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Research Article

Deciphering multi-cross trait correlations to enhance yield and drought resilience in soybean (*Glycine max*)

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Abstract
Soybean productivity is highly sensitive to water availability, especially in rainfed and drought-prone environments. Understanding the relationships among yield-related and morpho-physiological traits under varying moisture regimes can guide breeding programs for drought resilience and yield stability. This study investigates the interrelationships among morpho-physiological and yield-related traits in soybean under contrasting water regimes. Three soybean crosses (NRC 37 × EC 602288, JS 20-98 × EC 602288, and KDS 1173 × EC 602288) derived F_3 progenies were evaluated under drought and irrigated conditions. Simple correlation analysis was performed to elucidate the association patterns among traits contributing to yield per plant (YPP). Across all crosses, under drought stress, physiological traits *viz.* relative leaf water content, canopy temperature depression, specific leaf weight, normalized difference vegetation index (NDVI) at pod filling stage, canopy temperature, root-to-shoot ratio showed strong correlations with yield per plant (YPP). In contrast, phenological and reproductive traits, including days to 50% flowering (DFF), days to maturity (DPM), number of pods per plant (NPP), and harvest index (HI), exhibited higher correlations under irrigated regimes. The consistently high association of NDVI at R_5 stage with YPP across both conditions highlights its potential as a rapid, non-destructive selection index for soybean improvement. These consistent trait associations across genetic backgrounds support a dual strategy for breeding programs emphasizing physiological resilience under water stress and reproductive development under optimal conditions.

Keywords: Soybean, Drought tolerance, Correlation, Morpho-physiological traits

INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is one of the world's most important oilseed crops, valued not only for its high seed yield, nutritional value, and economic importance, but also for its role in improving soil fertility through symbiotic biological nitrogen fixation. Globally, soybean contributes significantly to food, feed, and industrial oil production. However, soybean is particularly vulnerable to environmental fluctuations, with drought stress emerging as one of the most persistent and damaging abiotic constraints in subtropical rainfed agro-ecosystems (Fenta *et al.,* 2014). Among the leguminous crops, soybean is especially susceptible to abiotic stresses compared to species like cowpea (*Vigna unguiculata*) and common bean (*Phaseolus vulgaris*) (Silveira *et al.,* 2003; Sepanlo *et al.,* 2014; Kachare *et al.*, 2019), as well as other field crops such as cotton, sorghum, and chickpea(Younis *et al.,* 2000; Talebi *et al.,* 2013; Gupta *et al.,* 2021). Drought episodes occurring during critical reproductive phases such as flowering and pod filling result in the most severe yield losses, reducing seed number, seed weight, and harvest index, while also compromising seed quality (Manavalan *et al.,* 2009; Igiehon *et al.,* 2021). It has been estimated that annual soybean yield losses due to drought average around 40% (Specht *et al.,* 1999), with reductions reaching up to 80% under severe, prolonged water deficits (Guimarães-Dias *et al.,* 2012; Du *et al.,* 2020).

Beyond restricting water availability, drought disrupts an intricate network of physiological, morphological, and phenological processes that govern plant growth, development, and reproduction (Wang *et al.,* 2024). In soybean, water scarcity significantly impairs essential physiological traits, including leaf water potential, relative water content (RWC), stomatal conductance, root exudation rate, and photosynthetic capacity (Hamayun *et al.,* 2010; Omae *et al.,* 2005, 2007). Among these, relative water content has been widely recognized as a reliable integrative indicator of plant water status and drought tolerance in crops such as soybean, French bean, and mustard (Parsons & Howe, 1984; Rosales-Serna *et al.,* 2004). Notably, cultivars maintaining higher midday leaf water content have been observed to produce more pods under drought conditions, illustrating the critical relationship between water economy and reproductive success (Omae *et al.,* 2005; Siddique *et al.,* 1999).

Other important physiological traits associated with drought resilience include canopy temperature (CT), an indicator of transpiration cooling, where lower canopy temperatures under drought reflect better plant water status and higher yield stability (Araus *et al.,* 2002). Similarly, specific leaf weight (SLW) is a key morphological trait, with higher SLW values typically associated with increased chlorophyll content and photosynthetic efficiency under stress (Jumrani *et al.,* 2017). Additionally, root-shoot length ratio, shoot-to-root biomass distribution, vigor index, stomatal conductance, and leaf turgidity are significant drought-adaptive attributes influencing plant survival and productivity in water-limited conditions (Hossain *et al.,* 2015; Kachare *et al.,* 2019; Sahu *et al.,* 2022). Remote sensing tools such as the normalized difference vegetation index (NDVI) and infrared thermometry have emerged as efficient, scalable, and non-destructive methods for assessing plant water status and drought responses. Carvalho *et al*. (2015) demonstrated the utility of NDVI and infrared thermometry in evaluating drought behaviour in Brazilian soybean cultivars, establishing strong associations between NDVI, chlorophyll content, photosynthetic rate, stomatal conductance, and transpiration.

Previous studies have identified individual drought-adaptive traits such as canopy temperature depression (CTD), relative leaf water content (RLWC), and NDVI. The present investigation attempted a multi-trait, multi-environment correlation analysis involving three biparental soybean crosses derived from diverse parental combinations, with the drought-tolerant genotype EC 602288 serving as a common donor parent. The objectives were to identify key physiological and agronomic traits associated with seed yield per plant (YPP) under drought and irrigated conditions, and to assess the consistency of these associations across diverse genetic backgrounds and moisture regimes in soybean.

