P when transplanted. Each genotype contained five lines and each line contained 10 plants. Herbicides like Thiobencarb ($C_{12}H_{16}ClNOS$) and Bifenox ($C_{14}H_9C_{l2}NO_5$) were used to control weeds. Insecticides were also utilized to avoid insect-borne pests and diseases. For instance, lambda-Cyhalothrin ($C_{23}H_{19}C_lF_3NO_3$).

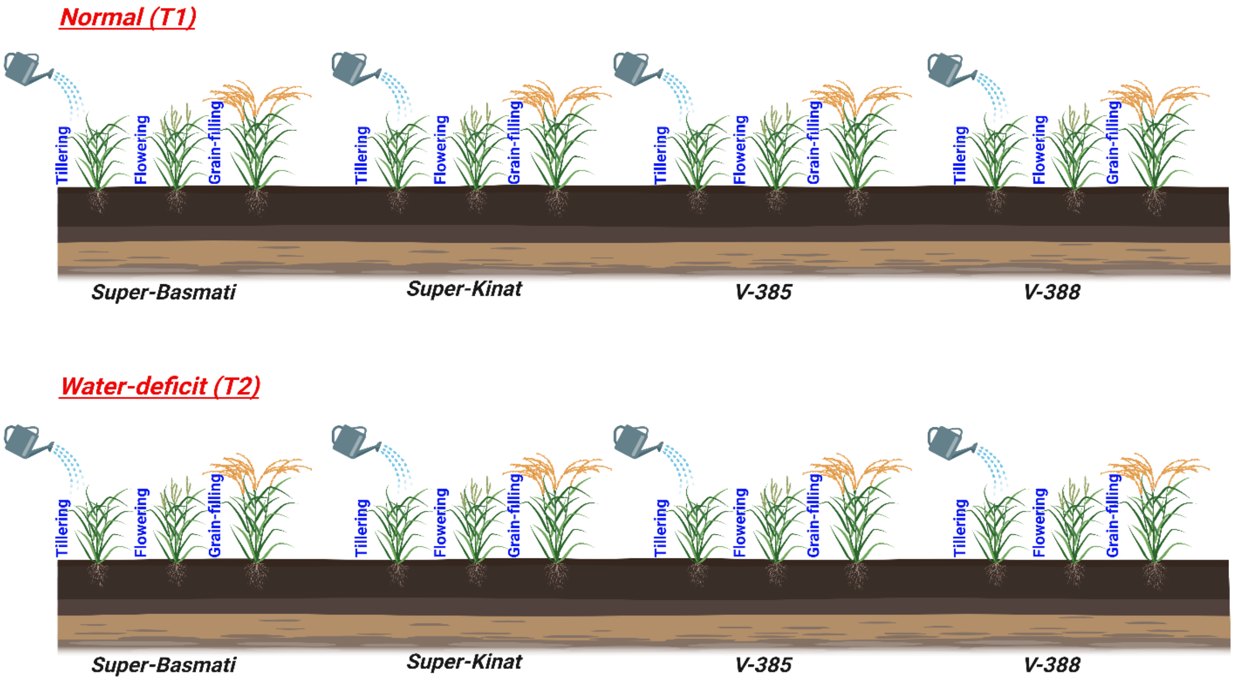

Fig. 1 The experimental lay out representing the normal (T1) and water-deficit (T2) application on different rice genotypes of Super-Basmati, Super-Kinat, V385, and V-385. T1 and T2 teatments were applied on different rice genotypes under field conditions during different rice growth stages, i.e., tillering, flowring, and graon-filling stages

Plant harvest

At maturity stage, rice plants were harvested, and data was recorded for the following traits i.e. plant height (PH), No. of fertile tillers per plant (NFTP), No. of fertile tillers per plant (NTPP), number of seeds per spike (NSPS), days to maturity (DM), number of grains per plant (NGPP), 1000 seed weight (TSW), seed length (SL), and seed weight (SW).

