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Integrating deep fuzzy clustering and multivariate analysis to assess rice milling quality under combined drought stress and thermal drying

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Abstract

Climate-driven drought events, together with post-harvest processing constraints, increasingly threaten rice milling quality, a critical determinant of market value, process efficiency, and food security. Although the individual effects of pre-harvest drought stress and post-harvest drying temperature have been reported, their combined impact on milling performance across rice genotypes has not been systematically evaluated from an engineering perspective. This study demonstrates, for the first time, that the interaction between drought stress and thermal drying induces genotype-specific trade-offs between drying efficiency and milling quality in a fluidized-bed drying system. Six rice genotypes were cultivated under normal and drought irrigation regimes over two growing seasons and subsequently dried at 40, 50, and 60°C in a controlled fluidized-bed dryer. Important process and milling quality indicators, including milling yield (MY), broken rice percentage (BRP), crack percentage (CP), degree of milling, and drying time (DT), were quantified to evaluate system performance. Multivariate statistical analyses (ANOVA, correlation analysis, and PCA) were integrated with deep fuzzy clustering (DFC) to resolve complex response patterns and support decision-oriented evaluation. Drought stress reduced the degree of milling by 12–15% and MY by 3–5%, while increasing BRP and CP by 10–25%. Increasing drying temperature shortened DT by up to 50% but significantly elevated kernel damage, particularly at 60°C, highlighting a critical process trade-off. DFC identified drought-tolerant genotypes that maintained higher MY and lower CP under combined stress. These findings provide an integrated framework for optimizing genotype selection and drying temperature, supporting resilient and resource-efficient rice processing systems.

1. Introduction

As the world population is expected to exceed 9 billion by 2050 and drought events are becoming more frequent due to climate change, improving the yield of staple crops such as rice (*Oryza sativa* L.) is essential to ensure global food security [1–3]. Drought is a major abiotic stress and one of the primary factors limiting rice productivity and grain quality, leading to substantial losses worldwide [4, 5].

Sustainable rice production can be supported through the use of drought-tolerant varieties and energy-efficient drying and processing methods that minimize grain damage [6]. Rice is a vital cereal crop, forming the dietary backbone for over half of the world's population [7]. The market value and consumer acceptance of rice grains are strongly influenced by their quality [8]. Final rice quality is mainly affected by two key factors: drought during the growth period and postharvest drying temperature. These factors, acting before and after harvest, directly influence grain formation and its physicochemical and structural properties [9].

Drought significantly affects rice plants, particularly during reproductive development and grain maturation, by disrupting photosynthesis, assimilate distribution, and grain development [10]. These effects often become evident as increased internal chalkiness, greater susceptibility to cracking, and reduced grain firmness. Such physical deterioration is frequently accompanied by notable changes in starch and protein biochemistry under drought stress [11].

Rice cultivars respond differently to drought conditions, with some exhibiting high tolerance while others experience a marked reduction in grain quality [6]. This variability indicates that standardized management approaches are insufficient. Instead, careful evaluation of genotypes-specific responses to drought is essential not only for short-term yield improvement but also for developing agronomic strategies that remain effective under shifting climate patterns. In this context, advanced artificial intelligence techniques may enable improved monitoring and mitigation of both biotic and abiotic stresses in rice production systems [12].

In the postharvest process, rice grains are first dried to reduce moisture content to a safe and stable level, thereby preventing quality loss during storage. This step is followed by milling, which converts paddy rice into white rice. In recent years, fluidized-bed dryers have gained popularity because they provide uniform heat and airflow distribution, shorten drying time, and improve energy efficiency [13]. However, drying temperature is a critical parameter. While high temperatures accelerate drying, they can impose thermal stress on grains, leading to cracking, increased breakage during milling, loss of natural color, and changes in starch and other physicochemical properties [14]. Conversely, drying at lower temperatures helps preserve grain quality but requires longer drying times and higher energy consumption. Therefore, optimizing drying conditions according to rice type and characteristics is essential [15].

Research on rice quality has often examined drought stress and drying temperature as independent factors. Relatively few studies have investigated their combined effects, particularly across different cultivars [7, 13, 15, 16]. Garcia-Llobodanin and Billiris (2022) studying a long-grain rice variety in Uruguay, reported that increasing drying-air temperature or decreasing relative humidity reduced milling quality, especially when the glass transition temperature was exceeded [17]. They showed that a moderate drying rate of approximately 3% moisture loss per hour, combined with a short one-hour tempering step, was sufficient to maintain high milling quality. Drought stress during flowering also has severe consequences. In a study of two rice cultivars, yield decreased by more than 23%, and physiological activity did not recover during grain filling, while chalkiness and the proportion of chalky kernels increased [18]. Luthra et al. (2021) demonstrated that dehumidified drying air improved moisture removal efficiency and enabled continuous drying under humid conditions without major losses in head rice yield or whiteness, with fluidized-bed systems generally outperforming fixed-bed dryers [19].

Because drought alters the structural and biochemical composition of rice grains, drought-stressed rice may respond differently to thermal and mechanical stresses during drying. Therefore, evaluating genotype-specific responses to both preharvest drought stress and postharvest drying

temperature is essential for understanding their combined impact on rice quality, as the economic value of rice is largely determined after milling. In light of these gaps, this study examines how drought stress during cultivation and drying temperature in a fluidized-bed dryer influence the milling quality of different rice genotypes. Key quality indicators include optical and mass-based degree of milling, broken rice percentage, milling yield, crack percentage, and drying time. By analyzing both individual and combined effects, this work aims to provide practical guidance for improving agronomic practices and postharvest processing, reducing losses, and strengthening rice competitiveness in local and export markets.

2. Material and methods

2.1. Rice sample

The present study involved six rice varieties evaluated under two irrigation treatments (normal and drought stress): tall-stature (Tarom-Ts, FR13A-Ts, and KDML105-Ts) and semi-dwarf (IR8-Sd, IR60-Sd, and Jijing 88-Sd), from the Rice Research Institute of Iran, Rasht, Iran (longitude 37°16'14" North and latitude 49°35'23" East) (Table 1). Field experiments were conducted over two consecutive summer growing seasons (2022–2023 and 2023–2024).

Table 1
Information about the six rice variety and their origins used in this study

Variety	Code	Growth duration (day)	Tall plant type	Origin
Tarom	Tarom-Ts	120–130	Tall-stature	Iran
FR13A	FR13A-Ts	130–150	Tall-stature	India
KDML105	KDML105-Ts	120–140	Tall-stature	Thailand
IR8	IR8-Sd	105–115	Semi-dwarf	IRRI, Philippines
IR60	IR60-Sd	110–120	Semi-dwarf	IRRI, Philippines
Jijing 88	Jijing 88-Sd	130–150	Semi-dwarf	China

2.2. Experimental procedure

Long-term climate data indicate this station has an average annual temperature of 15.7°C and a mean yearly rainfall of 1358 mm, located at 26 meters above sea level in north Iran, has the distinct features of a temperate and sub-Mediterranean Caspian climate. The trends in average humidity, rainfall, and temperature during the growing season (from March to August) in the Rasht region from 2022–2023 to 2023–2024 are presented in Fig. S1.

Grains of rice genotypes were sown in rows and ridges in the wet bed nursery on early April. After the seedlings reached a height of about 30 cm (depending on the genotype, about one month after sowing the seeds in the wet bed nursery), the seedlings were transferred to the field. This experiment was conducted in a randomized complete block design with three replications (2×2 m plots; 0.4×0.4 m spacing; 16 plants m^{-2}) for each genotype. The farm soil was silty clay in texture, with a pH level of 7.4 and without salinity or sodium. The soil electrical conductivity (EC) was measured at 1.4 dS m^{-1}. Additionally, the soil contained 20 g kg^{-1} of organic carbon (2%), 40 g kg^{-1} of calcium carbonate equivalent (4%), and 1.4 g kg^{-1} of total nitrogen (0.14%). Standard agronomic practices such as land preparation (plowing and leveling), precise sowing/transplanting, scheduled irrigation, balanced fertilizer application based on soil testing, and integrated pest and weed management, were implemented consistently from planting through the harvest time (in late August).

