Indian Journal of Agricultural Sciences **95** (4): 425–431, April 2025/Article
https://doi.org/10.56093/ijas.v95i4.146046

Assessing effectiveness of drought tolerance indices in selecting grape (*Vitis vinifera*) under induced drought stress conditions

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Received: 06 December 2023; Accepted: 10 January 2025

ABSTRACT

The present study was carried out during 2021–23 at ICAR-Indian Agricultural Research Institute, New Delhi, focusing on 10 diverse grape (*Vitis vinifera* L.) genotypes [Pusa Navrang (PN), Pusa Aditi (PA), Pusa Trisha (PT), Pusa Swarnika (PS), Pusa Purple Seedless (PPS), Flame Seedless (FS), St. George (SG), Dog Ridge (DR), *V. parviflora* (VP), and Male Hybrid (MH)] for their response to controlled moisture stress (21 days) and well-watered conditions in plastic pots (14) maintained under polyhouse conditions. Drought decreased plant height differently among genotypes (9.71–41.68%). Dogridge had the highest root: shoot ratio (0.79), St. George showed lower (0.44) in response to drought. Drought tolerance indices identified genotypes *Vitis parviflora* (VP), Pusa Navrang (PN), Male Hybrid (MH) and Dogridge (*Vitis × champini*) (DR) as more drought-tolerant, while Pusa Trishar (PT) and Flame Seedless (FS) were susceptible. Cluster analysis showcased distinct differences among genotypes, while principal component analysis (PCA) emphasized key indices predicting performance in varying conditions with 98.91% variance for plant height and 99.10% variance for index root: shoot ratio contributed from two primary principal components (PC1 and PC2). Correlations (P<0.001) highlighted the predictive value of specific indices, like the drought resistance index (DI), mean relative performance (MRP), stress tolerance index (STI) and relative efficiency index (REI) for drought tolerance. The above-identified genotypes were validated through multivariate stability trait index analysis outlining their utility as donor parents/rootstocks. In conclusion, the study underscores genetic diversities as pivotal in determining drought tolerance in grape genotypes. It has generated valuable insights for selecting drought-resistant genotypes which could contribute to sustainable viticulture under the changing climate situations.

Keywords: Drought stress, Drought tolerance indices, MGIDI, Plant height, Root: shoot ratio

Grapes (*Vitis vinifera* L.) play a multifaceted role in wielding a significant economic influence. Additionally, table grapes and raisin-making hold considerable popularity and economic importance, distinct from the wine industry. Beyond their financial impact, grapes boast many health benefits due to the presence of abundant antioxidants like resveratrol and quercetin. Drought is a noteworthy and urgent concern among climate change-related factors. Climate change predictions indicate that drought is likely to become a more severe challenge in the coming decades, posing a major threat to global grape production (Santillan *et al.* 2019). The impact of grape morphology on drought has been studied by researchers such as Wang *et al.* (2003), who have elucidated the intricate relationship between the physical characteristics of grapevines and their response to soil water scarcity. The morphology of grapevines plays a crucial role in their response to drought conditions. Drought significantly influences the physical characteristics of grape plants, including their growth patterns, structural adaptations, and alterations in the cell composition. Various drought indices have been employed in the context of grape cultivation, providing valuable insights into the impact of soil moisture scarcity on these plants. Researchers like Chaves *et al.* (2002) have utilized indices to assess and quantify grapevine drought stress. The central objective of the ongoing research was to assess morphological traits, particularly plant height and root: shoot ratio, in various grape genotypes subjected to drought stress conditions. The multi-trait genotype ideotype distance index (MGIDI) (Olivoto and Nardino 2020) serves as a valuable tool for assessing grape genotypes under drought stress, providing a comprehensive evaluation of their performance. This method thoroughly examines morphological attributes, including plant height and root:shoot ratio, offering insights

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into the adaptive capacities of different genotypes in water-scarce conditions. The present study sought to analyse and compare the efficacy of different drought tolerance indices using correlation and PCA to identify drought-tolerant grape genotypes in north Indian condition which can perform best under normal and stressful conditions.