MATERIALS AND METHODS

The present investigation was carried out at the Post Graduate Institute Research Farm, Mahatma Phule Krishi Vidyapeeth (M.P.K.V.), Rahuri, Maharashtra, India, over four consecutive seasons: *Kharif*-2022, Summer-2022, *Kharif*-2023, and Summer-2023. The experiments were conducted under both drought stress and irrigated conditions on uniformly managed fields with comparable soil fertility and topography. The study involved F_3 populations derived from three biparental soybean crosses: NRC 37 × EC 602288, JS 20-98 × EC 602288, and KDS 1173 × EC 602288. These populations were evaluated during Summer 2024 at the experimental farm of MPKV, Rahuri, under two contrasting moisture regimes: drought stress and irrigated conditions. The experiment was laid out in a Randomized Block Design (RBD) with three replications to ensure precision and minimize environmental variability.

The individual plant served as the experimental unit, and all phenotypic observations and statistical analyses were carried out at the single-plant level. For each cross, a total of 240 individual F_3 plants were evaluated, including 120 plants under drought stress and 120 under irrigated conditions. This total included an equal number of plants sampled from each replication under each treatment. The sample size was chosen to adequately capture the inherent variability in early segregating generations and to provide a robust dataset for statistical analysis. A total of 18 quantitative traits associated with yield and drought tolerance were recorded.

The breeding scheme began with crossing of selected parental lines in *Kharif* 2022, followed by the raising of F_1 plants during Summer 2023. Subsequently, F_2 segregating populations were developed in *Kharif* 2023, and advanced to the F_3 generation for evaluation in Summer 2024. Throughout the study, standard agronomic practices, recommended fertilizer schedules, pest and disease management, and other crop husbandry measures were uniformly applied across all treatments and replications.

Drought Stress Management: Drought stress was imposed by withholding irrigation at beginning of flower initiation (R_2) stage, while control plots were maintained under optimal irrigation. Physiological measurements related to drought tolerance were recorded between 11:00 AM and 3:00 PM on bright, cloud-free days to ensure reliable expression of stress-induced traits. Data were recorded for days to 50% flowering (DFF), days to physiological maturity (DPM), plant height (PH), number of clusters per plant (NCP), number of pods per cluster (NPC), number of pods per plant (NPP), number of primary branches per plant (NPBP), hundred seed weight (HSW), number of seeds per pod (NSP), harvest index (HI), relative leaf water content (RLWC), canopy temperature (CT), canopy temperature depression (CTD), specific leaf weight (SLW), normalized difference vegetation indices (NDVI) at flower initiation stage (R_2) stage, NDVI at pod filling stage (R_5) stage, root/shoot ratio (R/S), and yield per plant (YPP).

Canopy Temperature (CT): Measured at the R_5 stage using a non-contact infrared thermometer (Palmer Wahl DHS115XEL) directed southward to capture canopy readings without sensing the soil (Guendouz *et al.,* 2012). Observations were recorded between 11:00 AM and 3:00 PM under clear skies.

Canopy Temperature Depression (CTD): Calculated by subtracting canopy temperature from ambient air temperature.

Relative Water Content (RWC, %): Determined using whole leaf by the formula:

RWC (%) = fresh weight (FW) − dry weight (DW) / turgid weight (TW) − dry weight (DW) ×100

Number of seeds per pod: Obtained by counting seeds from ten randomly selected pods per plant and computing the average.

Harvest Index (HI, %): = economic yield (seed yield)/ total above-ground biomass×100

Normalized difference vegetation index (NDVI): Recorded using a GreenSeeker 505 handheld optical sensor during R_2 and R_5 stages. The sensor detects red (656 nm) and near-infrared (774 nm) wavelengths, with values displayed as NDVI readings ranging from 0.00 to 0.99.

Root-to-shoot ratio: At physiological maturity, whole plants were uprooted, and roots were separated, washed, oven-dried at 60°C for 48 hours, and weighed. Root-to-shoot ratio was determined as:

Root-to-Shoot Ratio = Root Dry Weight/Shoot Dry Weight

Specific Leaf Weight (SLW, g/cm²): Fully expanded terminal leaflets at the R_5 stage were sampled. Leaf area was measured using INDUS-Leaf Area Analysis Software, dried at 70°C for 72 hours, and weighed. SLW was computed as:

SLW (g/cm²) =leaf dry weight / leaf area

Simple correlation coefficients were computed separately for drought and irrigated environments using SPSS v25.0, with significance tested at 5% and 1% levels.

RESULTS AND DISCUSSION

The present study investigated the interrelationships among morphological, physiological, and yield-related traits in F_3 segregating progenies of three soybean crosses (NRC 37 × EC 602288, JS 20-98 × EC 602288, and KDS 1173 × EC 602288) under drought stress and irrigated conditions. Simple correlation analyses revealed differential patterns of association under contrasting moisture regimes, highlighting the complex interactions between drought tolerance mechanisms and yield components. These findings have practical implications for selecting traits contributing to yield stability under moisture-limited environments.

*Trait associations under drought conditions***:**Under drought stress, distinctive patterns of trait associations were observed across the three soybean crosses, revealing critical physiological and yield-contributing traits sustaining productivity under moisture deficit.

In the cross NRC 37 × EC 602288, days to 50% flowering (DFF) showed significant positive correlations with number of pods per plant (NPP; r = 0.96), number of clusters per plant (NCP; r = 0.65), and yield per plant (YPP; r = 0.70), (**Table 1, Fig. 1A**), reaffirming the advantage of timely flowering for reproductive success under drought stress (Blum, 2011). Relative leaf water content (RLWC) exhibited strong positive associations with canopy temperature depression (CTD; r = 0.82) and YPP (r = 0.78), confirming the role of plant water status in maintaining productivity during stress (Felisberto *et al.,* 2023). Canopy temperature (CT) negatively correlated with YPP (r = –0.71), whereas CTD was positively associated (r = 0.71), suggesting that genotypes with cooler canopies and efficient transpiration cooling had better yield under drought (Guendouz *et al.,* 2012; Jumrani and Bhatia, 2019). Notably, SLW demonstrated moderate positive correlation with CTD (r = 0.65) and NDVI at R5 (r = 0.62), while also being positively associated with YPP (r = 0.61). Similar findings were reported by Jumarani and Bhatia (2019), indicating the role of thicker leaves in supporting yield through improved water-use efficiency and photosynthetic performance. The root-to-shoot (R/S) ratio in this cross showed a strong positive correlation with YPP (r = 0.80) and RLWC (r = 0.81), and negative correlation with CT (r = –0.82), suggesting that a larger root system contributed to improved water uptake, lower canopy temperature, and higher yield. These results align with findings by Jumarani and Bhatia (2019), who emphasized the importance of root traits in drought resilience.