Irrigation of the experimental field in both moisture environments (normal and drought stress) was carried out uniformly and in the form of flooding until the end of the tillering stage for all varieties. Irrigation in the normal condition was conducted through flooding until one week before the harvest. In the drought stress condition, irrigation was stopped after the maximum tillering stage, marking the end of the vegetative stage and the beginning of the reproductive stage in mid-July, and continued until the physiological maturity stage.

Initial moisture content of rough rice was determined using the American Society of Agricultural Engineers Standard [20]. Initial moisture contents (d.b.) were 19.1, 18.5, 18.0, 18.9, 18.2, and 18.0 for Tarom-Ts, FR13A-Ts, KDML105-Ts, IR8-Sd, Jijing 88-Sd, and IR60-Sd, respectively. Samples (250 g) were dried (to 9% moisture, d.b.) at 40, 50, and 60 ˚C with three replications, at a constant inlet air speed of 4 m s^{-1}.

A laboratory fluidized bed dryer with capability of controlling temperature and input air to dryer chamber was used. In this dryer, Temperature controlling was done by electrical elements and a control circuit and adjustment of air speed was done with changing blower speed by frequency change system. Rice stripper machines with the SATAKE trademark (Model THU) were used. For milling the samples, a milling device with the BALDOR trademark was applied. Each sample was placed in the device for 45 seconds. To separate whole (head) rice from broken rice, a rotary sieve with the SATAKE trademark (Japan) was used.

2.3. Assessment of quality of dried rice

After milling, the amounts of brown rice, milled rice, head rice, and broken rice were measured, and the quality parameters were calculated as follows.

2.3.1. Degree of milling

degree of milling was evaluated using two complementary methods [21]: Optical degree of milling (Optical DoM): Optical degree of milling is an index of level of attraction of light reflection by white rice, and they are measured by milling meter. Optical DoM was measured using milling meter (C300 Model) made by KETT Company. Mass-based degree of milling (Mass DoM): This index was calculated by measuring the weight difference before and after milling. The proportion of mass removed during milling (primarily husk and bran) was used as an indirect indicator of the degree of milling. A higher Mass DoM corresponds to greater bran removal, reflecting a more polished grain.

2.3.2. Broken rice percentage

Broken rice percentage was calculated using Eq. 1 [13]:

$$\text{broken rice percentage} = \frac{\text{weight of broken rice}}{\text{milled rice}} \times 100 \quad (1)$$

2.3.3. Crack percentage

To measure the percentage of cracked kernels a crack detector device, designed and developed at the Iranian Rice Research Institute, was used. This device consists of a fluorescent lamp installed beneath a mesh screen. To calculate the initial cracking percentage before the drying process, three random samples of 100 grains from each rice genotype were selected. The outer husks of these grains were carefully removed by hand. The dehusked brown rice grains were then placed on the grooves of the crack detector device, and the cracked grains (those showing complete transverse cracks) were counted. This number was expressed as a percentage relative to the total number of grains. This initial cracking percentage represents the cracks caused by harvesting, threshing, transportation, or moisture stress. After each drying experiment, the crack percentage for each sample was measured again, and the pre-drying cracking value was subtracted to determine the cracks induced solely by the drying process [8].

2.3.4. Milling yield

Milling yield is calculated as the ratio of the total weight of milled rice (the sum of head rice and broken rice) to the initial weight of the paddy, multiplied by 100 [8].

2.3.5. Drying time

Drying time is the time required for rough rice to reach 9% moisture (d.b.).

2.4. Statistical analysis

Residuals were tested for normality (Kolmogorov–Smirnov) and variance homogeneity (Bartlett). Analysis of variance (ANOVA) was carried out with the GLM procedure in SAS 9.4 to assess variations due to environment, variety, and their interaction effects. Mean values of the treatments were compared using the least significant difference (LSD) test at a 5% probability level. Principal component analysis (PCA) was conducted using the correlation matrix, and the biplots were generated with statgraphics software version 17.2. The clustering of six rice genotypes evaluated under two irrigation treatments (normal and drought stress conditions) was performed using the deep fuzzy clustering (DFC) approach to better capture nonlinear relationships and overlapping group memberships among genotypes. In this method, each genotype x_i is assigned a degree of membership μ_{ij} to each cluster j, where $0 \leq \mu_{ij} \leq 1$ and $\sum_{j=1}^{c} \mu_{ij} = 1$. The DFC algorithm jointly optimizes a reconstruction loss and a fuzzy clustering loss in a latent feature space learned via deep neural networks [12, 22]. The total objective function is defined as Eq. 2 [23]:

$$J = \sum_{i=1}^{n} \left(\left\| x_i - \widehat{x}_i \right\|_2^2 \right) + \lambda \sum_{i=1}^{n} \sum_{j=1}^{c} \left(\mu_{ij} \right)^m \| z_i - v_j \|_2^2 \quad (2)$$

where $\widehat{x}_i$ is the reconstructed input, z_i is the latent embedding of x_i, $m > 1$ is the fuzzification coefficient (set to 2.0), v_j is the cluster centroid in latent space, and λ balances reconstruction and clustering fidelity. Feature representations are first extracted using a stacked autoencoder with nonlinear transformations, projecting the original trait data into a lower-dimensional latent space with improved cluster separability. Fuzzy membership values are then computed in this latent space using the updated rule Eq. 3 [23]:

$$\mu_{ij} = 1 / \sum_{k=1}^{c} \left(\frac{\| z_i - v_j \|}{\| z_i - v_k \|} \right)^{(2/(m-1))} \quad (3)$$

and cluster centroids are updated as Eq. 4 [23]:

$$v_j = \left(\sum_{i=1}^{n} \left(\mu_{ij} \right)^m z_i \right) / \left(\sum_{i=1}^{n} \left(\mu_{ij} \right)^m \right) \quad (4)$$

The model iterates until convergence of the joint objective J (change < 10^{-5}) or a maximum of 300 epochs. All computations and visualizations were performed in Python using deep clustering libraries, supplemented with customized scripts for parameter optimization and convergence control. A Python program was used to implement DFC (Fig. 1).

3.1. Analysis of variance

According to the analysis of variance (Table S1), irrigation treatments (normal and drought stress), drying temperature, and variety had significant effects on the evaluated postharvest traits. Drought stress significantly impacted Optical DoM, BRP, MY, CP, and DT. Drying temperature was significant at the 1% level for Optical DoM, MY, CP, and DT, and at the 5% level for Mass DoM and BRP. Varietal differences were significant at the 1% level for all traits. Significant interaction effects were also observed: irrigation and temperature for Optical DoM ($p < 0.05$), BRP ($p < 0.05$), MY ($p < 0.05$), CP ($p < 0.01$), and DT ($p < 0.05$); irrigation and variety for MY and CP ($p < 0.01$); temperature and variety for all traits ($p < 0.01$); and irrigation, temperature, and variety for Optical DoM ($p < 0.05$), MY ($p < 0.01$), and CP ($p < 0.01$). The coefficients of determination (R^2 = 0.77 to 0.96) and coefficients of variation (CV = 4.2 to 14.7%) supported the adequacy of the models and the reliability of the data.

