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Analysis of Genetic Variation, Correlation and Path Effects for Grain Yield Enhancement in Bread Wheat (*Triticum aestivum* L.) under Rainfed and Irrigated Conditions

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Drought constrains wheat productivity, making the identification of genetically variable and yield-associated traits important for selection under contrasting moisture regimes. This study evaluated 50 advanced bread wheat genotypes, including five standard checks, under rainfed and irrigated environments during the *Rabi* season of 2022–23 using a randomised block design with three replications. Two physiological and fourteen yield-related morphological traits were assessed using analysis of variance, phenotypic and genotypic coefficients of variation, broad-sense heritability, genetic advance, correlation, and path coefficient analyses. The phenotypic coefficient of variation exceeded the genotypic coefficient of variation for all traits in both

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environments. Canopy temperature depression at 14 days after heading (CTD 2) showed the highest PCV/GCV values, at 39.90/33.42% under rainfed and 34.26/29.45% under irrigated conditions. Productive tillers per plant and CTD 2 combined high heritability with comparatively large genetic advance in both environments. Under rainfed conditions, grain yield per plot was strongly and positively correlated with harvest index (r = 0.721), productive tillers per plant (r = 0.698), and biological yield per plot (r = 0.626). Under irrigation, the strongest positive associations were with peduncle length (r = 0.611), spike length (r = 0.606), flag leaf length (r = 0.563), and biological yield per plot (r = 0.552). Path analysis identified harvest index as the largest positive direct contributor under rainfed conditions (0.8029) and biological yield per plot under irrigated conditions (0.8620). These findings support consideration of these traits in selection across contrasting moisture regimes.

Keywords: Bread wheat; genetic variability; genotypic coefficient of variation; phenotypic coefficient of variation; broad-sense heritability; grain yield; rainfed conditions

1. Introduction

Wheat (*Triticum aestivum* L.) is an annual, predominantly self-pollinated cereal crop of significant importance to global food and nutritional security. It is among the major staple food crops worldwide and contributes substantially to the dietary requirements of nearly 35–40% of the global population (Erenstein et al., 2022).

Nationally, wheat was cultivated on 32.80 million hectares during 2024-25, yielding 117.94 million tonnes with an average productivity of 3.59 tonnes per hectare (UPAG, 2025). Among the leading wheat-producing states, Haryana accounts for a substantial share, cultivating the crop on 2.38 million hectares and producing 11.4 million tonnes annually (UPAG, 2025). The primary goal of wheat breeding programmes is to develop high-yielding cultivars possessing an optimum combination of desirable agronomic characteristics.

Grain yield in wheat, being governed by a complex network of interacting quantitative traits, is highly sensitive to environmental fluctuations, with numerous component characters contributing either directly or indirectly (Akram et al., 2008). Consequently, identifying germplasm harbouring exploitable genetic variation for agro-morphological and physiological traits linked to drought tolerance has remained a long-standing priority in wheat improvement research. Within drought-tolerance breeding programmes specifically, yield stability and the consistency of yield-contributing traits are of paramount importance when selecting genotypes for use as cultivars or as parental lines in hybridization. The effectiveness of selection largely depends on the assessment of important genetic parameters, including the genotypic coefficient of variation, phenotypic coefficient of variation, heritability and genetic advance (Johnson et al., 1955).

Partitioning the total variability within a population into its heritable and non-heritable components is achieved through estimation of genetic parameters such as variance, genotypic and phenotypic coefficients of variation (GCV and PCV), heritability, and genetic advance. While GCV and PCV estimates aid in identifying genotypes with promising genetic potential, heritability alone can be misleading when used in isolation; its integration with genetic advance provides a far more robust basis for discriminating superior genotypes with respect to grain yield and its associated traits (Kumar et al., 2014), thereby guiding breeders towards more precise selection strategies.

Correlation analysis further refines this understanding by elucidating how selection for one trait influences correlated responses in others (Ahmad et al., 2003), with yield–trait correlation coefficients often revealing a complex and variable pattern of associations. Given this complexity, a combined assessment of genetic variability, heritability and trait correlations with grain yield becomes essential for identifying genotypes with strong potential for yield enhancement. Path coefficient analysis extends this understanding further still by partitioning correlation coefficients into their direct and indirect components, thereby clarifying the causal contribution of each trait to yield. This analytical approach has long served as an indispensable tool for breeders in pinpointing traits most amenable to selection for yield improvement (Dewey & Lu, 1959; Ahmad et al., 2003).

Recent studies under drought-stressed and well-watered conditions have similarly used genetic variability, heritability, and trait associations to support selection for wheat improvement (Sewore & Abe, 2024; Alshaharni et al., 2025). Correlation and path coefficient analyses in bread wheat have also been applied to identify yield-contributing traits and clarify direct and indirect relationships with grain yield (Kumar et al., 2025; Pandey et al., 2026).

Despite the established usefulness of these genetic parameters, an integrated assessment within the same set of bread wheat genotypes under both rainfed and irrigated environments is needed to compare morpho-physiological trait expression and its relationship with grain yield across contrasting moisture regimes.

The present study was conducted to assess a diverse set of wheat genotypes with the aim of determining the magnitude of genetic variability and heritability for grain yield and its associated traits, estimating the expected genetic gain through selection, and elucidating the relationships among these characters to identify suitable selection criteria for enhancing grain yield.

2. Materials and Methods

The experimental material comprised fifty advanced bread wheat lines, including five standard checks (WH 1105, WH 1124, WH 1142, PBW 644, and WB 2), evaluated for genetic variability across two physiological and fourteen yield-related morphological traits (Table 1). The experiment was carried out under rainfed and irrigated environments at the research farm of the Wheat and

Barley Section, Department of Genetics and Plant Breeding, CCS Haryana Agricultural University, Hisar, during the *Rabi* season of 2022–23. The trial comprised the test genotypes arranged in a randomized block design (RBD) with three replications. The experimental location, situated at 29.09° N latitude and 75.43° E longitude, has an elevation of 215.2 m above mean sea level and falls within the subtropical North Western Plain Zone (NWPZ) of India.

Five plants were randomly selected from each replication for recording observations, and the corresponding mean values were considered for statistical analysis. Data were collected for days to heading, days to maturity, plant height, peduncle length, number of productive tillers per plant, spike length, number of spikelets per spike, flag leaf length, flag leaf width, number of grains per spike, thousand-grain weight, grain yield per plot, biological yield per plot, harvest index, normalized difference vegetation index (NDVI), and canopy temperature depression (CTD).

2.1 Statistical Analysis

Analysis of variance (ANOVA) was performed following the methodology proposed by Fisher (1958), as outlined by Panse and Sukhatme (1967). Estimates of phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), broad-sense heritability, and genetic advance as a percentage of the mean were obtained using the methods described by Burton and DeVane (1953) and Johnson et al. (1955). Trait associations were assessed through correlation coefficient analysis according to Al-Jibouri et al. (1958), whereas path coefficient analysis was conducted following the approach of Dewey and Lu (1959). Statistical analyses were carried out using Indostat, Hyderabad, and Windostat version 9.3 software.

Table 1. Details of genotypes

Sr. No.	GENOTYPES	Sr. No.	GENOTYPES
1	13HZAN-255	26	P30034
2	PBW644	27	WH1124
3	12HPYT-467	28	13HZAN-133
4	13HZAN-208	29	P30040
5	13HZAN-128	30	13HZWYT- 427
6	P30047	31	N3151
7	N3105	32	N3149
8	P14288	33	P14415
9	N3137	34	P20102
10	P30041	35	13HZWYT- 404
11	13HZAN-19	36	WH1105
12	P14413	37	P30048
13	N3031	38	13HZAN-55
14	P30037	39	P30032
15	P30043	40	13HZAN-52
16	WH1142	41	P30042
17	13HZAN-43	42	12HPYT-555
18	N3136	43	N3152
19	13HZWYT- 462	44	13HZAN-177
20	13HZAN-50	45	P30030
21	13HZAN-46	46	13HZAN-256
22	N3029	47	N3089
23	N3147	48	P14411
24	P14410	49	P20106
25	P20104	50	WB2

3. Results and Discussion

3.1 Analysis of Variance (ANOVA)

Fifty genotypes were evaluated across three replications using a randomized block design (RBD). The experimental data were analyzed through analysis of variance (ANOVA) following the method proposed by Fisher (1958). The analysis revealed highly significant genotypic differences ($p < 0.01$) for the majority of the traits, whereas the remaining traits exhibited significant variation at the 5% probability level ($p < 0.05$). In contrast, replication effects remained largely non-significant across most traits under both rainfed and irrigated regimes, suggesting that observed differences were predominantly attributable to genetic variation among the genotypes rather than to environmental heterogeneity within blocks (Tables 2 and 3). These results corroborate earlier reports by Kumar et al. (2017), Sharma et al. (2018), Barman et al. (2020), and Poudel et al. (2021), each of whom documented significant genotypic mean sums of squares for a range of morpho-physiological traits. These observations indicate the existence of considerable genetic diversity within the evaluated germplasm, which could be effectively utilized in wheat improvement programmes.

