Evaluation of drought-tolerant rice (*Oryza sativa* L.) genotypes under drought and irrigated conditions in Bhairahawa, Nepal

Evaluación de genotipos de arroz (*Oryza sativa* L.) tolerantes a la sequía en condiciones de sequía y riego en Bhairahawa, Nepal

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ABSTRACT

Rice production can be severely affected by drought stress and this could cause massive economic losses every year. Global climate change is steadily becoming an important issue. This research was conducted in order to identify drought-tolerant rice genotypes using stress tolerance indices. Employing a randomized complete block design, a total of nine rice genotypes were assessed under irrigated and drought-stress conditions from June to November 2022 at the Institute of Agriculture and Animal Science (IAAS), Paklihawa, Nepal. In particular, the stress susceptibility index (SSI), mean productivity (MP), and geometric mean productivity (GMP) revealed strong and highly significant positive correlations to agricultural yields under both irrigated and drought stress conditions. The stress tolerance index (STI) and yield stability index (YSI) showed strong and highly significant positive correlations to yield under drought conditions, while the tolerance index (TOL) and yield index (YI) showed strong and negative significant associations to yield under stress conditions. The highest STI, GMP, and MP were observed in the IR16L1713 genotype followed by IR17L1387, establishing these two as the steadiest and most efficient genotypes among nine genotypes of rice. These genotypes have the potential to be selected for maximum outputs under both irrigated and drought-stress situations. A biplot analysis showed a positive association of MP, GMP, and YI to rice yields in an irrigated environment and a negative correlation of SSI, STI, and TOL, with a reduction percentage in a drought-stressed environment. Therefore, these stress indicators can be used to evaluate rice genotypes under both normal and drought stress settings.

Key words: drought stress, stress tolerance indices, yield, stability.

RESUMEN

La producción de arroz podría verse gravemente afectada por el estrés provocado por la sequía, lo que podría causar enormes pérdidas económicas cada año. El problema del cambio climático global se está convirtiendo cada vez más en una cuestión importante. Esta investigación se llevó a cabo con el fin de identificar los genotipos de arroz tolerantes a la sequía utilizando índices de tolerancia al estrés. Empleando un diseño de bloques completos aleatorizados, se evaluaron un total de nueve genotipos de arroz en condiciones de riego y estrés por sequía de junio a noviembre de 2022 en el Instituto de Agricultura y Ciencia Animal (IAAS), Paklihawa, Nepal. En particular, el índice de susceptibilidad al estrés (ISE), la productividad media (PM) y la productividad media geométrica (PMG) revelaron correlaciones positivas fuertes y altamente significativas con el rendimiento tanto en condiciones de riego como de estrés por sequía. Asimismo, el índice de tolerancia al estrés (ITS) y el índice de estabilidad del rendimiento (IER) mostraron correlaciones positivas fuertes y altamente significativas con el rendimiento en condiciones de sequía, mientras que el índice de tolerancia (TOL) y el índice de rendimiento (IR) mostraron asociaciones significativas fuertes y negativas con el rendimiento en condiciones de estrés. Los mayores ITS, PMG y PM se observaron en IR16L1713, seguido por IR17L1387, estableciéndolos como los genotipos más estables y eficientes entre nueve genotipos de arroz. Estos genotipos tienen el potencial de ser seleccionados para una producción abundante tanto en condiciones de riego como de estrés por sequía. Un análisis biplot mostró una asociación positiva de PM, PMG e IR con el rendimiento en un ambiente irrigado y una correlación negativa de ISE, ITS y TOL con reducciones en el porcentaje en un ambiente de estrés por sequía. Por lo tanto, estos indicadores de estrés se pueden utilizar para evaluar genotipos de arroz tanto en condiciones normales como de estrés por sequía.

Palabras clave: estrés por sequía, índices de tolerancia al estrés, rendimiento, estabilidad.

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Introduction

Rice (*Oryza sativa* L.) is the world's second most important crop after wheat; it belongs to the Poaceae family and feeds over half of the world's total population (Fukagawa & Ziska, 2019). It represents 18.6% of cereal output and 11.14% of worldwide cereal commerce (FAO, 2020). Worldwide it was cultivated on 165.25 million ha in 2021, yielding 502.98 million t with a productivity of 3.04 metric t ha^{-1} (Statista, 2023). Global rice production was expected to reach 515 million t by 2022. This corresponds to a 0.23% rise in world output compared to the previous year (Rice, 2023). The area, productivity, and output of rice in Nepal are 1.48 million ha, 3.46 t ha^{-1}, and 5.13 million t, respectively. Rainfed rice farming accounts for 57% of the acreage utilized for rice agriculture in Nepal (MOALD, 2021). Despite the addition of 4,000 ha for rice cultivation, the total amount of rice produced dropped from 5.55 million t in 2020 to 5.13 million t in 2021, an 8.74% decrease in output (MOALD, 2021). Drought-prone zones are estimated to cover 0.8 million ha of agricultural land (MoAD, 2015/16). The current output is insufficient to fulfill the demands of the rising population and assure food security in Nepal (Shrestha *et al*., 2021).