3. Results and discussion

3.1. Analysis of variance

According to the analysis of variance (Table S1), irrigation treatments (normal and drought stress), drying temperature, and variety had significant effects on the evaluated postharvest traits. Drought stress significantly impacted Optical DoM, BRP, MY, CP, and DT. Drying temperature was significant at the 1% level for Optical DoM, MY, CP, and DT, and at the 5% level for Mass DoM and BRP. Varietal differences were significant at the 1% level for all traits. Significant interaction effects were also observed: irrigation and temperature for Optical DoM ($p < 0.05$), BRP ($p < 0.05$), MY ($p < 0.05$), CP ($p < 0.01$), and DT ($p < 0.05$); irrigation and variety for MY and CP ($p < 0.01$); temperature and variety for all traits ($p < 0.01$); and irrigation, temperature, and variety for Optical DoM ($p < 0.05$), MY ($p < 0.01$), and CP ($p < 0.01$). The coefficients of determination (R^2 = 0.77 to 0.96) and coefficients of variation (CV = 4.2 to 14.7%) supported the adequacy of the models and the reliability of the data.

3.2. Effects of drought stress on postharvest traits of rice

Table 2 shows that drought stress reduced both Optical DoM and Mass DoM, indicating less efficient bran removal and lower milling quality. Additionally, the BRP increased under drought stress compared to normal conditions, rising from 30.39% to 37.24%. Similarly, CP was higher under drought stress, likely due to drought-induced changes in kernel structure and moisture balance that increase sensitivity to mechanical stress [24]. Regarding MY, drought stress lowered milling yield from 69.07% to 66.92%, reducing marketable head rice for processors [25, 26]. Interestingly, DT was shorter under drought stress than in normal conditions, measuring 4.33 hours instead of 5.21 hours. This decrease may be explained by the lower initial grain moisture content in the drought-stressed plots and possible changes in the microstructural properties of the kernels, which eased moisture migration during drying [5]. Overall, drought stress significantly affected postharvest quality and processing traits. These changes, which include increased breakage and CP along with reduced MY, can hurt the marketability and economic value of rice.

Table 2
Means and se of postharvest traits in six varieties of rice under two irrigation treatments (normal and drought stress conditions).

Irrigation treatments	Optical DoM (%)	Mass DoM (%)	BRP (%)	MY (%)	CP (%)	DT (h)
Normal	29.39 ± 0.25^a	14.36 ± 0.13^a	30.39 ± 1.04^b	69.07 ± 0.20^a	13.32 ± 1.16^b	5.21 ± 0.17^a
Drought stress	25.96 ± 0.27^b	13.35 ± 0.20^b	37.24 ± 0.86^a	66.92 ± 0.26^b	17.60 ± 0.58^a	4.33 ± 0.18^b
$LSD_{0.05}$	0.26	0.65	3.12	0.35	0.13	0.24
In each column, means followed by a common letter are not significantly different according to the LSD test at an alpha level of *0.05*.						

3.3. Effect of drying temperature on postharvest traits of rice

Table 3 reveals the average values of postharvest traits in six rice varieties dried at 40, 50, and 60 ˚C. The drying temperature significantly affected most quality parameters. Raising the temperature from 40 to 60 ˚C greatly lowered the optical DoM, mass DoM, and MY. This indicates a drop in milling quality at higher drying temperatures. DT also dropped sharply with increasing temperature, from 6.65 h at 40 ˚C to just 3.25 h at 60 ˚C. This confirms the trade-off between faster drying and lower quality. Interestingly, both BRP and CP peaked at 50 ˚C (35.94% and 16.15%, respectively). In contrast, lower (40 ˚C) and higher (60 ˚C) temperatures led to much lower levels of BRP and CP. This trend suggests that intermediate drying temperatures might be especially harmful to kernel integrity. At 50 ˚C, the drying rate was fast enough to create moisture differences within the kernels but not so fast that it hardened the outer layers. This uneven moisture movement likely caused internal stress, making the grains more prone to damage during milling. At 40 ˚C, the slower and more even drying reduced internal stress buildup, while at 60 ˚C, the very quick drying decreased

kernel moisture and hardened the surface layers [27]. This may have offered some resistance to cracking, even though the overall milling quality was lower. Trait differences across drying temperatures also reflect genotype × environment interactions and a genetic basis for postharvest resilience. The variation in rice grain quality traits across different drying temperatures reflects strong genotype × environment interactions, highlighting the genetic basis of postharvest resilience [28–30]. Such approaches enable the development of rice varieties that sustain low BRP and CP values and high milling yield under high-temperature postharvest conditions, contributing to climate-resilient improvement of grain quality. Overall, these findings show that while higher drying temperatures significantly shorten DT, they negatively impact several postharvest quality traits. The noticeable damage at 50 ˚C highlights the importance of carefully optimizing drying conditions to find a balance between efficiency and product quality.

Table 3
Means of postharvest traits in six varieties of rice under three temperatures.

Temperature	Optical DoM (%)	Mass DoM (%)	BRP (%)	MY (%)	CP (%)	DT (h)
40 ˚C	29.52 ± 0.29[a]	13.95 ± 0.15a[b]	32.87 ± 1.26[b]	68.39 ± 0.30[a]	14.82 ± 0.69[b]	6.65 ± 0.17[a]
50 ˚C	27.64 ± 0.30[b]	14.12 ± 0.28[a]	35.94 ± 1.41[a]	68.01 ± 0.31[b]	16.15 ± 0.85[a]	4.41 ± 0.10[b]
60 ˚C	25.86 ± 0.41[c]	13.49 ± 0.20[b]	32.64 ± 0.98[b]	67.59 ± 0.32[c]	14.94 ± 1.61[b]	3.25 ± 0.15[c]
$LSD_{0.05}$	0.47	0.56	2.84	0.17	0.33	0.31
In each column, means followed by a common letter are not significantly different according to the LSD test at an alpha level of *0.05*.						

3.4. Interaction effects of drying temperatures and irrigation treatments on postharvest traits

Table 4 shows how the irrigation treatments and drying temperature levels affect the postharvest traits of six rice varieties. Under normal irrigation, the highest optical DoM (31.4%) and MY (69.4%) occurred at 40 ˚C. When the temperature rose to 60 ˚C, both values dropped significantly to 27.7% and 68.8%. Under drought stress, optical DoM and MY were even lower across all temperatures, with the lowest values recorded at 60 ˚C (24.0% and 66.4%). BRP rose significantly under drought stress, reaching a peak of 38.2% at 50 ˚C, compared to 28.2% at 40 ˚C under normal irrigation. Similarly, CP was much higher under drought stress, especially at 50 ˚C (19.6%) and 60 ˚C (17.8%). In contrast, under normal irrigation, CP remained relatively lower. These results suggest that the combination of drought stress and higher drying temperature increases kernel damage, which reduces overall grain quality. DT was longest at 40 ˚C (6.81 h in normal conditions and 6.49 h under drought stress) and decreased significantly as the temperature rose. The shortest DT (2.66 h) happened under drought stress at 60 ˚C, but this coincided with the lowest quality metrics. This trade-off between quicker drying and poorer milling quality highlights the need to improve drying methods. These findings are in line with previous studies that showed grain quality worsens at high drying temperatures. For example, the review by Müller et al. (2022) states that controlling the drying-air temperature between 40 ˚C and 60 ˚C, based on rice variety, can affect quality results [15]. Likewise, Martens et al. (2023) found that faster drying can increase physical damage and crack formation in polished rice [31]. Mechanistically, under drought stress, the grain's structural integrity may weaken, making it more vulnerable to damage from heat. Higher drying temperatures can create sharp moisture differences inside the kernels, leading to internal stresses and microfractures. This idea fits broader drying theories where quick moisture removal encourages crack formation [31]. Overall, the patterns in Table 4 highlight that moderate drying temperatures (for example, 40–50°C) under non-stress conditions may best balance drying efficiency and quality maintenance. High drying temperatures during drought stress seem to increase damage, suggesting that optimal drying should take both water status in the field and the drying method into account. Overall, the combined influence of drought stress and drying temperature reflects genotype-dependent differences in kernel integrity under stress [26].