Statistical analysis

A complete randomized block design was utilized to conduct a two-way analysis of variance (ANOVA) to examine the influence of genotypic variations and water stress on plant morphological traits, as well as their interactions. The least significant difference test (LSD0.05) was employed to assess the statistical significance of these effects. The statistical software used for the analysis was Statistix 8, version 8.1. Prior to the analysis, the data underwent tests for normal distribution (Shapiro-Wilk test; $p > 0.05$) and homogeneity of variance (Levene test; $p > 0.05$) to ensure the validity of the results. Furthermore, principal component analysis (PCA) and Pearson's correlation analysis were performed on the data. PCA was conducted using R, while Pearson's correlation analysis was carried out using Origin Pro.

Results

Traits variability in rice genotypes under water stress

The analysis of variance for means indicated that the differences among genotypes were highly significant for all the traits except for seed length (Table 1). In this study, significant mean squares results were observed for 8 out of 9 traits in all genotypes of rice under investigation. The analysis of variance for all morphological traits was significant, encompassing plant height (PH), number of fertile tillers per plant (NFT), number of tillers per plant (NT), number of seeds per spike (SPS), days to maturity (DM), number of grains per plant (GPP), thousand seed weight (TSW), and seed weight (SW) for both treatments, i.e., normal and water deficient conditions. Consistently, a similar trend of significance was observed under the treatment × Genotypes interaction for the mentioned traits. However, it is worth noting that seed length was found to be non-significant in all genotypes, treatments, and interactions. This showed that seed length is an ineffective parameter for screening resistant varieties under water deficit condition in rice. While other traits can be of interest for rice breeders to work with.

Table 1 Mean square values of different morphological traits in rice genotypes

SOV	PH	NFTP	NTPP	NSPS	DM	NGPP	TSW	SL	SW
Replications	0.492	0.987	1.125	0.95	3.043	8.155	0.172	0.1275	0.00346
Treatments	103.169**	153.52**	182.05**	132.54**	159.65**	500.507**	113.535**	9.79204	2.95441**
Varieties	2.635**	1.494**	1.862**	2.048**	8.528**	12.637**	0.236**	0.1477	0.00728**
Treatment × Varieties	0.68**	1.227**	2.353**	1.408**	10.38**	24.063**	0.103**	0.35768	0.01259**
Error	0.126	0.221	0.217	0.223	1.413	1.058	0.026	0.01657	0.00177

PH = Plant height; NFTP = Number of fertile tillers per plant; NTPP = Number of fertile tillers per plant; NSPS = Number of seeds per spike; DM = Days to maturity; NGPP = Number of grains per plant; TSW = 1000 seed weight; SL = Seed length; SW = Seed weight

Response of rice genotypes to water stress

Various rice genotypes showed significant differences in terms of various morphological traits like under normal and water deficit conditions (Fig. 2). The results showed that V4 (V-386) showed significantly higher plant height under both normal and water deficit conditions compared to other genotypes, while V1 (Super-Basmati) showed significantly lowest plant height compared to other genotypes under water stress conditions (Fig. 2A). Similarly, number of fertile tillers per plant (Fig. 2B) and number of tillers per plant (Fig. 2C) produced by V4 genotype were significantly higher under normal and water deficit conditions compared to other genotypes. Concerning the number of seeds per spike, notable variations were observed among the four rice genotypes under normal conditions, whereas no significant differences were observed among the four rice genotypes under water stress conditions. (Fig. 2D). It is interesting to note that all four rice genotypes exhibited improved performance in terms of seed production per spike under water stress conditions compared to their performance under normal conditions. In terms of days to maturity, significant differences were observed among rice genotypes under both normal and water stress conditions (Fig. 2E). The V4 rice genotype exhibited a longer time to reach maturity compared to other genotypes under water stress condition while under normal conditions, V4 required minimum days to maturity. This could lead to increase in growth span and ultimately delays crop maturity, hence would not be preferred by plant breeder. In term of number of grains per plant, V3 statistically showed lower number of grains per plant compared to three rice genotypes that were performed similarly, while no significant differences were observed under normal water conditions (Fig. 2F). However, under water stress conditions, V1 displayed a significantly lower number of grains per plant compared to the other three rice genotypes. In contrast, V2, V3, and V4 showed superior results in terms of the number of grains per plant under the same water stress conditions.