MATERIALS AND METHODS

Plant material and experiment condition: The present study was carried out during 2021–23 at ICAR-Indian Agricultural Research Institute, New Delhi. Ten grape genotypes, which included 9–10 year-old vines of Pusa Navrang (PN), Pusa Aditi (PA), Pusa Trisha (PT), Pusa Swarnika (PS), Pusa Purple Seedless (PPS), Flame Seedless (FS), St. George (SG), Dogridge (DR), *V. parviflora* (VP), and Male Hybrid (MH) was taken for the study. The six-month-old self-rooted cuttings were planted in 14 plastic pots under polyhouse conditions and were subjected to 21 days of induced drought stress condition by with-holding the irrigation which resulted in reducing the soil moisture from 70–25% volume water content (VWC), while well-watered control plants were maintained at 70% VWC for comparison. Soil moisture levels were regularly monitored using a ProCheck moisture meter. Each group had three biological replicates (15 plants). During July 2022 and 2023, it experienced an average temperature of 30.5°C. After 21 days of experimentation, the plants from each treatment were chosen to assess them for different traits. The collected plant tissues were dried at 70°C for 72 h, and their respective dry weights were documented.

Estimation of drought tolerance indices: To gauge drought tolerance in the examined genotypes, 10 selection indices were adapted. These drought tolerance index for each variable was determined using the following formula:

Stress susceptibility index (SSI) (Fischer and Maurer 1978) =

$$\frac{1-\left(\frac{\text{Ysi}}{\text{Ypi}}\right)}{\text{SI}}$$

Where *SI,* 1 − (Ys/Yp).

Tolerance index (TOL) (Rosielle and Hamblin 1981) = Ypi–Ysi;

Stress tolerance index (STI) (Fernandez 1992) = (Ysi×Ypi)/(Yp^2);

Drought resistance index (DI) (Lan 1998) = Ysi × (Ysi/Ypi)/Ys;

Drought tolerance efficiency (DTE) (Fisher and Wood 1981) = Ysi/Ypi × 100;

Relative drought index (RDI) (Fisher and Wood 1979) = (Ysi/Ypi)/(Ys/Yp);

Mean relative performance (MRP) (Hossain *et al.* 1999) = (Ysi/Ys) + (Ypi/Yp);

Relative efficiency index (REI) (Hossain *et al.* 1999) = (Ysi/Ys) × (Ypi/Yp);

Modified stress tolerance index 1 (MSTIK1) (Farshadfar and Sukta 2002) = (Ypi^2/Yp^2) × STI;

Modified stress tolerance index 2 (MSTIK2) (Farshadfar and Sukta 2002) = (Ysi^2/Ys^2) × STI.

Where, Ypi and Ysi denote the average trait values observed in the absence of stress conditions and under stress conditions for a specific genotype, respectively. The symbols Yp and Ys refer to the overall average trait values across all investigated genotypes without stress and under stress conditions, respectively, as defined by Zdravkovic *et al.* (2013).

Statistical analysis: Data analysis was performed using 'R' software version 4.3.2, and the least significant difference (LSD) was conducted to evaluate phenotypic data, collected separately under both control and drought conditions over two years using two-way factorial CRD. Principal Component Analysis (PCA) was performed using the R package "FactoMineR version 2.4", and Pearson's correlation coefficients were computed using the R package "corrplot".

Multi-trait genotype ideotype distance index: Agronomic traits and related characteristics undergo analysis of variance using the multi-trait genotype-ideotype distance index (MGIDI) within the METAN R package, designed for multi-environment trial analysis. This method, developed by Olivoto and Nardino (2020), identifies genotype variation and explores the selection criteria. Genotype was treated as the fixed variable in this analysis.

Table 1 Mean comparison of various traits of grape genotypes under standard and drought stress environments during 2022 and 2023

