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RESEARCH ARTICLE

Effect of sowing dates on genetic variability, correlation and path analysis in bread wheat (*Triticum aestivum* L.) under Ranchi conditions

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Abstract

Wheat (*Triticum aestivum* L.) is a vital staple crop, yet global climate change is expected to reduce its yield by about 6 % for every 1 °C rise in temperature. As genetic parameters that guide breeding strategies can vary under different environmental conditions, multi-environmental evaluation is essential. During the *Rabi* season of 2019-20, an experiment was conducted at the research farm of Birsa Agricultural University, Ranchi to evaluate 28 wheat genotypes under three sowing conditions: timely sown, late sown and very late sown. Data were analyzed using analysis of variance (ANOVA), heritability and genetic advance estimates, correlation analysis and path coefficient analysis. The analysis of variance revealed significant genetic variability among genotypes for most traits. Phenotypic variance exceeded genotypic variance for all traits, reflecting the environmental influence. However, high heritability coupled with high genetic advance for 1000-seed weight, number of effective tillers, grains per spike and grain yield per plant indicated the predominance of additive gene action and strong genetic control. Grain yield showed positive and significant associations with biological yield, effective tillers, plant height and grains per spike, which were further confirmed by path analysis as major contributors to yield. These results imply that simultaneous selection for these key traits can effectively improve grain yield across variable sowing conditions, thereby providing a robust basis for developing climate-resilient wheat breeding strategies.

Keywords: genetic parameters; genotypic variation; heritability; phenotypic variance

Introduction

Wheat (*Triticum aestivum* L. emend. Thell) is the most important cereal crop for a large portion of the global population, serving as a staple food for approximately two billion people. It provides nearly 20 % of the total dietary calories and protein (1). Bread wheat is hexaploid (AABBDD) with 2n = 6x = 42 chromosomes and is cultivated on 223.67 million hectares globally, producing 735.3 million tons of grain (2). India is the second-largest wheat producer after China. With global demand for wheat projected to increase by 50 % by 2050, breeding efforts must focus on developing high-yielding and stress-tolerant varieties to ensure food security (2).

Climate change, particularly rising temperatures, poses a critical threat to wheat production. Wheat is highly sensitive to heat stress and increasing growing-season temperatures have already been reported in major wheat-producing regions (3). Approximately 40 % of global wheat area experiences heat stress, especially in dry and semi-arid zones, resulting in significant yield losses. The sowing date is a key factor influencing phenological development and yield stability (4). Delayed planting exposes wheat to terminal heat stress, which can reduce grain yield by up to 45 % (5).

Traditionally, wheat breeding programs have focused on developing disease-resistant and high-yielding varieties (6). However, limited studies have evaluated genetic variability, heritability and genetic advance for yield-related traits across multiple sowing environments (7). Most previous work has been restricted to single environments, limiting the identification of stable, high-yielding genotypes. This represents a significant research gap in breeding climate-resilient wheat (8, 9).

The present study was therefore undertaken during the *Rabi* season of 2019-20 at Birsa Agricultural University, Ranchi to evaluate 28 wheat genotypes under three sowing environments: timely, late and very late. The objectives were to: (i) assess genetic variability, heritability and genetic advance for yield and associated traits, (ii) determine correlations among grain yield and related morpho-agronomic traits and (iii) partition the direct and indirect effects of these traits on yield using path coefficient analysis.

Materials and Methods

The experiment was conducted at Birsa Agricultural University, Kanke, Ranchi (634 m above MSL; 23°25' N, 85°18' E). The experimental material for the present study comprised of twenty-eight wheat genotypes, along with four check varieties: K-307, BG-3, DBW-14 and WR-544 (Table 1). The experiment was carried out in three different date of sowing, as mentioned in Table 2. The experimental design used in the experiment was a randomized block design (RBD) with two replications, having a plot size of 0.6 m × 4 m. Although three replications are generally preferred, only two were used in this study due to space and resource constraints; however, with uniform field conditions and proper randomization, two replications are sufficient to obtain reliable estimates.

The distance maintained between rows and between plants was 23 cm and 10 cm, respectively. Three sowing dates were considered as distinct environments: E1 (27 Nov), E2 (12 Dec) and E3 (27 Dec), with 15-day intervals between each (Table 2). A recommended agronomic package of practices was implemented to ensure healthy crop growth. Data collection included both pre-harvest and post-harvest observations. Pre-harvest traits included phenological traits, such as days to 50 % flowering and chlorophyll content (%) measured using a soil and plant analysis device (SPAD) and flag leaf area calculated as length × width × 0.65, while post-harvest observations comprised morphological and yield-related traits such as plant height, spike length, number of effective tillers per plant, protein content (measured using a grain analyser), number of grains per spike and 1000-kernel weight.

Data were collected from five plants per genotype, averaged within each replication and the mean values were used for statistical analysis. The statistical evaluation was conducted using R software version 4.3.1 (R Core Team, Vienna, Austria). Descriptive statistics such as mean, range and coefficient of variation (CV) were computed. Genotypic (GCV) and phenotypic coefficients of variation (PCV) were estimated (10, 11). Broad-sense heritability (h^2bs) was calculated, while genetic advance (GA) and genetic advance as percent of mean (GAPM) were estimated (12, 13). Correlation coefficient analysis was carried out and path coefficient analysis was performed to partition direct and indirect effects (14, 15). Coefficients for determining leaf area calculated (16). Prior to analysis, the assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were verified to ensure validity of ANOVA and related parametric procedures.

Results

ANOVA for three different environments (E1, E2 and E3)

The ANOVA detected statistically significant differences among genotypes for most traits ($p < 0.05$ or $p < 0.01$), confirming substantial genetic variability that can be utilized in breeding programs (Table 3-5). Traits such as spike length, flag leaf area, 1000-seed weight, flowering and maturity days, grain yield and protein content consistently showed significant differences across environments (E1-E3). The strong genotype effect for these traits suggests that they are largely under genetic control, making them promising targets for selection and improvement. For example, yield-contributing traits such as 1000-seed weight and grain yield generally exhibit high heritability, while variation in flowering and maturity time reflects the adaptive strategies of genotypes under different growing conditions.

By contrast, traits such as chlorophyll content (%) did not exhibit statistically significant variation among genotypes. This lack of significance may reflect either narrow genetic variability for chlorophyll-related traits within the tested population or strong environmental sensitivity, since chlorophyll levels are known to fluctuate with microclimate, soil fertility and measurement timing. Consequently, chlorophyll content may not provide a stable or reliable selection criterion in this set of genotypes.

Across environments (E1-E3), most yield-related and phenological traits retained significance, underscoring their stability and genetic basis, whereas physiological traits such as chlorophyll content showed inconsistent responses, pointing to greater environmental modulation. This contrast emphasizes the importance of multi-environment testing to distinguish heritable, selection-relevant traits from those primarily influenced by the environment.

Genetic parameters

The existence of significant genetic diversity within the base material provides greater potential for developing desirable plant types. Therefore, understanding the extent of genetic variability is highly valuable. This has been demonstrated through various parameters, GCV and PCV; broad-sense heritability, GA and GAPM under timely, late sown and very late sown conditions (Table 6-8). In all the three environments (timely, late and very late sown), the phenotypic variance exceeded the genotypic variance, suggesting that environmental factors contributed significantly to the total variation observed.