In the cross JS 20-98 × EC 602288, CTD (r = 0.89), RLWC (r = 0.59), and SLW (r = 0.63) were significantly and positively correlated with yield per plant (YPP), highlighting their physiological relevance for sustaining yield under water deficit (**Table 3, Figure 1C**). SLW also had positive associations with CTD (r = 0.70) and NDVI at R2 (r = 0.71), indicating efficient canopy maintenance. R/S ratio positively correlated with YPP (r = 0.74) and SLW (r = 0.87), suggesting that greater root allocation supports water uptake and leaf development.

Similarly, in KDS 1173 × EC 602288, YPP showed highly significant correlations with NPP (r = 0.95), number of

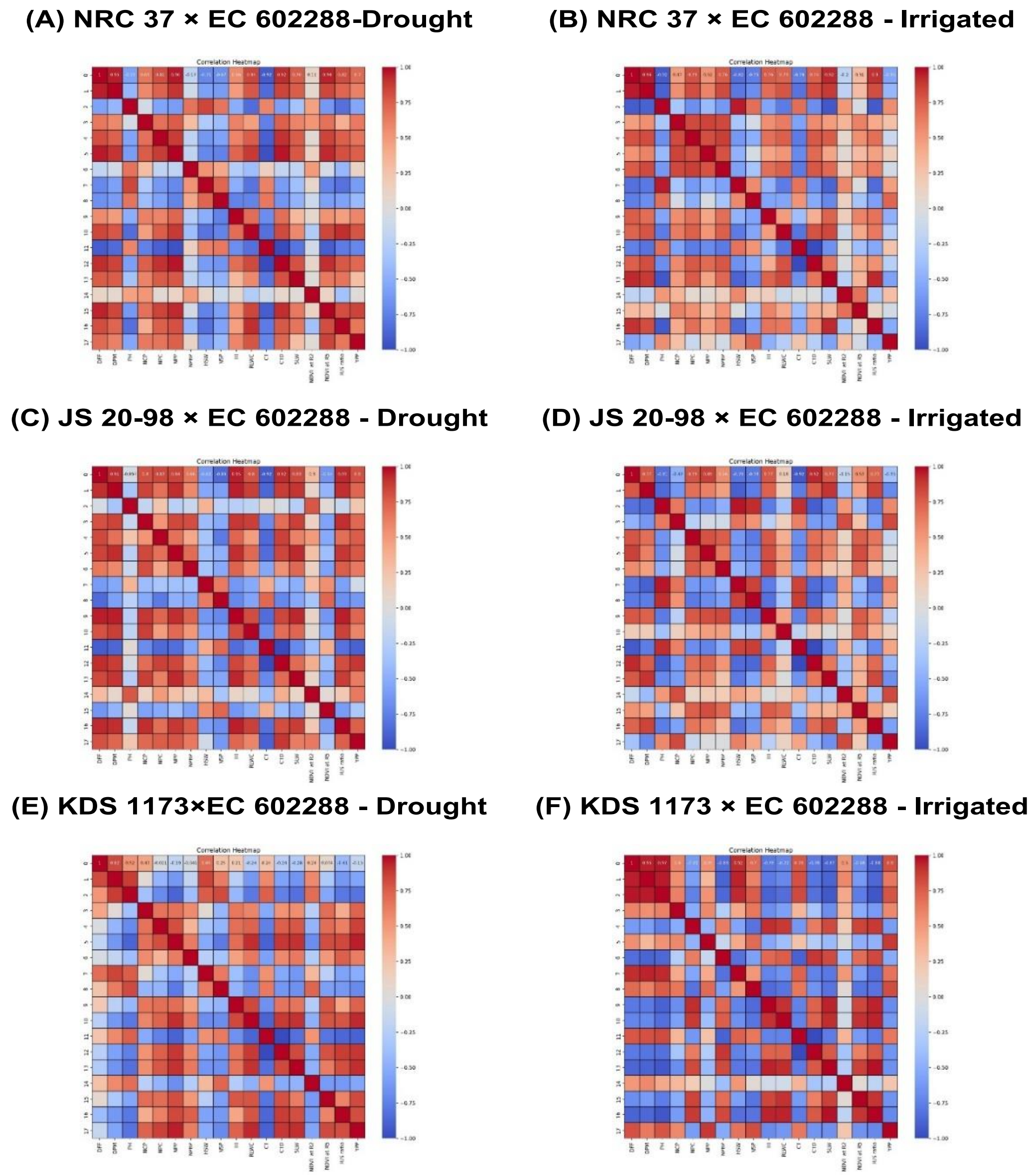

Fig. 1. Correlation heatmaps depicting interrelationships among morpho-physiological and yield-related traits in three soybean crosses under drought and irrigated conditions

Note: The figure illustrates correlation heatmaps for three soybean crosses evaluated under drought (left column) and irrigated (right column) conditions. Positive correlations are represented by red shades and negative correlations by blue shades, with intensity corresponding to the strength of the correlation (ranging from −1.00 to +1.00). The traits analysed include growth, physiological, and yield-related parameters: Days to 50% flowering (DFF), Days to maturity (DPM), Plant height (PH), Number of clusters per plant (NCP), Number of pods per cluster (NPC), Number of pods per plant (NPP), Number of primary branches per plant (NPBP), 100 seed weight (HSW), Number of seeds per pod (NSP), Harvest index (HI), Relative leaf water content (RLWC), Canopy temperature (CT), Canopy temperature depression (CTD), Specific leaf weight (SLW), NDVI at R5 and R6, Root to Shoot ratio (R/S ratio), and Yield per plant (YPP).