Genotype	Plant height (cm)		Root: shoot ratio		Plant height reduction (%)
	C	D	C	D	
PN	106.89^{b}	90.87^{b}	0.79^{ab}	0.72^{ab}	14.99
PA	97.07^{bcd}	69.79^{c}	0.71^{bc}	0.60^{bcd}	28.11
PT	84.38^{e}	49.21^{de}	0.61^{c}	0.53^{de}	41.68
PS	101.64^{bc}	70.37^{c}	0.62^{c}	0.60^{bcd}	30.77
PPS	52.43^{f}	45.01^{e}	0.78^{ab}	0.70^{abc}	14.15
FS	87.24^{de}	56.57^{d}	0.60^{c}	0.56^{cde}	35.15
SG	93.53^{cde}	68.73^{c}	0.75^{ab}	0.44^{e}	26.51
DR	103.09^{bc}	93.07^{b}	0.84^{a}	0.79^{a}	9.71
VP	122.99^{a}	107.14^{a}	0.74^{ab}	0.71^{ab}	12.88
MH	122.13^{a}	97.16^{b}	0.69^{bc}	0.66^{abcd}	20.44
Mean ± SD	97.15 ± 19.28	74.8 ± 20.24	0.72 ± 0.08	0.64 ± 0.1	
CV%	19.84	27.05	11.11	15.62	
LSD Genotype	7.44		0.09		
Treatment	3.33		0.04		
G × T	10.53		0.13		

C, Control; D, Drought; PN, Pusa Navrang; PA, Pusa Aditi; PT, Pusa Trisha; PS, Pusa Swarnika; PPS, Pusa Purple Seedless; FS, Flame Seedless; SG, St. George; DR, Dogridge; VP, *Vitis parviflora;* MH, Male Hybrid.

RESULTS AND DISCUSSION

Mean performances for induced drought: Ten grape genotypes were studied over a two-year period under two different moisture regimes, induced drought and well-watered conditions, revealing considerable diversity in vegetative traits such as plant height and shoot: root ratio under optimal and drought conditions (Table 1). The imposition of drought conditions led to a notable decrease the height of affected plants compared to the control, with reductions ranging from 9.71% in DR to 41.68% in PT. A reduction in plant height of range from 12.32–40.66% under the influence of drought was recorded (Zdravkovic *et al.* 2013). Additionally, significant variations were observed among genotypes concerning the root: shoot dry weight ratio, highlighting substantial diversity that facilitated the identification of drought-tolerant genotypes. These findings underscore the diverse responses of root growth to drought situations across the investigated genotypes. Karami *et al.* (2017) found a 75% and 85% reduction in shoot: root dry weight ratio under drought stress in 'BidanehSefid grapevines. In specific genotypes like ST, PA and PT, drought stress decreased the root: shoot ratio compared to thoroughly watered plants. The diminished root: shoot ratio suggested that in specific genotypes, drought induction resulted in reduced root growth.

Comparing genotypes based on the resistance/ tolerance indices: Various methods exist for assessing stress intensity, yet some stand out as the most advantageous when comparing the stress effect indicators (Bennani *et al.* 2017). Different quantitative drought tolerance indices were employed to assess the drought responses of the studied grape genotypes based on their plant height and root:shoot ratio under control and drought conditions (Table 2 and 3). In terms of plant height, genotypes DR, VP, and PN showcased the lowest

Table 2 The drought index on the base of plant height values

Genotype	PH-C	PH-D	SSI	TOL	STI	DI	DTE	RDI	MRP	REI	MSTIK1	MSTIK2	Cluster
PN	106.89	90.87	0.65	16.02	1.03	1.03	85.01	1.10	2.32	1.34	1.25	1.52	4
PA	97.07	69.78	1.22	27.30	0.72	0.67	71.88	0.93	1.93	0.93	0.72	0.63	3
PT	84.38	49.20	1.81	35.18	0.44	0.38	58.30	0.76	1.53	0.57	0.33	0.19	1
PS	101.64	70.36	1.34	31.28	0.76	0.65	69.23	0.90	1.99	0.98	0.83	0.67	3
PPS	52.42	45.00	0.61	7.42	0.25	0.52	85.85	1.12	1.14	0.32	0.07	0.09	2
FS	87.23	56.56	1.53	30.67	0.52	0.49	64.84	0.84	1.65	0.68	0.42	0.30	1
SG	93.52	68.72	1.15	24.80	0.68	0.68	73.48	0.95	1.88	0.88	0.63	0.58	3
DR	103.08	93.05	0.42	10.03	1.02	1.12	90.27	1.17	2.31	1.32	1.15	1.57	4
VP	122.98	107.13	0.56	15.85	1.40	1.25	87.11	1.13	2.70	1.81	2.24	2.87	5
MH	122.11	97.15	0.89	24.96	1.26	1.03	79.56	1.03	2.56	1.63	1.99	2.12	5