3.2 Genotypic and Phenotypic Coefficient of Variation

Across all traits examined, phenotypic coefficient of variation (PCV) estimates consistently exceeded their genotypic coefficient of variation (GCV) counterparts, though the magnitude of divergence between the two remained narrow throughout, pointing to a relatively limited role of environmental factors in shaping trait expression. Under rainfed conditions, canopy temperature depression at 14 days after heading (CTD 2) recorded the highest estimates of both PCV (39.90%) and GCV (33.42%), a pattern followed by productive tillers per plant (22.79% and 19.64%), canopy temperature depression at heading (CTD 1; 21.62% and 19.50%), grain yield per plot (14.27% and 14.03%), flag leaf width (18.78% and 15.12%), spike length (12.50% and 12.19%), number of grains per spike (11.86% and 11.21%), and harvest index (11.80% and 10.44%). Following the convention that PCV and GCV values exceeding 20% denote high variability, these traits were classified accordingly. Moderate PCV and GCV (10–20%) characterised number of spikelets per spike (12.10% and 9.64%), biological yield per plot (10.28% and 9.08%), NDVI recorded 14 days post-heading (9.90% and 8.44%), peduncle length (8.26% and 7.88%), flag leaf length (8.24% and 6.24%), NDVI at heading (7.52% and 6.95%), and thousand-grain weight (6.87% and 6.82%). The remaining traits displayed low PCV and GCV values (below 10%) (Table 4; Figs. 1, 2). The consistent observation of PCV values exceeding their corresponding GCV estimates across the studied traits is in accordance with the findings of Anu et al. (2019), Tolwani and Shukla (2022), and Aashu et al. (2021).

Table 2. ANOVA for different traits under rainfed condition

Source of Variation	d.f.	Mean sum of square								
		DH	PH	PT/PL	PL	FLL	FLW	SL	NS/S	NG/S
Replication	2	1.647	11.420	0.500	0.819	141.78**	0.008	0.163	2.907	2.536
Treatment	49	26.33*	71.633**	5.485**	21.89*	9.321**	0.105*	3.091**	9.405*	68.533**
Error	98	1.164	2.372	0.568	0.699	1.851	0.016	0.053	1.519	2.636

*** Significant at 1% (p < 0.01), * Significant at 5% (p < 0.05)*

DH: Days to Heading; PH: Plant height (cm); PT/PL: Productive tillers/plant; PL: Peduncle length (cm); FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%); NDVI 1: Normalized difference vegetative index recorded at heading; NDVI 2: Normalized difference vegetative index recorded at 14days after heading; CTD 1: Canopy temperature depression recorded at heading; CTD 2: Canopy temperature depression recorded at 14 days after heading and GY: Grain yield per plot (Kg)

Table 3. ANOVA for different traits under irrigated condition

Source of Variation	d.f.	Mean sum of square								
		DH	PH	PT/PL	PL	FLL	FLW	SL	NS/S	NG/S
Replication	2	14.48*	90.744**	0.14	2.854	0.775	0.001	0.26	1.52	8.167
Treatment	49	10.409**	59.459**	8.047*	20.174**	25.15**	0.063*	3.318**	9.725**	47.361*
Error	98	1.351	4.956	0.48	0.661	0.389	0.001	0.117	1.493	4.391

Source of Variation	d.f.	Mean sum of square								
		TGW	DM	BY	HI	NDVI 1	NDVI 2	CTD 1	CTD 2	GY
Replication	2	4.165	4.927	0.35	65.721	0.001	0.005**	0.829*	0.346	0.01
Treatment	49	19.374*	15.765**	0.474**	59.913**	0.004*	0.011**	0.871**	0.787**	0.065**
Error	98	4.12	1.151	0.066	14.401	0.01	0.01	0.069	0.083	0.001

*** Significant at 1% (p < 0.01), * Significant at 5% (p < 0.05).*

DH: Days to Heading; PH: Plant height (cm); PT/PL: Productive tillers/plant; PL: Peduncle length (cm); FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%); NDVI 1: Normalized difference vegetative index recorded at heading; NDVI 2: Normalized difference vegetative index recorded at 14days after heading; CTD 1: Canopy temperature depression recorded at heading; CTD 2: Canopy temperature depression recorded at 14 days after heading and GY: Grain yield per plot (Kg)

Table 4. Genotypic and phenotypic coefficient of variation

Source of Variation	d.f.	Mean sum of square								
		TGW	DM	BY	HI	NDVI 1	NDVI 2	CTD 1	CTD 2	GY
Replication	2	0.269	2.94	0.031	13.675	0.003	0.005	1.423	0.513	0.004
Treatment	49	26.041**	17.642**	0.31*	56.173**	0.005*	0.007**	1.428**	0.768**	0.107**
Error	98	0.132	1.328	0.027	4.739	0.001	0.001	0.102	0.095	0.001

A broadly similar trend emerged under irrigated conditions, where CTD 2 again showed the highest PCV and GCV (34.26% and 29.45%), followed by productive tillers per plant (23.61% and 21.64%), CTD 1 (15.53% and 13.85%), biological yield per plot (13.28% and 10.91%), and spike length (11.66% and 11.07%). Moderate variability was observed for number of spikelets per spike (12.19% and 9.81%), flag leaf length (11.00% and 10.75%), flag leaf width (10.69% and 10.45%), NDVI at 14 days after heading (10.54% and 9.87%), and harvest index (11.50% and 8.24%), while the remaining traits exhibited comparatively low PCV and GCV values (Table 5; Fig. 1, 2). The present findings are comparable with those reported by Kumari et al. (2017), Kumar et al. (2017), and Jaiswal et al. (2022), who also observed relatively higher genotypic and phenotypic variability for canopy temperature depression, productive tillers per plant, and grain yield per plot.

3.3 Heritability and Genetic Advance (%)

According to Johnson et al. (1955), heritability is considered high when the estimate exceeds 60%, moderate when it ranges from 30 to 60%, and low when it is below 30%. Although heritability provides an estimate of the genetic contribution to the observed phenotypic variation, its usefulness in predicting selection response is enhanced when considered together with genetic advance. The combined interpretation of these parameters provides a better indication of the probable gene action governing the expression of a trait. Characters associated with high genetic advance are generally indicative of a greater contribution of additive genetic effects and are therefore expected to respond effectively to selection. In contrast, low genetic advance may suggest a relatively greater influence of non-additive genetic effects, such as dominance and epistatic interactions, on trait expression.