Table 1. List of material used in the study and their origin

S. No.	Genotypes	Origin	S. No.	Genotypes	Origin
1.	RW-5	Karnal (IIWBR)	15.	WH-1239	CCSHAU(HR)
2.	HI-1628	IARI, (Indore)	16.	HD-2932	Delhi (IARI)
3.	DBW-252	Karnal (IIWBR)	17.	HD-3237	Delhi (IARI)
4.	K-307(C)	Kanpur (U.P)	18.	LBP-2017-2	Karnal (Haryana)
5.	NIAW-3170	Niphad (M.H)	19.	DBW-14(C)	Karnal (IIWBR)
6.	RAJ-4529	Durgapura (Raj)	20.	PBW-773	Ludhiana (Punjab)
7.	NI-5439	Niphad (MH)	21.	MP-1331	Powarkheda (MP)
8.	WH-1235	CCS HAU(HR)	22.	RIL-5138	Tata research
9.	DBW-273	Karnal (IIWBR)	23.	DBW-110	Karnal (IIWBR)
10.	BG-3(C)	Ranchi (B.A.U)	24.	M-516	AICRP (Wheat)
11.	RWP-2018-31	AICRP (Wheat)	25.	DBW-136	Karnal (IIWBR)
12.	DBW-233	Karnal (IIWBR)	26.	UP-2981	Pantnagar (U.K)
13.	MACS-6696	Pune, (ARI)	27.	HI-1621	IARI, (Indore)
14.	K-1317	Kanpur (U.P)	28.	WR-544(C)	Delhi (IARI)

Table 2. Description of environments

Environment	Date of sowing
Environment 1 (timely sown- E1)	27/11/2019
Environment 2 (late sown-E2)	12/12/2019
Environment 3 (very late sown-E3)	27/12/2019

Table 3. Analysis of variance (ANOVA) for environment (E1)

		Mean square											
SOV	**D.F**	**Plant height (cm)**	**Spike length (cm)**	**Flag leaf area (cm²)**	**1000-seed weight (g)**	**Days to 50 % flowering**	**Days to maturity**	**Grain yield/ plant (g)**	**No of grains / spike**	**No effective tillers**	**Chlorophyll content (%)**	**Protein content (%)**	**Biological yield (g/ plant)**	**Harvest index (%)**
Replication	1	44.98	2.10	0.66	0.25	1.14	0.071	1.54	0.113	0.004	13.12	0	27.34	36.85
Treatment	27	28.69 *	4.410**	18.11**	51.33 *	26.58 **	41.69 **	3.25**	64.46**	2.22**	16.08 *	4.70*	15.93 *	62.47**
Error	27	13.58	0.58	3.93	3.006	0.47	0.51	0.53	12.45	0.48	8.12	0.02	6.75	14.96

**= significant at 1 %, *= significant at 5 %

Table 4. Analysis of variance (ANOVA) for environment (E2)

		Mean square												
SOV	**D.F**	**Plant height (cm)**	**Spike length (cm)**	**Flag leaf area (cm²)**	**1000-seed weight (g)**	**Days to 50 % flowering**	**Days to maturity**	**Grain yield/ plant (g)**	**No of grains / spike**	**No effective tillers**	**Chlorophyll content (%)**	**Protein content (%)**	**Biological yield (g/ plant)**	**Harvest index (%)**
Replication	1	0.34	2.47	0.71	9.17	0.28	0.16	0.90	5.08	0.44	12.48	0.005	1.44	6.61
Treatment	27	38.85 *	5.01**	49.27 **	61.97 **	152.42**	44.42**	6.80 **	32.05*	2.29 **	6.37	4.48 **	22.02 **	65.82**
Error	27	15.84	0.618	3.56	2.23	0.50	0.56	0.45	16.09	0.58	10.03	0.017	8.02	13.007

**= significant at 1 %, *= significant at 5 %

Table 5. Analysis of variance (ANOVA) for environment (E3)

		Mean square												
SOV	**D.F**	**Plant height (cm)**	**Spike length (cm)**	**Flag leaf area (cm²)**	**1000- seed weight (g)**	**Days to 50 % flowering**	**Days to maturity**	**Grain yield/ plant (g)**	**No of grains / spike**	**No effective tillers**	**Chlorophyll content (%)**	**Protein content (%)**	**Biological yield (g/ plant)**	**Harvest index (%)**
Replication	1	1.42	1.62	3.036	0.22	0.28	0.071	0.29	9.31	1.49	0.27	0	12.22	44.92
Treatment	27	56.90**	3.18**	23.86 **	57.08**	27.01**	66.08**	1.84 **	99.31**	1.95 **	30.58 **	4.63**	9.51 *	71.46**
Error	27	16.70	0.54	4.32	0.65	0.50	0.51	0.55	8.53	0.52	9.82	0.020	4.68	28.17

**= significant at 1 %, *= significant at 5 %

Table 6. Genetic variability estimates of environment (E1)

Source of variation	**Plant height (cm)**	**Spike length (cm)**	**Flag leaf area (cm²)**	**1000-seed weight (g)**	**Days to 50 % flowering**	**Days to maturity**	**Grain yield / plant (g)**	**No of grains / spike**	**No effective tillers**	**Chlorophyll content (%)**	**Protein content (%)**	**Biological yield (g/ plant)**	**Harvest index (%)**
δ^2g	11.50	2.19	22.85	29.86	75.95	21.92	3.17	7.98	0.85	-1.82	2.23	7.00	26.40
δ^2ph	27.34	2.81	26.42	32.10	76.46	22.49	3.63	24.07	1.44	8.20	2.25	15.02	39.41
GCV	3.32	17.13	13.74	11.95	1.46	2.54	17.64	12.73	18.38	4.07	11.14	10.20	6.90
PCV	5.13	19.39	21.70	12.48	8.18	3.77	23.11	15.94	24.94	8.41	11.28	19.35	17.03
h^2	42.06	79.17	40.10	91.69	3.20	45.62	58.25	63.74	54.33	23.51	97.53	27.80	16.42
Genetic advance	4.51	2.52	3.42	10.23	0.38	4.75	1.79	8.181	1.29	1.77	3.05	1.913	2.20
Genetic advance mean	4.44	29.03	17.92	23.58	0.54	3.54	27.73	20.93	27.91	4.07	22.67	11.08	5.76

Table 7. Genetic variability estimates of environment (E2)

Source of variation	Plant height (cm)	Spike length (cm)	Flag leaf area (cm^2)	1000-seed weight (g)	Days to 50 % flowering	Days to maturity	Grain yield / plant (g)	No of grains / spike	No Effective tillers	Chlorophyll Content (%)	Protein content (%)	Biological yield (g plant)	Harvest index (%)
δ^2g	7.55	1.91	7.08	24.16	13.05	20.58	1.36	26.00	0.86	3.97	2.33	4.59	23.75
δ^2ph	21.13	2.49	11.02	27.17	13.53	21.10	1.89	38.45	1.35	12.10	2.36	11.34	38.72
GCV	2.75	16.07	11.72	11.24	5.20	3.38	17.85	12.67	19.60	4.46	11.31	12.73	12.42
PCV	4.60	18.34	14.62	11.92	5.29	3.43	21.06	15.41	24.51	7.79	11.37	20.01	15.86
h^2	35.72	76.73	64.28	88.93	96.48	97.55	71.79	67.61	63.95	32.86	99.08	40.47	61.34
Genetic advance	3.38	2.49	4.39	9.54	7.311	9.23	2.03	8.63	1.53	2.35	3.13	2.80	7.86
Genetic advance mean	3.39	29.00	19.36	21.84	10.52	6.89	31.16	21.46	32.29	5.27	23.20	16.68	20.05