Table 4
Interaction of means of postharvest traits in six varieties of rice in three temperatures and two irrigation treatments.

Irrigation treatments	Temperature	Optical DoM (%)	BRP (%)	MY (%)	CP (%)	DT (h)
Normal	40 ˚C	31.4 ± 0.37^{a}	28.2 ± 1.87^{c}	69.4 ± 0.42^{a}	14.2 ± 1.93^{d}	6.81 ± 0.34^{a}
	50 ˚C	29.1 ± 0.43^{b}	33.7 ± 3.11^{b}	69.1 ± 0.45^{b}	13.7 ± 1.74^{e}	4.97 ± 0.16^{b}
	60 ˚C	27.7 ± 0.44^{c}	29.3 ± 1.86^{c}	68.8 ± 0.51^{c}	12.1 ± 1.30^{f}	3.84 ± 0.32^{c}
Drought stress	40 ˚C	27.6 ± 0.22^{c}	37.5 ± 2.20^{a}	67.4 ± 0.40^{d}	15.5 ± 1.12^{c}	6.49 ± 0.32^{a}
	50 ˚C	26.2 ± 0.44^{d}	38.2 ± 2.38^{a}	67.0 ± 0.55^{e}	19.6 ± 1.37^{a}	3.84 ± 0.14^{c}
	60 ˚C	24.0 ± 0.62^{e}	36.0 ± 1.19^{ab}	66.4 ± 0.56^{f}	17.8 ± 1.13^{b}	2.66 ± 0.21^{d}
$LSD_{0.05}$		0.35	3.07	0.24	0.38	0.53

In each column, means followed by a common letter are not significantly different according to the LSD test at an alpha level of *0.05*.

3.5. Interaction of variety and irrigation regime on postharvest rice quality

In Table 5, The results indicate that both the irrigation treatments and rice variety had significant impacts on milling quality, breakage, and drying characteristics. The observed variation in genotype responses under drought stress reflects the combined influence of genetic differences, environmental conditions, and genotype×environment interactions, which together shape the expression of drought tolerance and grain quality traits [32–34].

Under normal irrigation, KDML105-Ts (31.4%) and IR60-Sd (30.2%) had the highest optical DoM, while IR8-Sd had the lowest at 26.3%. Drought stress significantly lowered the optical DoM for all varieties, especially IR8-Sd (22.8%) and Tarom-Ts (25.7%). This reduction under drought stress is due to incomplete grain filling and increased chalkiness. These factors lead to an uneven endosperm structure and reduced translucency of the kernels during polishing [35]. Mass DoM followed a similar trend, with reductions under stress from 15.9% (KDML105-Ts) to 12.6% (Jijing 88-Sd). Previous studies have thoroughly documented the impact of drought stress on yield, chalkiness, and physical and chemical traits of rice grains [15, 36]. However, to our knowledge, no earlier research has specifically looked at how pre-harvest water deficit affects the DOM after drying and polishing. The current findings provide new evidence that drought stress not only influences yield and chemical composition but also affects postharvest milling appearance traits.

Both the variety and the drought stress had an impact on the BRP. Under water deficit, BRP rose for all varieties, though the amount of increase varied. The highest sensitivity was demonstrated by IR8-Sd, whose BRP increased from 42.8% during regular irrigation to 50.5% during drought. The Tarom-Ts and FR13A-Ts stayed more stable, showing increases of 3% to 5%, but IR60-Sd and Jijing 88-Sd also displayed significant increases. These results imply that internal stress gradients within the grain are increased by drought stress. This causes more cracking and breakage during drying and milling, as does an uneven distribution of moisture [37].

The variation between varieties shows genetic differences in tolerance, with sensitive varieties like IR8-Sd being more vulnerable to postharvest damage and stress-tolerant genotypes like FR13A-Ts maintaining kernel integrity more successfully. These findings are consistent with previous studies showing the influence of cultivar and genetics on fracture percentage [38]. These findings demonstrate how crucial it is to choose stress-resistant genotypes along with efficient drying techniques in order to reduce BRP and raise total milling yield in climate-stressed environments. Also, these genotype-specific responses highlight the importance of genetic variation in tolerance to combined pre- and postharvest stresses.

Table 5
Means and se of postharvest traits in six varieties of rice subjected to three temperatures (40, 50, and 60 ˚C) under two irrigation levels (normal and drought stress).

Variety	Optical DoM (%)		Mass DoM (%)		BRP (%)		MY (%)		CP (%)		DT (h)	
	Normal	Drought stress	Normal	Drought stress	Normal	Drought stress	Normal	Drought stress	Normal	Drought stress	Normal	Drought stress
Tarom-Ts	29.6 ± 0.56a	25.7 ± 0.43b	14.4 ± 0.04a	12.8 ± 0.02b	35.7 ± 0.44a	38.7 ± 0.38a	67.9 ± 0.29a	65.9 ± 0.14b	9.66 ± 0.06b	17.9 ± 0.11a	5.20 ± 0.05a	3.67 ± 0.02a
FR13A-Ts	28.8 ± 0.18a	25.7 ± 0.19b	13.0 ± 0.16a	12.9 ± 0.19a	16.5 ± 0.15b	25.7 ± 0.28a	69.5 ± 0.13a	66.5 ± 0.11b	4.00 ± 0.07b	10.4 ± 0.16a	4.77 ± 0.07a	4.36 ± 0.10b
KDML105-Ts	31.4 ± 0.10a	28.0 ± 0.26b	15.9 ± 0.19a	15.1 ± 0.26b	32.8 ± 0.53b	37.9 ± 0.76a	68.6 ± 0.11a	66.6 ± 0.22b	15.5 ± 0.58b	18.6 ± 0.12a	5.94 ± 0.16a	5.14 ± 0.23b
IR8-Sd	26.3 ± 0.38a	22.8 ± 0.33b	14.2 ± 0.39a	13.7 ± 0.24a	42.8 ± 0.95a	50.5 ± 3.00a	72.8 ± 0.03a	71.2 ± 0.70a	25.2 ± 0.06a	25.8 ± 0.03a	5.02 ± 0.27a	4.10 ± 0.56b
IR60-Sd	30.2 ± 0.02ba	26.6 ± 0.03b	14.4 ± 0.06a	13.0 ± 0.04b	26.2 ± 0.26b	34.3 ± 0.34a	68.9 ± 0.13a	66.4 ± 0.20b	9.70 ± 0.05b	14.1 ± 0.03a	5.25 ± 0.04a	4.37 ± 0.10b
Jijing 88-Sd	30.0 ± 0.22a	27.0 ± 0.17b	14.3 ± 0.07a	12.6 ± 0.06b	28.3 ± 0.67b	36.3 ± 0.56a	66.7 ± 0.04a	65.0 ± 0.09b	15.8 ± 0.05b	18.8 ± 0.08a	5.08 ± 0.03a	4.38 ± 0.06b
$LSD_{0.05}$	0.55	0.77	0.53	0.81	5.10	3.36	0.25	0.41	0.31	0.36	1.15	0.84

In each row (among two irrigation treatments) means followed by a common letter are not significantly different according to the LSD test at an alpha level of *0.05*.

In each column, If the difference between the means is greater than the $LSD_{0.05}$, then the means are significantly different.

