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Evaluation of Drought Tolerance and Adaptation of Large-seeded Soybean Genotypes under Various Drought Stress Levels

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ABSTRACT

Background: Adapting large-seeded soybean to drought stress is essential, requiring development drought-tolerant cultivars and management practices to sustain yield under water-limited conditions. This study aimed to evaluate and identify drought-tolerant soybean genotypes using drought indices in order to recommend promising genotypes for cultivation in drought-affecting regions.

Methods: The experiment employed Split-Plot Design in Completely Randomized Design. The main plots were drought stress levels consisting of four levels, non-stress, 10% PEG6000, 20% PEG6000 and 65% field capacity. The sub-plots were 20 large-seeded soybean genotypes, replicated four times. Based on yield performance under non-stress (Yp) and drought stress (Ys), drought indices (Stress tolerance index, Stress adaptation index, geometric mean productivity, mean productivity, harmonic mean, yield stability index, yield index, drought response index, tolerance index, stress susceptibility Index) were calculated, Pearson correlation and PCA biplot analyses were computed. All statistical analyses were done using the SmartStatXL add-in.

Result: Seed yield of large-seeded soybean genotypes varied significantly under different drought stress levels. Drought tolerance indices, STI, SAI, GMP, MP, HM, DRI and YSI, were strong positive correlated with yield, confirming their effectiveness in identifying drought-tolerant and stable genotypes. PCA biplot analysis effectively separated drought-tolerant from susceptible genotypes and classified Grobogan, Dega-1, KH-1 and Biosay-2 as tolerant under 10% PEG6000 ≈ -0.19 MPa, Grobogan, Dega-1, KH-1 and Burangrang under 20% PEG6000 ≈ -0.67MPa and Grobogan and Dega-1 under 65% field capacity. Of all the drought stress, Grobogan and Dega-1 consistently exhibited superior yield and drought tolerance, making them valuable genetic resources for breeding drought-tolerance soybean.

Key words: Drought-indices, Drought-stress, Drought-tolerant, Large-seeded-genotype, Soybean.

INTRODUCTION

Water is among the most crucial factors in agriculture. Drought due to lack of water during plant growth will affect plant growth and productivity (Liliane *et al.*, 2020). Therefore, plant tolerance and adaptation to drought stress are very necessary for all crops including soybeans. Drought tolerance soybean enables it to thrive in challenging lack of water environments. Understanding and enhancing this trait is essential for sustainable agriculture and ecosystem management in the face of drought stress and climate change. Soybean breeders and agronomists aim to develop economically *via*ble varieties that maintain yield under drought. Selecting high-yielding and stable yield genotypes under limited-water stress is a key criterion for evaluating (Mahantesh *et al.*, 2018; Yan *et al.*, 2020; Zafer *et al.*, 2023).

In Indonesia, more than 110 varieties of soybean have been officially released by government, range from large- to small-seeded, with large-seeded types preferred by farmers and industries for their higher productivity and better suitability for processed products like tempeh and tofu (Prasetiaswati *et al.*, 2022; Xu *et al.*, 2022). The large-seeded genotypes often have tolerance to sub-marginal environmental conditions including drought stress due to their ability to access moisture in deeper soil layers (Riduan *et al.*, 2022). However, many prior studies reported large-seeded genotypes might require more water since morphologically wider leaves more transpiration rate than small-seeded one, making drought tolerance a critical trait for these genotypes in water-limited regions (Kisman *et al.*, 2021, 2023; Kisman, Sumarjan, *et al.*, 2022; Kisman, Yakop, *et al.*, 2022). Developing drought-tolerant soybean varieties with favorable agronomic traits is essential. This process relies on access to tolerant genetic resources, effective screening, identification of key tolerance traits and

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targeted genetic improvement (Bagheri *et al*., 2023; Emmanuel *et al*., 2020; Madhu *et al*., 2023; Malinowska *et al*., 2020).

In identifying drought-tolerant genotypes, numerous effective screening methods have been established and documented. Among these methods, drought indices are commonly utilized, focusing on genotypes that consistently produce a high yield in both stressful and favorable conditions (Shahrokhi *et al*., 2020), namely stress tolerance index (STI) (Fernandez, 1992) and stress adaptation Index (SAI) (Howeler, 1991a), mean productivity (MP) (Rosielle and Hamblin, 1981), tolerance index (TOL) (Askari *et al*., 2017), geometric mean productivity (GMP) (Fernandez, 1992), stress susceptability index (SSI) (Fischer and Maurer, 1978), drought resistance index (DI) (Lan, 1998), yield stability index (YSI) (Bouslama and Schapaugh Jr., 1984) and yield index (YI) (Gavuzzi *et al*., 1997). Those indices have been employed to assess the drought tolerance and adaptation on various crop genotypes by focusing on yield performance, including soybean (Kisman *et al*., 2021; Riduan *et al*., 2022; Wang *et al*., 2022; Zafer *et al*., 2023), wheat (Eid and Sabry, 2019; Khosravizad, 2023; Sedghiyeh *et al*., 2025), haricot beans (Wasae, 2021), sweet potato (Gitore *et al*., 2021), rice (Heinemann *et al*., 2019; Kumar *et al*., 2018), barley (Fekadu *et al*., 2022) and common bean bush (Sánchez-reinoso *et al*., 2020). Those drought stress indices can be evaluated on planting media under simulated low water potential conditions induced by PEG 6000, a high-molecular-weight osmotic agent (Jincya *et al*., 2019; Shobanadevi *et al*., 2021).

This study aimed to evaluate and identify drought-tolerant soybean genotypes using drought tolerance indices in order to recommend promising genotypes for cultivation in drought-affecting regions.