Table 8. Genetic variability estimates of environment (E3)

Source of variation	Plant height (cm)	Spike length (cm)	Flag leaf area (cm^2)	1000 -seed weight (g)	Days to 50 % flowering	Days to maturity	Grain yield / plant (g)	No of grains / spike	No effective tillers	Chlorophyll content (%)	Protein content (%)	Biological yield (g/ plant)	Harvest index (%)
δ^2g	20.10	1.32	9.77	28.21	13.25	32.78	0.64	45.39	0.71	10.38	2.30	2.41	21.64
δ^2p	36.80	1.86	14.09	28.87	13.76	33.29	1.20	53.92	1.24	20.20	2.32	7.09	49.81
GCV	4.90	13.05	19.65	12.70	5.56	4.37	13.73	20.28	20.76	7.71	11.26	11.00	11.06
PCV	6.63	15.50	23.60	12.85	5.67	4.41	18.72	22.11	27.39	10.76	11.31	18.85	16.79
h^2	54.62	70.89	69.34	97.72	96.30	98.45	53.74	84.18	57.46	51.37	99.13	34.02	43.44
Genetic advance	6.82	1.99	5.36	10.81	7.35	11.70	1.21	12.73	1.32	4.75	3.11	1.86	6.31
Genetic advance mean	7.46	22.64	33.71	25.88	11.25	8.94	20.73	38.34	32.42	11.39	23.11	13.21	15.02

Genetic estimate for environment: timely sown (E1)

Table 6 indicated that phenotypic variance was higher than genotypic variance for all the studied traits. The highest phenotypic variance (76.95) and genotypic variance (75.95) were observed for days to 50 % flowering, followed by 1000-seed weight (32.10 and 29.86, respectively). The small difference between PCV and GCV for traits such as days to 50 % flowering and 1000-seed weight indicates low environmental influence and strong genetic control, making these traits suitable for selection in breeding programs.

The GCV ranged from 1.46 % (days to 50 % flowering) to 18.38 % (effective tillers), while the PCV ranged from 3.77 % (days to maturity) to 24.94 % (effective tillers). The high GCV and PCV values for the number of effective tillers reflect substantial genetic variability and thus greater potential for selection. In contrast, the low GCV and PCV values for traits such as days to 50 % flowering and days to maturity suggest limited genetic variability and a greater role for environmental influence.

Heritability estimates were highest for spike length (79.17 %), 1000-seed weight (91.69 %), protein content (97.03 %), number of grains per spike (63.74 %) and grain yield per plant (58.25 %). GA as a percentage of mean was highest for 1000-seed weight (23.58 %), grain yield per plant (27.73 %), number of grains per spike (20.93 %) and protein content (22.67 %). High heritability coupled with high genetic advance as a percentage of mean for traits such as 1000-seed weight, grain yield per plant, number of grains per spike and protein content indicates that these traits are primarily governed by additive gene action. This suggests strong genetic control with minimal environmental influence, making them highly responsive to selection in breeding programs.

Genetic estimate for environment: late sown (E2)

Table 7 revealed that yield-contributing traits, such as 1000-seed weight, days to maturity, number of grains per spike and harvest index, recorded the highest phenotypic and genotypic variances, indicating ample variability and scope for selection. As expected, PCV values were consistently higher than GCV values across traits, highlighting the role of environmental factors. Traits such as grain yield per plant and number of effective tillers showed high GCV and PCV, suggesting strong genetic variability and their suitability as selection criteria. In contrast, traits like plant height and days to maturity exhibited low GCV and PCV, reflecting limited genetic variation and greater environmental influence.

Heritability estimates were generally high, with protein content, days to maturity, days to 50 % flowering and 1000-seed weight showing particularly strong values. When coupled with high genetic advance as a percentage of mean as seen for grain yield, spike length, effective tillers and 1000-seed weight, this indicates additive gene action and a high likelihood of genetic gain through selection. By contrast, traits with high heritability but moderate genetic advance (e.g. protein content, days to maturity) are more likely influenced by non-additive gene effects, making direct selection less effective.

Overall, under the conditions tested, traits such as grain yield, effective tillers, spike length and 1000-seed weight emerged as reliable targets for genetic improvement, whereas traits with low variability or strong environmental sensitivity may be less responsive to selection.

Genetic estimate for environment: very late sown (E3)

Table 8 showed that under very late sowing, traits such as 1000-seed weight, number of grains per spike and days to maturity exhibited both high genotypic and phenotypic variances, reflecting substantial genetic diversity. The relatively small differences between GCV and PCV for most traits suggest low environmental influence, indicating that their expression is largely under genetic control. Effective tillers showed particularly high GCV and PCV, highlighting wide genetic variability and strong potential for selection.

Heritability estimates were generally high, especially for 1000 -seed weight, days to 50 % flowering, days to maturity and number of grains per spike. When coupled with moderate to high GA as a percentage of the means observed in traits such as grains per spike, effective tillers, flag leaf area and grain yield per plant, this points to additive gene action and reliable transmission of these traits to subsequent generations.

Overall, under terminal heat stress, yield-related traits including grain yield per plant, effective tillers and 1000-seed weight demonstrated stable heritability and GA. This indicates that these traits are resilient under late sowing and hold strong promise as selection targets in breeding programs aimed at improving performance under stress conditions.

Correlation studies for yield and yield-attributing characters under different environments

Correlation studies across environments (E1-E3)

The correlation analysis revealed that grain yield per plant consistently exhibited strong positive associations with biological yield, number of effective tillers and number of grains per spike across all environments (E1, E2 and E3). These traits, which directly reflect resource capture, biomass accumulation and reproductive efficiency, appear to be the most reliable determinants of yield potential.

In E1 (timely sown): grain yield showed strong positive correlations with biological yield (r = 0.756), effective tillers (r = 0.728) and grains per spike (r = 0.728), indicating that higher biomass production, better tiller survival and improved spike fertility are major determinants of yield under favorable sowing conditions (Table 9, Fig. 1). Plant height (r = 0.480), 1000-seed weight (r = 0.418) and harvest index (r = 0.375) also contributed positively, suggesting that taller plants with larger seed size and efficient partitioning of assimilates can further enhance productivity. Spike length (r = 0.053) exhibited only a weak association, implying that its role in yield formation is minor when growing conditions are optimal.

In E2 (late sown): grain yield per plant exhibited strong positive correlations with biological yield (r = 0.756), number of effective tillers (r = 0.801) and plant height (r = 0.729), underscoring the critical roles of biomass accumulation, productive tillering and adequate stature in supporting higher yield (Table 10, Fig. 2). Grains per spike (r = 0.672), harvest index (r = 0.731) and 1000-seed weight (r = 0.371) also showed significant positive associations, indicating that under late sowing, efficient partitioning of assimilates and maintenance of seed size become important for yield determination. The strength of these correlations reflects the physiological adjustments of wheat under heat stress, where plants that maintain fertile spikes, more tillers and efficient biomass utilization are able to sustain productivity despite shortened growth duration.