Rice represents more than 21% and 76% of human caloric and the calorific requirements of Southeast Asian people (Mohidem *et al*., 2022). According to the OECD-FAO Agricultural Outlook 2023-2032, global rice intake is estimated to increase by 0.9% per year over the decade, compared to 1.1% annually in the past decade. The demand for edible rice in Nepal is estimated to be 4.270 to 4.818 million metric t by 2030 and between 4.784 and 6.238 million metric t by 2050 (Timsina *et al*., 2023). Nepal should increase rice production by between 42-85% by 2050 to meet future consumption requirements (Timsina *et al*., 2023). This highlights numerous improvement strategies for increasing both yield and productivity as a 21st-century urgency (Poudel & Poudel, 2020). This could be achieved via vigorous selection in the field to produce high-yielding, climate-adapted, and abiotic stress-tolerant rice cultivars (Riaz *et al*., 2021).

The ideal precipitation and temperature for cultivation of rice is 1300-1500 mm at between 25°C to 35°C (Hussain *et al*., 2019; Rice Knowledge Bank, 2023). Temperature beyond 35°C during growth and reproductive stages is harmful (Xie *et al*., 2023). Under extreme drought stress, yield losses in rice vary from 65% to 85% as compared to regular irrigation conditions (Kumar *et al*., 2008). Combined heat and drought reduce rice output by 0.7% (0.4% to 1.0%) on average, while cold-wet circumstances have no effect. Moisture stress may lower biomass by limiting photosynthesis, mostly via decreased stomatal conductance (Heino *et al*., 2023).

The number of tillers was decreased by water stress during the vegetative stage, while the quantity and weight of grains is lowered by stress during the reproductive and grain-filling stages (Bhattarai *et al*., 2024). According to Bouman and Tuong (2001), the quantity of tillers and panicles per hill decreases when conditions are too dry, either before or during plowing. Since late-maturity cultivars drastically hinder panicle growth, they are not appropriate when late-season dry conditions were the primary cause of poor production. When drought stress is experienced during blooming, the total quantity of grains per panicle is significantly decreased. Drought during blooming causes crop growth to decrease. During blooming, 46% of the grain is empty because of drought stress, compared to 22% under control circumstances of adequate irrigation. At the grain filling stage, the 1000-grain weight is 17% lower in the drought stress group compared to the control group. Therefore, during the blooming stage, drought stress reduces yield mostly due to a drop in the 1000-grain weight and an increase in empty grain relative to filled grain, as well as causing a decrease in the total number of grains per panicle (Sarvestani *et al*., 2008). Drought has a greater impact on pre-dawn mitochondrial respiration, the highest speed of RuBisCO carboxylation, and the maximum rate of electron transport (Perdomo *et al*., 2016). Drought-induced malfunctioning of important physiological systems includes reduced photosynthetic activity, lower water use efficiency, reduced transpiration rate, inadequate stomatal conductance, lower CO_2 fixation, unbalanced water relations, and membrane degradation (Dash *et al*., 2018; Panda *et al*., 2021; Zhu *et al*., 2020).

Drought tolerance indices can be computed using a variety of metrics, including the stress tolerance index (STI), the tolerance index (TOL), the stress susceptibility index (SSI), and the drought tolerant efficiency (DTE), which may be used to detect superior varieties of cultivars in harsh environmental settings (Kandel *et al*., 2022). TOL or the tolerance index is the difference between yield in a stress condition (Ys) and yield in a non-stress condition (Yns) as well as mean productivity as the average of Ys and Yp (Lamba *et al*., 2023). The stress tolerance index (STI) is used to discover high producing genotypes under stress conditions (Anwaar *et al*., 2020). The concept of SSI is introduced by Mokhtari *et al*. (2022). The combination of high relative production and yield stability may be a significant preference benchmark for characterizing genotypic overall performance under varying degrees of drought stress (Bhattarai *et al*., 2024; Paudel *et al*., 2021). The purpose of our research was to discover rice cultivars with robust yield potential and stability under drought-stressed circumstances by studying drought tolerance indicators throughout key developmental stages under the rainfed scenario of western Terai conditions of Nepal.