MATERIALS AND METHODS

Experimental location and materials

The experiment took place from May to November 2023 in a greenhouse at "Farm KU", Tanjung Karang village (8°36′ 39.505″S, 116°4′ 34.714″E; 9 m a.s.l.), approximately 2 km from the University of Mataram, West Nusa Tenggara, Indonesia. The 2023 average monthly rainfall was 137mm, with February recording the highest (454 mm over 23 rainy days) (BPS Kota Mataram, 2024). Twenty large-seeded soybean genotypes sourced from various institutions (Table 1) were used. Supporting materials included PEG6000, NPK Phonska (16-16-16), organic fertilizers,

Table 1: Genetic materials consisting of 18 large-seeded and 2 medium-seeded soybean genotypes obtained from various sources.

Treatment code	Genotype (seed class)	Status (year released)	100-seed weight (seed size class)	Origin (cross)	Source (Institution)
G_1	Detam-2 (ES)	Variety (2008)	13.5 g (LS)	9837 Introduction × Wilis	ILETRI
G_2	Denasa-2 (BS)	Variety (2020)	18.6 g (LS)	Grobogan × IAC 100	ILETRI
G_3	Denasa-1 (BS)	Variety (2020)	18.1 g (LS)	IAC100/Burangrang/ Kaba × Argopuro	ILETRI
G_4	Devon-2 (BS)	Variety (2017)	16.9 g (LS)	G511H × Anjasmoro	ILETRI
G_5	Detam-1 (FS)	Variety (2008)	14.8 g (LS)	9837 line × Kawi	ILETRI
G_6	Derap-1 (BS)	Variety (2017)	17.6 g (LS)	G511H × Anjasmoro	ILETRI
G_7	Argomulyo (BS)	Variety (1998)	16.0 g (LS)	Thailand Nakhon Sawan I	ILETRI
G_8	Anjasmoro (BS)	Variety (2001)	14.8-15.3 g (LS)	Mansurian lines	ILETRI
G_9	Local A (-)	Commercial (2023)	14-18 g (LS)	-	Sophie, online
G_{10}	Edamame Ryoko 75 (-)	Variety (2002)	15 g (LS)	Introduction from Taiwan	ARDI
G_{11}	Kemuning-1 (FS)	Variety (2019)	18.0 g (LS)	Panderman radiation mutation	INEA
G_{12}	Grobogan (BS)	Variety (2008)	16-18 g (LS)	Malabar purification	ILETRI
G_{13}	Burangrang (BS)	Variety (1999)	17 g (LS)	Segregated pure lines	ILETRI
G_{14}	Kemuning-2 (FS)	Variety (2019)	18.0 g (LS)	Panderman radiation mutation	INEA
G_{15}	Dega-1(BS)	Variety (2016)	23.0 g (LS)	Grobogan × Malabar	ILETRI
G^{16}	Biosoy-2 (FS)	Variety (2014)	22.4 g (LS)	Chinese mutant × Japanese	ARDI
G_{17}	Detap (FS)	Variety (2017)	15.4 g (LS)	G511H × Anjasmoro	ILETRI
G_{18}	KH-1 (line)	Line	16-18 g (LS)	Brown-seeded pure line	Kismans' seed collection
G_{19}	Kaba (FS)	Variety (2011)	10.4 g (MS)	Double cross of 16 parents	ILETRI
G_{20}	Dering-1 (BS)	Variety (2012)	10.7 g (MS)	Davros × MLG 2984	ILETRI

Notes: BS: Breeder seed; FS (Foundation seed); ES (Extension seed); LS: Large-seeded, MS-Medium-seeded; INEA: Indonesian Nuclear Energy Agency (BATAN); ILETRI: Indonesian Legumes and Tuber Crops Research Institute (Balitkabi); ARDI: Agricultural Research and Development Institute (Balitbangtan).

goat manure, pesticides (Cruiser 350FS, Furadan 3G, Antracol 70WP, Corona 325SC, Decis 25EC), polybags, burnt rice husks and topsoil collected from rice fields in Pegilen, Kuranji village.

Experimental design

The study utilized a completely randomized design (CRD) arranged in a split-plot design within a greenhouse. The main plots comprised for drought levels: S_0 (non-stress), S_1 (10% PEG6000 ≈ -0.19 MPa), S_2 (20% PEG6000 ≈ -0.67 MPa) and S_3 (65% field capacity). Subplots consisted of 20 genotypes, with four replications each genotype.

Experimental procedures

Each 30 cm polybag was filled with 7 kg of a 2:1:1 mixture of dry topsoil, burnt husks and goat manure. Two pre-treated seeds (Cruiser 350FS) were sown per polybag, followed by Furadan 3G application to nitigate soil pests. After three weeks, one healthy plant was retained per polybag. Fertilizer (NPK Phonska) was applied at 50 kg ha^{-1} both pre-sowing and at 21 DAS. Manual weeding and pest control using Decis 25 EC were conducted twice at 3 and 5 weeks after sowing. Drought stress treatments began at the trifoliate stage, with PEG6000 applied weekly (40 ml) until the reproduktive phase (~30 DAS). The 65% field capacity treatment was managed by watering 1.5 L upon visible wilting symptoms (Kisman *et al*., 2023). The primary trait measured was seed weight (g plant^{-1}).

Drought tolerance and adaptation indices

Ten indices (STI, SAI, SSI, DRI, YSI, YI, MP, GMP, HM and TOL) were used to assess genotype performance under stress and non-stress conditions, calculated using standard formulas (Table 2).

Statistical analyses

Analysis of variance (ANOVA) at a 5% significance level was conducted to assess genotype performance across stress levels, followed by Tukey's HSD test. Drought indices were computed as per Table 2 and Pearson correlation analysis (Fekadu *et al*., 2022) was used to identify significant associations between yield and indices. Genotypes were categorized based on correlation strength into tolerant/ adapted and susceptible groups. Principal Component Analysis (PCA) and biplot visualizations were employed to identify high-yielding genotypes under both stress and non-stress conditions. All analyses were conducted using the SmartStatXL add-in (https://www.smartstat.info/download/category/22-excel-add-in.html#google_vignette).