pods per cluster (NPC; r = 0.85), harvest index (HI; r = 0.73), RLWC (r = 0.92), CTD (r = 0.89), and SLW (r = 0.91) (**Table 5, Fig. 1 E**). The strong association of YPP with NPP and NPC emphasized the importance of effective pod retention and seed setting under drought. Negative correlation of CT with YPP (r = -0.89**) further affirmed the role of canopy cooling. Additionally, NDVI at R2 and R5 stages correlated positively with YPP,

Table 1. Simple correlation among all traits in cross NRC 37 × EC 602288 under drought condition

Characters	DFF	DPM	PH	NCP	NPC	NPP	NPBP	HSW	NSP	HI	RLWC	CT	CTD	SLW	NDVI at R2	NDVI at R5	R/S ratio	YPP
DFF	1.0 **	0.95 **	-0.57 *	0.65 **	0.81 **	0.96 **	-0.17	-0.71 **	-0.67 **	0.56 *	0.84**	-0.92**	0.92 **	0.76 **	0.11	0.94 **	0.82 **	0.70 **
DPM		1.0 **	-0.44	0.57 *	0.74**	0.89 **	-0.09	-0.58 *	-0.60 *	0.48	0.78 **	-0.84**	0.84 **	0.75 **	0.06	0.84 **	0.72 **	0.61 *
PH			1.0 **	-0.06	-0.56 *	-0.59 *	0.67 **	0.84**	0.66 **	-0.50	-0.84**	0.59 *	-0.59 *	-0.35	0.46	-0.62*	-0.82**	-0.54 *
NCP				1.0 **	0.68 **	0.76 **	0.29	-0.29	-0.40	0.60*	0.46	-0.74 **	0.74 **	0.60 *	0.51	0.67 **	0.38	0.64 *
NPC					1.0 **	0.87**	-0.19	-0.63 *	-0.57 *	0.60 *	0.75 **	-0.90 **	0.90 **	0.76 **	0.05	0.85 **	0.74 **	0.66 **
NPP						1.0 **	-0.19	-0.70 **	-0.74 **	0.72 **	0.88 **	-0.96**	0.96 **	0.77 **	0.12	0.92 **	0.80 **	0.74**
NPBP							1.0 **	0.53 *	0.43	-0.26	-0.39	0.16	-0.16	-0.19	0.49	-0.07	-0.44	0.11
HSW								1.0 **	0.73**	-0.5	-0.81**	0.61 *	-0.61 *	-0.38	0.09	-0.74**	-0.81 **	-0.61 *
NSP									1.0 **	-0.74 **	-0.73 **	0.64 *	-0.64 *	-0.47	-0.11	-0.59 *	-0.56 *	-0.42
HI									-	1.0 **	0.69 **	-0.69 **	0.69 **	0.32	0.07	0.53 *	0.47	0.58 *
RLWC											1.0 **	-0.82 **	0.82 **	0.57 *	-0.28	0.84 **	0.91**	0.78 **
CT												1.0 **	-1.0 **	-0.80 **	-0.09	-0.91 **	-0.77 **	-0.71 **
CTD													1.0 **	0.80 **	0.09	0.91 **	0.77 **	0.71 **
SLW														1.0 **	0.02	0.66 **	0.66**	0.29
NDVI at R_2															1.0 **	0.12	-0.37	0.02
NDVI at R_5																1.0 **	0.82**	0.85 **
R/S Ratio																	1.0 **	0.65 **

Note: *, ** Significant at 5% and 1% level of significance, respectively. DF: Days to 50% flowering, DPM: Days to physiological maturity, PH: Plant height, NCP: Number of clusters per plant, NPC: Number of pods per cluster, NPP: Number of pods per plant, NPBP: Number of primary branches per plant, HSW: Hundred seed weight, YPP: Yield per plant, NSP: Number of seeds per pod, HI: Harvest index, RLWC: Relative leaf water content (%), CT: Canopy temperature at grain filling stage (˚C), CTD: Canopy temperature depression (˚C), SLW: Specific leaf area (g/cm^2), NDVI at R_2: Normalized difference vegetation index at full bloom stage, NDVI at R_5: Normalized difference vegetation index at Beginning seed filling stage, R/S ratio: Root to Shoot Ratio

Table 2. Simple correlation among all traits in cross NRC 37 × EC 602288 under irrigated condition