Materials and methods

Site selection and experimental materials

This research was carried out on the Agronomy farm of the Institute of Agriculture and Animal Science (IAAS, Nepal), Paklihawa campus from June to November 2022. The study area is situated at 79 m a.s.l. with the coordinates 27˚30'N and 83˚27'E. The National Rice Research Program (NRRP), Hardinath provided the nine rice genotypes indicated in Table 1. These genotypes were chosen as stable genotypes among several available genotypes and with superior yield relative to the others. Common availability of these genotypes also means that these can be studied relatively easy.

TABLE 1. Rice genotypes utilized in the study.

Treatments	Genotypes	Source
T1	IR17L1408	Coordinated varietal trial (CVT)
T2	IR16L1713	Coordinated varietal trial (CVT)
T3	IR16L1704	Coordinated varietal trial (CVT)
T4	IR16L1831	Coordinated farmers field trial (CFFT)
T5	IR17L1323	Coordinated farmers field trial (CFFT)
T6	IR17L1387	Coordinated farmers field trial (CFFT)
T7	Sukhdhan 3	Coordinated farmers field trial (CFFT)
T8	IR16L1801	Coordinated farmers field trial (CFFT)
T9	Vandana	Breeders seed

Experimental details

The experiment was carried out with three replicates in a randomized complete block design. There were nine plots in each replicate measuring 5 m × 2.5 m in size.

Agro-meteorological data

Figure 1 shows the agro-meteorological records during the experiment from June 7, 2022 to November 2, 2022. The average temperature during the trial period was almost constant, but at the end of the trial the minimum temperature dropped, resulting in a drop of the average temperature. The precipitation during the trial period increased and reached a maximum at the middle of the trial and decreased at harvest.

Crop management

The field was ploughed and a nursery bed was prepared. On June 7, 2022, rice seeds were soaked overnight and were planted on the next day. After 4-5 weeks the seedlings were transplanted to the main rice field at a spacing of 20 cm × 20 cm. The number of seedlings per hill was controlled at 2 seedlings. The farmyard manure (FYM) was applied at the rate of 5 t ha^{-1} and a recommended dose of NPK, *i.e.* 100:40:30 kg ha^{-1} (Nepalese government recommended dose) was used on individual plots (5 m × 2.5 m.) Half a dosage of nitrogen was administered as a baseline dose, with the remainder applied in two separate doses, the first at 20-25 d after transplant (DAT) and the second at 40-60 DAT. Weeding was performed twice, first at 20 DAT and again at 40 DAT following the initial weeding. Harvesting took place on November 2, 2022.

Preparation of drought conditions

The soil moisture level was maintained by preparing a structure of bamboo poles covered with plastic to protect

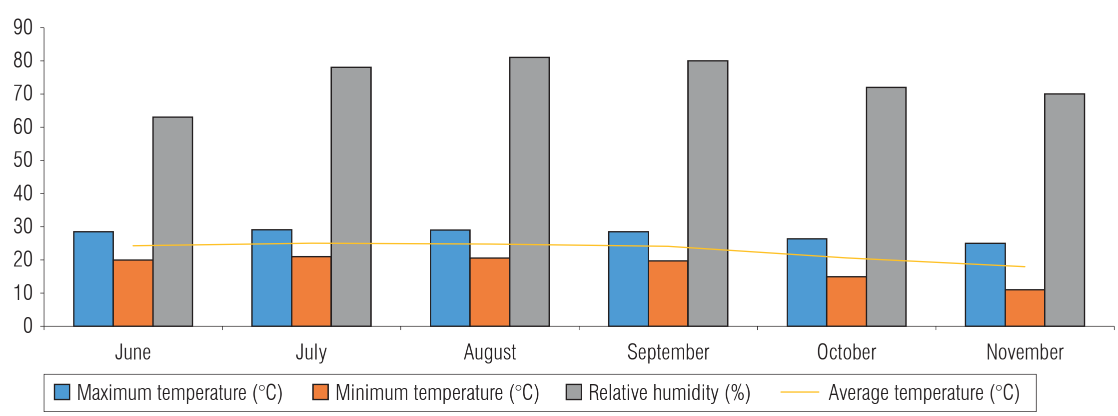

FIGURE 1. Monthly meteorological conditions at Bhairahawa, Nepal from June to November 2022. Source: Weather-2-Visit (https://www.weather-2visit.com/asia/nepal/bhairahawa.htm).

rain in the rice fields. Two to three irrigations were applied to the field after transplanting. Each artificial irrigation was applied during the vegetative stage while drought conditions were maintained during the reproductive stage. Irrigation was used when the water level in the vegetative stage fell below 5 cm. This was regularly monitored during the entire experiment. Irrigation used underground water from bores. The total amount of water applied to each field was about 0.42 acre-foot equal to 518 m^3.