Under normal irrigation, IR8-Sd had the highest MY at 72.8%, with FR13A-Ts following at 69.5%. Although drought stress diminished MY in most varieties, IR8-Sd and KDML105-Ts maintained relatively stable yields (71.2% and 66.6%, respectively). This stability may be linked to their stronger hull and endosperm structures, which protect the kernels during dehusking and milling. In contrast, Tarom-Ts experienced a sharp drop (67.9% to 65.9%), showing its greater vulnerability to stress-induced quality loss. These results align with findings from Müller et al. (2022), who noted that differences in kernel hardness and chalkiness significantly affect MY retention under stress [15]. This variation can be leveraged to develop genotypes that maintain higher MY and lower BRP under drought and higher drying temperatures.

CP also differed among varieties across irrigation treatments. Tarom-Ts had the largest increase, rising from 9.66% under normal irrigation to 17.9% under drought stress. Similarly, FR13A-Ts increased from 4.00% to 10.4%, and Jijing 88-Sd went from 15.8% to 18.8%. In contrast, IR8-Sd showed only a small rise, from 25.2% to 25.8%, indicating a more stable response. These findings suggest that drought stress increases the vulnerability of kernels to cracking during drying and milling. This primarily happens by intensifying internal moisture differences and weakening the starch-protein matrix of the endosperm. Deng et al. (2021) reported that rice lines with stronger grain structure and less chalkiness are less likely to crack, which matches the results for IR8-Sd [37]. Additionally, Shi et al. (2022) noted that genotyps with a more stable starch multi-layer structure had fewer cracks under postharvest stress conditions [39]. Together, these results highlight the importance of varietal resistance in lowering crack percentage and stress the need to choose stress-tolerant genotypes such as IR8-Sd to reduce quality losses during drought.

DT was consistently shorter under drought stress, likely due to lower initial moisture content and faster drying kinetics. Similar results have been found in rice drying studies. Li et al. (2023) reported that grains with lower initial moisture and higher porosity showed faster moisture removal rates [40]. In another study, Zhou et al. (2018) demonstrated that pre-harvest water deficit reduced drying time in cereals due to structural changes in grain tissues that help moisture diffusion [41].

Together, when comparing the varieties, IR8-Sd showed better resilience, maintaining high MY and steady CP under drought stress, making it potentially more suitable for growth in water-limited areas. Conversely, FR13A-Ts and Tarom-Ts were the most sensitive, showing significant increases in CP and marked decreases in DoM and MY. Modern varieties like IR60-Sd and Jijing 88-Sd performed moderately, indicating that genetic background plays a significant role in postharvest quality under stress. These results highlight the importance of variety selection in reducing postharvest quality losses during water shortages. Therefore, combining stress-resistant varieties like IR8-Sd with moderate drying temperatures (40–50 ˚C) may be the best approach to balance drying efficiency and grain quality.

3.6. Correlation analysis of postharvest traits under normal and drought stress condition

Table 6 presents the correlation coefficients among postharvest traits in six rice varieties at three drying temperatures (40, 50, and 60 ˚C) under both normal irrigation and drought stress. These correlations provide insights into how grain quality parameters co-vary under different environmental and processing conditions. The results presented in Table 6 revealed that the relationships among some traits were not affected by irrigation treatments (normal and drought stress) or postharvest processes (drying at 40, 50, and 60°C). Under both irrigation regimes and across all

temperature levels, the correlation between Optical DoM and MY was consistently negative, whereas that between BRP and CP remained positive. Moreover, under drought stress, the relationship between DT and Optical DoM was positive and significant at all three temperature levels. The stability of correlations among certain traits under different moisture and thermal conditions might suggest the presence of stable genetic and physiological control over these relationships. When similar metabolic or genetic pathways influence two traits, environmental variations such as reduced humidity or elevated temperature may alter their mean values but tend to preserve their co-directional patterns of change; consequently, their correlation coefficients remain relatively constant. For instance, the persistent negative correlation between Optical DoM and MY, and the positive correlation between BRP and CP, indicate that these relationships are intrinsic, physiologically based, and largely independent of environmental influences. Overall, it can be concluded that environmental factors primarily affect the absolute levels of traits while exerting limited influence on the structure of inter-trait relationships. This stability may reflect underlying genetic correlations and the efficiency of shared regulatory mechanisms operating under variable environmental conditions [42, 43].

Table 6
Correlation coefficients among postharvest traits in six varieties of rice in temperatures (40, 50 and 60 ˚C) and under normal and drought stress conditions.

Temperatures 40 ˚C and under normal condition (above diagonal) and drought stress condition (below diagonal)						
Traits	Optical DoM	Mass DoM	BRP	MY	CP	DT
Optical DoM	1	0.22^{ns}	-0.42^{ns}	-0.80^{**}	-0.49^{*}	0.64^{**}
Mass DoM	-0.76^{**}	1	0.70^{**}	-0.21^{ns}	0.39^{ns}	0.12^{ns}
BRP	-0.73^{**}	0.72^{**}	1	0.25^{ns}	0.71^{**}	-0.16^{ns}
MY	-0.86^{**}	0.73^{**}	0.52^{*}	1	0.35^{ns}	-0.37^{ns}
CP	-0.47^{*}	0.48^{*}	0.91^{**}	0.24^{ns}	1	0.04^{ns}
DT	0.54^{*}	-0.65^{**}	-0.48^{*}	-0.50^{*}	-0.19^{ns}	1
Temperatures 50 ˚C and under normal condition (above diagonal) and drought stress condition (below diagonal)						
Optical DoM	1	0.44^{ns}	-0.14^{ns}	-0.77^{**}	-0.30^{ns}	0.50^{*}
Mass DoM	0.17^{ns}	1	0.76^{**}	-0.01^{ns}	0.41^{ns}	-0.03^{ns}
BRP	-0.34^{ns}	0.58^{*}	1	0.48^{*}	0.80^{**}	-0.36^{ns}
MY	-0.58^{*}	0.37^{ns}	0.72^{**}	1	0.58^{*}	-0.33^{ns}
CP	-0.44^{ns}	0.30^{ns}	0.88^{**}	0.77^{**}	1	-0.31^{ns}
DT	0.76^{**}	0.24^{ns}	-0.22^{ns}	-0.18^{ns}	-0.19^{ns}	1
Temperatures 60 ˚C and under normal condition (above diagonal) and drought stress condition (below diagonal)						
Optical DoM	1	0.72^{**}	-0.29^{ns}	-0.71^{**}	-0.60^{**}	-0.48^{*}
Mass DoM	0.69^{**}	1	0.09^{ns}	-0.33^{ns}	-0.08^{ns}	-0.07^{ns}
BRP	-0.57^{**}	-0.62^{**}	1	0.25^{ns}	0.65^{**}	0.86^{**}
MY	-0.68^{**}	-0.42^{ns}	0.47^{ns}	1	0.55^{**}	0.33^{ns}
CP	-0.58^{*}	-0.57^{*}	0.94^{**}	0.53^{**}	1	0.61^{**}
DT	0.65^{**}	-0.37^{ns}	0.53^{*}	0.66^{**}	0.66^{**}	1
*: Significant at the *0.05* probability level, **: Significant at the *0.01* probability level, ns: non-significant						

At 40°C and normal irrigation, Optical DoM had a strong negative correlation with MY (r = -0.80). This suggests that a better polishing appearance often results in lower milling recovery. However, under drought stress, Optical DoM showed a significant positive correlation with DT (r = 0.54), indicating that grains needing longer drying tended to maintain a better visual appearance after polishing. Also, Mass DoM was positively correlated with BRP (r = 0.70) at this temperature. At 50 ˚C, Optical DoM continued to have a strong negative correlation with MY (r = -0.77), while BRP was highly correlated with CP (r = 0.88). These results show that cracking and breakage have similar physiological and structural roots during drying and milling. At 60°C, stronger connections appeared. Optical DoM had a negative correlation with MY (r = -0.71), and BRP showed a very strong correlation with CP (r = 0.94).