Results of current study showed lowest thousand seed weight (TSW) was recorded under V2, while V1, V3, and V4 showed significantly higher thousand seed weight than V1 under normal water conditions (Fig. 2G). While under water stress conditions, V4 showed significantly higher TSW compared to other rice genotypes. Overall, performance of all rice genotypes in terms of TSW was better under water stress than normal conditions. Further enhancement of this plant trait can play a crucial role in the development of resistant germplasm and the screening of tolerant materials for drought conditions in rice cultivars. For seed length, significant differences were observed among all genotypes under both water normal and stress conditions, while rice genotypes under water stress conditions showed significantly higher seed length than normal conditions (Fig. 2H). Moreover, under water conditions, V4 genotype showed significantly higher seed length compared to other rice genotypes. While for seed weight, significant differences were observed among four rice genotypes under both normal and water conditions (Fig. 2I). Under normal conditions, V4 significantly showed lower seed weight compared to other genotypes while in water stress conditions, V3 and V4 genotypes performed well and showed significantly higher seed weight compared to V1 and V2 genotypes. This study represents another favourable outcome, particularly in the context of exploring resistant germplasm.

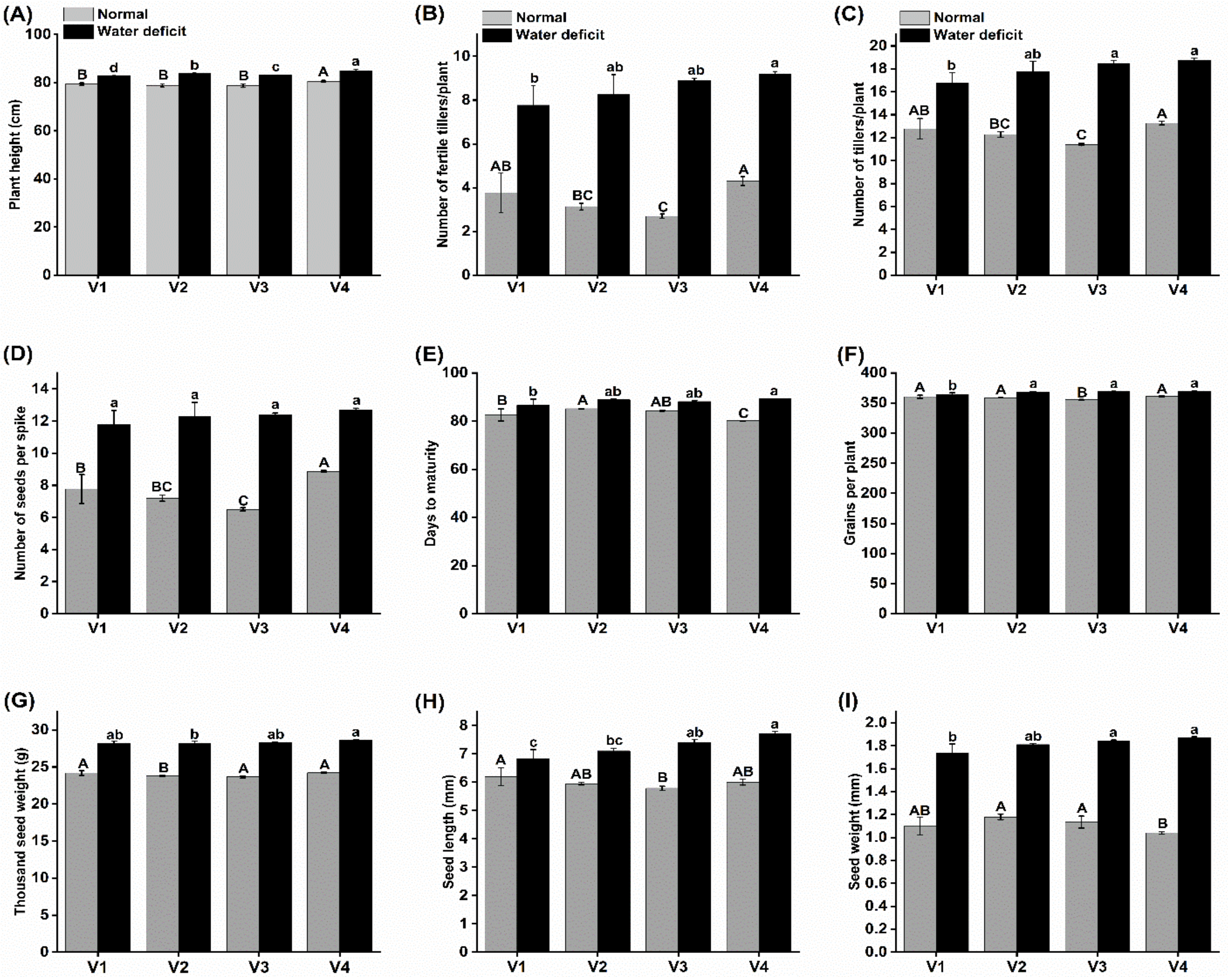

Fig. 2 Respnse of various rice genotypes'morphological traits to normal and water deficit conditions; (A) plant height (PH), (B) number of fertile tillers per plant (NFT), (C) number of tillers per plant (NT), (D) number of seeds per spike (SPS), (Ee) days to maturity (DM), (F) number of grains per plant (GPP), (G) 1000 seed weight (TSW), (H) Seed length (SL), (I) Seed weight (SW).The different letters indicate a significant difference at $P < 0.05$ among different rice cultivars (means ± standard deviation). Upper case letters showing significant differences for rice genotypes in normal condition (T1), while lower case letters for water-deficit condition (T2)