The normally irrigated condition in the field was prepared by applying artificial irrigation during different growth stages (vegetative and reproductive stages). The moisture status in the field was regularly observed and irrigation was applied when the water level fell below 5 cm during the vegetative stage. The level of water in the rice field was maintained at 5 cm throughout the growth phase (vegetative stage).

Traits under study

Ten plants were randomly chosen for data collection. We noted the days to 50% flowering (DTF), plant height (PH), panicle length (PL), panicle weight (PW), and the number of grains per panicle (NGPP), and we reported these data as yield-attributing characteristics. We used an average area of 1 m^2 per plot to represent the entire plot. Additional data collected were the effective panicle per m^2 (EP/m^2), grain yield (GY), and 1000 grain weight (TGW).

Statistical analysis

We performed an analysis of variance (ANOVA) for mean comparison and least significant difference (LSD) at 5% level of probability using the R software (R 4.3.1). We identified resilient and susceptible genotypes using principal component analysis (PCA), biplot diagrams, and correlation between stress tolerance indices with yield utilizing IBM SPSS Statistics (version 25).

Results and discussion

Yield performance

Under drought stress conditions PL, TGW, and GY of different rice genotypes (Tab. 2) showed significant variation, as seen in Table 3, while DTF, TGW, and GY showed significant differences ($P<0.05$) among different rice genotypes in irrigated conditions (Tab. 4). IR17L1387 (4.37 t ha^{-1}) had a superior yield in irrigated conditions, followed by IR16L1713 (4.30 t ha^{-1}) and IR16L1831 (4.01 t ha^{-1}), and Vandana (2.79 t ha^{-1}) showed the lowest yield. Additionally, IR16L1801 (3.35 t ha^{-1}) had the highest yield under drought stress conditions followed by IR16L1713 (3.20 t ha^{-1}) and Sukhdhan 3 (3.14 t ha^{-1}). The high yield of rice genotypes is associated with panicle length (PL), panicle weight (PW), number of grains per panicle (NGPP), panicle yield per m^2 (EP/m^2), and thousand-grain weight (TGW). Plant height (PH) is a critical factor that determines or enhances yield-contributing characteristics and ultimately shapes the grain yield (Reddy & Reddy, 1997). Diverse genetically controlled variables are a product of intricate characters, the majority are governed by genotype genetic composition and are normally defined by the number of nodes and the internode lengths (Rahman *et al.*, 2018).

The average yields under drought stress and irrigated conditions were 2.65 t ha^{-1} and 3.60 t ha^{-1}. The average grain yield dropped by 26.5%. The mean reduction in effective shoots per m^2 was 52.21%. The decline in effective shoot formation under low soil moisture conditions might be attributed to the restricted availability of assimilates under water stress conditions. It may also occur due to insufficient

TABLE 2. Eight indices of stress tolerance used in evaluating the rice genotypes.

Drought tolerance indices	Formula equation	References
Tolerance index (TOL)	$TOL = Y_{ns} - Y_s$	(Anwaar *et al.*, 2020; Hossain *et al.*, 1990; Rosielle & Hamblin, 1981)
Mean productivity index	$MP = (Y_{ns} + Y_s)/2$	(Adhikari *et al.*, 2019; Hossain *et al.*, 1990; Rosielle & Hamblin, 1981)
Geometrical mean productivity	$GMP = \sqrt{} (Y_{ns} \times Y_s)$	(Fernández, 1992)
Stress tolerance index	$STI = Y_{ns} \times Y_s/(Y_{ns}^2)$	(Anwaar *et al.*, 2020; Hao *et al.*, 2011)
Yield stability index	$YSI = Y_s/Y_{ns}$	(Bouslama & Schapaugh Jr., 1984)
Stress susceptibility index	$SSI = 1- (Y_s/Y_{ns})/SI$ where $SI = 1-(Y_s/Y_{ns})$	(Fischer & Maurer, 1978)
Yield index	$YI = Y_s/ Y_{s-}$	(Khan & Kabir, 2015)
Reduction percentage	$Red = (Y_{ns}-Y_s)/ Y_{ns})*100$	(Bennani *et al.*, 2017)

water uptake for the adequate mineral nutrition and the inhibition of cell division of meristematic tissue (Bhattarai *et al.*, 2024). The lack of availability of soil water at grain filling and other development stages is detrimental for the panicle initiation stage and affects days to flowering, panicle length, panicle weight, effective tillers, number of tillers per hill, thousand-grain weight, grains per panicle, etc. (Paudel *et al.,* 2021). This might be due to a considerable decrease in photosynthetic rate that results in less assimilate generation for panicle development and filling of rice grains. As a result, rice yield is substantially reduced (Moonmoon & Islam, 2017). Drought stress at various phases of development may reduce assimilate transfer to grains, lowering grain weight and increasing the quantity of empty grains. Drought stress at crucial developmental phases reduces rice yield (Cattivelli *et al.*, 2008; Pantuwan *et al.*, 2002).