These findings emphasize how high drying temperatures and drought can worsen kernel damage and lower overall milling quality. Overall, the correlations show several important trends: 1) Trade-off between appearance and yield. The consistent negative correlation between Optical DoM and MY across temperatures shows that better surface translucency often comes at the expense of milling yield, 2) Link between breakage and cracking. The strong positive correlation between BRP and CP, especially at 50 and 60°C, indicates that kernels prone to cracking are also more likely to break during milling, 3) Stress-dependent relationships. Under drought stress, some correlations shifted direction. For instance, at 40°C, Optical DoM and DT were positively correlated. This may reflect those grains with greater moisture differences required longer drying, leading to a better polishing appearance and, 4(Non-significant correlations. Several associations were non-significant (ns), showing that relationships among traits are not general but strongly depend on environmental conditions, genetic background, and processing temperature. These results support studies that have shown the interactive effects of variety, drying temperature, and water availability on milling quality and physical traits of rice [27, 37, 44]. They highlight the need to choose stress-tolerant varieties and use moderate drying temperatures to reduce kernel damage while keeping grain appearance appealing to consumers.

3.7. Principal component analysis of postharvest quality traits

PCA biplots of six postharvest quality traits (Optical DoM, Mass DoM, BRP, MY, CP, and DT) for six genotypes of rice at three drying temperatures (40, 50, and 60°C) and two irrigation treatments (normal and drought stress) are displayed in Fig. 2. The PCA results showed that PC1 and PC2 were able to describe more than 75% of the genetic variation in all irrigation and temperature conditions, making it easy to see how traits and genotypes co-vary across irrigation and temperature regimes.

Overall, the PCA summarizes and confirms patterns already visible in the mean and correlation tables. In particular, genotype positions and trait loadings in the biplots correspond closely to the variety means in Table 5 (e.g., IR8-Sd's relatively high MY and stable CP) and to the trait interrelationships reported in Table 6 (e.g., strong negative associations between Optical DoM and MY in several temperature × irrigation combinations). The ANOVA (Table S1) demonstrated that irrigation, temperature and variety (and several interactions) significantly affected postharvest traits, which justifies the strong genotype × environment structure observed in the PCA plots.

Under normal irrigation at 40°C (Fig. 2a), PC1 clearly distinguished varieties with better appearance quality (Optical and Mass DoM) from those more likely to sustain mechanical damage (BRP and CP). KDML105-Ts and IR60-Sd were located close to the DoM vectors, matching their higher polishing quality listed in Table 5. In contrast, Tarom-Ts and FR13A-Ts grouped near BRP and CP, indicating a higher risk of fractures. This pattern agrees with correlation analysis (Table 6), where Optical DoM and MY were negatively related. This confirms that better endosperm integrity and less chalkiness help improve milling recovery. These findings align with earlier studies that indicated grain translucency and hardness are crucial for achieving high-quality milling results [45]. When drought stress was applied at the same temperature (Fig. 2d), the PCA showed a change in the trait space. BRP and CP vectors moved further away from DoM and MY, suggesting that even slight drying conditions could not lessen drought-related kernel damage. The increased impact of BRP and CP on the total variance matched higher average values of these traits under drought in Table 5 and the significant irrigation × temperature interaction in Table S1. Similar findings were noted by Mondal et al. (2025) and Deng et al. (2021) [37, 46]. They showed that pre-harvest drought stress increases grain chalkiness, weakens kernel structure, and results in more CP and BRP during drying.

BRP and CP vectors became more prevalent, especially during drought, as the drying temperature rose to 50°C (Figs. 2b and e). Genotypes like IR60-Sd and Jijing 88-Sd moved closer to these vectors, suggesting a relationship between moderate heat stress and pre-harvest water deficit. The combined sensitivity of starch-protein matrices to heat and moisture gradients is reflected in this trend. Khodadadi et al. (2017) and Bruce et al. (2023) also noted that increased drying intensity lowers milling yield by accelerating internal stresses and fissure formation [8, 47].

At 60°C (Figs. 2c and f), especially under drought stress condition (Fig. 2f), the PCA pattern changed sharply: BRP, CP, and DT dominated PC1, while DoM became a minor contributor. This shift indicates that under high-temperature and low-moisture regimes, the drying behavior and mechanical damage traits explain most of the variation among genotypes. These findings are consistent with Tables 3–5, where MY declined and BRP increased with temperature, and with the significant temperature and interaction effects shown in Table S1. Similar high-temperature effects on CP and MY reduction were reported by Chitsuthipakorn and Thanapornpoonpong (2022) and Odek et al., (2021), who emphasized that rapid moisture removal at high temperatures creates steep moisture gradients that cause structural stress and cracking [48, 49].

The PCA verified that genotypes varied significantly in their postharvest resilience across all treatments (Figs. 3a-f). Under normal and drought stress conditions, IR8-Sd continuously plotted close to the MY vector, retaining low CP and high milling yield, demonstrating its strong structural robustness and resistance to heat stress. For structurally robust cultivars with dense endosperm and low chalkiness, this behavior is similar to that reported by Wu et al. (2021) [50]. Conversely, under stress, Jijing 88-Sd and IR60-Sd showed larger positional shifts toward BRP and CP, indicating their vulnerability to fissuring. Variations in endosperm microstructure and starch composition have also been linked to this genotype-dependent variability [51].

In conclusion, the relationships seen in Tables 3–6 and Table S1 are amply demonstrated and validated by the PCA biplots. The overall postharvest quality profile gradually changed from traits linked to grain appearance (DoM) to those linked to structural damage (BRP, CP, DT) as the drying temperature and pre-harvest drought intensity increased. This shift emphasizes how mechanical fragility brought on by stress is increasingly taking precedence over optical quality characteristics. Together, these results highlight the significance of combining genetic and processing techniques:

choosing drought-tolerant and structurally robust cultivars, like IR8-Sd, and keeping drying temperatures between 40 and 50°C can effectively balance drying efficiency and milling quality while reducing breakage and fissuring losses in water-limited environments.

3.8. Cluster analysis of rice genotypes under irrigation treatments

Figure 3 presents DFC results for the six genotypes under normal and drought stress, showing how genotypes cluster based on postharvest traits, with fuzzy membership across groups. Cluster robustness was validated using six internal indices (FPC, RMSE, silhouette, D-B, Dunn, and partition entropy). Jin et al. (2025) were able to cluster a large rice germplasm into different clusters based on salt stress tolerance, using a combination of correlation analysis, PCA, and fuzzy method [52].

Under normal condition, the results indicated that the optimal organization of the genotypes was achieved with four distinct clusters (K = 4). This conclusion was supported by the convergent evidence from the validity indices; specifically, the configurations for K = 4 simultaneously minimized five of the six indices FPC, RMSE, silhouette, D-B index, and partition entropy while uniquely maximizing the Dunn index. The concurrent optimization of these metrics confirms that a four-cluster solution provides the most compact, well-separated, and internally valid grouping of the rice genotypes based on the studied traits. DFC identified the genotypes into three distinct groups. The first group consisted solely of IR8-Sd. The second group contained FR13A-Ts. The third and most diverse group comprised three genotypes from the two tall-stature and semi-dwarf, including Tarom-Ts, IR60-Sd, and Jijing 88-Sd, indicating a cluster with shared characteristics (Fig. 3).