Table 5. Genetic Variability Parameters: Mean, GCV, PCV, Broad-Sense Heritability and Genetic Advance in Wheat Genotypes under Rainfed Condition

Characters	Mean	GCV (%)	PCV (%)	Heritability (%)	Genetic Advance (as % mean)
DH	93.49	3.10	3.31	87.82	5.98
PH	95.38	5.04	5.29	90.68	9.88
PT/PL	6.52	19.64	22.79	74.26	34.86
PL	33.75	7.88	8.26	90.99	15.48
FLL	25.29	6.24	8.24	57.36	9.74
FLW	1.14	15.12	18.78	64.78	25.07
SL	8.26	12.19	12.50	94.99	24.47
NS/S	16.83	9.64	12.10	63.38	15.80
NG/S	41.81	11.21	11.86	89.29	21.82
TGW	43.09	6.82	6.87	98.49	13.94
DM	131.94	1.77	1.97	80.38	3.26
BY	3.38	9.08	10.28	78.01	16.52
HI	39.65	10.44	11.8	78.34	19.04
NDVI 1	0.57	6.95	7.52	85.31	13.21
NDVI 2	0.55	8.44	9.90	72.67	14.82
CTD 1	3.41	19.5	21.62	81.28	36.21
CTD 2	1.42	33.42	39.9	70.17	57.67
GY	1.34	14.03	14.27	96.77	28.44

DH: Days to Heading; PH: Plant height (cm); PT/PL: Productive tillers/plant; PL: Peduncle length (cm); FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%); NDVI 1: Normalized difference vegetative index recorded at heading; NDVI 2: Normalized difference vegetative index recorded at 14days after heading; CTD 1: Canopy temperature depression recorded at heading; CTD 2: Canopy temperature depression recorded at 14 days after heading and GY: Grain yield per plot (Kg)

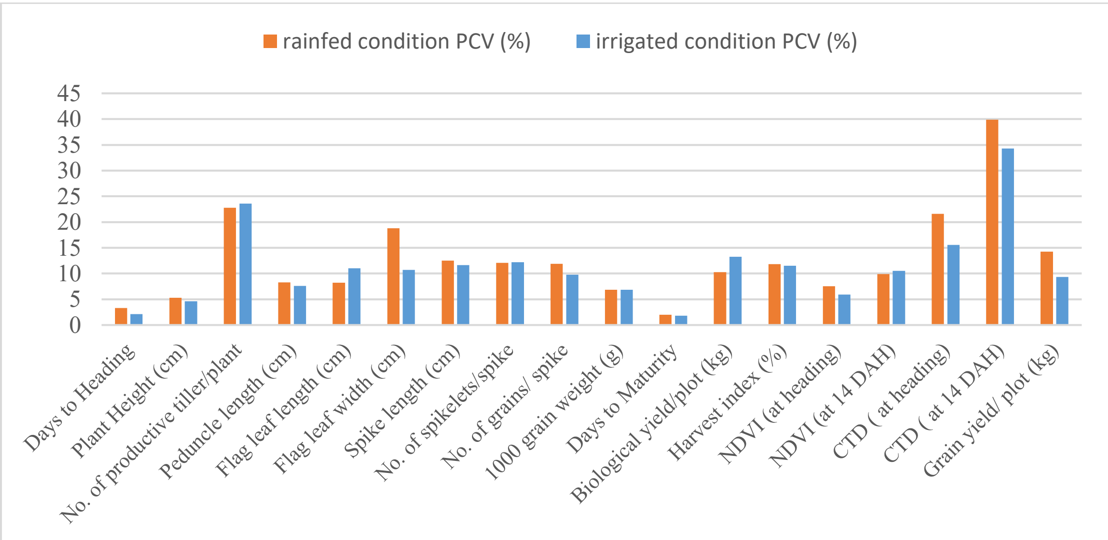

Fig. 1. Phenotypic coefficient of variation for morpho- physiological traits in wheat genotypes under rainfed and irrigated conditions

Under rainfed conditions, high heritability was recorded across the majority of traits, with thousand-grain weight showing the highest estimate (98.49%), followed in descending order by grain yield per plot (96.77%), spike length (94.99%), peduncle length (90.99%), plant height (90.68%), number of grains per spike (89.29%), days to heading (87.82%), NDVI at heading (NDVI 1; 85.31%), CTD at heading (CTD 1; 81.28%), days to maturity (80.38%), harvest index (78.34%), biological yield per plot (78.01%), number of productive tillers per plant (74.26%), etc. The remaining traits fell within the moderate heritability range (50–80%) (Table 4; Fig. 3). When genetic advance was expressed as a percentage of the mean at 5% selection intensity, CTD 2 (57.67%), CTD 1 (36.21%), and number of productive tillers per plant (34.86%) stood out with comparatively high values, pointing to a predominance of additive gene action for these traits and favourable prospects for direct selection. All other traits recorded genetic advance below 30% (Table 5; Fig. 4).

Table 6. Genetic Variability Parameters: Mean, GCV, PCV, Broad-Sense Heritability and Genetic Advance in Wheat Genotypes under Irrigated Condition

Characters	Mean	GCV (%)	PCV (%)	Heritability (%)	Genetic Advance (as % mean)
DH	98.24	1.77	2.13	69.09	3.03
PH	104.26	4.09	4.61	78.57	7.47
PT/PL	7.34	21.64	23.61	84.01	40.86
PL	35.36	7.21	7.57	90.78	14.16
FLL	26.74	10.75	11.00	95.50	21.63
FLW	1.37	10.45	10.69	95.58	21.04
SL	9.33	11.07	11.66	90.09	21.65
NS/S	16.88	9.81	12.19	64.77	16.27
NG/S	44.13	8.58	9.80	76.54	15.45
TGW	44.18	5.10	6.87	55.24	7.82
DM	136.21	1.62	1.80	80.89	3.00
BY	3.38	10.91	13.28	67.47	18.46
HI	47.29	8.24	11.50	51.30	12.15
NDVI 1	0.64	5.23	5.92	77.94	9.51
NDVI 2	0.59	9.87	10.54	87.58	19.02
CTD 1	3.73	13.85	15.53	79.58	25.45
CTD 2	1.65	29.45	34.26	73.89	52.15
GY	1.58	9.23	9.37	97.13	18.75

DH: Days to Heading; PH: Plant height (cm); PT/PL: Productive tillers/plant; PL: Peduncle length (cm); FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%); NDVI 1: Normalized difference vegetative index recorded at heading; NDVI 2: Normalized difference vegetative index recorded at 14days after heading; CTD 1: Canopy temperature depression recorded at heading; CTD 2: Canopy temperature depression recorded at 14 days after heading and GY: Grain yield per plot (Kg)

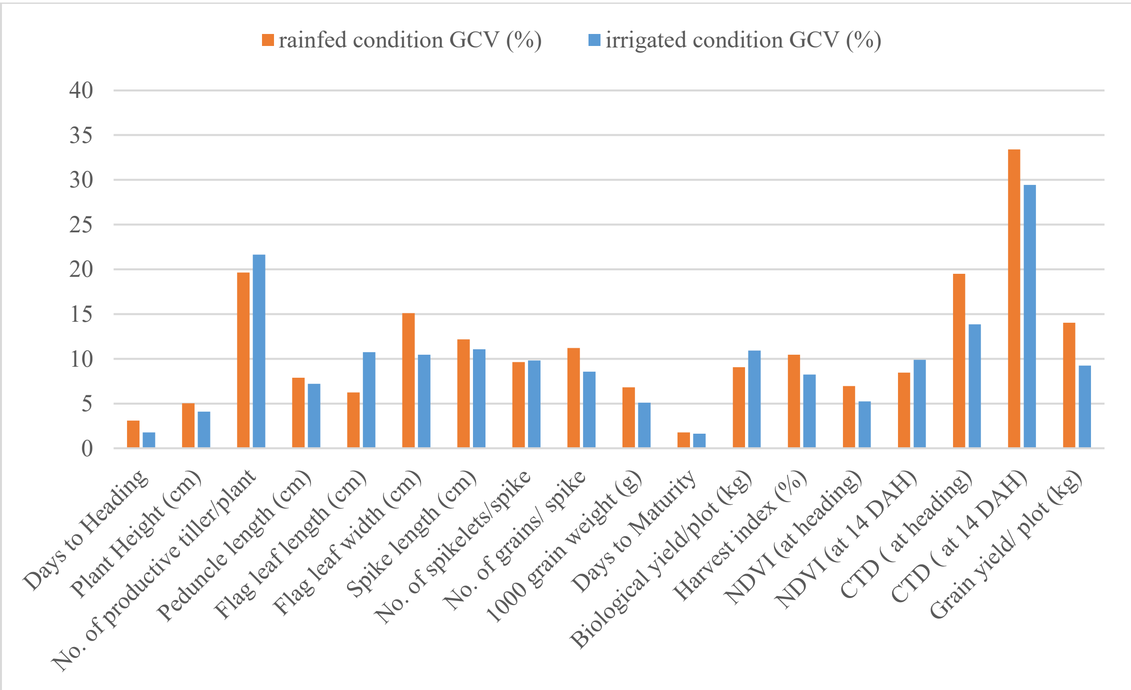

Fig. 2. Genotypic coefficient of variation for morpho- physiological traits in wheat genotypes under rainfed and irrigated conditions

A broadly comparable pattern was observed under irrigated conditions, where high heritability was estimated for grain yield per plot (97.13%), flag leaf width (95.58%), flag leaf length (95.50%), peduncle length (90.78%), spike length (90.09%), NDVI 2 (87.58%), number of productive tillers per plant (84.01%), days to maturity (80.89%), CTD 1 (79.58%), plant height (78.57%), NDVI 1 (77.94%), number of grains per spike (76.54%), CTD 2 (73.89%), days to heading (69.09%), biological yield per plot (67.47%), and number of spikelets per spike (64.77%), with the remaining traits falling into the moderate category (30–60%). Genetic advance as a percentage of the mean suggested significant potential for improvement in CTD 2 (52.15%) and the number of productive tillers per plant (40.86%). The remaining traits showed low genetic advance (<30%) (Table 6; Fig. 4).