Characters	DFF	DPM	PH	NCP	NPC	NPP	NPBP	HSW	NSP	HI	RLWC	CT	CTD	SLW	NDVI at R2	NDVI at R5	R/S ratio	YPP
DFF	1.0 **	0.96 **	-0.92 **	0.46	0.79 **	0.52 *	0.76 **	-0.82 **	-0.75 **	0.75 **	0.73 **	-0.74 **	0.74 **	0.92 **	-0.20	0.31	0.90 **	-0.55 *
DPM		1.0 **	-0.89 **	0.54 *	0.82 **	0.60 *	0.82 **	-0.79 **	-0.68 **	0.69 **	0.79 **	-0.81 **	0.81 **	0.88 **	-0.21	0.30	0.82 **	-0.44
PH			1.0 **	-0.32	-0.68 **	-0.43	-0.62 *	0.96 **	0.68 **	-0.55 *	-0.77 **	0.69 **	-0.68 **	-0.93 **	0.50	-0.05	-0.92 **	0.55 *
NCP				1.0 **	0.83 **	0.84**	0.83 **	-0.33	-0.07	0.55 *	0.63 *	-0.57 *	0.57 *	0.48	0.35	0.60*	0.40	0.27
NPC					1.0 **	0.81 **	0.86 **	-0.62 *	-0.50	0.67**	0.75**	-0.77 **	0.77 **	0.76 **	0.08	0.54*	0.68 **	-0.13
NPP						1.0 **	0.79 **	-0.48	-0.05	0.44	0.51 *	-0.70 **	0.70 **	0.44	0.05	0.30	0.45	0.15
NPBP							1.0 **	-0.57 *	-0.35	0.68 **	0.74 **	-0.77**	0.77 **	0.71 **	0.15	0.52 *	0.63 *	-0.07
HSW								1.0 **	0.57*	-0.47	-0.77 **	0.67 **	-0.67**	-0.88 **	0.57*	-0.01	-0.85 **	0.47
NSP									1.0 **	-0.55 *	-0.55 *	0.52 *	-0.52*	-0.70**	0.14	-0.35	-0.52 *	0.72 **
HI										1.0 **	0.48	-0.38	0.38	0.73**	0.17	0.60 *	0.67 **	-0.48
RLWC											1.0 **	-0.80 **	0.80**	0.83 **	-0.12	0.41	0.64 *	-0.25
CT												1.0 **	-1.0 **	-0.66 **	0.02	-0.38	-0.53 *	0.25
CTD													1.0 **	0.66 **	-0.02	0.38	0.53 *	-0.25
SLW														1.0 **	-0.25	0.35	0.93 **	-0.57 *
NDVI at R_2															1.0 **	0.68 **	-0.34	0.28
NDVI at R_5																1.0 **	0.11	-0.07
R/S Ratio																	1.0 **	-0.52 *

Note: *, ** Significant at 5% and 1% level of significance, respectively. DF: Days to 50% flowering, DPM: Days to physiological maturity, PH: Plant height, NCP: Number of clusters per plant, NPC: Number of pods per cluster, NPP: Number of pods per plant, NPBP: Number of primary branches per plant, HSW: Hundred seed weight, YPP: Yield per plant, NSP: Number of seeds per pod, HI: Harvest index, RLWC: Relative leaf water content (%), CT: Canopy temperature at grain filling stage (˚C), CTD: Canopy temperature depression (˚C), SLW: Specific leaf area (g/cm^2), NDVI at R_2: Normalized difference vegetation index at full bloom stage, NDVI at R_5: Normalized difference vegetation index at Beginning seed filling stage, R/S ratio: Root to Shoot Ratio

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Table 3. Simple correlation among all traits in cross JS 20-98 × EC 602288 under drought condition

Characters	DFF	DPM	PH	NCP	NPC	NPP	NPBP	HSW	NSP	HI	RLWC	CT	CTD	SLW	NDVI at R2	NDVI at R5	R/S ratio	YPP
DFF	1.0 **	0.91 **	-0.05	0.80 **	0.83 **	0.84 **	0.66 **	-0.61 *	-0.85 **	0.95 **	0.80 **	-0.91 **	0.91 **	0.83 **	0.30	-0.64 *	0.92 **	0.80 **
DPM		1.0 **	-0.33	0.84 **	0.67 **	0.92 **	0.57 *	-0.54 *	-0.58 *	0.95 **	0.87**	-0.87**	0.87 **	0.89 **	0.09	-0.45	0.91 **	0.72 **
PH			1.0 **	-0.16	0.24	-0.23	-0.14	0.36	-0.22	-0.24	-0.20	0.06	-0.06	-0.25	0.78 **	0.04	-0.16	0.22
NCP				1.0 **	0.52 *	0.83 **	0.81 **	-0.41	-0.52 *	0.88 **	0.86 **	-0.69 **	0.69 **	0.86 **	0.13	-0.57 *	0.91 **	0.72 **
NPC					1.0 **	0.67 **	0.42	-0.33	-0.78 **	0.72 **	0.47	-0.86 **	0.86 **	0.61*	0.48	-0.53 *	0.67 **	0.76 **
NPP						1.0 **	0.69 **	-0.38	-0.49	0.91 **	0.71 **	-0.84 **	0.84 **	0.93 **	0.27	-0.38	0.89 **	0.78 **
NPBP							1.0 **	-0.35	-0.52 *	0.73 **	0.50	-0.53 *	0.53 *	0.71 **	0.13	-0.57 *	0.76 **	0.64 *
HSW								1.0 **	0.64 *	-0.63 *	-0.53 *	0.40	-0.40	-0.51	0.30	0.55 *	-0.58 *	-0.09
NSP									1.0 **	-0.71 **	-0.56 *	0.71 **	-0.71 **	-0.54 *	-0.34	0.72 **	-0.68 **	-0.62 *
HI										1.0 **	0.82**	-0.84 **	0.84 **	0.94 **	0.11	-0.64 *	0.95 **	0.72 **
RLWC											1.0 **	-0.69 **	0.69**	0.72 **	0.05	-0.50	0.86 **	0.59 *
CT												1.0 **	-1.0 **	-0.70**	-0.39	0.39	-0.82 **	-0.89 **
CTD													1.0 **	0.70 **	0.39	-0.39	0.82 **	0.89 **
SLW														1.0 **	0.10	-0.52 *	0.87 **	0.63 *
NDVI at R_2															1.0 **	0.03	0.22	0.63 *
NDVI at R_5																1.0 **	-0.60 *	-0.31
R/S Ratio																	1.0 **	0.74**