Fuzzy deep clustering analysis effectively categorized the genotypes under drought stress, with the most robust grouping emerging at three clusters (K = 3). This optimal number was determined through a consensus of validation metrics. The K = 3 model demonstrated superior performance by minimizing five main indices, including FPC, RMSE, silhouette, D-B index, and partition entropy, while concurrently maximizing the Dunn index, indicating well-separated, compact, and distinct clusters. Genotypes such as IR8-Sd under drought largely fall into clusters characterized by higher MY and lower damage traits, indicating that this genotype maintains quality more stably even under stress. Other genotypes, e.g., Jijing 88-Sd and IR60-Sd, move toward clusters with higher BRP and CP under drought- evidence of greater sensitivity to environmental stress, which agrees with clustering studies in rice germplasm diversity under drought [52].

These DFC patterns are consistent with earlier clustering studies that separated rice genotypes into tolerant vs susceptible under groups [53, 54]. These studies reinforce the clustering separation seen in our results: under drought stress, genotypes diverge clearly in damage-vs-quality trait space, supporting our grouping of IR8-Sd, Jijing 88-Sd, IR60-Sd, etc., according to their response profiles. Practically, the clustering results suggest that under drought stress, rice genotypes can be clearly stratified based on their overall profile of damage, milling yield, and drying behavior. These clusters are useful for breeders to select genotypes with stable performance under stress e.g., choosing those that remain in low-damage/high MY clusters under drought.

Overall, the combined effects of pre-harvest drought stress and post-harvest drying temperature on milling quality were strongly genotype-dependent. By integrating multivariate statistics with deep fuzzy clustering, we clarify trade-offs between drying efficiency and kernel integrity under combined drought and thermal stress, supporting genotype-specific post-harvest strategies.

Conclusions

This work is the first to provide an integrated, genotype-level assessment of how pre-harvest drought stress and post-harvest drying temperature jointly shape rice milling quality and drying performance. Pre-harvest drought consistently degraded milling appearance (optical and mass DoM), increased BRP and CP, and-because of lower initial kernel moisture-reduced drying time; however, reduced DT under drought did not translate to preserved milling quality. High drying temperatures shorten the drying period but often at the expense of grain quality. For most genotypes, maintaining temperatures between 40 and 50°C provides a workable trade-off between efficiency and quality retention. Interestingly, drying at 50°C produced the greatest levels of grain breakage and cracking, suggesting that rice kernels respond irregularly to mid-range heat stress. The multivariate analyses (PCA and DFC) echoed these results, distinguishing genotypes by their drying responses. Also, the tall or short type of rice plant, including tall-stature and semi-dwarf, had no effect on postharvest traits. Among them, IR8-Sd performed consistently well, showing stable milling yield and limited cracking, whereas IR60-Sd and Jijing 88-Sd appeared more vulnerable to thermal stress during drying. Reducing postharvest losses in water-limited production systems practically necessitates an integrated approach: (1) give preference to endosperm-robust and drought-tolerant genotypes when choosing genotypes and breeding, and (2) adjust drying protocols to initial moisture-favoring moderate temperatures and controlled drying rates rather than consistent high-temperature schedules. In order to inform adoption at scale, future research should (a) broaden genotype panels to identify genetic determinants of fissure resistance (e.g., starch composition, Wx alleles), (b) assess tempering/intermittent drying techniques in fluidized systems, and (c) quantify economic trade-offs (energy, throughput vs. head-rice recovery). In general, the best way to protect milling quality as the risk of climatic drought increases is through coordinated genetic and processing interventions.

Glossary

ANOVA	Analysis of variance
BRP	Broken rice percentage
CP	Crack percentage
DFC	Deep fuzzy clustering
DT	Drying time
FC	Field capacity
LSD	Least significant difference
Mass DoM	Mass-based degree of milling
MY	Milling yield
Optical DoM	Optical degree of milling
PCA	Principal component analysis

Declarations

Authorship contribution statement

Gulnoza Djakhangirova: Conceptualization, Methodology, Supervision, Writing – review & editing. **Djabborov Baxtiyor:** Investigation, Validation, Data curation, Writing – original draft. **Mohsen Shokouhifard:** Formal analysis, Software, Visualization, Correspondence, Writing – review & editing. **Sherzod Rakhimov:** Resources, Investigation, Methodology. **Kurbonalijon Zokirov:** Data curation, Validation, Investigation. **Gulnihol Sharipova:** Methodology, Validation, Review. **Nasiba Ibragimova:** Investigation, Data curation, Writing – original draft. **Nadira Alimova:** Formal analysis, Editing, Project administration.

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Competing interests

The authors declare no competing interests.

Data Availability

The datasets used or analyzed during the current study available from the corresponding author on reasonable request. Data access is restricted to research and educational applications.

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Figures

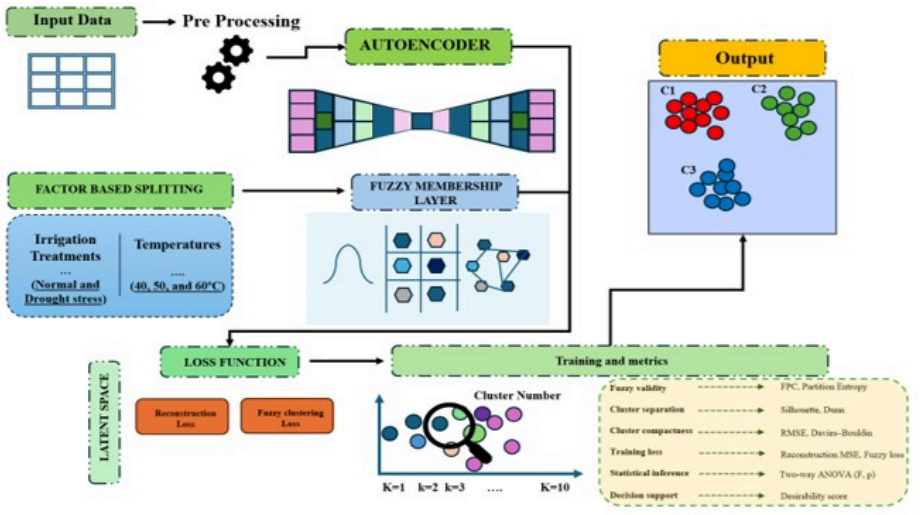


Figure 1

Overview of the deep fuzzy clustering (DFC) framework used in this study. Schematic overview of the DFC framework applied in this study under irrigation treatments (normal and drought stress), showing factor-based data splitting, autoencoder-based latent representation learning, fuzzy clustering with joint optimization, cluster validation via K-sweep indices, and final genotype clustering and ranking outputs.