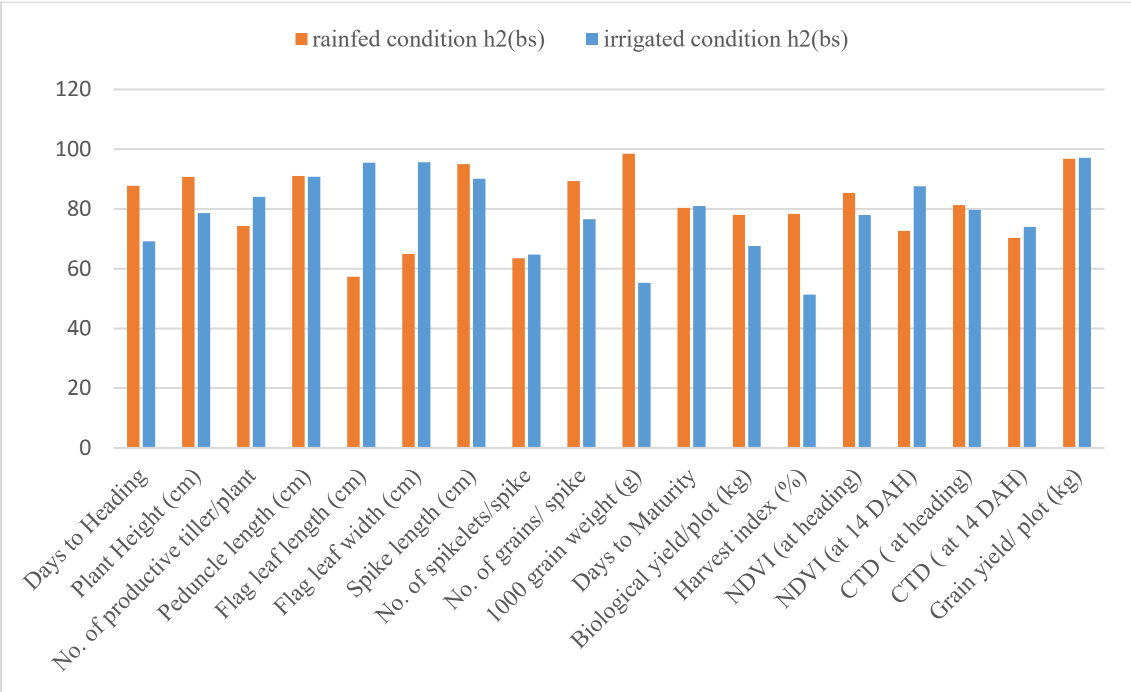

Fig. 3. Heritability (broad sense) for morpho- physiological traits in wheat genotypes under rainfed and irrigated conditions

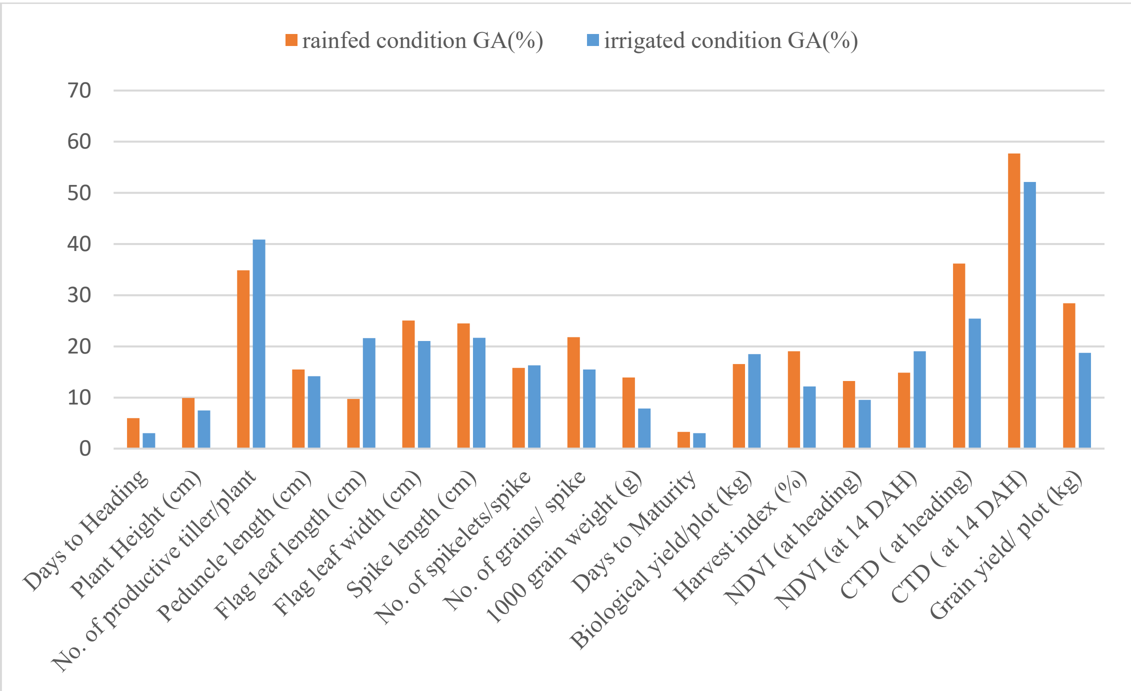

Fig. 4. Genetic advance (% of mean) for morpho- physiological traits in wheat genotypes under rainfed and irrigated conditions

The concurrence of high heritability with high genetic advance for traits such as canopy temperature depression and productive tiller number, observed under both conditions, indicates that additive gene effects predominantly govern their inheritance, making early-generation phenotypic selection an effective breeding strategy for these characters. The present findings are in agreement with earlier studies. Similar results for days to heading and plant height were reported by Naik et al. (2015), while Arya et al. (2017), Kumari et al. (2017), Upadhyay et al. (2019), Barman et al. (2020), and Jaiswal et al. (2022) documented comparable trends for productive tillers per plant. Haydar et al. (2019) reported similar observations for grain yield and thousand-grain weight, whereas the findings of Poudel et al. (2021) support the results obtained for grain yield per plot.

3.4 Correlation Coefficient

Phenotypic correlation coefficient for morphological traits: Under rainfed conditions, grain yield per plot showed positive and significant phenotypic associations with all the traits studied, except days to heading. The strongest positive association was observed with harvest index (r = 0.721**), followed by productive tillers per plant (r = 0.698**), biological yield per plot (r = 0.626**), spikelets per spike (r = 0.566**), peduncle length (r = 0.523**), spike length (r = 0.510**), and thousand-grain weight (r = 0.448**). Significant positive relationships were also recorded with plant height (r = 0.292**), flag leaf length (r = 0.262**), flag leaf width (r = 0.260**), and grains per spike (r = 0.203**). Among the traits, harvest index exhibited significant positive correlations with productive tillers per plant, spike length, spikelets per spike, peduncle length, thousand-grain weight, flag leaf length, plant height, and grains per spike. In contrast, its association with biological yield per plot was negative and non-significant (r = −0.086) (Table 6).