Table 9. Correlation analysis for yield and yield attributing traits of wheat (*Triticum aestivum* L.) genotypes under timely sown environment (E1)

Characters		Plant height (cm)	Spike length (cm)	Flag leaf area (cm^2)	1000 Seed weight (g)	Days to 50 % flowering	Days to maturity	No of grains/ spike	No of effective tillers	Biological yield (g/plant)	Harvest Index (%)	Grain yield / plant (g)
Plant height (cm)	P	1	0.077	0.128	0.200	-0.136	-0.244	0.507**	0.571 **	0.570 **	0.491**	0.729 **
Spike length (cm)	P		1	-0.364 **	0.272 *	0.134	-0.153	0.252	0.239	0.214	0.083	0.197
Flag Leaf area (cm^2)	P			1	-0.2756*	-0.0244	0.0034	-0.1261	-0.0121	-0.0014	0.026	0.001
1000 seed weight (g)	P				1	-0.274 *	-0.274 *	0.444 **	0.467 **	0.367 **	0.181	0.3708**
Days to 50 % flowering	P					1	0.1214*	-0.105	0.006	-0.1001	0.0266	-0.0437
Days to maturity	P						1	-0.344 **	-0.423 **	-0.263 *	-0.34**	-0.043**
No. of grains/ spike	P							1	0.764 **	0.438 **	0.588**	0.6719 **
No. of effective tillers	P								1	0.540 **	0.643**	0.8007 **
Biological yield (g/plant)	P									1	0.125	0.759 **
Harvest index (%)	P										1	0.7309**

**= significant at 1 %, *= significant at 5 %

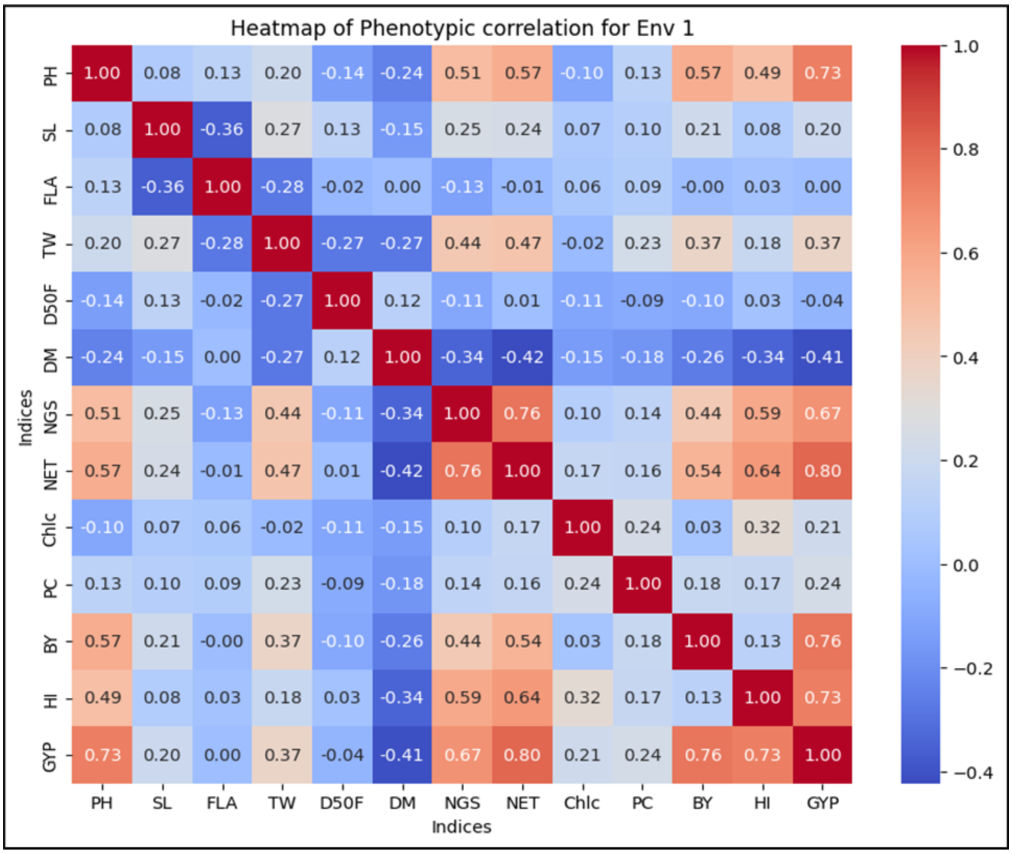

Fig. 1. Correlation heatmap for yield and yield attributing traits of wheat genotypes under timely sown environment (E1). PH-plant height, SL-spike length, FLA-flag leaf area, TW- 1000-seed weight, D50F- days to 50 % flowering, NGS- number of grains per spike, NET-number of effective tillers/plant, Chlc- chlorophyll content %, PC- protein content %, BY- biological yield, HI- harvest index and GYP- grain yield per plant.

Table 10. Correlation analysis for yield and yield attributing traits of wheat genotypes in late sown environment (E2)

Characters		Plant height (cm)	Spike length (cm)	Flag leaf area(cm^2)	1000-seed weight (g)	Days to 50 % flowering	Days to maturity	No of grains/ spike	No of Effective tillers	Biological yield (g/plant)	Harvest index (%)	Grain yield / plant (g)
Plant height (cm)	P	1	0.092	-0.181	0.290 *	-0.184	-0.268 *	0.533 **	0.463**	0.314 *	0.285 *	0.480 **
Spike length (cm)	P		1	0.2144	0.229	0.005	-0.108	0.080*	0.009	-0.055	0.142	0.053*
Flag Leaf area (cm^2)	P			1	0.0438	0.129	0.0744	-0.278 *	-0.387**	-0.3611 **	-0.092	-0.426 **
1000 seed weight (g)	P				1	0.154	-0.169	0.401**	0.2985 *	0.1733	0.343**	0.418 **
Days to 50 % flowering	P					1	0.448 **	-0.155	-0.041	-0.0525	-0.089	-0.1058
Days to maturity	P						1	-0.364 **	-0.187	-0.304 *	-0.0618	-0.351 **
No. of grains/ spike	P							1	0.6469**	0.4623 **	0.4199**	0.728 **
No. of effective tillers	P								1	0.412 **	0.476 **	0.728 **
Biological yield (g/plant)	P									1	-0.298 *	0.756 **
Harvest index (%)	P										1	0.375 **