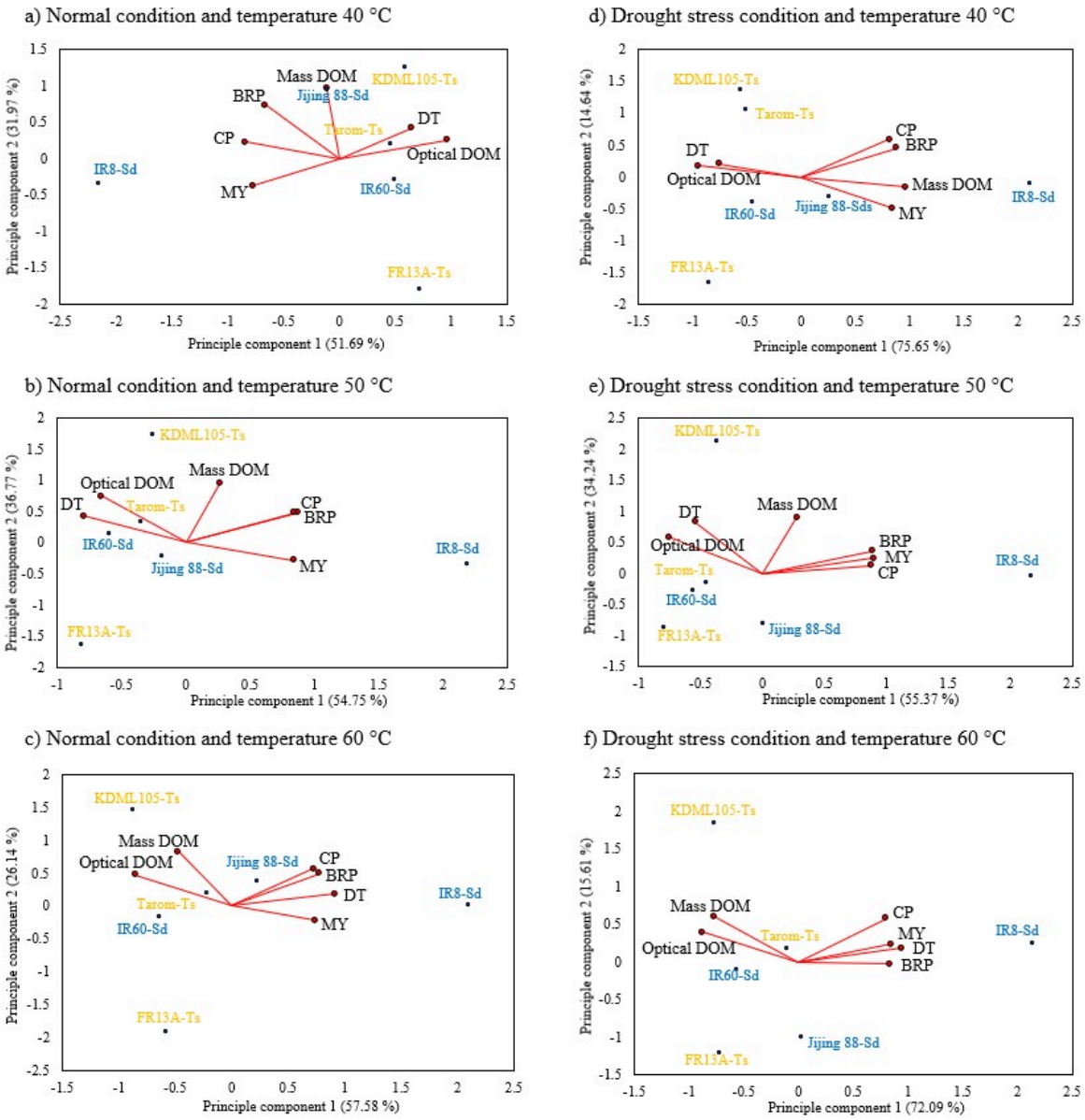


Figure 2

PCA biplots showing trait–genotype relationships across irrigation and temperature conditions. The biplot of principle component analysis (PCA) showing relationships among traits and 6 genotypes of rice in three temperatures (40, 50 and 60 °C) and under two irrigation treatments (normal and drought stress conditions). a: normal condition and temperature 40 °C, b: normal condition and temperature 50 °C, c: normal condition and temperature 60 °C, d: drought stress condition and temperature 40 °C, e: drought stress condition and temperature 50 °C, and f: drought stress condition vs temperature 60 °C. The origin of the varieties is listed in Table S1.

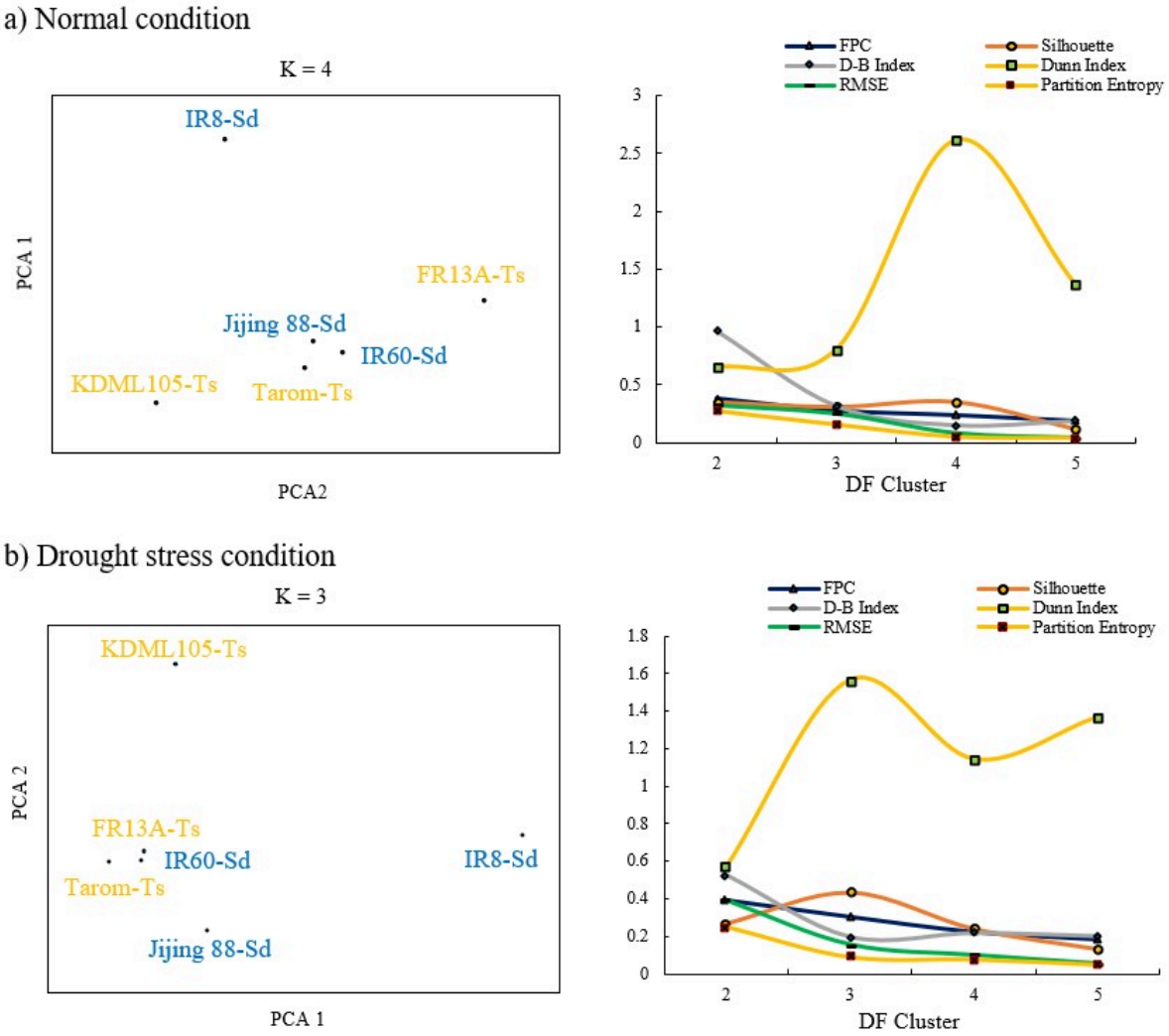


Figure 3

Deep fuzzy clustering reveals genotype grouping and fuzzy membership patterns under contrasting irrigation conditions. (a) Clustering results of six rice genotypes under normal irrigation conditions, showing genotype distribution and fuzzy membership across clusters. (b) Clustering results of the same genotypes under drought stress conditions, illustrating changes in cluster structure and stress-dependent membership patterns.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- supplementarymaterials.pdf