Under irrigated conditions, the pattern of phenotypic associations differed to some extent from that observed under rainfed conditions. Grain yield per plot maintained significant positive relationships with most of the morphological and yield-related traits, while days to heading and days to maturity did not show significant associations. The highest correlation with grain yield was recorded for peduncle length (r = 0.611**), followed by spike length (r = 0.606**), flag leaf length (r = 0.563**), biological yield per plot (r = 0.552**), productive tillers per plant (r = 0.429**), and spikelets per spike (r = 0.429**). Moderate but significant positive correlations were also observed for harvest index (r = 0.244**), grains per spike (r = 0.229*), thousand-grain weight (r = 0.228**), and flag leaf width (r = 0.218**). Furthermore, biological yield per plot exhibited significant positive associations with flag leaf length, spikelets per spike, peduncle length, and spike length, indicating the contribution of these traits to overall biomass production and grain yield under irrigated conditions (Table 7). The present findings are in broad agreement with earlier reports by Kumar et al. (2013), Ozukum et al. (2019), Alnajjar and Dawod (2020), Khan et al. (2020), Baye et al. (2020), Dashora et al. (2022), and Gebremariam et al. (2022).

Phenotypic correlation coefficients for physiological traits: Regarding physiological traits, grain yield per plot under rainfed conditions exhibited significant positive phenotypic associations with NDVI 1, NDVI 2, CTD 1, and CTD 2, with the strength of correlation decreasing in the same order (Table 8). Under irrigated conditions, a similar association was observed, with NDVI 1 showing the strongest positive correlation with grain yield, followed by CTD 1 and NDVI 2 (Table 9). The repeated positive association of grain yield with canopy-related physiological parameters under both moisture conditions suggests that NDVI and CTD can serve as useful secondary traits for identifying high-yielding wheat genotypes and may have potential for indirect selection in breeding programmes. These findings are consistent with those reported by Narendra et al. (2021).

3.5 Path Coefficient Analysis

Correlation analyses alone are not sufficient to fully grasp the complex interrelationships among traits, making it essential to evaluate the true contribution of each trait to grain yield. Path coefficient analysis addresses this limitation by partitioning the correlation between each trait and grain yield into its direct component and the sum of its indirect components mediated through other traits, thereby offering a more precise appraisal of each trait's genuine contribution to yield. This analysis was performed for morpho-physiological traits under both rainfed and irrigated conditions, with the results detailed in Tables 10 and 11.

Direct Effects: Under rainfed conditions, harvest index emerged as the dominant contributor to grain yield per plot, exerting the highest positive direct effect (0.8029). Biological yield per plot ranked next, followed by peduncle length, number of spikelets per spike, days to heading, flag leaf length and NDVI 2, indicating their relatively greater direct contribution to yield. On the other hand, CTD 1 and days to maturity showed negative direct effects on grain yield.

Under irrigated conditions, biological yield per plot had the highest positive direct effect (0.8620) on grain yield, followed by harvest index, spike length, CTD 1, number of spikelets per spike, peduncle length, flag leaf width, etc. In contrast, negative direct effects were observed for CTD measured at 14 days after heading, days to maturity, and both NDVI indices. Comparable direct-effect hierarchies for harvest index and biological yield have previously been reported by Abinasa et al. (2011), Kumar et al. (2013), Dutamo et al. (2015), Ozukum et al. (2019), Baye et al. (2020), Alnajjar and Dawod (2020), and Jeannie et al. (2022).

Indirect Effects: Under rainfed conditions, harvest index served as the principal conduit through which several traits exerted an indirect influence on grain yield. Traits including productive tillers per plant, spike length, spikelets per spike, NDVI 1, peduncle length, NDVI 2, thousand-grain weight, flag leaf length, and CTD 1 showed substantial indirect effects on grain yield through harvest index. Biological yield per plot also acted as an important intermediate trait, through which NDVI 1, productive tillers per plant, peduncle length, thousand-grain weight, spikelets per spike, and NDVI 2 contributed indirectly to grain yield.

Under irrigated conditions, biological yield per plot assumed a correspondingly larger mediating role, channelling indirect contributions to grain yield. Flag leaf length, spikelets per spike, peduncle length, spike length, CTD 1, and NDVI 1 exhibited appreciable indirect effects through biological yield. Harvest index also served as an important intermediary, with productive tillers per plant, grains per spike, spike length, peduncle length, thousand-grain weight, NDVI 2, plant height, NDVI 1, and flag leaf length showing indirect contributions to grain yield through this trait. These results indicate that the relative importance of indirect pathways varied with the moisture regime, with harvest index being particularly influential under rainfed conditions and biological yield assuming greater importance under irrigation.

Table 7. Phenotypic correlations of grain yield and morphological traits under rainfed conditions

	DH	PH	PT/PL	PL	FLL	FLW	SL	NS/S	NG/S	TGW	DM	BY	HI	GY
DH														
PH	0.455**													
PT/PL	0.110	0.197*												
PL	0.154	0.144	0.505**											
FLL	-0.152	-0.058	0.244**	0.328**										
FLW	-0.083	0.190*	0.089	0.011	0.428**									
SL	0.089	0.105	0.391**	0.364**	0.073	0.071								
NS/S	-0.065	0.105	0.400**	0.377**	0.040	-0.036	0.282**							
NG/S	-0.009	0.026	0.083	-0.105	0.308**	0.189*	0.197*	0.124						
TGW	0.058	0.216**	0.375**	0.481**	0.008	-0.051	0.248**	0.476**	-0.145					
DM	0.205*	0.372**	0.118	0.047	0.120	0.286**	-0.182	0.125	0.073	0.140				
BY	-0.174*	0.134	0.362**	0.362**	0.074	0.228**	0.119	0.272**	0.036	0.284**	0.037			
HI	0.097	0.248**	0.572**	0.364**	0.275**	0.146	0.551**	0.506**	0.230**	0.336**	0.012	-0.086		
GY	-0.037	0.292**	0.698**	0.523**	0.262**	0.260**	0.510**	0.566**	0.203*	0.448**	0.018	0.626**	0.721**	

*** Significant at 1%, * Significant at 5%*

DH: Days to Heading; PH: Plant height (cm); PL: Peduncle length (cm); PT/PL: productive tillers/plant; FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%) and GY: Grain yield per plot (Kg)

Table 8. Phenotypic correlation of grain yield and morphological traits under irrigated condition

	DH	PH	PT/PL	PL	FLL	FLW	SL	NS/S	NG/S	TGW	DM	BY	HI	GY
DH														
PH	0.355**													
PT/PL	0.177*	0.155												
PL	-0.022	0.147	0.293**											
FLL	0.034	0.186*	0.339**	0.375**										
FLW	-0.111	-0.142	-0.098	0.170	0.092									
SL	0.091	0.216**	0.422**	0.202*	0.474**	0.015								
NS/S	-0.067	0.141	0.282**	0.249**	0.103	0.110	0.294**							
NG/S	-0.045	0.020	0.228**	0.234**	0.094	0.126	0.171*	0.173*						
TGW	0.215**	0.208*	0.256**	0.042	0.310**	0.046	0.072	-0.069	-0.066					
DM	0.540**	0.190	0.151	0.033	-0.005	0.059	0.274**	0.095	0.307**	0.027				
BY	0.003	0.080	0.130	0.318**	0.399**	0.171*	0.299**	0.365**	-0.001	0.122	0.111			
HI	-0.131	0.056	0.244**	0.163	0.012	-0.027	0.167*	-0.060	0.208*	0.066	-0.158	-0.667**		
GY	-0.136	0.174*	0.429**	0.611**	0.563**	0.218**	0.606**	0.429**	0.229**	0.228**	-0.029	0.552**	0.244**	

Table 9. Phenotypic correlation analysis of grain yield and physiological traits under rainfed condition

	NDVI 1	NDVI 2	CTD 1	CTD 2	GY
NDVI 1					
NDVI 2	0.416**				
CTD 1	0.262**	0.381**			
CTD 2	0.030	0.408**	0.400**		
GY	0.580**	0.448**	0.349**	0.199*	

Table 10. Phenotypic correlation analysis of grain yield and physiological traits under irrigated condition

	NDVI 1	NDVI 2	CTD 1	CTD 2	GY
NDVI 1					
NDVI 2	0.106				
CTD 1	-0.003	0.203*			
CTD 2	-0.018	0.258**	0.414**		
GY	0.333**	0.240**	0.293**	0.116	