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

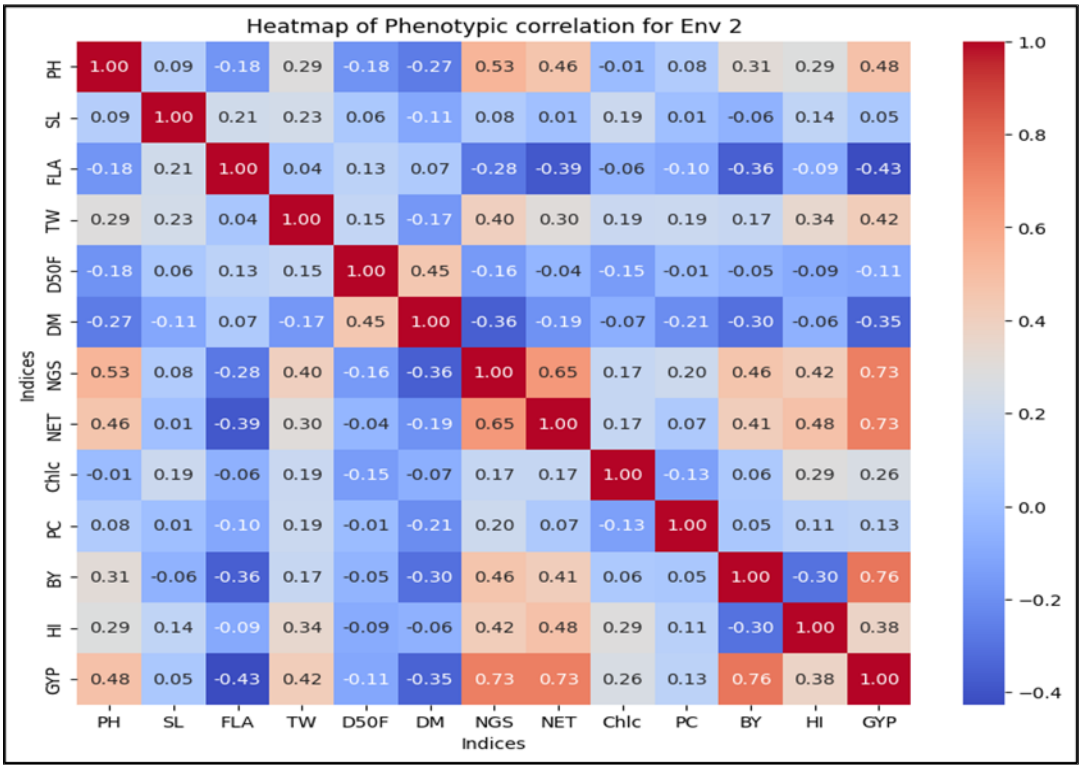

Fig. 2. Correlation heatmap for yield and yield attributing traits of wheat genotypes under late sown environment (E2). PH-plant height, SL-spike length, FLA-flag leaf area, TW- 1000-seed weight, D50F- days to 50 % flowering, NGS- number of grains per spike, NET-number of effective tillers/plant, Chlc- chlorophyll content %, PC- protein content %, BY- biological yield, HI- harvest index and GYP- grain yield per plant.

In E3 (very late sown): correlations with grains per spike (r = 0.663), effective tillers (r = 0.626) and biological yield (r = 0.616) persisted, though at slightly reduced magnitudes compared with E1 and E2 (Table 11, Fig. 3). This reduction reflects the effect of terminal heat stress, which restricts tiller survival and biomass production. Plant height (r = 0.607), harvest index (r = 0.423) and 1000-seed weight (r = 0.294) remained significant contributors, suggesting that under severe stress, traits linked to efficient biomass partitioning and the ability to maintain grain filling become more critical for sustaining yield.

Synthesis across environments

Biological yield, number of effective tillers and grains per spike consistently showed strong and significant correlations with grain yield across all three sowing environments (E1, E2 and E3). This indicates that these traits are stable and robust selection criteria, irrespective of planting time. Plant height also maintained a positive relationship, though its contribution increased under late sowing, suggesting that taller plants support better photosynthetic area and assimilate translocation when growth duration is shortened. Harvest index and 1000-seed weight contributed positively in all conditions, but their correlation strengths were stronger under late sowing (E2, E3) compared to timely sowing (E1). This variation reflects their greater importance under stress conditions, where efficient biomass partitioning and the ability to maintain grain size become crucial for sustaining yield. Spike length, by contrast, showed weak or inconsistent correlations, implying a limited role in yield formation across environments.

Physiological interpretation

The consistent associations of biological yield, effective tillers and grains per spike with grain yield demonstrate that wheat productivity is fundamentally determined by biomass accumulation, survival of productive tillers and spike fertility. Under

Table 11. Correlation analysis for yield and yield attributing traits of wheat genotypes in very late sown environment (E3)

Characters		Plant height (cm)	Spike length (cm)	Flag leaf area (cm²)	1000-seed weight (g)	Days to 50 % flowering	Days to maturity	No of grains/ spike	No of Effective tillers	Biological yield (g/plant)	Harvest index(%)	Grain yield / plant (g)
Plant height (cm)	P	1	-0.130	-0.1786	0.3542**	-0.090	-0.100	0.643**	0.657**	0.458**	0.113	0.6067 **
Spike length (cm)	P		1	-0.0444	0.108	0.099	0.024	0.064*	-0.016	0.144	-0.1	0.001
Flag Leaf area (cm²)	P			1	-0.1866	0.323 *	0.034	-0.280*	-0.300 *	-0.060	-0.108	-0.163
1000 seed weight (g)	P				1	0.106	-0.100	0.430**	0.356 **	0.083	0.223	0.294 *
Days to 50 % flowering	P					1	0.367 **	-0.084	-0.037	-0.127	0.110	-0.072
Days to maturity	P						1	-0.119	-0.1654	-0.163	-0.111	-0.228
No of grains/ spike	P							1	0.8712 **	0.515 **	0.105	0.663 **
No of effective tillers	P								1	0.505 **	0.088	0.626 **
Biological yield (g/ plant)	P									1	-0.357**	0.616**
Harvest index (%)	P										1	0.423 **