C, Control; D, Drought; PH, Plant height, SSI, Stress susceptibility index; TOL, Tolerance index; STI, DI, Drought resistance index; DTE, Drought tolerance efficiency; RDI, Relative drought index; MRP, Mean relative performance; REI, Relative efficiency index; MSTIK 1, Modified stress tolerance index 1; MSTIK 2, Modified stress tolerance index 2; PN, Pusa Navrang; PA, Pusa Aditi; PT, Pusa Trisha; PS, Pusa Swarnika; PPS, Pusa Purple Seedless; FS, Flame Seedless; SG, St. George; DR, Dogridge; VP, *Vitis parviflora;* MH, Male Hybrid.

Table 3 The drought index on the base of root: shoot ratio values

Genotype	RSR-C	RSR-D	SSI	TOL	STI	DI	DTE	RDI	MRP	REI	MSTIK1	MSTIK2	Cluster
PN	0.79	0.72	0.75	0.07	1.13	1.05	91.14	1.03	2.26	1.28	1.40	1.49	3
PA	0.70	0.59	1.33	0.11	0.82	0.79	84.29	0.96	1.93	0.93	0.80	0.73	2
PT	0.61	0.52	1.25	0.09	0.63	0.71	85.25	0.97	1.69	0.71	0.46	0.43	2
PS	0.62	0.60	0.27	0.02	0.74	0.93	96.77	1.10	1.83	0.84	0.56	0.68	2
PPS	0.77	0.70	0.77	0.07	1.07	1.02	90.91	1.03	2.20	1.21	1.26	1.34	3
FS	0.54	0.60	0.57	0.04	0.64	0.82	93.22	1.06	1.71	0.73	0.44	0.50	2
SG	0.75	0.43	3.61	0.32	0.64	0.39	57.33	0.65	1.74	0.73	0.71	0.30	1
DR	0.83	0.78	0.51	0.05	1.28	1.17	93.98	1.07	2.42	1.46	1.76	1.99	3
VP	0.74	0.71	0.34	0.03	1.04	1.09	95.95	1.09	2.18	1.18	1.13	1.34	3
MH	0.70	0.66	0.48	0.04	0.92	0.99	94.29	1.07	2.04	1.04	0.89	1.02	3

PN, Pusa Navrang; PA, Pusa Aditi; PT, Pusa Trisha; PS, Pusa Swarnika; PPS, Pusa Purple Seedless; FS, Flame Seedless; SG, St. George; DR, Dogridge; VP, *Vitis parviflora;* MH, Male Hybrid; C, Control; D, Drought; RSR, Root: shoot ratio; SSI, Stress susceptibility index; TOL, Tolerance index; STI, DI, Drought resistance index; DTE, Drought tolerance efficiency; RDI, Relative drought index; MRP, Mean relative performance; REI, Relative efficiency index; MSTIK 1, Modified stress tolerance index 1; MSTIK 2, Modified stress tolerance index 2

SSI values (0.42, 0.56 and 0.65, respectively) and TOL values (10.03, 15.85 and 16.02, respectively), indicating minimal reduction in plant height under stress indicating the highest drought tolerance. On the contrary, genotype PT exhibited the highest SSI (1.81) and TOL (35.18) values, followed by PS and FS, indicating a significant reduction in plant height and relatively lower drought tolerance. Optimal genotype selection was contingent upon the lowest SSI and TOL values (Pour and Poczai 2021). Indices like STI, DI, DTE, RDI, MRP, REI, and MSTK1 and 2 indicated varying degrees of resilience to drought. Genotypes VP (STI = 1.40) and MH (STI = 1.26) displayed higher tolerance, while PT and PPS exhibited susceptibility to drought stress with values below 0.50. The genotypes with SSI values lower than the average SSI values for each trait was considered drought-tolerant (Harish *et al.* 2020) while that genotype characterized by high values of STI exhibited superior performance and stress tolerance (Kumar *et al.* 2024). Regarding DI values, genotypes VP (DI = 1.25) and DR (DI = 1.12) demonstrated higher drought tolerance, contrasting with PT's lowest DI values (0.38). DTE scores emphasized DR (DTE = 90.27) and VP (DTE = 87.11) as highly suitable under stress, whereas PT showed the least tolerance (DTE = 58.30). Genotypes with higher RDI, like DR (RDI = 1.17) and VP (RDI = 1.13), indicated the potential for high yields under controlled and drought stress conditions. At the same time, PT (RDI = 0.76) and FS (RDI = 0.84) displayed lower RDI values, indicating higher sensitivity to drought stress. Considerable diversity was observed among genotypes for traits like MRP and REI, with genotypes VP, MP, PN and DR exhibiting higher values, signifying tolerance. In contrast, PPS displayed the lowest MRP (1.14) and REI (0.32), profoundly impacted by terminal stress. MSTIK1 and 2 indices identified VP, MH, and PN as the most tolerant (MSTIK1 = 2.24, 1.99 and 1.25, MSTIK2 = 2.87, 2.12 and 1.52, respectively), while PPS, PT, and FS were more sensitive, displaying lower MSTIK1 and 2 values (MSTIK1 = 0.07, 0.33 and 0.42, MSTIK2 = 0.09, 0.19 and 0.30, respectively). This comprehensive analysis aids in genotype selection for enhanced drought resilience, emphasizing the importance of specific indices in assessing tolerance levels in different genotypes.