RESULTS AND DISCUSSION

Variance analysis of seed yield

The analysis of variance of seed yield (g plant^{-1}) of soybean genotypes evaluated (Table 3) revealed that a highly significant difference in soybean seed yield due to the single factor (drought stress levels (S), soybean genotypes (G)

Table 2: The formulas used for indexing plant drought tolerance and adaptation under drought stresses.

Indices	Formulas	Criteria	References
Stress tolerance index (STI)	$\frac{(Ys)(Yp)}{(\bar{Y}p)^2}$	STI > 1.0 (tolerant); STI ≤ 0.5 (susceptible); 0.5 < STI ≤ 1.0 (moderate-tolerant)	Fernandez (1992)
Stress adaptation index (SAI)	$\frac{(Ys)(Yp)}{(\bar{Y}s)(\bar{Y}p)}$	SAI > 1.0 (adapted); SAI < 1.0 (non-adapted)	Howeler (1991b)
Stress susceptibility index (SSI)	$\frac{(1-(Ys/Yp)}{(1-(\bar{Y}s/\bar{Y}p)}$	SSI > 1.0 (more susceptible); SSI < 1.0 (less susceptible)	Fischer and Maurer (1978)
Drought resistance index (DRI)	$\frac{(Ys*(Ys/Yp)}{(\bar{Y}s)}$	High DRI (high yield under stress and non-stress)	Lan (1998)
Yield stability index (YSI)	$\frac{Ys}{\bar{Y}s}$	High YSI (stable under stress and non-stress)	Bouslama and Schapaugh Jr. (1984)
Yield index (YI)	$\frac{Ys}{\bar{Y}p}$	High YI (suitable for drought stress)	Gavuzzi et al. (1997)
Mean productivity (MP)	$\frac{(Yp+Ys)}{2}$	High MP (more tolerance to stress)	Fernandez (1992)
Geometric mean Productivity (GMP)	$\sqrt{Yp*Ys}$	High GMP (high yield in stress and non-stress)	Fernandez (1992)
Harmonic mean (HM)	$\frac{2*(Yp*Ys)}{(Yp+Ys)}$	High HM (more desirable)	Jafari et al. (2012)
Tolerance (TOL)	Yp - Ys	High TOL (susceptible to stress)	Fernandez (1992)

Notes: Yp and Ys = Seed yield of each genotype under non-stress and under-stress conditions, respectively; $\bar{Y}p$ and $\bar{Y}s$ = mean seed yield of all genotypes under non-stress and under-stress conditions, respectively.

and the interaction of drought stress levels and soybean genotype (S × G).

Tukey's HSD (Table 4) showed that mean seed yield under stress (S_1, 11.09±0.57 g plant^{-1}; S_2, 9.41±0.51 g plant^{-1}; S_3, 9.65±0.54 g plant^{-1}) was consistently lower than under non-stress (S_0, 17.75±0.69 g plant^{-1}). Genotype G_{12} (Grobogan, 21.40±1.69 g plant^{-1}) and G_{15} (Dega-1, 18.26± 1.62 g plant^{-1}) exhibited the highest yields, while G_1 (Detam-2, 4.70±0.39 g plant^{-1}) and G_5 (Detam-1, 6.39±0.46 g plant^{-1}) produced the lowest. Genotypes with consistent high yield (G_{12}, G_{15}, G_{16}, G_{18}, G_{20}) or low (G_1, G_5, G_{10}, G_{11}) under non-stress conditions showed similar patterns under stress.

Yield reductions varied among genotyps across stress levels (Fig 1), consistent with Fekadu *et al.* (2022) in barley. The smallest reductions occurred in G_4 (S_1: -1.77%), G_1 (S_2: -12.58%) and G_5/G_1 (S_3: -28.15%/-28.39%), while G_8, G_{11} and G_4 experienced the greatest reductions (-70.95%, -66.94% and -60.17%, respectively). G_1 (Detam-2) exhibited the least and G_8 (Anjasmoro) the most, yield loss across all stress levels.

However, yield reduction alone is not a definitive indicator of drought tolerance. Akbar *et al*. (2018) dan Purbowahyuani *et al*. (2019) emphasized that high yields under optimal conditions reflect genetic potential, essential in evaluating stress tolerance. Pertiwi *et al*. (2022) further noted that tolerance indices prioritize the ability to express genetic potential under non-stress conditions. Thus, yield decline under stress may result from environmental influences rather than poor adaptability. Supporting this, Shahrokhi *et al*. (2020) indicated that genotypes maintaining high seed yield under both stress and non-stress conditions, reflected in indeces like STI, tends to exhibit superior drought resilience.

Drought tolerance and adaptation indices

Drought tolerance refers to a plant's ability to sustain productivity under water-limited conditions (Shoaib *et al*., 2022), while adaptation involves physiological mechanisms like stomatal closure and osmoprotectant accumulation (Haghpanah *et al*., 2024; Seleiman *et al*., 2021). The Stress Adaptation Index (SAI) is a key tool for identifying drought-resilient soybean genotypes, emphasizing high yield potential, as initially propsed by Slamet and Suyamto (2001). Common indices used to assess drought response include STi, SAI, SSI, DRI, YSI, YI, MP, GMP, HM and TOL (Kisman *et al*., 2021; Riduan *et al*., 2022; Suhartina *et al*., 2021; Wasae, 2021).

Table 3: Analysis of variance (ANOVA) of seed yield per plant under various drought stress levels.

Source of Variance	Degree of Freedom	Sum of Square	Mean of Square	F-Value	P-Value	F-0.05
Drought stress (S)	3	3686.962	1228.987	84.417**	0.000	3.490
Error (a)	12	174.701	14.558			
Genotypes (G)	19	4967.929	261.470	25.444**	0.000	1.632
S × G	57	1042.827	18.295	1.780**	0.002	1.385
Error (b)	228	2343.019	10.276			
Total	319	12215.438				

Notes: ** = Significantly different at the 1% level; CV(a) = 31.86%; CV(b) = 26.76%.