Relationship among different morphological traits

The association among all morphological traits was studied using Pearson correlation analysis under two different water conditions: normal water application (Fig. 3A) and water deficit conditions (Fig. 3B). This analysis aimed to explore the relationships between the various morphological traits under these distinct irrigation conditions. Under normal water conditions, overall, a positive association was recorded among plant height (PH), number of fertile tillers per plant (NFT), number of tillers per plant (NT), number of seeds per spike (SPS), number of grains per plant (GPP) and thousand seed weight (TSW). While a negative association was recorded for days to maturity (DM) with PH, NFT, and SPS. For example, PH was found to be positively and significantly correlated with NFT, SPS, while negatively and significantly correlated with DM. Likewise, NFT had positive correlation with SPS, GPP, TSW, and SL, while negative correlated with DM) and SW. These results imply that various morphological traits were positively or negatively correlated as shown in Fig. 3A. In contrast, the results of correlation study under water deficit conditions showed a completely different trend as compared to normal water application, and only found positive correlation among different morphological traits and no negative correlation was recorded (Fig. 3B).

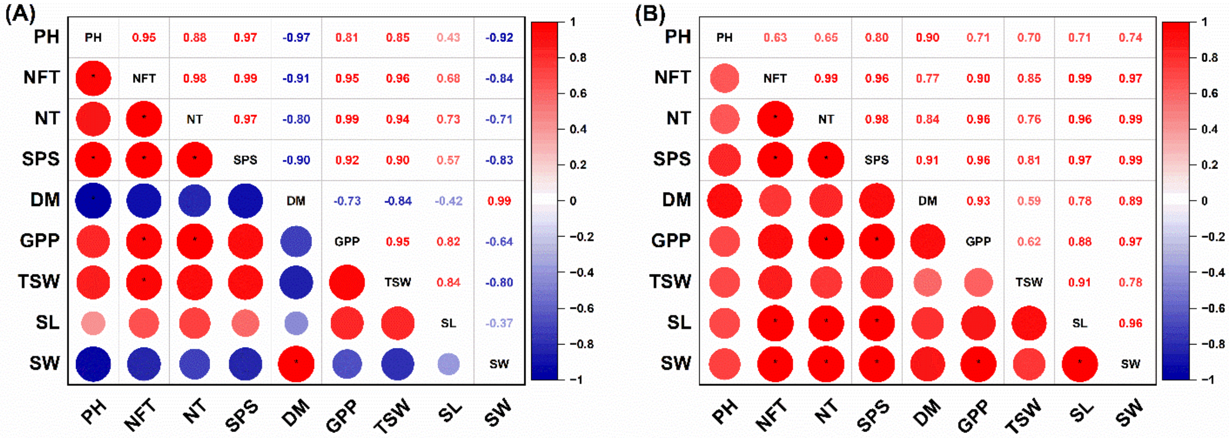

Fig. 3 Pearson correlation analysis between different morphological traits; (a) normal water application (T1), (b) water-deficit treatment (T2). * Represents the significance at *P*≤.05. PH (plant height), NFT (No. of fertile tillers per plant), NT (No. of fertile tillers per plant), SPS (number of seeds per spike), DM (days to maturity), GPP (number of grains per plant), TSW (1000 seed weight), SL (Seed length), SW (Seed weight)