Root: shoot ratio: Evaluating drought-stress genotypes revealed distinct responses measured by various indices. Genotypes VP, MH, and DR exhibited the lowest SSI values (0.34, 0.48, and 0.51, respectively) and minimal TOL values (0.03, 0.04, and 0.05, respectively), indicating minimal reduction in plant biomass and high drought tolerance. Conversely, ST displayed the highest SSI (3.61) and TOL (0.32) values, portraying a significant reduction in plant biomass and lower drought tolerance, with PA and PT showing similar trends. Yucel (2014) emphasized identifying genotypes with lower SSI and TOL values for drought tolerance in chickpeas. Higher values in indices like STI, DTE, RDI, MRP, REI and MSTIK1 and 2 indicated increased resilience to drought. DR (STI = 1.28) and PN (STI = 1.13) displayed superior tolerance, whereas PT, FS and ST exhibited susceptibility to drought stress. Genotypes with higher STI values showcased greater tolerance to terminal drought, exemplified by DR (DI = 1.17) and VP (DI = 1.09) compared to ST (DI = 0.39). PS demonstrated the highest DTE (96.77), followed closely by VP (95.95), while ST showed the least tolerance (57.33). PS (RDI = 1.10) and VP (RDI = 1.09) displayed the highest RDI values, indicating their capacity for high yields under both controlled and drought-stress conditions. Conversely, ST had the lowest RDI values (0.65), indicating higher sensitivity to drought stress. Diversity was evident among genotypes in MRP and REI, with DR and PN showing high values (MRP = 2.42 and 2.26, REI = 1.46 and 1.28 respectively), signifying significant tolerance, whereas PT exhibited notably lower values (MRP = 1.69, REI = 0.71) under terminal stress. Similar ranks of varieties were observed by REI and MRP, which suggests that these two indices have equal importance for selecting genotypes under stress and non-stress conditions (Akcura and Ceri 2011). The MSTIK1 and 2 indices highlighted in genotypes DR, PN, and VP as the most tolerant (MSTIK1 = 1.76, 1.40, and 1.13, MSTIK2 = 1.99, 1.49, and 1.34, respectively), FS, PT and ST (MSTIK1 = 0.07, 0.33, and 0.42, respectively) showcased lower MSTIK1 values, while ST, PT, and FS (MSTIK2 = 0.30, 0.43, and 0.50, respectively) displayed lower MSTIK2 values, indicating higher sensitivity among these genotypes. Clustering methods utilizing drought indices for plant height (Table 2) and root: shoot ratio (Table 3) identified five and three clusters, respectively, indicating divergence among selected grape genotypes regarding drought tolerance. These findings help in selecting grape genotypes with enhanced drought resilience.