Stress tolerance index (STI)

Table 5 shows the stress index of nine distinct rice genotypes. The average grain yield for all cultivars differed significantly under stressed and non-stressed conditions. The average yield performance under non-stressful conditions was superior to that under stressful conditions. Under

TABLE 3. Yield attributing characteristics of different rice genotypes under a drought stress environment.

Genotypes	DTF (d)	PH (cm)	PL (cm)	PW (g)	NGPP	EP/m^2	TGW (g)	GY (t ha^{-1})
IR17L1408	73.33±6.11	73.21±10.90	20.53^{b}c±0.73	22.86±2.72	87.33±7.74	160.33±20.50	26.33^{bcd}±2.33	2.02^{ab}±0.42
IR16L1713	74.67±5.03	82.47±5.11	20.80^{c}±0.59	19.37±1.86	76.93±7.60	275.00±56.10	25.03^{a}±2.54	3.20^{ab}±0.79
IR16L1704	71.00±9.16	76.42±7.13	19.27^{c}±0.44	20.00±2.60	104.58±14.30	214.67±50.70	23.57^{de}±0.81	2.15^{b}±0.53
IR16L1831	73.67±3.79	81.73±3.28	19.10^{bc}±0.79	19.43±1.33	68.50±3.74	177.00±57.70	30.83^{cde}±0.58	2.22^{a}±0.38
IR17L1323	75.33±4.93	90.64±2.95	22.76^{a}±1.21	24.03±2.76	98.63±13.30	223.33±46.10	26.03^{bcde}±0.03	3.00^{a}±0.16
IR17L1387	78.67±3.06	83.76±3.91	21.46^{bc}±0.58	20.47±1.03	74.73±5.46	186.33±8.00	29.47^{cde}±0.76	2.97^{b}±0.36
Sukhdhan 3	71.67±2.31	84.76±3.83	21.71^{ab}±0.18	20.57±1.24	94.83±3.53	218.33±12.40	21.93^{e}±1.21	3.14^{a}±0.33
IR16L1801	75.67±4.04	84.27±5.63	21.12^{ab}±0.74	20.57±1.29	82.70±12.10	240.67±19.80	28.00^{abc}±1.16	3.35^{a}±0.12
Vandana	69.67±3.22	85.20±3.51	20.01^{ab}±0.84	21.07±1.80	92.77±12.30	112.00±40.40	24.90^{ab}±0.96	1.59^{a}±0.68
LSD (*P*<0.05)	8.33	16.46	1.84*	6.07	30.35	108.17	4.27**	1.26*
CV %	6.52	11.53	5.12	16.75	20.21	31.11	9.41	27.56
Mean	73.74	82.50	20.75	20.93	86.78	200.85	26.23	2.65

Note: DTF: days to flowering in 50% plants; PH: plant height; PL: panicle length; PW: panicle weight; NGPP: number of grains per panicle; EP/m^2: effective panicle per m^2; TGW: thousand-grain weight; GY: grain yield; LSD: least significant difference; CV: coefficient of variation; * and ** indicate significant differences at 5% and 1% level. Means followed by the same letters within the same columns are not significantly different based on LSD at *P*<0.05.

TABLE 4. Yield-attributing characteristics of different rice genotypes under an irrigated environment.

Genotypes	DTF (d)	PH (cm)	PL (cm)	PW (g)	NGPP	EP/m^2	TGW (g)	GY (t ha^{-1})
IR17L1408	72.33^{ab}±3.53	81.39±10.90	19.93^{bc}±0.73	22.00±2.72	87.07±7.74	256.00±20.50	28.33^{ab}±2.33	3.15^{cd}±0.45
IR16L1713	72.67^{ab}±2.91	76.73±5.11	19.24^{d}±0.59	16.67±1.86	62.70±7.60	239.00±56.10	25.83^{bcd}±2.54	4.30^{ab}±0.30
IR16L1704	71.00^{ab}±5.29	82.56±7.13	19.94^{abc}±0.44	22.00±2.60	86.33±14.30	276.00±50.70	22.67^{ef}±0.81	3.90^{abc}±0.41
IR16L1831	71.67^{bc}±2.19	82.05±3.28	18.91^{de}±0.79	23.33±1.33	75.63±3.74	234.00±57.70	32.63^{e}±0.58	4.01^{a}±0.17
IR17L1323	79.00^{a}±2.85	84.45±2.95	21.75^{a}±1.21	25.33±2.76	88.90±13.30	209.33±46.10	22.67^{e}±0.03	3.13^{cd}±0.75
IR17L1387	73.67^{ab}±1.76	86.81±3.91	21.24^{a}±0.58	22.67±1.03	85.33±5.46	258.67±8.00	27.33^{ab}±0.76	2.79^{d} ±0.18
Sukhdhan 3	70.00^{bcde}±1.33	68.02±3.83	20.58^{ab}±0.18	24.27±1.24	107.23±3.53	170.33±12.40	24.17^{cde}±1.21	3.18^{bcd}±0.33
IR16L1801	78.3^{a}±2.33	85.29±5.63	21.70^{ab}±0.74	24.00±1.29	87.40±12.10	207.00±19.80	26.00^{abc}±1.16	3.60^{abcd}±0.61
Vandana	69.33^{c}±1.86	95.08±3.51	19.86^{abc}±0.84	22.00±1.80	86.40±12.30	184.00±40.40	24.00^{abcd}±0.96	4.37^{a}±0.34
LSD (*P*<0.05)	7.32*	16.46	1.84*	6.07	30.35	108.17	4.27**	0.85**
CV%	6.52	11.53	5.12	16.75	20.21	31.11	9.41	13.69
Mean	73.11	82.49	20.35	22.47	85.22	226.04	25.96	3.60