Principal component analysis

Principal Component Analysis (PCA) involves grouping input and response variables into distinct clusters based on similarities in variance and correlations. In this study, PCA was conducted to assess the impact of various water treatments on different rice genotypes, analysing their cumulative influence on plant response traits. PCA separated the four genotypes into distinct divisions, revealing differences in the effects of these genotypes on various plant response traits. Additionally, the PCA grouped the response variables of rice plants differently under normal (T1) and water stress (T2) conditions (Fig. 4). Under T1, the individual biplot reveals that both V3 and V4 individuals exhibited elevated PCA scores, and a substantial portion of the variance is accounted for by these two individuals. Therefore, it is advisable to consider the selection of these two individuals for treatment 1 (Fig. 4A). PC-1 and PC-2 collectively accounted for a total variance of 96.9%. Variables such as NT, NFT, TSW, and GPP exhibited positive factor loadings on PC-1, where NFT has the highest factor loading value. On the other hand, DM and SW showed negative factor loadings on PC-1. PC-2 was mainly influenced by PH and SPS, with PH contributing significantly to this component. In contrast, SL, SW, and DM displayed negative factor loadings on PC-2 (Fig. 4B). The relative length of each variable signifies the extent of its contribution to the total variation. DM, PH, and NFT play significant roles in explaining the variation, whereas SL and SW exhibit less variation across the principal components (PCs). Notably, although V3 contributes less to the variation in other traits, it demonstrates substantial variation in DM and SW. V1 particularly stands out for its effective representation of SL, while V4 is most effective in representing PH (Fig. 4C). Under T2, V3 exhibited notably lower PCA scores in contrast to the other individuals, V1 and V2, which demonstrated the highest possible PCA scores. This discrepancy in PCA scores implies that, in the context of Treatment 2, V3's performance is comparatively less robust. Consequently, it is advisable not to choose V3 as the preferred candidate for Treatment 2 due to its relatively lower performance in this specific treatment condition (Fig. 4D). In PC-1, SW and SPS exhibited positive factor loadings, while in PC-2, SL, SW, NT, and NFT displayed positive factor loadings. Conversely, PH and DM had negative factor loadings on PC-2. TSW, NT had positive factor loading on PC-3 while GPP, SPS and DM, PH had negative factor loading on PC-2. The PC-3 variance explains by PH and DM had positive factor loading on PC3 while other variables had negative factor loading on this PC (Fig. 4E). The relative length of each variables showed its proportion of variation. NFT, SL, SPS, DM and NT had contributed to maximum variation. TSW showed less variation. V4 best for SL and SW. The V3 are good for TSW and NFT (Fig. 4F).