Principle component analysis (PCA): The analysis used PCA to condense 10 indices into two components (PCA1 and PCA2) to assess the relationship between grape genotypes and drought tolerance. In Fig. 1C, both PCA components had eigen values above one (9.02 and 2.84), collectively explaining 98.91% variance across drought stress indices. This aligns with previous research on rice (Rahimi *et al.* 2013, Baghyalakshmi *et al.* 2016). PCA1, explaining 75.20% of the variation, was associated with higher plant height and drought tolerance, encompassing DI, PH-D, MSTIK2, STI, REI, MSTIK1, MRP, and PH-C. PCA2 (23.70% variance) showed a positive correlation with TOL, SSI, DTE and RDI, consistent with findings by Jha *et al.* (2018). Genotypes with high PCA1 and low PCA2 values suit drought and irrigated environments. The relationship between genotypes and drought indices was illustrated using a biplot, indicating strong positive correlations between REI, STI, MRP, MSTIK1, MSTIK2, DI and plant height under both control (PH-C) and drought (PH-D) conditions. Conversely, traits like SSI and TOL exhibited negative correlations with PH-C, PH-D, REI, STI, MRP, MSTIK1, MSTIK2, DI, RDI, and DTE. Similar genotype rankings aligned with El-Hashash *et al.* (2018). Oblique angles between SSI, TOL and other indices indicated distinct relationships. Significantly, no strong associations were found between SSI, TOL and

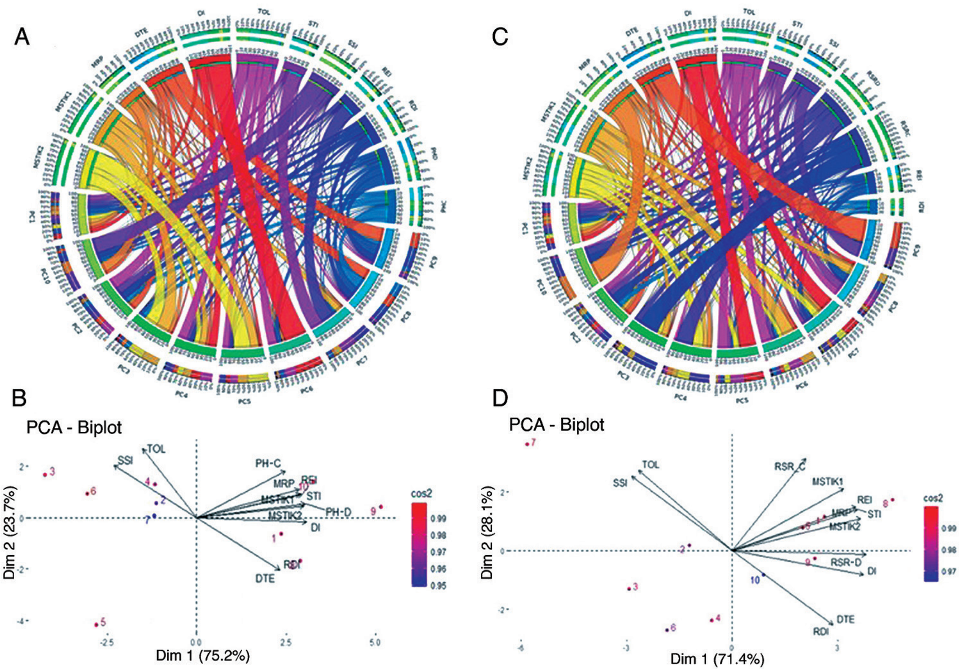

Fig. 1 Circos plot showing genotypes contribution to plant height (A) and root: shoot ratio (B) with respective IPCAs. Multivariate analysis between selection indices and plant height biplot (C) and root-shoot ratio (D).

C, Control; D, Drought; PH, Plant height, SSI, Stress susceptibility index; TOL, Tolerance index; STI, DI, Drought resistance index; DTE, Drought tolerance efficiency; RDI, Relative drought index; MRP, Mean relative performance; REI, Relative efficiency index; MSTIK 1, Modified stress tolerance index 1; MSTIK 2, Modified stress tolerance index 2; PN, Pusa Navrang; PA, Pusa Aditi; PT, Pusa Trisha; PS, Pusa Swarnika; PPS, Pusa Purple Seedless; FS, Flame Seedless; SG, St. George; DR, Dogridge; VP, *Vitis parviflora;* MH, Male Hybrid.

other drought indices. The chosen genotypes (PN, DR, VP, and MH) exhibited positive performance under varied conditions based on the biplot's positive value in PCA for rainfed and irrigated scenarios. The results of the PCA analysis showed that these traits are important for selection and future breeding programmes. They also highlight the genetic diversity of the trait's contribution to the studied material (Baranwal *et al.* 2024).