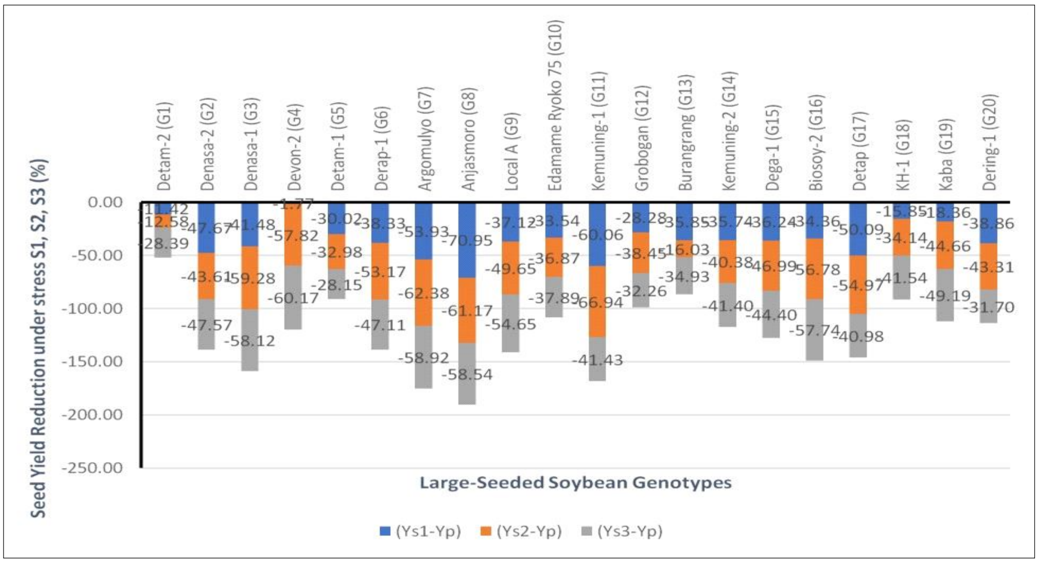

Fig 1: Percentage mean reduction of seed yield per plant (%) of 20 large-seeded soybean genotypes under varying drought stress levels, S_0 (normal, 0% PEG6000), S_1 (10% PEG6000), S_2 (20% PEG6000), S_3 (65% field capacity).

Table 4: Mean seed yield per plant of 20 soybean genotypes under various drought stress levels drought stress levels (S).

G	Yp ±SE (g)	Ys1 ±SE (g)	Ys2 ±SE (g)	Ys3 ±SE (g)	HSD (5%)	$\overline{Y}$s±SE (g)
G_1	5.41±1.15^{a}	4.79±0.66^{a}	4.73±0.88^{a}	3.87±0.32^{a}	5.99	4.70±0.39
	H	G	D	E		J
G_2	15.96±0.50^{a}	8.35±1.22^{b}	9.00±0.68^{b}	8.37±0.88^{b}	5.99	10.42±0.91
	CDEFG	DEFG	BCD	BCDE		FGHI
G_3	18.79±0.76^{a}	11.00±2.32^{b}	7.65±1.05^{b}	7.87±0.76^{b}	5.99	11.33±1.32
	BCDEF	BCDEFG	CD	BCDE		EFGH
G_4	13.74±1.75^{a}	13.50±2.11^{a}	5.80±1.26^{b}	5.47±0.89^{b}	5.99	9.63±1.25
	DEFG	ABCDE	D	DE		FGHI
G_5	8.28±0.97^{a}	5.79±0.80^{a}	5.55±0.54^{a}	5.95±0.88^{a}	5.99	6.39±0.46
	GH	EFG	D	CDE		IJ
G_6	18.23±0.49^{a}	11.24±2.77^{b}	8.54±1.31^{b}	9.64±1.15^{b}	5.99	11.91±1.22
	CDEF	BCDEFG	CD	BCDE		DEFG
G_7	23.04±2.54^{a}	10.62±0.42^{b}	8.67±0.97^{b}	9.47±1.99^{b}	5.99	12.95±1.70
	ABC	BCDEFG	CD	BCDE		CDEF
G_8	20.69±1.33^{a}	6.01±0.32^{b}	8.03±1.48^{b}	8.58±1.42^{b}	5.99	10.83±1.59
	ABCDE	EFG	CD	BCDE		EFGH
G_9	16.34±1.10^{a}	10.28±0.52^{b}	8.23±0.72^{b}	7.41±0.56^{b}	5.99	10.56±0.96
	CDEFG	BCDEFG	CD	BCDE		FGH
G_{10}	11.79±1.95^{a}	7.83±0.31^{a}	7.44±0.87^{a}	7.32±0.98^{a}	5.99	8.59±0.71G
	FGH	DEFG	CD	BCDE		HIJ
G_{11}	13.30±1.96^{a}	5.31±0.44^{b}	4.40±1.08^{b}	7.79±0.85^{ab}	5.99	7.70±1.05
	DEFGH	FG	D	BCDE	HIJ	
G_{12}	28.43±0.94^{a}	20.39±2.35^{b}	17.50±1.92^{b}	19.26±4.89^{b}	5.99	21.40±1.69
	A	A	A	A		A
G_{13}	20.17±0.50^{a}	12.94±2.96^{b}	16.94±4.12^{ab}	13.13±1.37^{b}	5.99	15.79±1.41
	BCDE	ABCDEF	AB	ABCD		BCD
G_{14}	17.15±1.03^{a}	11.02±1.43^{b}	10.23±1.16^{b}	10.05±2.95^{b}	5.99	12.11±1.11
	CDEF	BCDEFG	ABCD	BCDE		DEFG
G_{15}	26.81±1.95^{a}	17.10±1.86^{b}	14.21±2.42^{b}	14.91±2.32^{b}	5.99	18.26±1.62
	AB	ABC	ABC	AB		AB
G_{16}	23.42±0.18^{a}	15.37±0.47^{b}	10.12±2.01^{b}	9.90±1.78^{b}	5.99	14.70±1.54
	ABC	ABCD	ABCD	BCDE		BCDE
G_{17}	18.80±0.87^{a}	9.38±0.81^{b}	8.46±0.79^{b}	11.09±1.53^{b}	5.99	11.93±1.15
	BCDEF	CDEFG	CD	BCDE		DEFG
G_{18}	21.21±0.54^{a}	17.85±3.63^{ab}	13.97±0.65^{b}	12.40±2.04^{b}	5.99	16.35±1.30
	ABCD	AB	ABC	ABCD		BC