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

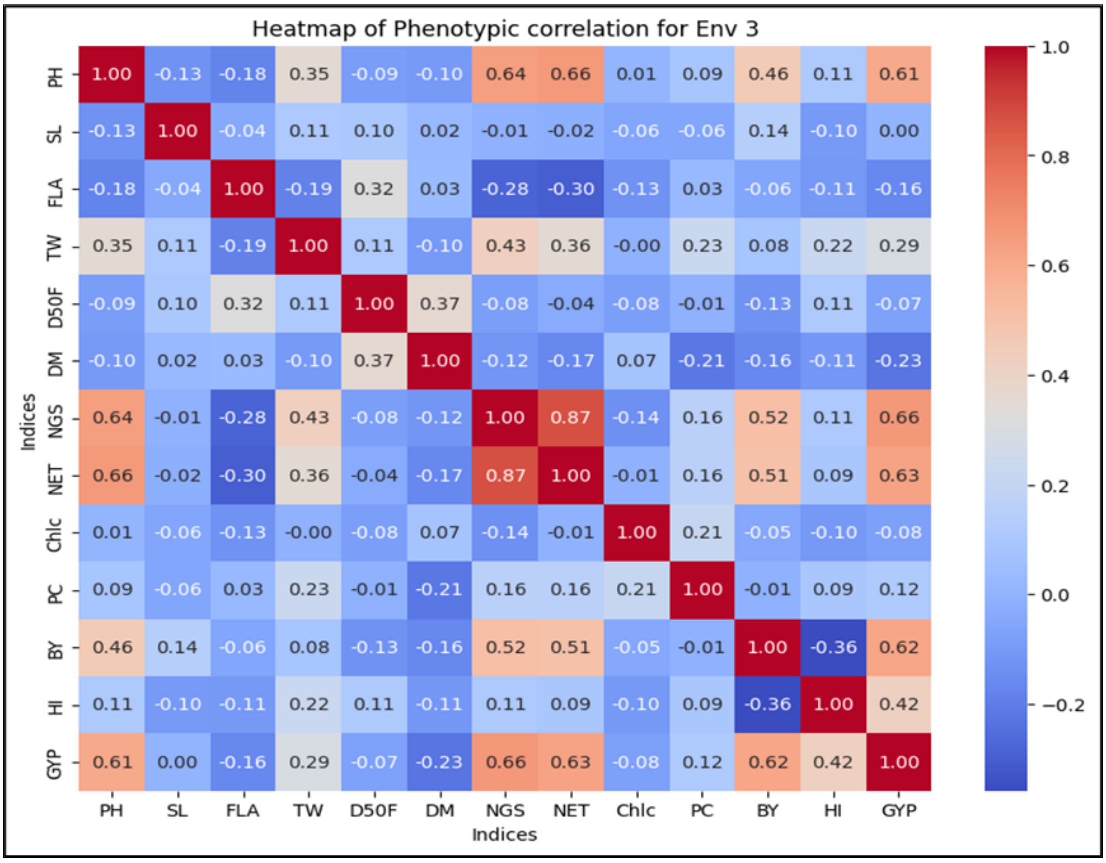

Fig. 3. Correlation heatmap for yield and yield attributing traits of wheat genotypes under very late sown environment (E3). PH-plant height, SL-spike length, FLA-flag leaf area, TW- 1000-seed weight, D50F- days to 50 % flowering, NGS- number of grains per spike, NET-number of effective tillers/plant, Chlc- chlorophyll content %, PC- protein content %, BY- biological yield, HI- harvest index and GYP- grain yield per plant.

favorable timely sowing (E1), plants with higher biomass and better reproductive efficiency translate these advantages into higher yields. In late sowing (E2), where heat stress accelerates phenology, traits like effective tillers, harvest index and 1000-seed weight gain prominence, as maintaining assimilate partitioning efficiency and grain filling becomes essential for compensating reduced growth duration. In very late sowing (E3), terminal heat stress further reduces tiller survival and biomass production, lowering correlation magnitudes. However, the persistence of significant associations even under severe stress highlights the importance of maintaining a balance between source capacity (biological yield, plant height) and sink strength (tillers, grains per spike, seed weight). Thus, these traits can serve as reliable physiological markers for breeding wheat genotypes resilient to both optimal and stress-prone environments.

Path analysis for yield and yield attributing characters under different environments

Path analysis for environment: timely sown (E1)

Under E1 conditions, plant height, effective tillers and grains per spike were the major contributors that showed strong positive direct effects on grain yield (Table 12, Fig. 4). Taller plants likely contributed more biomass and assimilates, supporting grain filling. Effective tillers directly increased the number of productive spikes, while grains per spike improved sink capacity, leading to higher yield potential. Traits like seed weight and protein content also showed smaller positive contributions, reflecting their supportive role in resource allocation. Conversely, days to flowering and maturity exhibited negative effects, indicating that delayed phenology may reduce yield by shortening the effective grain-filling period under timely sowing.

Path analysis for environment: late sown (E2)

Under E2 conditions, grains per spike, effective tillers and plant height again emerged as the major contributors with strong positive direct effects on grain yield (Table 13, Fig. 5). Here, more grains per spike enhanced sink strength, while greater tiller numbers ensured sufficient spike production even under shortened growing periods. Plant height contributed positively by maintaining adequate biomass for resource partitioning. Seed weight and chlorophyll content showed moderate positive effects, suggesting that both larger seed size and sustained photosynthesis still aid yield under stress. However, days to maturity, flag leaf area and harvest index exerted negative direct effects, implying that excessive vegetative growth or prolonged maturity may reduce yield potential by exposing plants to terminal heat stress.

Path analysis for environment: very late sown (E3)

In E3, effective tillers, grains per spike and biological yield had the strongest positive direct effects on grain yield (Table 14, Fig. 6), underlining their role in sustaining productivity under very late sowing stress. Higher tiller numbers ensured adequate spike-bearing shoots despite reduced crop duration, while more grains per spike compensated for stress-induced reductions in other traits. Biological yield reflected overall biomass capture, which remained essential for supporting reproductive sinks. Plant height and harvest index also contributed positively but with lower magnitude, indicating that moderate plant stature and efficient assimilate partitioning favour yield even under stress. In contrast, flag leaf area and days to maturity showed negative effects, suggesting that under severe heat stress, smaller leaves (reducing transpiration load) and earlier maturity (escaping stress) are advantageous for maintaining yield.

Table 12. Path analysis for thirteen characters of wheat (*Triticum aestivum* L.) genotypes under timely sown environment (E_1)

Characters		Plant height (cm)	Spike length (cm)	Flag leaf area (cm²)	1000- seed weight (g)	Days to 50 % flowering	Days to maturity	No of grains/ spike	No of Effective tillers	Chlorophyll content (%)	Protein content (%)	Biological yield (g/plant)	Harvest index (%)
Plant height (cm)	P	**0.055**	-0.00097	-0.0043	-0.0011	-0.00081	0.00188	-0.0256	0.04403	0.00085	0.0018	0.36114	0.2970
Spike length (cm)	P	0.00433	**-0.01245**	0.01219	-0.00154	0.00080	0.00119	-0.01280	0.01844	-0.00055	0.00149	0.13566	0.05024
Flag leaf area (cm²)	P	0.00720	0.00454	**-0.03347**	0.00156	-0.00015	-0.00003	0.00639	-0.00093	-0.00045	0.00133	-0.00089	0.01590
1000-seed weight (g)	P	0.01121	-0.00339	0.00922	**-0.00565**	-0.00164	0.00212	-0.02249	0.03601	0.00013	0.00336	0.23232	0.10960
Days to 50 % flowering	P	-0.00761	-0.00168	0.00082	0.00155	**0.00598**	-0.00093	0.00046	0.00534	0.00091	-0.00126	-0.06337	0.01608
Days to maturity	P	-0.01368	0.00192	-0.00011	0.00155	0.00073	**-0.00770**	0.01746	-0.03261	0.00124	-0.00259	-0.16699	-0.20820
No of grains/ spike	P	0.02837	-0.00315	0.00422	-0.00251	-0.00063	0.00265	**-0.05064**	0.05892	-0.00085	0.00207	0.27777	0.35576
No of effective tillers	P	0.03194	-0.00298	0.00040	-0.00264	0.00004	0.00326	-0.03870	**0.07711**	-0.00140	0.00238	0.34221	0.38907
Chlorophyll content (%)	P	-0.00482	-0.00070	-0.00154	0.00007	-0.00055	0.00096	-0.00437	0.01089	**-0.00684**	0.00292	0.01798	0.16219
Protein content (%)	P	0.00716	-0.00127	-0.00304	-0.00130	-0.00051	0.00136	-0.00716	0.01254	-0.00197	**0.01463**	0.11268	0.10476
Biological yield (g/ plant)	P	0.03190	-0.00267	0.00005	-0.00207	-0.00060	0.00203	-0.02222	0.04168	-0.00028	0.00260	**0.63303**	0.07575
Harvest index (%)	P	0.02747	-0.00104	0.00088	-0.00103	0.00016	0.00265	-0.02980	0.04962	-0.00265	0.00254	0.07932	**0.60453**