Note: *, ** Significant at 5% and 1% level of significance, respectively. DF: Days to 50% flowering, DPM: Days to physiological maturity, PH: Plant height, NCP: Number of clusters per plant, NPC: Number of pods per cluster, NPP: Number of pods per plant, NPBP: Number of primary branches per plant, HSW: Hundred seed weight, YPP: Yield per plant, NSP: Number of seeds per pod, HI: Harvest index, RLWC: Relative leaf water content (%), CT: Canopy temperature at grain filling stage (˚C), CTD: Canopy temperature depression (˚C), SLW: Specific leaf area (g/cm^2), NDVI at R_2: Normalized difference vegetation index at full bloom stage, NDVI at R_5: Normalized difference vegetation index at Beginning seed filling stage, R/S ratio: Root to Shoot Ratio

Table 4. Simple correlation among all traits in cross JS 20-98 × EC 602288 under irrigated condition

Characters	DFF	DPM	PH	NCP	NPC	NPP	NPBP	HSW	NSP	HI	RLWC	CT	CTD	SLW	NDVI at R2	NDVI at R5	R/S ratio	YPP
DFF	1.0 **	0.77**	-0.81 **	-0.47	0.79 **	0.85 **	0.56*	-0.79 **	-0.78 **	0.77**	0.18	-0.92 **	0.92 **	0.77 **	-0.15	0.53 *	0.73 **	-0.35
DPM		1.0 **	-0.85 **	-0.63 *	0.68 **	0.61 *	0.46	-0.89 **	-0.76**	0.74 **	0.19	-0.76 **	0.76 **	0.89 **	-0.41	0.46	0.84 **	-0.70 **
PH			1.0 **	0.65 **	-0.65 **	-0.62 **	-0.49	0.96 **	0.91**	-0.77 **	-0.36	0.91 **	-0.91 **	-0.71 **	0.50	-0.41	-0.76 **	0.58 *
NCP				1.0 **	-0.24	-0.08	-0.09	0.66**	0.52 *	-0.23	0.16	0.62 *	-0.62 *	-0.61 *	0.81 **	0.25	-0.58 *	0.82 **
NPC					1.0 **	0.79 **	0.75 **	-0.62*	-0.78 **	0.77 **	0.38	-0.69 **	0.68 **	0.59*	0.10	0.74**	0.66 **	-0.15
NPP						1.0 **	0.65**	-0.65 **	-0.69 **	0.81 **	0.47	-0.73 **	0.73 **	0.58 *	0.19	0.81 **	0.59*	-0.02
NPBP							1.0 **	-0.45	-0.59 *	0.83 **	0.46	-0.51*	0.51*	0.24	0.18	0.72**	0.30	-0.01
HSW								1.0 **	0.86 **	-0.77 **	-0.30	0.85 **	-0.85 **	-0.77 **	0.45	-0.41	-0.81 **	0.61*
NSP									1.0 **	-0.82 **	-0.35	0.87**	-0.87 **	-0.56*	0.33	-0.49	-0.65 **	0.41
HI										1.0 **	0.45	-0.74 **	0.74**	0.53 *	-0.01	0.76 **	0.56 *	-0.23
RLWC											1.0 **	-0.22	0.22	-0.0	0.09	0.70 **	0.38	0.13
CT												1.0 **	-1.0 **	-0.65 **	0.36	-0.38	-0.70 **	0.432
CTD												-1.0 **	1.0 **	0.65 **	-0.36	0.38	0.70 **	-0.43
SLW														1.0 **	-0.35	0.34	0.82 **	-0.66 **
NDVI at R_2															1.0 **	0.44	-0.38	0.82 **
NDVI at R_5																1.0 **	0.47	0.18
R/S Ratio																	1.0 **	-0.58 *

Note: *, ** Significant at 5% and 1% level of significance, respectively. DF: Days to 50% flowering, DPM: Days to physiological maturity, PH: Plant height, NCP: Number of clusters per plant, NPC: Number of pods per cluster, NPP: Number of pods per plant, NPBP: Number of primary branches per plant, HSW: Hundred seed weight, YPP: Yield per plant, NSP: Number of seeds per pod, HI: Harvest index, RLWC: Relative leaf water content (%), CT: Canopy temperature at grain filling stage (˚C), CTD: Canopy temperature depression (˚C), SLW: Specific leaf area (g/cm^2), NDVI at R_2: Normalized difference vegetation index at full bloom stage, NDVI at R_5: Normalized difference vegetation index at Beginning seed filling stage, R/S ratio: Root to Shoot Ratio

Table 5. Simple correlation among all traits in cross KDS 1173 × EC 602288 under drought condition

Characters	DFF	DPM	PH	NCP	NPC	NPP	NPBP	HSW	NSP	HI	RLWC	CT	CTD	SLW	NDVI at R2	NDVI at R5	R/S ratio	YPP
DFF	1.0 **	0.82 **	0.51 *	0.43	-0.02	-0.19	-0.04	0.69 **	0.25	0.21	-0.24	0.24	-0.24	-0.28	0.26	0.07	-0.41	-0.15
DPM		1.0 **	0.87 **	0.03	-0.45	-0.63 *	-0.17	0.85 **	0.63 *	-0.23	-0.62 *	0.57 *	-0.57 *	-0.64 **	0.57 *	-0.30	-0.63 *	-0.56 *
PH			1.0 **	-0.37	-0.70 **	-0.88 **	-0.40	0.76 **	0.82 **	-0.43	-0.79 **	0.74 **	-0.74 **	-0.83 **	0.69 **	-0.54 *	-0.79 **	-0.81 **
NCP				1.0 **	0.67 **	0.68 **	0.56 *	0.05	-0.44	0.65 **	0.59 *	-0.53 *	0.53 *	0.55 *	-0.24	0.69 **	0.39	0.73 **
NPC					1.0 **	0.81 **	0.35	-0.33	-0.46	0.68 **	0.73 **	-0.74 **	0.74 **	0.78 **	-0.45	0.69 **	0.62 *	0.85 **
NPP						1.0 **	0.63 *	-0.53 *	-0.78 **	0.69 **	0.91 **	-0.89 **	0.89 **	0.90 **	-0.68 **	0.82 **	0.83 **	0.95 **
NPBP							1.0 **	-0.24	-0.35	0.46	0.64 **	-0.58 *	0.58 *	0.63 *	-0.27	0.50	0.75 **	0.62 *
HSW								1.0 **	0.63 *	-0.38	-0.68 **	0.53 *	-0.53 *	-0.64 *	0.32	-0.24	-0.57 *	-0.51 *
NSP									1.0 **	-0.46	-0.68 **	0.64 *	-0.64 *	-0.66 **	0.72 **	-0.59 *	-0.62 *	-0.70 **
HI										1.0 **	0.83 **	-0.67 **	0.67 **	0.66 **	-0.27	0.78 **	0.43	0.73 **
RLWC											1.0 **	-0.88 **	0.88 **	0.90 **	-0.48	0.79 **	0.78 **	0.92 **
CT												1.0 **	-1.0 **	-0.82 **	0.52 *	-0.80 **	-0.87 **	-0.89 **
CTD													1.0 **	0.82 **	-0.52 *	0.80 **	0.87 **	0.89 **
SLW														1.0 **	-0.47	0.62 *	0.81 **	0.91 **
NDVI at R_2															1.0 **	-0.62 *	-0.62 *	-0.55 *
NDVI at R_5																1.0 **	0.60 *	0.82 **
R/S Ratio																	1.0 **	0.82 **