To delve deeper into the connection between root-to-shoot ratio and drought tolerance indices, the PCA findings unveiled that the initial pair of factors in the principal component analysis accounted for over 71.38% of the variation involving RSR-D, DI, MSTIK2, STI, REI, and MRP. In comparison, the second principal component accounted for 28.08% of the overall variability, including RSR-C, TOL, SSI, RDI, DTE and MSTIK1 (Fig. 1D). Additionally, the indices RDI and DTE exhibited overlapping vectors in both cases, as illustrated in Fig. 1B and 1D. Similar findings were observed in studies conducted by Mousavi *et al.* (2008), Yarnia *et al.* (2011) and Nouraein *et al.* (2013). Consequently, this primary dimension could encompass plant biomass potential and drought resilience. Constructing a biplot revealed that the DI, MSTIK2, STI, REI, and MRP indices were the most appropriate criteria for identifying genotypes under irrigated and drought conditions. These findings align with Fernandez's (1992) and Golabadi *et al.* (2006) studies. By observing genotypes with higher scores in component-1 and lower in component-2 on the biplot, stable genotypes were identified as PN, PPS, DR, VP and MH. In comparison, genotypes with lower scores in component-1 and higher scores in component-2 exhibited less stable genotypes.

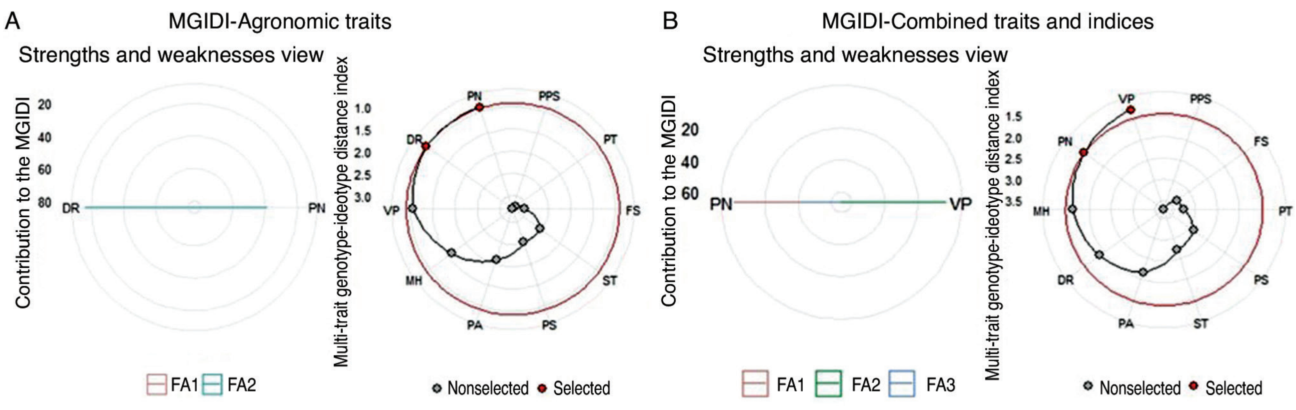

Fig. 2 The selected grape genotypes where strengths and weaknesses are illustrated by displaying the proportion and ranking of each factor, arranged in ascending order based on the MGIDI for (A) agronomic traits alone and (B) combined agronomic traits and drought-tolerance indices.

PN, Pusa Navrang; PA, Pusa Aditi; PT, Pusa Trisha; PS, Pusa Swarnika; PPS, Pusa Purple Seedless; FS, Flame Seedless; SG, St. George; DR, Dogridge; VP, *Vitis parviflora;* MH, Male Hybrid.