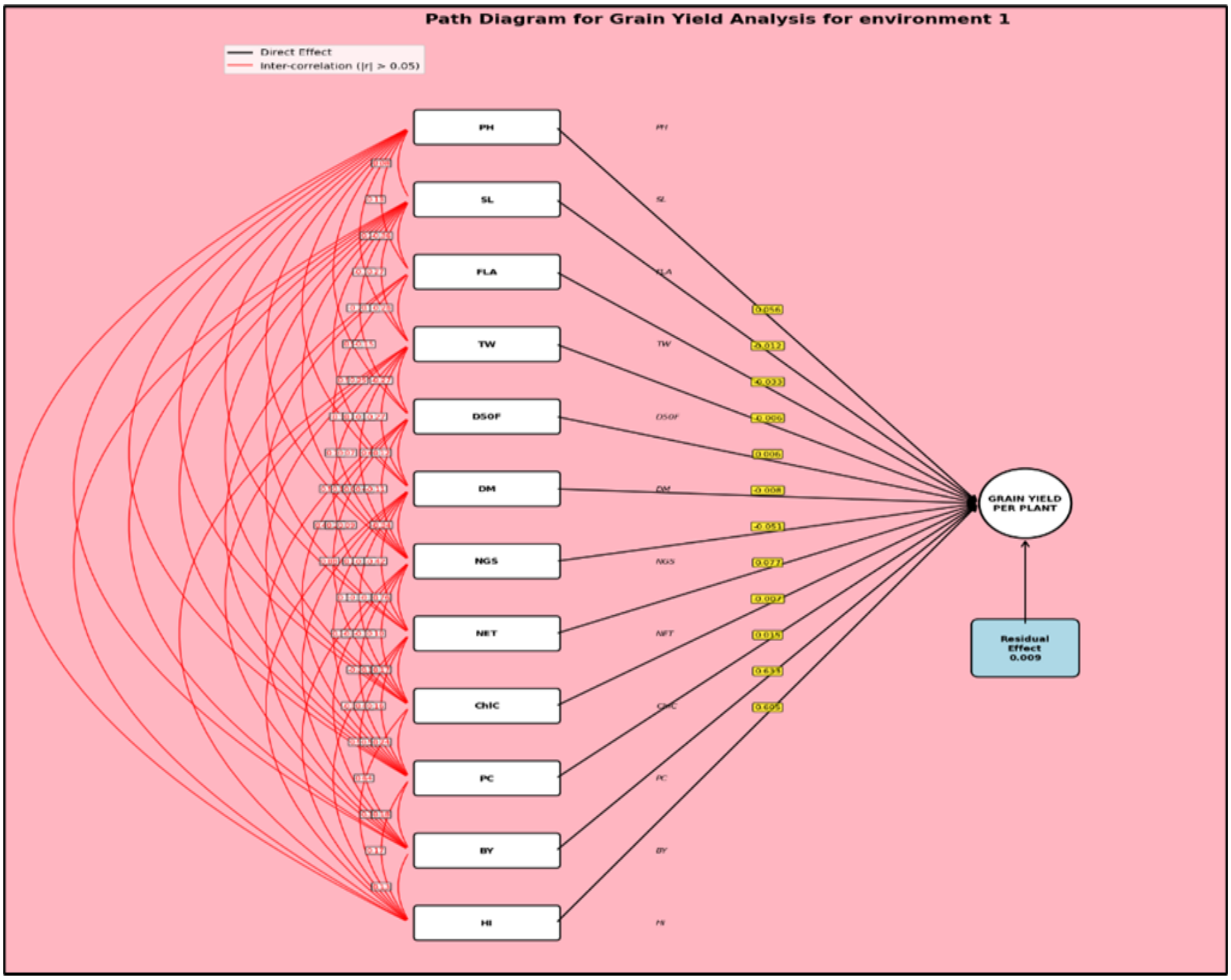

Fig. 4. Phenotypic path diagram depicting direct and indirect effects of twelve characters in wheat genotypes under timely sown environment (E1). PH-plant height, SL-spike length, FLA-flag leaf area, TW- 1000-seed weight, D50F- days to 50 % flowering, NGS- number of grains per spike, NET-number of effective tillers/plant, Chlc- chlorophyll content %, PC- protein content %, BY- biological yield, HI- harvest index and GYP - grain yield per plant.

Table 13. Path analysis for thirteen characters of wheat (*Triticum aestivum* L.) genotypes under late sown environment (E2)

Characters		Plant height (cm)	Spike length (cm)	Flag leaf area (cm²)	1000-seed weight (g)	Days to 50 % flowering	Days to maturity	No of grains/ spike	No of Effective tillers	Chlorophyll content (%)	Protein content (%)	Biological yield (g/plant)	Harvest index (%)
Plant height (cm)	**P**	**-0.02308**	0.00122	0.00643	0.01112	-0.00116	0.00802	0.00381	0.02089	-0.00006	-0.00046	0.28121	0.17296
Spike length (cm)	**P**	-0.00214	**0.01318**	-0.00759	0.00877	0.00036	0.00323	0.00057	0.00044	0.00098	-0.00003	-0.05015	0.08618
Flag leaf area (cm²)	**P**	0.00419	0.00282	**-0.03544**	0.00167	0.00082	-0.00222	-0.00199	-0.01744	-0.00032	0.00059	-0.32330	-0.05598
1000-seed weight (g)	**P**	-0.00670	0.00302	-0.00155	**0.03828**	0.00097	0.00504	0.00287	0.01346	0.00094	-0.00107	0.15520	0.20794
Days to 50 % flowering	**P**	0.00425	0.00075	-0.00459	0.00591	**0.00630**	-0.01339	-0.00111	-0.00189	-0.00076	0.00006	-0.04702	-0.05440
Days to maturity	**P**	0.00620	-0.00143	-0.00264	-0.00647	0.00283	**0.02984**	-0.00260	-0.00847	-0.00038	0.00118	-0.27288	-0.03740
No of grains/ spike	**P**	-0.01230	0.00106	0.00986	0.01537	-0.00098	0.01088	**0.00714**	0.02915	0.00084	-0.00115	0.41402	0.25411
No of effective tillers	**P**	0.00013	-0.01070	0.01371	0.01143	-0.00026	0.00561	0.00462	**0.04506**	0.00085	-0.00037	0.36942	0.28860
Chlorophyll content (%)	**P**	0.00027	0.00254	0.00227	0.00712	-0.00095	0.00224	0.00119	0.00757	**0.00505**	0.00075	0.05597	0.17447
Protein content (%)	**P**	-0.00186	0.00008	0.00371	0.00719	-0.00007	0.00619	0.00145	0.00294	-0.00067	**-0.00568**	0.04639	0.06614
Biological yield (g/ plant)	**P**	-0.00725	-0.00074	0.01279	0.00663	-0.00033	0.00909	0.00330	0.01859	0.00032	-0.00029	**0.89557**	-0.18088
Harvest index (%)	**P**	-0.00660	0.00188	0.00328	0.01315	-0.00057	0.00184	0.00300	0.02149	0.00146	-0.00062	-0.26768	**0.60517**