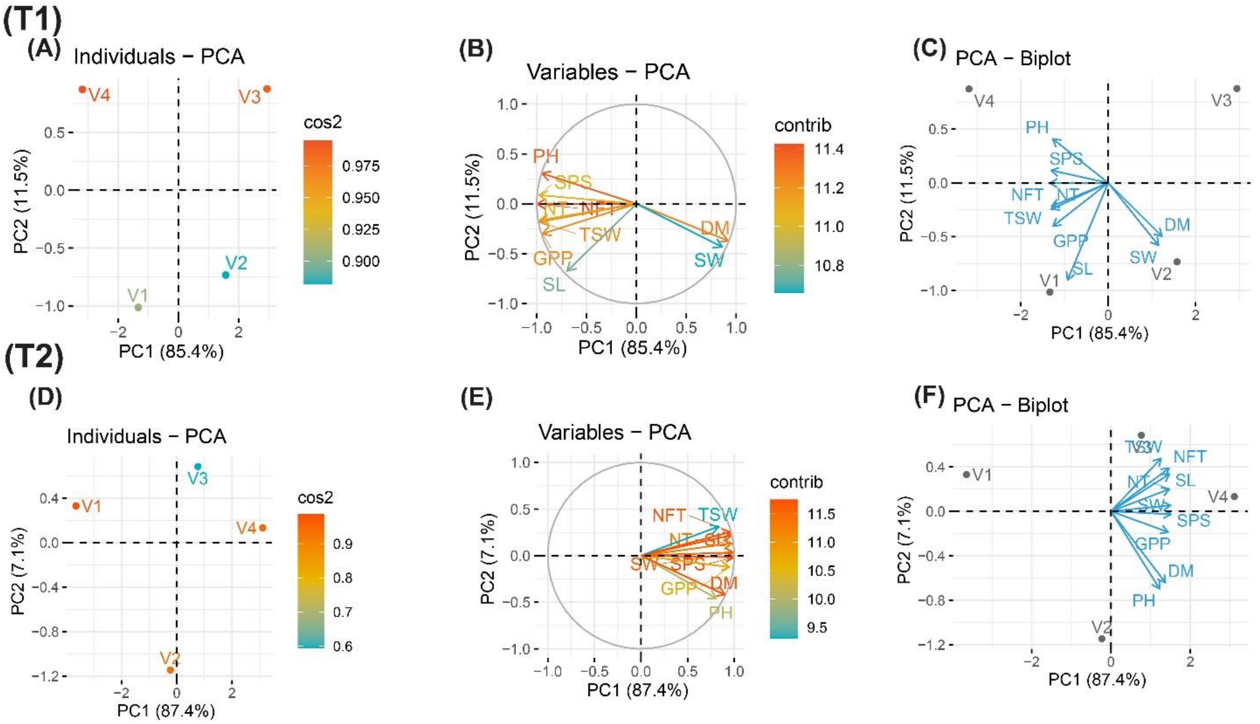

Fig. 4 The PCA biplot illustrates the relationship between estimated variables and rice cultivars under normal water treatment (T1); (A) PCA for individuals of rice genotypes, (B) PCA for variables different rice morphological traits, (C) biplot showing relationship between morphological traits and rice cultivars. PC1, representing 85.4 % of the total variability, is displayed on the x-axis, while PC2, explaining 11.5 % of the total variability, is shown on the y-axis. While for water-deficit (T2); (D) PCA for individuals of rice genotypes, (E) PCA for variables different rice morphological traits, (F) biplot showing relationship between morphological traits and rice cultivars. PC1, representing 87.4 % of the total variability, is displayed on the x-axis, while PC2, explaining 7.1 % of the total variability, is shown on the y-axis. While for water-deficit (T2); V1, V2, V3, V4 represents Super-Basmati, Super Kinat, V-385 and V-386 rice cultivars, respectively. PH (plant height), NFT (No. of fertile tillers per plant), NT (No. of fertile tillers per plant), SPS (number of seeds per spike), DM (days to maturity), GPP (number of grains per plant), TSW (1000 seed weight), SL (Seed length), SW (Seed weight).

Discussion

Yield in plants represents the ultimate outcome resulting from the mutual action of numerous traits, each exerting its influence either directly or indirectly on grain production. These traits encompass a broad spectrum, ranging from the plant's physiological processes, reproductive capabilities, and stress tolerance mechanisms to its ability to efficiently utilize resources (Singh et al., 2018). Among abiotic constraints, drought stress stands out as a predominant factor, particularly in regions facing water scarcity (Sabar et al., 2019). Rice cultivation accounts for nearly 80% of total freshwater resources allocated for irrigation (Bouman, 2007).

The global production of rice is constrained by the limited availability of freshwater and the effectiveness of rice cultivars in tolerating drought stress (Pandey et al., 2007). Drought can have severe consequences on rice yields, leading to significant losses. Under mild drought conditions, yield losses can reach up to 21%, while under moderate drought, it can increase up to 51%. In severe cases, where drought stress is particularly intense, rice yields may experience extreme losses, reaching up to 90.6% (Zhang et al., 2018). The impact of drought stress on rice growth has been extensively investigated across various growth stages. Drought stress can affect rice plants at any developmental phase, and the responses to this stress vary at different stages of growth (Yang et al., 2019). Different rice genotypes exhibited notable variations in morphological traits under both normal and water-deficit conditions. In the current study all four varieties were distinguished from each other due to significant ANOVA results of plant height (PH) No. of fertile tillers per plant (NFT), No. of fertile tillers per plant (NTP), number of seeds per spike (SPS), days to maturity (DM), number of grains per plant (GPP), 1000 seed weight (TSW), and seed weight (SW). Only seed length showed non-significant difference (Table. 1). A similar trend of some of these traits was observed in a research by (Yang et al., 2019).