Table 4 Continue....

Table 4 Continue...

G_{19}	12.92 ± 1.64^{a}	10.55 ± 0.74^{ab}	7.15 ± 1.35^{ab}	6.57 ± 1.17^{b}	5.99	9.30 ± 0.88
	EFGH	BCDEFG	CD	CDE		FGHI
G_{20}	20.56 ± 2.14^{a}	12.57 ± 1.08^{b}	11.66 ± 0.79^{b}	14.04 ± 2.34^{b}	5.99	14.71 ± 1.18
	ABCDE	ABCDEFG	ABCD	ABC		BCDE
HSD (5%)	8.13	8.13	8.13	8.13		4.07
$\bar{Y}S\pm SE$ (g)	17.75 ± 0.69^{a}	11.09 ± 0.57^{b}	9.41 ± 0.51^{b}	9.65 ± 0.54^{b}	1.79	

Notes: G = Soybean genotypes: SE = Standard error; Yp = Seed yield under normal; Y_{s1} = Seed yield under PEG6000 10%; Y_{s2} = Seed yield under PEG6000 20%; Y_{s3} = Seed yield under soil fc 65%; $\bar{Y}$ S = Mean of seed yield of all genotypes under each stress; $\bar{Y}$ G = Mean of seed yield of each genotype under all stresses; The mean values sharing the same letter are not significantly different based on the Tukey (HSD) Test at a 0.05 significance level; Lowercase letters are interpreted horizontally, comparing two levels of S within the same G level; Capital letters are interpreted vertically, comparing two levels of G within the same S level.

Table 5 shows considerable variation in drought tolerance indices across genotypes and stress levels (PEG6000 10%, 20% and 65% FC). STI values ranged from 0.1-1.8 with 10-20% of genotypes scoring >1.0 depending on stress level. SAI ranged from 0.1-3.2 with 40% of values >1.0 under all stress conditions. GMP, MP and HM each identified 10-20% exceeding 1.0, while YSI showed higher proportions (40-60%) of genotypes with values >1.0. YI values mostly fell below 1.0 with only 5% exceeding that threshold under S_1. TOL and SSI values varied widely but did not indicate consistent tolerance trends. These results are consistent with previous findings in wheat by Eid and Sabry (2019), Khosra*viz*ad (2023) and Sedghiyeh *et al*. (2025).

Correlation analysis among all drought indices

Pearson correlation analysis is essential for identifying effective drought indices to determine genotypes with high yield potential and drought tolerance (Kumar *et al*., 2018). According to Anwar *et al*. (2011), indices that strongly correlate with seed yield under both stress and non-stress conditions are considered the most reliable indicators.

As shown in Table 6, significant positive correlations were observed among several drought indices, STI, SAI, GMP, MP, HM, DRI and YSI, with seed yields under normal (Yp) and drought stress conditions (Ys_1, Ys_2, Ys_3). These correlations varied with drought severity, as indicated by yield differences between Yp and Ys. These results suggest that these indices are effective in identifying drought-tolerant genotypes capable of maintaining higher yields under stress. These findings align with previous research in wheat (Eid and Sabry, 2019; Khosra*viz*ad, 2023; Sedghiyeh *et al*., 2025).

Tolerant/adapted/stable large-seeded soybean genotypes under drought stress

Biplot analysis enables effective identification of superior genotypes by simultaneously evaluating yield performance and drought-related indices under varying stress levels. In this current study, biplots constructed using two principal components (PC_1 and PC_2) illustrated genotype performance under stress levels of 10% PEG6000 (S_1), 20% PEG6000 (S_2) and 65% field capacity (S_3) (Fig 2). PC_1 represented overall yield stability and drought tolerance (Yp, Ys, STI, SAI, MP, GMP, HM, DRI, YSI), while PC_2 captured drought susceptibility, distinguishing genotypes with high yield only in non-stress conditions. Genotypes with high PC_1 and low PC_2 were considered optimal (Golabadi and Arzani, 2006).

Using Fernandez (1992) classification, genotypes were grouped based on yield performance: Group A (tolerant), Group B (non-stress specific), Group C (stress specific) and Group D (susceptible). Under S_1, G_{12} (Grobogan), G_{15} (Dega-1), G_{18} (KH-1) and G_{16} (Biosoy-2) were tolerant. Under S_2, G_{12} (Grobogan), G_{15} (Dega-1), G_{13} (Burangrang) and G_{18} (KH-1) remained in Group A, while under S_3, only G_{12} (Grobogan) and G_{15} (Dega-1) maintained their tolerat classification. These genotypes, especially KH-1,

Table 5: Drought stress tolerance and adaptation indices of 20 large-seeded soybean genotypes under various drought stress levels (PEG6000 10%, PEG6000 20%, 65% field capacity).