The Circos plots in Fig. 1A and 1C illustrate how different grape genotypes contribute to plant height and root: shoot ratio under drought conditions. These Circos plots act like a visual fingerprint of genotype performance and variability; Larger arcs indicate more stable and stress-resilient genotypes. Circos plot for plant height (Fig. 1A) interprets genotype like VP, MH, DR and PN show higher contributions PCA1 that aligns with drought-tolerant indices such as STI, DI, MRP, REI, MSTIK1, MSTIK2 that indicates more drought-tolerance in terms of plant height. PCA2 reflects traits more related to stress susceptibility (like SSI and TOL), and genotypes scoring higher here are less stable under stress. Circos plot for root: shoot ratio (Fig. 1C) indicates genotypes like DR, PN, and VP again show strong contributions, indicating higher root biomass retention under drought which is a key drought adaptation trait whereas genotypes like SG or PT, which performed poorly under drought, contribute less.

Correlation analysis of different drought tolerant indices with plant height and root:shoot ratio: The correlation analysis between plant height (PH) and root:shoot ratio (RSR) concerning drought tolerance indices, serves as a critical criterion for genotype selection and drought tolerance assessment. The strong correlation ($P<0.001$) observed between PH-C and PH-D indicates that superior performance under full irrigation conditions predicts similar performance under drought stress, aligning with Pantuwan *et al.* (2002), Rizza *et al.* (2004) and Wasae (2021), suggesting high-yield varieties adapt well to moderate stress. Under stress conditions, PH-D positively correlates ($P<0.001$) with DI, MRP, STI, REI, MSTIK1 and MSTIK2, while RDI, DTE, TOL, and SSI exhibit non-significance ($P\geq0.05$). Consequently, the positive correlation ($P<0.001$) was observed between MRP, STI, REI, and MSTIK1 with PH-C and the positive correlation ($P<0.01$) of DI and MSTIK2 with PH-C, alongside its non-significance ($P\geq0.05$) with RDI, DTE, TOL and SSI indices. Conversely, RSR-C and RSR-D exhibit statistically insignificant relationships ($P\geq0.05$), suggesting that high plant biomass under normal conditions does not necessarily translate to a higher root-to-shoot ratio in drought scenarios. Indices like MRP, MSTIK2, STI, REI, and DI demonstrate strong positive correlations ($P<0.001$) with RSR-D, while MSTIK1, RDI, and DTE exhibit significant positive correlations ($P<0.01$, <0.05 and <0.05, respectively) with RSR-D. Additionally, SSI and TOL showed significant negative correlations ($P<0.05$) with RSR-D. The RSR-C showed a positive correlation with MSTIK2 ($P<0.001$), MSTIK1 ($P<0.05$), MRP ($P<0.01$), STI ($P<0.01$), and REI ($P<0.01$) and a non-significant correlation ($P\geq0.05$) with DI, DRI, DTE, TOL and SSI indices. Therefore, solely relying on results from normal conditions might not effectively predict performance under drought stress.

Selection of drought-tolerant genotypes: The multi-trait genotype-ideotype distance (MGIDI) index was computed to choose drought-tolerant genotypes, considering all the measured traits (plant height and root: shoot ratio) (Fig. 2A) and combined traits with drought tolerance indices (Fig. 2B). The evaluation of genotypes through the multivariate stability trait index (MSTI) using MGIDI revealed the ranking of each factor's influence and depicted the strengths and weaknesses across 10 grape genotypes. The analysis for the agronomic traits (Fig. 2A) revealed that for genotypes PN and DR, the primary factor (FA1) made the most significant contribution, indicating that these genotypes perform better under stress. In the second scenario (Fig. 2B) illustrated for the combined traits with drought tolerance indices, FA successfully reduced 24 component traits to three factors. The selection of drought-tolerant genotypes was in the order of VP, PN, MH, and DR, indicating their potentially exciting characteristics. A similar result of ranking genotypes was also seen by different researchers (Mezzomo *et al.* 2023). These traits could be crucial in future studies to screen tolerant genotypes during early growth. Applying the MGIDI index in plant crop investigations is anticipated to expand rapidly. Similarly, Olivoto *et al.* (2021) employed this index to select optimal strawberry genotypes.

Present study concluded that the specific indices like DI, MRP, STI, REI, MSTIK1 and MSTIK2 emerged as the most reliable indicators for distinguishing drought-tolerant genotypes. Principal component analysis also grouped grape genotypes into clusters of five and three for PH and RSR based on their performance under drought. MGIDI imply that genotypes VP, PN, MH and DR showed superior drought tolerance traits within the population. Comprehensive conclusions require molecular analyses of these genotypes for further clarity.

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