Note: DTF: days to flowering in 50% plants; PH: plant height; PL: panicle length; PW: panicle weight; NGPP: number of grains per panicle; EP/m^2: effective panicle per m^2; TGW: thousand grain weight; GY: grain yield; LSD: least significant difference; CV: coefficient of variation; * and ** indicate significant differences at 5% and 1% level. Means followed by the same letters within the same columns are not significantly different based on LSD at *P*<0.05.

stress and non-stress environments, the average grain yield varied from 1.59-3.35 t ha^{-1} to 2.79-4.37 t ha^{-1}, respectively.

The highest TOL was observed in IR16L1831 followed by IR16L1704 and IR17L1387 while the least TOL value was recorded for Sukhdhan 3 followed by IR17L1323. A lower TOL (stress tolerance) rating indicates that a certain cultivar is highly stress tolerant. Table 6 indicates that TOL has a negative connection to yield under stress situations. As a result, these genotypes produced abundant grain yield under non-stress settings but not such high yield in stress situations. As a result, they may be regarded as stress-vulnerable genotypes. Sukhdhan 3 and IR17L1323 performed poorly under irrigated and drought stress environments. Modest TOL resulted from a modest difference among yields in the two situations. IR16L1704 had the highest SSI while Sukhdhan 3 had the lowest SSI. So, IR16L1704 was the most susceptible genotype and Sukhdhan 3 was the least susceptible genotype to drought stress. An SSI value greater than one indicates intensified susceptibility, whereas SSI less than one shows below-average susceptibility. Low TOL and SSI do not mean that these were highly producing genotypes. Crop yield should also be considered when selecting stress resistant genotypes (Thapa *et al*., 2022). The highest STI, MP, and GMP were seen in IR16L1713, followed by IR17L1387, indicating that these genotypes were the most stable and productive of the nine rice genotypes tested. Kamrani *et al*. (2017) also determine genotypes with maximum MP, GMP, and STI as top yielding genotypes.

Correlation among yield and drought stress indices

We computed the association between Y_{ns}, Y_s, and the other stress tolerant indices shown in Table 6 to discover the most acceptable stress tolerance selection criterion. Our study found a link between crop output under irrigated conditions and drought stress. This suggested that genotypes with large grain yields under normal irrigated settings were more likely to have higher grain yields than under drought stress conditions. A similar finding is shown by Kandel *et al*. (2022), who shows a link between grain productivity in irrigated fields and heat stress associations. Similarly, under drought stress conditions, SSI showed a positive and significant connection with yield, indicating that an increase in SSI would result in a significant increase in production. Adhikari *et al*. (2019) find a significant association between SSI and yield under stress. YSI also showed a significant and positive connection with yield under stress, but a positive and non-significant correlation with yield under irrigation (Tab. 6). As a result, choosing genotypes with higher SSI and YSI values under drought stress conditions will aid in the identification of superior varieties. Adhikari *et al*. (2019) and Kandel *et al*. (2022) also report that the genotypes with higher SSI and YSI would have better results under drought stress conditions.

STI had a negative and non-significant correlation with yield under irrigated circumstances, but it had a positive and significant correlation with yield under stress conditions (Tab. 6). YI, on the other hand, showed a positive and

TABLE 5. Yield (kg ha^{-1}) of rice genotypes with stress tolerance indices under irrigated and drought stress environments.