	Stress	Soybean genotype																			
	(S)	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	G_{11}	G_{12}	G_{13}	G_{14}	G_{15}	G_{16}	G_{17}	G_{18}	G_{19}	G_{20}
	p	5.4	16.0	18.8	13.7	8.3	18.2	23.0	20.7	16.3	11.8	13.3	28.4	20.2	17.2	26.8	23.4	18.8	21.2	12.9	20.6
Y (g/plant)	s1	4.8	8.4	11.0	13.5	5.8	11.2	10.6	6.0	10.3	7.8	5.3	20.4	12.9	11.0	17.1	15.4	9.4	17.9	10.6	12.6
	s2	4.7	9.0	7.7	5.8	5.6	8.5	8.7	8.0	8.2	7.4	4.4	17.5	16.9	10.2	14.2	10.1	8.5	14.0	7.2	11.7
	s3	3.9	8.4	7.9	5.5	6.0	9.6	9.5	8.6	7.4	7.3	7.8	19.3	13.1	10.1	14.9	9.9	11.1	12.4	6.6	14.0
STI	s1	0.1	0.4	0.7	0.6	0.2	0.7	0.8	0.4	0.5	0.3	0.2	1.8	0.8	0.6	1.5	1.1	0.6	1.2	0.4	0.8
	s2	0.1	0.5	0.5	0.3	0.2	0.5	0.6	0.5	0.4	0.3	0.2	1.6	1.1	0.6	1.2	0.8	0.5	0.9	0.3	0.8
	s3	0.1	0.4	0.5	0.2	0.2	0.6	0.7	0.6	0.4	0.3	0.3	1.7	0.8	0.6	1.3	0.7	0.7	0.8	0.3	0.9
SAI	s1	0.1	0.7	1.1	0.9	0.2	1.0	1.2	0.6	0.9	0.5	0.4	2.9	1.3	1.0	2.3	1.8	0.9	1.9	0.7	1.3
	s2	0.2	0.9	0.9	0.5	0.3	0.9	1.2	1.0	0.8	0.5	0.4	3.0	2.0	1.1	2.3	1.4	1.0	1.8	0.6	1.4
	s3	0.1	0.8	0.9	0.4	0.3	1.0	1.3	1.0	0.7	0.5	0.6	3.2	1.6	1.0	2.3	1.4	1.2	1.5	0.5	1.7
GMP	s1	5.1	11.5	14.4	13.6	6.9	14.3	15.6	11.2	13.0	9.6	8.4	24.1	16.2	13.8	21.4	19.0	13.3	19.5	11.7	16.1
	s2	5.1	12.0	12.0	8.9	6.8	12.5	14.1	12.9	11.6	9.4	7.7	22.3	18.5	13.2	19.5	15.4	12.6	17.2	9.6	15.5
	s3	4.6	11.6	12.2	8.7	7.0	13.3	14.8	13.3	11.0	9.3	10.2	23.4	16.3	13.1	20.0	15.2	14.4	16.2	9.2	17.0
MP	s1	5.1	12.2	14.9	13.6	7.0	14.7	16.8	13.4	13.3	9.8	9.3	24.4	16.6	14.1	22.0	19.4	14.1	19.5	11.7	16.6
	s2	5.1	12.5	13.2	9.8	6.9	13.4	15.9	14.4	12.3	9.6	8.9	23.0	18.6	13.7	20.5	16.8	13.6	17.6	10.0	16.1
	s3	4.6	12.2	13.3	9.6	7.1	13.9	16.3	14.6	11.9	9.6	10.6	23.9	16.7	13.6	20.9	16.7	14.9	16.8	9.7	17.3
HM	s1	5.1	11.0	13.9	13.6	6.8	13.9	14.5	9.3	12.6	9.4	7.6	23.8	15.8	13.4	20.9	18.6	12.5	19.4	11.6	15.6
	s2	5.0	11.5	10.9	8.2	6.6	11.6	12.6	11.6	10.9	9.1	6.6	21.7	18.4	12.8	18.6	14.1	11.7	16.8	9.2	14.9
	s3	4.5	11.0	11.1	7.8	6.9	12.6	13.4	12.1	10.2	9.0	9.8	23.0	15.9	12.7	19.2	13.9	14.0	15.7	8.7	16.7
DRI	s1	0.4	0.4	0.6	1.2	0.4	0.6	0.4	0.2	0.6	0.5	0.2	1.3	0.8	0.6	1.0	0.9	0.4	1.4	0.8	0.7
	s2	0.4	0.5	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.5	0.2	1.1	1.5	0.7	0.8	0.5	0.4	1.0	0.4	0.7
	s3	0.3	0.5	0.3	0.2	0.4	0.5	0.4	0.4	0.4	0.5	0.5	1.4	0.9	0.6	0.9	0.4	0.7	0.8	0.4	1.0
YSI	s1	0.4	0.8	1.0	1.2	0.5	1.0	1.0	0.5	0.9	0.7	0.5	1.8	1.2	1.0	1.5	1.4	0.9	1.6	1.0	1.1
	s2	0.5	1.0	0.8	0.6	0.6	0.9	0.9	0.9	0.9	0.8	0.5	1.9	1.8	1.1	1.5	1.1	0.9	1.5	0.8	1.2
	s3	0.4	0.9	0.8	0.6	0.6	1.0	1.0	0.9	0.8	0.8	0.8	2.0	1.4	1.0	1.5	1.0	1.2	1.3	0.7	1.5
YI	s1	0.9	0.5	0.6	1.0	0.7	0.6	0.5	0.3	0.6	0.7	0.4	0.7	0.6	0.6	0.6	0.7	0.5	0.8	0.8	0.6
	s2	0.9	0.6	0.4	0.4	0.7	0.5	0.4	0.4	0.5	0.6	0.3	0.6	0.8	0.6	0.5	0.4	0.5	0.7	0.6	0.6
	s3	0.7	0.5	0.4	0.4	0.7	0.5	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.6	0.6	0.4	0.6	0.6	0.5	0.7
TOL	s1	0.6	7.6	7.8	0.2	2.5	7.0	12.4	14.7	6.1	4.0	8.0	8.0	7.2	6.1	9.7	8.1	9.4	3.4	2.4	8.0
	s2	0.7	7.0	11.1	8.0	2.7	9.7	14.4	12.7	8.1	4.4	8.9	10.9	3.2	6.9	12.6	13.3	10.3	7.2	5.8	8.9
	s3	1.5	7.6	10.9	8.3	2.3	8.6	13.6	12.1	8.9	4.5	5.5	9.2	7.1	7.1	11.9	13.5	7.7	8.8	6.4	6.5
SSI	s1	0.3	1.3	1.1	0.1	0.8	1.0	1.4	1.9	1.0	0.9	1.6	0.8	1.0	1.0	1.0	0.9	1.3	0.4	0.5	1.0
	s2	0.3	0.9	1.3	1.2	0.7	1.1	1.3	1.3	1.1	0.8	1.4	0.8	0.3	0.9	1.0	1.2	1.2	0.7	1.0	0.9
	s3	0.6	1.0	1.3	1.3	0.6	1.0	1.3	1.3	1.2	0.8	0.9	0.7	0.8	0.9	1.0	1.3	0.9	0.9	1.1	0.7