Note: *, ** Significant at 5% and 1% level of significance, respectively. DF: Days to 50% flowering, DPM: Days to physiological maturity, PH: Plant height, NCP: Number of clusters per plant, NPC: Number of pods per cluster, NPP: Number of pods per plant, NPBP: Number of primary branches per plant, HSW: Hundred seed weight, YPP: Yield per plant, NSP: Number of seeds per pod, HI: Harvest index, RLWC: Relative leaf water content (%), CT: Canopy temperature at grain filling stage (˚C), CTD: Canopy temperature depression (˚C), SLW: Specific leaf area (g/cm^2), NDVI at R_2: Normalized difference vegetation index at full bloom stage, NDVI at R_5: Normalized difference vegetation index at Beginning seed filling stage, R/S ratio: Root to Shoot Ratio

Table 6. Simple correlation among all traits in cross KDS 1173 × EC 602288 under irrigated condition

Characters	DFF	DPM	PH	NCP	NPC	NPP	NPBP	HSW	NSP	HI	RLWC	CT	CTD	SLW	NDVI at R2	NDVI at R5	R/S ratio	YPP
DFF	1.0 **	0.95 **	0.97 **	0.60 *	-0.61 *	0.55 *	-0.83 **	0.92 **	0.70 **	-0.78 **	-0.72 **	0.78 **	-0.78 **	-0.87 **	0.50	-0.68 **	-0.88 **	0.80 **
DPM		1.0 **	0.96 **	0.54 *	-0.59 *	0.33	-0.88 **	0.94 **	0.60 *	-0.78 **	-0.71 **	0.8 **	-0.80 **	-0.88 **	0.58 *	-0.61 *	-0.86 **	0.64 *
PH			1.0 **	0.61 *	-0.75 **	0.52 *	-0.86 **	0.92 **	0.76 **	-0.89 **	-0.83 **	0.82 **	-0.82 **	-0.93 **	0.41	-0.76 **	-0.95 **	0.78 **
NCP				1.0 **	-0.51	0.57 *	-0.26	0.41	0.65 **	-0.68 **	-0.58 *	0.34	-0.34	-0.68 **	0.32	-0.51	-0.61 *	0.58 *
NPC					1.0 **	-0.47	0.62 *	-0.55 *	-0.81 **	0.91 **	0.87 **	-0.63 *	0.63 *	0.82 **	0.19	0.85 **	0.88 **	-0.60 *
NPP						1.0 **	-0.15	0.40	0.70 **	-0.53 *	-0.38	0.26	-0.26	-0.42	0.00	-0.48	-0.47	0.88 **
NPBP							1.0 **	-0.81 **	-0.58 *	0.71 **	0.75 **	-0.88 **	0.88 **	0.82 **	-0.39	0.69 **	0.83 **	-0.52 *
HSW								1.0 **	0.51	-0.73 **	-0.66 **	0.74 **	-0.74 **	-0.79 **	0.50	-0.58 *	-0.82 **	0.67 **
NSP									1.0 **	-0.85 **	-0.80 **	0.65 **	-0.65 **	-0.81 **	0.06	-0.80 **	-0.81 **	0.82 **
HI										1.0 **	0.90 **	-0.74 **	0.74 **	0.94 **	-0.09	0.84 **	0.94 **	-0.69 **
RLWC											1.0 **	-0.74 **	0.74 **	0.92 **	-0.08	0.90 **	0.94 **	-0.63 *
CT												1.0 **	-1.0 **	-0.77 **	0.35	-0.62 *	-0.77 **	0.64 *
CTD												-1.0 **	1.0 **	0.77 **	-0.35	0.62 *	0.77 **	-0.64 *
SLW														1.0 **	-0.25	0.86 **	0.97 **	-0.66 **
NDVI at R_2															1.0 **	0.04	-0.20	0.23
NDVI at R_5																1.0 **	0.89 **	-0.65 **
R/S Ratio																	1.0 **	-0.70 **

Note: *, ** Significant at 5% and 1% level of significance, respectively. DF: Days to 50% flowering, DPM: Days to physiological maturity, PH: Plant height, NCP: Number of clusters per plant, NPC: Number of pods per cluster, NPP: Number of pods per plant, NPBP: Number of primary branches per plant, HSW: Hundred seed weight, YPP: Yield per plant, NSP: Number of seeds per pod, HI: Harvest index, RLWC: Relative leaf water content (%), CT: Canopy temperature at grain filling stage (˚C), CTD: Canopy temperature depression (˚C), SLW: Specific leaf area (g/cm^2), NDVI at R_2: Normalized difference vegetation index at full bloom stage, NDVI at R_5: Normalized difference vegetation index at Beginning seed filling stage, R/S ratio: Root to Shoot Ratio reflecting the importance of canopy development and photosynthetic efficiency under moisture stress (Liang *et al.,* 2024). These correlations were in alignment with the physiological frameworks proposed by Sofi *et al.* (2018). Moreover, R/S ratio was positively associated with YPP (r = 0.82), CTD (r = 0.89), and NDVI R5 (r = 0.82), supporting the role of deeper rooting and canopy vigor in drought adaptation. Similar results were obtained by Mundhe *et al.* (2021).