It is interesting to note that all four rice genotypes demonstrated enhanced seed production per spike when subjected to water stress conditions as compared to their performance under normal conditions (Fig. 2). Specifically, V4 (V-386) showed significantly higher plant height under both normal and water deficit conditions compared to other genotypes, while V1 (Super-Basmati) showed significantly lowest plant height compared to other genotypes under water stress conditions (Fig. 2a). (Rice show variety dependent response. According to this study, V4 is a better-performing variety as compared to others under drought conditions. However, V4 took more days to mature which is not desired (Fig. 2). Drought stress has a profound impact on the development of reproductive structures, influencing the timing of flowering and grain filling, which in turn contributes to delayed maturity (Yang et al., 2019). In the current study, a similar trend was observed where days to maturity increased under drought stress compared to normal water conditions. Specifically, under normal conditions, V4 genotype exhibited the minimum days to maturity, while under water stress conditions, the V4 genotype took a longer time to reach maturity compared to other genotypes. This characteristic, leading to delayed crop maturity, would likely not align with the preferences of breeders in the selection of desirable traits.

Likewise, thousand seed weight was observed different in normal and water deficit conditions. In the current study, V4 showed maximum TSW among all other varieties under water deficit conditions. It means drought stress at grain filling stage can alter the seed weight (SW) and thousand seed weight (TSW). A similar trend was observed in previous research (Moonmoon & Islam, 2017). Indeed, the formation of rice panicle and spikelet morphogenesis plays a crucial role in determining rice yield. These processes are essential stages in the reproductive development of rice plants, directly influencing the number of grains (Chang et al., 2016; Gravois & Helms, 1992). Certainly, various studies have indicated that the booting stage is among the most sensitive periods of rice development to drought stress. The booting stage is a critical phase in the rice growth cycle, marking the transition from the vegetative to the reproductive phase (Shao et al., 2014). Other studies found that the flowering stage is the most sensitive stage influencing final yield (Liu et al., 2006). Indeed, drought stress during the flowering or grain-filling stages can significantly disrupt grain formation and development, affecting the overall number of seeds per spike (Shao et al., 2014). Similarly, in current study, an increase was observed in the number of seeds per spike under water stress conditions compared to normal water conditions. Notably, the V4 genotype exhibited the maximum number of seeds per spike under water deficit conditions. This observation suggests that, under the influence of drought stress, V4 may exhibit adaptive responses that enhance seed production per spike.

Pearson Correlation Analysis is employed to check the association among traits reveals valuable information observed (Liu et al., 2006). The relation among PH (plant height), NFT (No. of fertile tillers per plant), NT (No. of tillers per plant), SPS (number of seeds per spike), DM (days to maturity), GPP (number of grains per plant), TSW (1000 seed weight), SL (Seed length), SW (Seed weight) was different under normal and drought stress condition. The trend of trait association under normal water conditions was according to a similar previous research by Amegan et al. (2020). However, the trait association recorded under drought was notably different, and more traits were positively correlated with each other. Hence, understanding the effects of drought stress on rice is crucial for developing resilient varieties and implementing sustainable agricultural practices in regions vulnerable to water scarcity. This knowledge contributes to the identification of genotypes with improved tolerance to drought, which is essential for ensuring food security and enhancing the productivity of rice cultivation in challenging environmental conditions (Swamy & Kumar, 2013).

Conclusion

The study highlights the intricate interplay of morphological traits in rice genotypes, emphasizing their varied responses to water stress conditions. V4 displayed a significantly lower seed weight compared to other genotypes, whereas, under water stress conditions, both V3 and V4 outperformed V1 and V2 with significantly higher seed weights. V-386 demonstrated notable resilience by maintaining higher plant height and enhanced seed production per spike under drought stress. However, this was coupled with a trade-off, as it exhibited delayed maturity compared to its performance under normal conditions. The study underscores the significance of understanding the nuanced effects of drought stress on rice cultivation, particularly during critical growth stages, to inform the development of resilient varieties and ensure sustainable food production in regions vulnerable to water scarcity. This study opens the windows for the scholars, students, and researchers to work more on these genotypes based on given information to overcome the challenge of food security through using improved tolerance to drought, which is a challenging issue in these days in general, and especially in the scenario of climate change.

Conflict of interest: The authors declare that they have no conflict of interest.

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