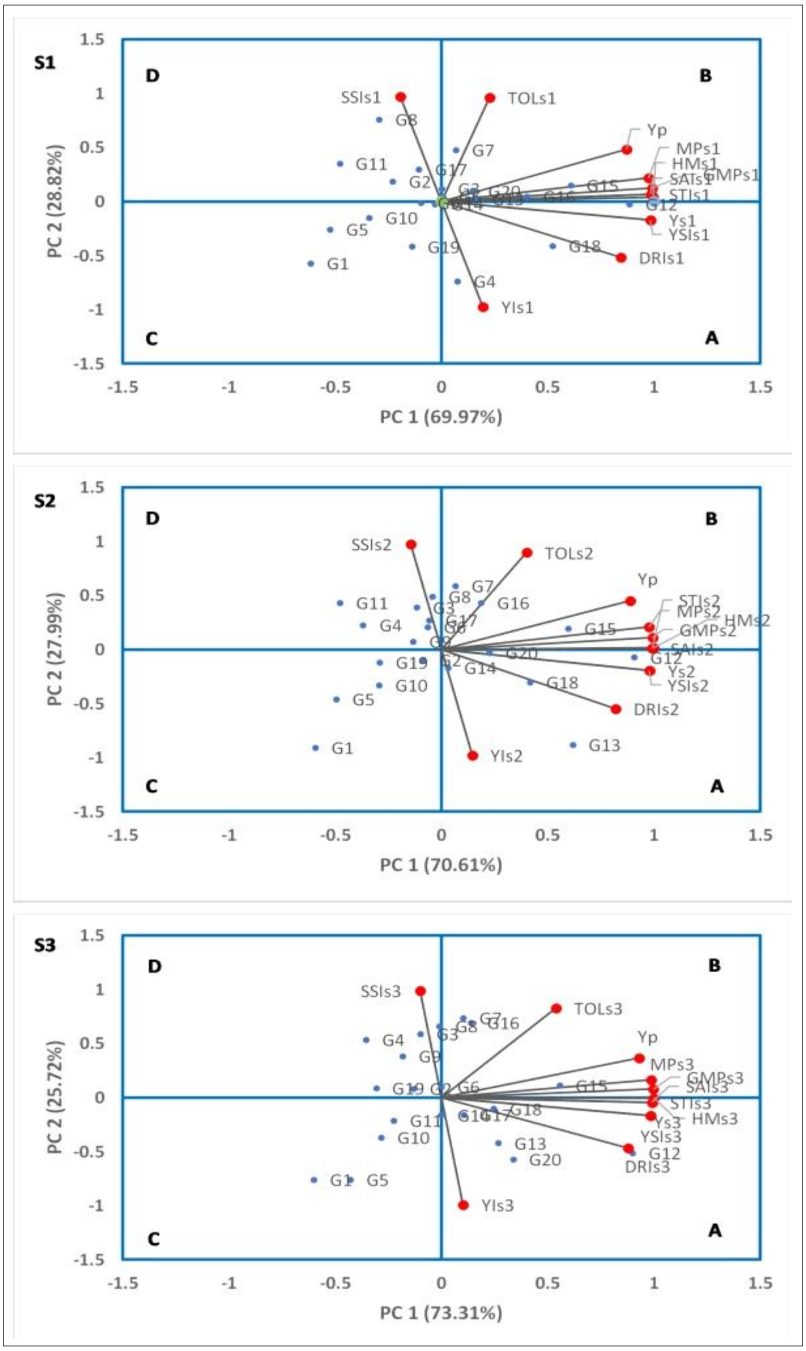

Fig 2: Biplot diagram of 20 soybean genotypes based on seed yield under stress and non-stress and drought indices under different drought stress levels: S_1 (10% PEG6000), S_2 (20% PEG6000), S_3 (65% field capacity).

showed enhanced drought adaptation (Kisman, Yakop, *et al*., 2022).

Group B include G_7 (Argomulyo) under S_1 and also G_{16} (Biosoy-2), G_8 (Anjasmoro) under S_2 and S_3. Group D, comprising drought-susceptible genotypes with low yield under all conditions, included G_8, G_{11} (Kemuning^{-1}), G_2 (Denasa-2) and G_{17} (Detap) at S_1; G_{11}, G_4, G_8, G_3 (Denasa-1) at S_2; and G_4, G_3, G_9 (Local A) at S_3. Genotypes G_1, G_5 (Detam-1), G_{10} (edamame Ryoko 75) and G_{19} (Kaba) were consistently identified in Group C across all stress levels. Prior research also recognized Grobogan and Dega-1 for their drought resilience (Saputra *et al*., 2015; Sukmasari, 2018; Wahono *et al*., 2018), with Grobogan noted performance in both drought and waterlogged conditions (Sukmasari, 2018).