*Trait Associations Under Irrigated Conditions:*Under well-watered conditions, the influence of physiological traits on yield decreased, while morphological and yield component traits emerged as more critical.

In the cross NRC 37 × EC 602288, plant height (PH) demonstrated a strong positive correlation with hundred seed weight (HSW; *r* = 0.96) and a moderate association with yield per plant (YPP; *r* = 0.55) under irrigated conditions (**Table 2, Fig.1B**). In contrast, physiological traits such as canopy temperature depression (CTD) and relative leaf water content (RLWC) exhibited weaker correlations with yield. This pattern indicates that under favourable, non-stress conditions, yield determination in this cross is predominantly influenced by structural and reproductive growth attributes rather than physiological water status indicators.

In JS 20-98 × EC 602288, number of pods per plant (NPP; r = 0.88) and PH (r = 0.58) were key yield drivers **(Table 4, Fig. 1D)**. NDVI values at R_2 and R_5 also correlated positively with YPP (r = 0.82 and 0.47, respectively), confirming its utility in predicting biomass and yield in non-stress environments (Mundhe *et al.,*2021). SLW had a substantial correlation with YPP (r = 0.82), underscoring the role of leaf density in enhancing photosynthetic efficiency under favourable moisture.

In KDS 1173 × EC 602288, Yield per plant correlated significantly with Days to 50% flowering (r = 0.80), DPM (r = 0.64), PH (r = 0.78), and NPP (r = 0.88), **(Table 6, Fig. 1F).** Interestingly, No. of pods per cluster (r = –0.60) and No. of primary branches per plant (r = −0.52) were negatively correlated with YPP, indicating that excessive branching might divert assimilates away from pods. NDVI at R_5 (r = 0.89) remained a reliable canopy vigor indicator. Basal and Szabó (2020) similarly reported that NDVI values decreased significantly with increased drought intensity, while irrigation positively influenced NDVI, as confirmed through Partial Eta Squared analysis. Furthermore, earlier studies by Suzuki *et al.* (2000) and Wang *et al.* (2001) established positive correlations between irrigation levels and NDVI, supporting its consistent performance as a reliable canopy health indicator across various crops and environments. These findings collectively corroborate the present study's observations, emphasizing NDVI's potential as an effective tool for screening drought-tolerant soybean genotypes.

Notably, SLW had an extremely strong association with YPP (r = 0.97), highlighting the importance of a well-developed photosynthetic apparatus. The R/S ratio was negatively associated with YPP (r = –0.70), suggesting that under irrigation, excessive root investment does not translate into higher yield, possibly due to competition for assimilates between root and reproductive sinks.

Across all crosses, it was evident that drought stress enhanced the importance of physiological traits (CTD, RLWC, SLW, NDVI) in determining yield, while under irrigated conditions, yield was more strongly governed by morphological and yield component traits (NPP, NSP, HI, NDVI at R_5). The contrasting trait-yield relationships across environments highlight the necessity for environment-specific breeding strategies in soybean improvement programs.

Schonfeld *et al.* (1988) reported that cultivars exhibiting drought resistance typically maintain higher relative water content (RWC), a trend also observed in the present investigation, where better-performing genotypes recorded higher RWC values under stress. Relative water content is widely recognized as one of the most reliable indicators of plant water status, reflecting the physiological consequences of cellular water deficits.

The significant positive correlation of canopy temperature depression and relative leaf water content with yield per plant under drought in all three crosses confirms their reliability as indirect selection indices for drought tolerance, aligning with earlier drought studies in soybean by Jumrani and Bhatia (2019) and Kumar *et al*. (2017).

Similarly, consistent associations of NDVI at R_5 with seed yield under both moisture regimes suggest that remote sensing-based indices can serve as robust proxies for canopy health, biomass status, and yield prediction in soybean breeding programs, corroborating the utility of NDVI reported by Mundhe *et al.* (2021).

The present study comprehensively elucidated the interrelationships between morphological, physiological, and yield-related traits in three soybean crosses evaluated under contrasting moisture regimes. The correlation analysis highlighted that under drought stress, physiological traits such as canopy temperature depression (CTD), relative leaf water content (RLWC), specific leaf weight (SLW), NDVI at R_5, and root-to-shoot (R/S) ratio demonstrated consistently strong positive associations with yield per plant (YPP) across all crosses. These findings reinforce their utility as reliable secondary selection criteria for enhancing drought tolerance in soybean breeding programs.Conversely, under irrigated conditions, agronomic and reproductive traits including number of pods per plant (NPP), plant height (PH), days to 50% flowering (DFF), and SLW were more influential in determining yield outcomes. Notably, NDVI at R_5 stage exhibited significant and stable positive correlations with yield under both stress and non-stress environments, establishing it as a robust, non-destructive proxy for canopy health, biomass accumulation, and yield prediction. Among the three crosses, KDS 1173 × EC 602288 consistently displayed stronger trait associations with yield under drought, particularly for RLWC, CTD, SLW, and R/S ratio, suggesting superior physiological adaptation potential in this cross. This underscores the importance of integrating physiological resilience traits into breeding pipelines targeting rainfed and drought-prone agro-ecologies.

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