*** Significant at 1%, * Significant at 5%*

NDVI 1: Normalized difference vegetative index (at heading); NDVI 2: Normalized difference vegetative index (at 14days after heading); CTD 1: Canopy temperature depression (at heading); CTD 2: Canopy temperature depression (at 14 days after heading) and GY: Grain yield per plot (Kg)

Table 11. Path coefficient analysis of direct (diagonal and bold) and indirect (other) effects of morpho-physiological traits on grain yield per plot under rainfed conditions

Trait	DH	PH	PT/ PL	PL	FLL	FLW	SL	NS/S	NG/S	TGW	DM	BY	HI	NDVI 1	NDVI 2	CTD 1	CTD 2	r with GY
DH	**0.0088**	0.0021	-0.0001	-0.0039	-0.0018	0.0022	0.0003	0.0015	0.0001	-0.0004	-0.0002	-0.1248	0.0778	-0.0001	0.0015	-0.0004	0.0004	-0.0370
PH	0.0039	**0.0047**	0.0003	-0.0037	-0.0007	-0.0047	0.0001	-0.0024	-0.0001	-0.0016	-0.0004	0.0961	0.1992	0.0004	0.0020	-0.0015	0.0002	0.2918
PT/PL	0.0010	0.0009	**0.0006**	-0.0129	0.0025	-0.0022	0.0002	-0.0095	-0.0004	-0.0028	-0.0001	0.2597	0.4591	0.0010	0.0014	-0.0007	0.0003	0.6981
PL	-0.0052	0.0006	0.0006	**0.0114**	0.0019	-0.0043	-0.0067	-0.0117	0.0005	-0.0076	0.0004	0.2593	0.2923	0.0017	0.0015	-0.0076	-0.0042	0.5229
FLL	-0.0043	-0.0033	0.0003	0.0084	**0.0082**	-0.0105	0.0002	-0.0039	-0.0016	-0.0001	-0.0041	0.0528	0.2204	0.0004	-0.0003	-0.0016	0.0005	0.2615
FLW	-0.0047	0.0009	-0.0016	-0.0003	0.0031	**0.0026**	0.0015	0.0008	-0.0040	0.0008	-0.0071	0.1634	0.1168	0.0005	0.0019	-0.0084	-0.0047	0.2615
SL	0.0008	0.0005	-0.0013	-0.0093	0.0011	-0.0017	**0.0008**	-0.0065	-0.0010	-0.0015	0.0002	0.0849	0.4419	0.0013	0.0014	-0.0012	-0.0004	0.5100
NS/S	-0.0046	0.0005	0.0004	0.0011	-0.0075	0.0009	0.0007	**0.0129**	-0.0026	-0.0064	-0.0092	0.1943	0.4062	0.0010	-0.0082	-0.0092	-0.0042	0.5661
NG/S	-0.0001	0.0001	0.0003	0.0027	0.0037	-0.0046	0.0005	0.0018	**0.0022**	0.0011	-0.0045	0.0255	0.1842	-0.0032	-0.0003	-0.0043	-0.0023	0.2028
TGW	0.0005	0.0010	0.0001	0.0012	0.0001	0.0013	0.0004	-0.0319	0.0008	**0.0036**	-0.0035	0.2031	0.2698	0.0022	0.0024	-0.0039	0.0004	0.4476
DM	0.0018	0.0017	-0.0006	-0.0014	0.0018	-0.0071	0.0009	-0.0029	-0.0004	-0.0011	**-0.0010**	0.0264	0.0003	-0.0001	0.0013	-0.0020	0.0008	0.0184
BY	-0.0015	0.0006	-0.0003	-0.0094	0.0009	-0.0057	0.0006	-0.0062	-0.0002	-0.0022	0.0002	**0.7167**	-0.0690	0.0012	0.0016	-0.0017	0.0005	0.6261
HI	0.0011	0.0012	-0.0011	-0.0091	0.0033	-0.0034	0.0009	-0.0116	-0.0012	-0.0024	0.0003	-0.0614	**0.8029**	0.0011	0.0019	-0.0019	0.0001	0.7207
NDVI 1	-0.0001	0.0007	0.0001	-0.0140	0.0016	-0.0006	0.0004	-0.0076	0.0007	-0.0019	0.0001	0.2763	0.3202	**0.0031**	0.0027	-0.0018	0.0001	0.5800
NDVI 2	0.0021	0.0011	-0.0003	-0.0058	-0.0007	-0.0073	0.0012	-0.0040	0.0003	-0.0022	-0.0003	0.1860	0.2719	0.0013	**0.0066**	-0.0026	0.0008	0.4481
CTD 1	0.0009	-0.0033	-0.0009	-0.0039	0.0015	-0.0121	0.0015	-0.0075	-0.0016	-0.0008	-0.0023	0.1838	0.1891	0.0008	0.0038	**-0.0018**	0.0015	0.3487
CTD 2	0.0016	0.0003	-0.0003	-0.0031	0.0029	-0.0089	0.0006	-0.0057	-0.0008	-0.0001	-0.0002	0.1589	0.0518	0.0001	0.0027	-0.0027	**0.0021**	0.1992

Residual effect = 0.0527

DH: Days to Heading; PH: Plant height (cm); PT/PL: No. of productive tillers/plant; PL: Peduncle length (cm); FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%); NDVI 1: : Normalized difference vegetative index at heading; NDVI 2: Normalized difference vegetative index at 14days after heading; CTD 1: Canopy temperature depression at heading; CTD 2: Canopy temperature depression at 14 days after heading and GY: Grain yield per plot (Kg)

Table 12. Path coefficient analysis of direct (diagonal and bold) and indirect (other) effects of morpho-physiological traits on grain yield per plot under irrigated conditions

Trait	DH	PH	PT/ PL	PL	FLL	FLW	SL	NS/S	NG/S	TGW	DM	BY	HI	NDVI 1	NDVI 2	CTD 1	CTD 2	r with GY
DH	**0.0037**	0.0013	-0.0042	-0.0009	0.0011	-0.0036	0.0072	-0.0027	-0.0004	-0.0005	-0.0064	0.0031	-0.1309	0.0019	0.0001	-0.0005	-0.0043	-0.1360
PH	0.0013	**0.0036**	-0.0036	0.0059	0.0061	-0.0047	0.0171	0.0054	0.0001	-0.0005	-0.0023	0.0920	0.0565	-0.0009	0.0003	0.0029	-0.0052	0.1740
PT./PL	0.0007	0.0006	**0.0035**	0.0108	0.0113	-0.0033	0.0334	0.0114	0.0017	-0.0028	-0.0098	0.1504	0.2450	-0.0042	0.0004	-0.0093	-0.0106	0.4292
PL	-0.0001	0.0005	-0.0069	**0.0399**	0.0122	0.0056	0.0160	0.0100	0.0017	-0.0001	-0.0004	0.3672	0.1631	-0.0044	-0.0001	0.0104	-0.0035	0.6111
FLL	0.0001	0.0007	-0.0080	0.0150	**0.0326**	0.0030	0.0374	0.0041	0.0008	-0.0008	0.0001	0.4598	0.0119	-0.0068	0.0001	0.0148	-0.0016	0.5632
FLW	-0.0004	-0.0005	0.0023	0.0068	0.0030	**0.0329**	0.0012	0.0044	0.0010	-0.0001	-0.0007	0.1977	-0.0271	-0.0023	0.0002	-0.0048	0.0045	0.2181
SL	0.0003	0.0008	-0.0099	0.0081	0.0155	0.0005	**0.0791**	0.0118	0.0012	-0.0002	-0.0033	0.3450	0.1672	-0.0069	-0.0001	-0.0008	-0.0025	0.6058
NS/S	-0.0002	0.0005	-0.0066	0.0100	0.0035	0.0036	0.0230	**0.0401**	0.0012	0.0003	-0.0011	0.4205	-0.0604	-0.0066	0.0002	0.0020	-0.0010	0.4290
NG/S	-0.0002	0.0002	-0.0054	0.0092	0.0031	0.0043	0.0135	0.0070	**0.0072**	0.0002	-0.0037	-0.0014	0.2089	-0.0074	-0.0002	-0.0067	0.0001	0.2287
TGW	0.0008	0.0009	-0.0060	0.0017	0.0101	0.0016	0.0056	-0.0028	-0.0005	**0.0012**	-0.0034	0.1407	0.0666	-0.0045	0.0001	0.0158	-0.0004	0.2275
DM	0.0020	0.0007	-0.0035	0.0013	-0.0002	0.0019	0.0219	0.0038	0.0022	-0.0001	**-0.0119**	0.1275	-0.1589	-0.0013	-0.0001	-0.0132	-0.0006	-0.0285
BY	0.0025	0.0041	0.0094	0.0135	0.0161	0.0115	0.0237	0.0195	0.0035	-0.0003	-0.0013	**0.8620**	-0.4262	-0.0060	0.0012	0.0189	0.0002	0.5523
HI	-0.0005	0.0003	-0.0057	0.0065	0.0009	-0.0009	0.0132	-0.0024	0.0014	-0.0002	0.0019	-0.5320	**0.7650**	-0.0005	0.0001	-0.0025	-0.0005	0.2441
NDVI 1	-0.0003	0.0001	-0.0009	0.0064	0.0081	0.0027	0.0200	0.0096	0.0019	-0.0005	-0.0088	0.2951	0.0178	**-0.0074**	0.0003	-0.0072	-0.0043	0.3326
NDVI 2	0.0006	0.0004	-0.0018	0.0132	0.0055	-0.0022	0.0190	-0.0004	0.0009	0.0002	0.0004	0.1449	0.0581	-0.0029	**-0.0002**	0.0084	-0.0042	0.2399
CTD 1	0.0001	0.0003	0.0013	0.0099	0.0116	-0.0038	-0.0016	0.0019	-0.0014	-0.0009	0.0038	0.2973	-0.0613	0.0001	0.0002	**0.0417**	-0.0067	0.2925
CTD 2	0.0010	0.0012	-0.0058	0.0086	0.0031	-0.0095	0.0120	0.0025	-0.0001	-0.0001	-0.0004	0.0687	0.0337	0.0005	-0.0001	0.0173	**-0.0162**	0.1164