Genotypes	Y_{ns}	Drought tolerance indices								
		Y_s	TOL	STI	MP	GMP	YSI	SSI	YI	Red%
IR17L1408	3153.33^{cd}±452	2202.33^{ab}±421	951.00±337	0.56±0.17	2677.83^{bc}±403	2623.72^{bc}±406	0.70^{ab}±	1.12^{ab}±0.32	0.83^{ab}±0.16	29.77±8.58
IR16L1713	4296.67^{ab}±301	3203.67^{ab}±790	1093.00±864	1.07±0.25	3750.17^{a}±413	3704.07^{a}±509	0.74^{ab}±0.09	0.97^{ab}±0.74	1.21^{a}±0.30	25.83±19.70
IR16L1704	3900.00^{abc}±413	2154.67^{ab}±527	1745.33±496	0.66±.019	3027.33^{ab}±403	2867.69^{abc}±437	0.55^{b}±0.19	1.70^{a}±0.45	0.81^{ab}±0.20	45.11±11.80
IR16L1831	4007.67^{a}±171	2226.00^{a}±379	1781.67±231	0.68±0.17	3116.83^{ab}±270	2893.46^{abc}±287	0.56^{b}±0.12	1.65^{a}±0.23	0.84^{ab}±0.14	43.84±5.98
IR17L1323	3136.67^{cd}±74.50	2995.00^{a}±16	141.67±69.30	0.72±0.02	3065.83^{ab}±41.2	3064.65^{ab}±40.4	0.96^{a}±0.06	1.17^{b}±0.08	1.13^{a}±0.01	4.42±2.06
IR17L1387	2790.33^{d} ±177	2969.00^{b}±358	1404.33±513	0.99±0.06	3671.17^{a}±111	3533.18^{a}±184	0.69^{ab}±0.02	1.15^{ab}±0.60	1.12^{a}±0.14	30.55±15.80
Sukhdhan 3	3176.67^{bcd}±328	3144.00^{a}±329	32.67±8.19	0.79±0.17	3160.33^{ab}±328	3160.28^{ab}±328	0.99^{a}±0.16	0.04^{b}±0.01	1.19^{a}±0.12	1.05±0.30
IR16L1801	3600.00^{abcd}±61.10	3346.67^{a}±116	253.33±135	0.93±0.04	3473.33^{a}±63.6	3469.65^{ab}±65.1	0.93^{a}±0.04	0.26^{b}±0.14	1.26^{a}±0.04	6.97±3.64
Vandana	4373.33^{a}±337	1589.07^{a}±682	1201.27±824	0.33±0.24	2189.70^{c}±346	2063.65^{c}±447	0.59^{b}±0.18	1.56^{a}±0.68	0.60^{b}±0.26	41.32±18.00
LSD ($P<0.05$)	853.73**	1263.10*	1477.61	0.44	785.05*	902.15*	0.34*	1.29*	0.48*	34.30
CV%	13.69	27.56	89.30	34.02	14.51	17.13	26.57	77.93	27.56	77.93
Grand mean	3603.85	2647.82	956.03	0.75	3125.84	3042.26	0.75	0.96	1.00	25.43

Note: Y_{ns}: yield under irrigated condition; Y_s: yield under drought stress environment; TOL: tolerance index; SSI: stress susceptibility index; MP: mean productivity; GMP: geometric mean productivity; STI: stress tolerance index; YSI: yield stability index; YI: yield index; Red%: reduction percentage; LSD: least significant difference; CV: coefficient of variation; * and ** indicate significance at 5% and 1% levels. Means followed by the same letters within the same columns are not significantly different based on LSD at $P<0.05$.

non-significant association with yield while irrigated but showed a negative and significant correlation with yield when stressed. As a result, all these characteristics should be considered while choosing high producing genotypes under both environments.

The biplot analysis was done to find out the most stable and least stable genotypes under drought stress and irrigated condition in the field. Figure 2 illustrates the ranking of genotypes according to mean performance and stability. The average environment coordinate (AEC) axis, which is defined by the average PC1 and PC2 scores of all the environments, is the line that goes through the biplot origin and the average environment. The yield stability of genotypes was assessed using the AEC approach, which uses the average principal components in all conditions. IR16L1831 exhibited the highest yield and excellent stability under both drought stress and irrigated conditions, as depicted in Figure 2. The Vandana variety demonstrated the highest average yield but with low stability. Additionally, IR16L1704 and IR17L1408 exhibited moderate yield but low stability. The genotype with moderate yield and highest stability was Sukhadhan 3. IR17L1387 and Vandana are the least stable genotypes according to their yield as revealed by biplot analysis.

TABLE 6. Correlation of rice yield with stress tolerance indices under irrigated and drought stress conditions.