Table 6: Pearson correlation matrix of drought indices based on seed yield under PEG6000 10% (S_1), PEG6000 20% (S_2) and 65% field capacity (S_3) drought stress conditions.

Index	Drought stress PEG6000 10% (S1)											
	Yp	Ys1	STIs1	SAIs1	GMPs1	MPs1	HMs1	DRIs1	YSIs1	YIs1	TOLs1	SSIs1
Yp	1.00											
Ys1	0.85 *	1.00										
STIs1	0.91 *	0.97 *	1.00									
SAIs1	0.91 *	0.97 *	1.00 *	1.00								
GMPs1	0.96 *	0.97 *	0.98 *	0.98 *	1.00							
MPs1	0.98 *	0.94 *	0.97 *	0.97 *	1.00 *	1.00						
HMs1	0.93 *	0.98 *	0.98 *	0.98 *	1.00 *	0.99 *	1.00					
DRIs1	0.63 *	0.94 *	0.87 *	0.87 *	0.83 *	0.78 *	0.87 *	1.00				
YSIs1	0.85 *	1.00 *	0.97 *	0.97 *	0.97 *	0.94 *	0.98 *	0.94 *	1.00			
YIs1	-0.36	0.16	0.04	0.04	-0.08	-0.16	-0.01	0.47 *	0.16	1.00		
TOLs1	0.81 *	0.38	0.51 *	0.51 *	0.60 *	0.67 *	0.54 *	0.05	0.38	-0.80 *	1.00	
SSIs1	0.36	-0.16	-0.04	-0.04	0.08	0.16	0.01	-0.47 *	-0.16	-1.00 *	0.80 *	1.00

Index	Drought stress PEG6000 20% (S2)											
	Yp	Ys2	STIs2	SAIs2	GMPs2	MPs2	HMs2	DRIs2	YSIs2	YIs2	TOLs2	SSIs2
Yp	1.00											
Ys2	0.78 *	1.00										
STIs2	0.88 *	0.96 *	1.00									
SAIs2	0.88 *	0.96 *	1.00 *	1.00								
GMPs2	0.93 *	0.95 *	0.98 *	0.98 *	1.00							
MPs2	0.97 *	0.91 *	0.97 *	0.97 *	0.99 *	1.00						
HMs2	0.89 *	0.98 *	0.98 *	0.98 *	1.00 *	0.98 *	1.00					
DRIs2	0.47 *	0.92 *	0.79 *	0.79 *	0.75 *	0.68 *	0.81 *	1.00				
YSIs2	0.78 *	1.00 *	0.96 *	0.96 *	0.95 *	0.91 *	0.98 *	0.92 *	1.00			
YIs2	-0.30	0.32	0.14	0.14	0.04	-0.06	0.13	0.63 *	0.32	1.00		
TOLs2	0.77 *	0.20	0.41	0.41	0.50 *	0.58 *	0.41	-0.19	0.20	-0.80 *	1.00	
SSIs2	0.30	-0.32	-0.14	-0.14	-0.04	0.06	-0.13	-0.63 *	-0.32	-1.00 *	0.80 *	1.00

Index	Drought stress 65% field capacity (S3)											
	Yp	Ys3	STIs3	SAIs3	GMPs3	MPs3	HMs3	DRIs3	YSIs3	YIs3	TOLs3	SSIs3
Yp	1.00											
Ys3	0.85 *	1.00										
STIs3	0.90 *	0.97 *	1.00									
SAIs3	0.90 *	0.97 *	1.00 *	1.00								
GMPs3	0.95 *	0.97 *	0.98 *	0.98 *	1.00							
MPs3	0.98 *	0.94 *	0.96 *	0.96 *	1.00 *	1.00						
HMs3	0.93 *	0.99 *	0.98 *	0.98 *	1.00 *	0.98 *	1.00					
DRIs3	0.64 *	0.95 *	0.88 *	0.88 *	0.84 *	0.79 *	0.88 *	1.00				
YSIs3	0.85 *	1.00 *	0.97 *	0.97 *	0.97 *	0.94 *	0.99 *	0.95 *	1.00			
YIs3	-0.26	0.26	0.14	0.14	0.02	-0.06	0.10	0.54 *	0.26	1.00		
TOLs3	0.81 *	0.38	0.50 *	0.50 *	0.60 *	0.67 *	0.53 *	0.07	0.38	-0.75 *	1.00	
SSIs3	0.26	-0.26	-0.14	-0.14	-0.02	0.06	-0.10	-0.54 *	-0.26	-1.00 *	0.75 *	1.00

*Significant at the alpha level of 0.05.
The number in the Table body is the value of the correlation coefficient.

CONLUSION

Seed yield of large-seeded soybean genotypes varied significantly under different drought stress levels (10% PEG6000, 20% and 65% field capacity). Drought tolerance indices (STI, SAI, GMP, MP, HM, DRI and YSI) were significantly positive correlations with yields suggesting their reliability for identifying drought-tolerant and stable large-seeded soybean genotypes. Biplot analysis effectively separated drought-tolerant from susceptable genotypes and classified Grobogan, Dega-1 and Biosoy-2 as tolerant under

10% PEG6000 ≈ -0.19 MPa stress, Grobogan, Dega-1, KH-1 and Burangrang under 20% PEG6000 ≈ -0.67MPa and Grobogan and Dega-1 under 65% field capacity. Of all the drought stress, Grobogan and Dega-1 were consistently superior high-yielding under both stress and non-stress conditions, showing the most tolerant and high dought stability genotypes. These genotypes serve as valuable genetic resources for enhancing drought tolerance in soybean breeding programs.

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Conflict of interest

We, all authors declare no conflict of interest.

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