Residual effect = 0.1028

DH: Days to Heading; PH: Plant height (cm); PT/PL: No. of productive tillers/plant; PL: Peduncle length (cm); FLL: Flag leaf length (cm); FLW: Flag leaf width (cm); SL: Spike length (cm); NS/S: No. of spikelets per spike; NG/S: No. of grains per spike; TGW: Thousand grain weight (g); DM: Days to Maturity; BY: Biological yield per plot (Kg); HI: Harvest index (%); NDVI 1: : Normalized difference vegetative index at heading; NDVI 2: Normalized difference vegetative index at 14 days after heading; CTD 1: Canopy temperature depression at heading; CTD 2: Canopy temperature depression at 14 days after heading and GY: Grain yield per plot (Kg)

4. Conclusion

The study revealed considerable genetic variation among the 50 advanced wheat lines, including five standard checks, for the morpho-physiological traits evaluated. The observed variability indicates the availability of useful genetic resources that can be effectively utilised in subsequent wheat breeding programmes for developing superior genotypes. High heritability combined with high genetic advance was observed for traits such as CTD 2, CTD 1, the number of productive tillers per plant, and spike length under both conditions. These traits are likely to respond well to selection due to their strong additive gene effects, highlighting their importance for selection. Such traits are expected to respond favourably to direct phenotypic selection, positioning them as reliable targets for early-generation selection in breeding programmes. Complementing these heritability-based inferences, correlation and path coefficient analyses converged in identifying harvest index, biological yield per plot, number of productive tillers per plant, peduncle length and NDVI 1 as the traits exerting the most pronounced direct and indirect influence on grain yield under both rainfed and irrigated environments. The consistency of these associations across contrasting environments lends them particular value as selection indices, offering breeders a robust and physiologically grounded framework for the development of high-yielding, drought-resilient wheat genotypes.

5. Limitation

The study was conducted during a single *Rabi* season at one research location, and the 50 genotypes were evaluated under the specified rainfed and irrigated environments. Consequently, the observed genetic parameters, trait associations, and path effects represent the conditions of this experiment. Validation across additional seasons and locations would be required to determine the stability of the identified relationships and selection criteria across a wider range of production environments.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Aashu, Solanki, Y. P. S., Phougat, D., & Barpanda, T. (2021). Effect of two different dates of sowing on genetic variability of morpho-physiological traits in advance lines of wheat (*Triticum aestivum* L.). *Biological Forum – An International Journal, 13*(4), 1120–1128.

Abinasa, M., Ayana, A., & Bultosa, G. (2011). Genetic variability, heritability and trait associations in durum wheat (*Triticum turgidum* L. var. *durum*) genotypes. *African Journal of Agricultural Research, 6*(17), 3972–3979. https://doi.org/10.5897/AJAR10.880

Ahmad, M., Mohammad, F., Maqbool, K., Azim, A., & Iqbal, S. (2003). Genetic variability and traits correlation in wheat. *Sarhad Journal of Agriculture, 19*(3), 347–351.

Akram, Z., Ajmal, S. U., & Munir, M. (2008). Estimation of correlation coefficient among some yield parameters of wheat under rainfed conditions. *Pakistan Journal of Botany, 40*(4), 1777–1781.

Al-Jibouri, H. A., Miller, P. A., & Robinson, H. F. (1958). Genotypic and environmental variances and covariances in an upland cotton cross of interspecific origin. *Agronomy Journal, 50*, 633–636. https://doi.org/10.2134/agronj1958.00021962005000100020x

Alnajjar, S., & Dawod, K. M. (2020). Correlation and path coefficient analysis in bread wheat. *Mesopotamia Journal of Agriculture, 48*(1), 25–35. https://doi.org/10.33899/magrj.2020.126461.1019

Alshaharni, M. O., Safhi, F. A., Al Aboud, N. M., Kucher, D. E., Fayad, E., Alqurashi, M., Al-Qthanin, R. N., Almami, I. S. M., Ghamry, H. I., Abd El-Moneim, D., Kamara, M. M., & Ali, A. M. (2025). Genetic variability and trait associations for physiological and agronomic characteristics in bread wheat genotypes under drought stress and well-watered conditions. *PeerJ, 13*, e19341. https://doi.org/10.7717/peerj.19341

Anu, Singh, V., Yashveer, S., Niwas, R., Malik, P., Arpit, Dey, S., & Ahlawat, U. (2019). Assessment of genetic variability, heritability and genetic advance for grain yield and its contributing traits in wheat (*Triticum aestivum*). *International Journal of Current Microbiology and Applied Sciences, 8*(8), 1169–1174. https://doi.org/10.20546/ijcmas.2019.808.137

Arya, V. K., Singh, J., Kumar, L., Kumar, R., Kumar, P., & Chand, P. (2017). Genetic variability and diversity analysis for yield and its components in wheat (*Triticum aestivum* L.). *Indian Journal of Agricultural Research, 51*(2), 128–134. https://doi.org/10.18805/ijare.v0iOF.7634

Barman, M., Choudhary, V. K., Singh, S. K., Singh, M. K., & Parveen, R. (2020). Genetic variability analysis in bread wheat (*Triticum aestivum* L.) genotypes for morpho-physiological characters and grain micronutrient content. *International Research Journal of Pure and Applied Chemistry, 21*(22), 1–8. https://doi.org/10.9734/irjpac/2020/v21i2230291

Baye, A., Berihun, B., Bantayehu, M., & Derebe, B. (2020). Genotypic and phenotypic correlation and path coefficient analysis for yield and yield-related traits in advanced bread wheat (*Triticum aestivum* L.) lines. *Cogent Food & Agriculture, 6*(1), 1752603. https://doi.org/10.1080/23311932.2020.1752603

Burton, G. W., & DeVane, E. M. (1953). Estimating heritability in tall fescue (*Festuca arundinacea*) from replicated clonal material. *Agronomy Journal, 45*, 478–481. https://doi.org/10.2134/agronj1953.00021962004500100005x