	Y_{ns}	Y_s	TOL	SSI	MP	GMP	STI	YSI	YI	Red
Y_{ns}	1									
Y_s	0.295	1								
TOL	0.446*	-0.724**	1							
SSI	0.626**	0.918**	-0.408*	1						
MP	0.745**	0.857**	-0.265	0.978**	1					
GMP	0.621**	0.930**	-0.423*	0.993**	0.984**	1				
STI	-0.253	0.836**	-0.966**	0.555**	0.448*	0.584**	1			
YSI	0.295	1.000**	-0.724**	0.918**	0.857**	0.930**	0.836**	1		
YI	0.253	-0.836**	0.966**	-0.555**	-0.448*	-0.584**	-1.000**	-0.836**	1	
Red	0.253	-0.836**	0.966**	-0.555**	-0.448*	-0.584**	-1.000**	-0.836**	1.000**	1

Note: Y_{ns}: yield under irrigated condition; Y_s: yield under drought stress environment; TOL: tolerance index; SSI: stress susceptibility index; MP: mean productivity; GMP: geometric mean productivity; STI: stress tolerance index; YSI: yield stability index; YI: yield index; Red: reduction percentage. * and ** indicate significance at 5% and 1% level, respectively.

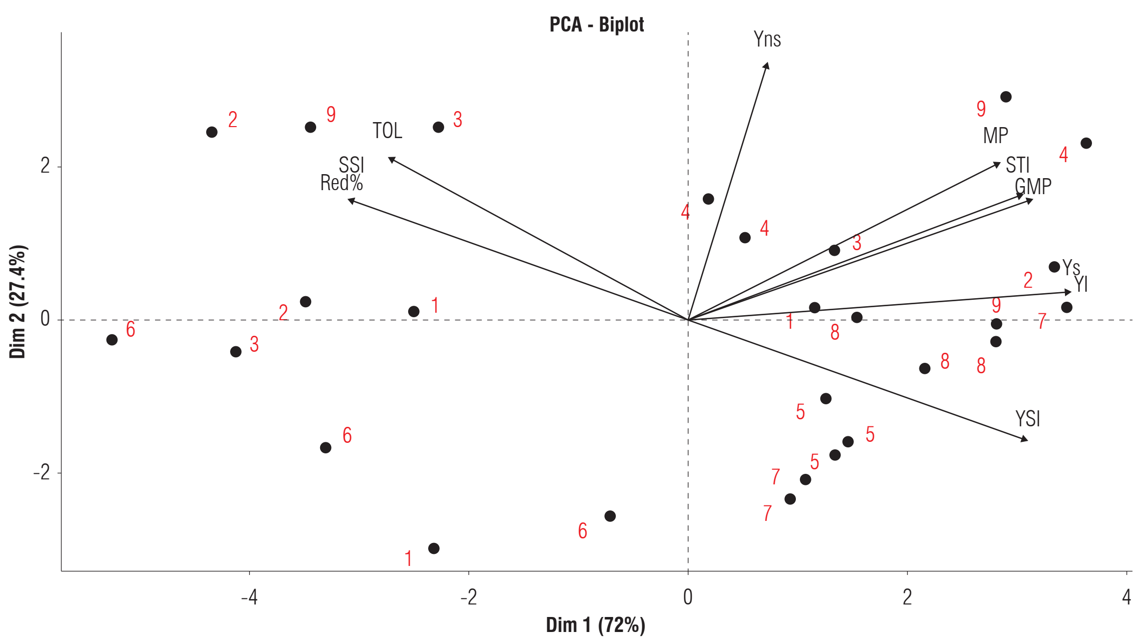

FIGURE 2. Biplot based on PC1 and PC2 using the values from principal component analysis.

Conclusion

This study showed that drought stress during the critical growth period of rice has a significant impact on the yield of different rice cultivars. It also suggests that choosing cultivars on the basis of moisture tolerance indices might be a viable way to discover improved drought resistant cultivars with enhanced production potential and stability. Based on data examined from numerous drought tolerance index factors, we determined that the rice cultivars IR16L1713 and IR17L1387 had a high degree of drought resistance since they had low SSI and TOL values with high STI values compared to other genotypes. The stable yield of Sukhadhan in both irrigated and drought stress environments indicated that it was the most stable rice genotype compared to other studied cultivars. These cultivars produced the highest yield in irrigated areas and performed well under drought stress conditions. As a result, in rainfed and drought-prone locations, these drought-tolerant rice cultivars could be superior to traditional, basic, and untested cultivars.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

Methodology, investigation, software, validation, data curation: H. C., M. R. P., P. K., B. K., B. P., J. B., B .R. M., P. B., P. L., P. B., and N. P. P., writing, original draft preparation: N.P.P., conceptualization, review, editing, and supervision: M. R. P. The final version of the manuscript was read and approved by all authors.

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