Dashora, A., Mehta, R., Singh, D., Urmila, & Singh, S. K. (2022). Genetic variability, association and diversity studies in wheat (*Triticum* spp. L.). *Journal of Environmental Biology, 43*(3), 390–400. https://doi.org/10.22438/jeb/43/3/MRN-1972

Dewey, D. R., & Lu, K. H. (1959). A correlation and path-coefficient analysis of components of crested wheatgrass seed production. *Agronomy Journal, 51*(9), 515–518. https://doi.org/10.2134/agronj1959.00021962005100090002x

Dutamo, D., Alamerew, S., Eticha, F., & Assefa, E. (2015). Path coefficient and correlation studies of yield and yield associated traits in bread wheat (*Triticum aestivum* L.) germplasm. *World Applied Sciences Journal, 33*(11), 1732–1739. https://doi.org/10.5829/idosi.wasj.2015.33.11.15617

Erenstein, O., Jaleta, M., Mottaleb, K. A., Sonder, K., Donovan, J., & Braun, H.-J. (2022). Global trends in wheat production, consumption and trade. In M. P. Reynolds & H.-J. Braun (Eds.), *Wheat improvement: Food security in a changing climate* (pp. 47–66). Springer. https://doi.org/10.1007/978-3-030-90673-3_4

Fisher, R. A. (1958). *Statistical methods for research workers* (13th ed.). Oliver and Boyd.

Gebremariam, K., Alamirew, S., & Gebreselassie, W. (2022). Evaluation of bread wheat (*Triticum aestivum* L.) germplasm at Kafa Zone, South West Ethiopia. *Advances in Agriculture, 2022*, 1682961. https://doi.org/10.1155/2022/1682961

Haydar, F. M. A., Ahamed, M. S., Siddique, A. B., Uddin, G. M., Biswas, K. L., & Alam, M. F. (2019). Estimation of genetic variability, heritability and correlation for some quantitative traits in wheat (*Triticum aestivum* L.). *Journal of Bio-Science, 28*, 81–86. https://doi.org/10.3329/jbs.v28i0.44713

Jaiswal, A., Tiwari, S., Shukla, R. S., Kumar, V., Pandey, S., Biswal, M., & Singh, S. K. (2022). Genetic analysis of hybrid wheat under timely and late sown conditions. *The Pharma Innovation Journal, 11*(3), 1721–1725.

Jeannie, S., Kumar, R., Chaudhari, S. B., Ujwala, K., & Kumar, B. S. (2022). Unveiling true association between grain yield and its contributing traits of bread wheat through association studies and path coefficient analysis. *The Pharma Innovation Journal, 11*(5S), 389–399.

Johnson, H. W., Robinson, H. F., & Comstock, R. E. (1955). Estimates of genetic and environmental variability in soybeans. *Agronomy Journal, 47*, 314–318. https://doi.org/10.2134/agronj1955.00021962004700070009x

Khan, A., Ahmad, M., Shah, M. K. N., & Ahmed, M. (2020). Performance of wheat genotypes for morpho-physiological traits using multivariate analysis under terminal heat stress. *Pakistan Journal of Botany, 52*(6), 1981–1988. https://doi.org/10.30848/PJB2020-6(30)

Kumar, A., Gaurav, S. S., Bahuguna, D. K., Sharma, P., Singh, T., & Chand, P. (2017). Analysis of variability, heritability and genetic advance for yield and yield-related traits in wheat (*Triticum aestivum* L.) genotypes. *International Journal of Agricultural Science and Research, 7*(4), 583–590. https://doi.org/10.24247/ijasraug201775

Kumar, B., Singh, C. M., & Jaiswal, K. K. (2013). Genetic variability, association and diversity studies in bread wheat (*Triticum aestivum* L.). *The Bioscan, 8*(1), 143–147.

Kumar, J., Kumar, M., Kumar, A., Singh, S. K., & Singh, L. (2017). Estimation of genetic variability and heritability in bread wheat under abiotic stress. *International Journal of Pure & Applied Bioscience, 5*(1), 156–163. https://doi.org/10.18782/2320-7051.2475

Kumar, N., Markar, S., & Kumar, V. (2014). Studies on heritability and genetic advance estimates in timely sown bread wheat (*Triticum aestivum* L.). *Bioscience Discovery, 5*(1), 64–69.

Kumar, S., Singh, P. N., Gaur, S. C., Quatadah, S. M., Singh, K., Gautam, U., Singh, S. K., Yadav, M., Gaur, A. K., & Kumar, K. (2025). Assessment of genetic variability, correlation and path analysis in bread wheat (*Triticum aestivum* L.) genotypes for yield and its attributing traits. *Journal of Advances in Biology & Biotechnology, 28*(1), 612–620. https://doi.org/10.9734/jabb/2025/v28i11914

Kumari, M., Kumar, M., Singh, V., Kumar, S. V., & Rathi, M. (2017). Trait association and morphological diversity in wheat (*Triticum aestivum* L.) genotypes. *Electronic Journal of Plant Breeding, 8*(2), 534–540. https://doi.org/10.5958/0975-928X.2017.00080.1

Naik, V. R., Biradar, S. S., Yadawad, A., Desai, S. A., & Veeresha, B. A. (2015). Study of genetic variability parameters in bread wheat (*Triticum aestivum* L.) genotypes. *Research Journal of Agricultural Sciences, 6*(1), 123–125.

Narendra, M. C., Roy, C., Kumar, S., Virk, P., & De, N. (2021). Effect of terminal heat stress on physiological traits, grain zinc and iron content in wheat (*Triticum aestivum* L.). *Czech Journal of Genetics and Plant Breeding, 57*(2), 43–50. https://doi.org/10.17221/63/2020-CJGPB

Ozukum, W., Avinashe, H., Dubey, N., Kalubarme, S., & Kumar, M. (2019). Correlation and path coefficient analyses in bread wheat (*Triticum aestivum* L.). *Plant Archives, 19*(2), 3033–3038.

Pandey, A., Singh, N., Mishra, G., Prasad, D., Maurya, D., Varun, S., Shukl, R. P., Gawde, A. N., & Kumar, V. (2026). Correlation and path coefficient analysis of yield and yield-contributing traits in bread wheat (*Triticum aestivum* L.) genotypes. *Plant Cell Biotechnology and Molecular Biology, 27*(7–8), 346–359. https://doi.org/10.56557/pcbmb/2026/v27i7-810864

Panse, V. G., & Sukhatme, P. V. (1967). *Statistical methods for agricultural workers* (2nd ed.). Indian Council of Agricultural Research. Official ICAR/IARI library record

Poudel, P. B., Poudel, M. R., & Puri, R. R. (2021). Evaluation of heat stress tolerance in spring wheat (*Triticum aestivum* L.) genotypes using stress tolerance indices in western region of Nepal. *Journal of Agriculture and Food Research, 5*, 100179. https://doi.org/10.1016/j.jafr.2021.100179

Sewore, B. M., & Abe, A. (2024). Genetic variability and trait associations in bread wheat (*Triticum aestivum* L.) genotypes under drought-stressed and well-watered conditions. *CABI Agriculture and Bioscience, 5*, 64. https://doi.org/10.1186/s43170-024-00259-6

Sharma, P., Kamboj, M. C., Singh, N., Chand, M., & Yadava, R. K. (2018). Path coefficient and correlation studies of yield and yield associated traits in advanced homozygous lines of bread wheat germplasm. *International Journal of Current Microbiology and Applied Sciences, 7*(2), 51–63. https://doi.org/10.20546/ijcmas.2018.702.008

Tolwani, S., & Shukla, R. S. (2022). Role of genetic variability, heritability and genetic advance for various traits of bread wheat (*Triticum aestivum* L.) under variable sowing times. *International Journal of Bio-Resource & Stress Management, 13*(2), 122–130. https://doi.org/10.23910/1.2022.2722

Unified Portal for Agricultural Statistics (UPAg). (2025). *All India crop-wise area, production & yield*. Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. Official Government of India UPAg page

Upadhyay, K., Adhikari, N. R., G. B. K. C., & Sharma, S. (2019). Genetic variability and cluster analysis of wheat (*Triticum aestivum* L.) genotypes in foot hill of Nepal. *Archives of Agriculture and Environmental Science, 4*(3), 350–355. https://doi.org/10.26832/24566632.2019.0403013

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