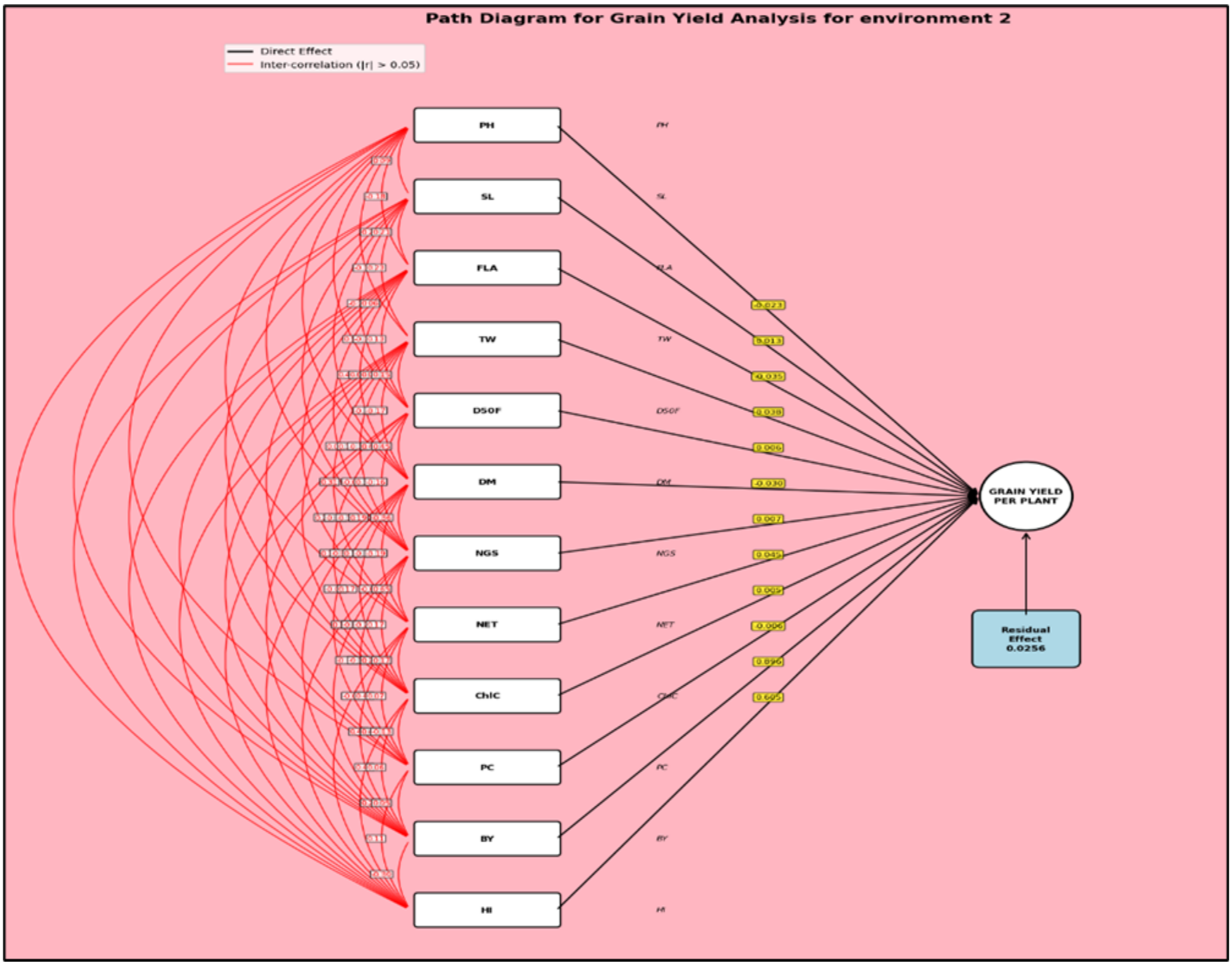

Fig. 5. Phenotypic path diagram depicting direct and indirect effects of twelve characters in wheat genotypes under late sown environment (E2). PH-plant height, SL-spike length, FLA-flag leaf area, TW- 1000-seed weight, D50F- days to 50 % flowering, NGS- number of grains per spike, NET-number of effective tillers/plant, Chlc- chlorophyll content %, PC- protein content %, BY- biological yield, HI- harvest index and GYP - grain yield per plant.

Table 14. Path analysis for thirteen characters of wheat genotypes under very late sown environment (E3)

Characters		Plant height (cm)	Spike length (cm)	Flag leaf area (cm²)	1000-seed weight (g)	Days to 50 % flowering	Days to maturity	No of grains/ spike	No of Effective tillers	Chlorophyll content (%)	Protein content (%)	Biological yield (g/plant)	Harvest index (%)
Plant height (cm)	P	**0.08911**	0.00172	-0.00548	-0.00605	0.00321	-0.00074	0.11674	-0.00341	0.00029	0.00185	0.33403	0.07545
Spike length (cm)	P	-0.01166	**-0.01311**	-0.00136	-0.00185	-0.00353	0.00018	-0.00187	0.00008	-0.00240	-0.00125	0.10484	-0.06677
Flag leaf area (cm²)	P	-0.01591	0.00058	**0.03068**	0.00319	-0.01151	0.00025	-0.05086	0.00156	-0.00513	0.00059	-0.04419	-0.07244
1000-seed weight (g)	P	0.03156	-0.00142	-0.00572	**-0.01709**	-0.00377	-0.00074	0.07812	-0.00185	-0.00015	0.00489	0.06101	0.14936
Days to 50 % flowering	P	-0.00804	-0.00130	0.00993	-0.00181	**-0.03558**	0.00269	-0.01525	0.00019	-0.00336	-0.00025	-0.09312	0.07391
Days to maturity	P	-0.00899	-0.00032	0.00106	0.00172	-0.01307	**-0.02162**	0.00731	0.00086	0.00293	-0.00456	-0.11911	-0.07471
No of grains/ spike	P	0.05735	0.00014	-0.00860	-0.00736	0.00299	-0.00087	**0.18138**	-0.00452	-0.00546	0.00338	0.37494	0.07044
No of effective tillers	P	0.05855	0.00021	-0.00922	-0.00609	0.00131	-0.00121	0.15802	**-0.00519**	-0.00030	0.00340	0.36788	0.05896
Chlorophyll content (%)	P	0.00064	0.00079	-0.00393	0.00006	0.00298	0.00053	-0.02470	0.00004	**0.04012**	0.00452	-0.03291	-0.06944
Protein content (%)	P	0.00775	0.00077	0.00086	-0.00393	0.00043	-0.00157	0.02884	-0.00083	0.00853	**0.02125**	-0.00823	0.06323
Biological yield (g/ plant)	P	0.04088	-0.00189	-0.00186	-0.00143	0.00455	-0.00120	0.09341	-0.00262	-0.00181	-0.00024	**0.72797**	-0.23896
Harvest index (%)	P	0.01007	0.00131	-0.00333	-0.00382	-0.00394	-0.00082	0.01914	-0.00046	-0.00417	0.00201	-0.26057	**0.66768**

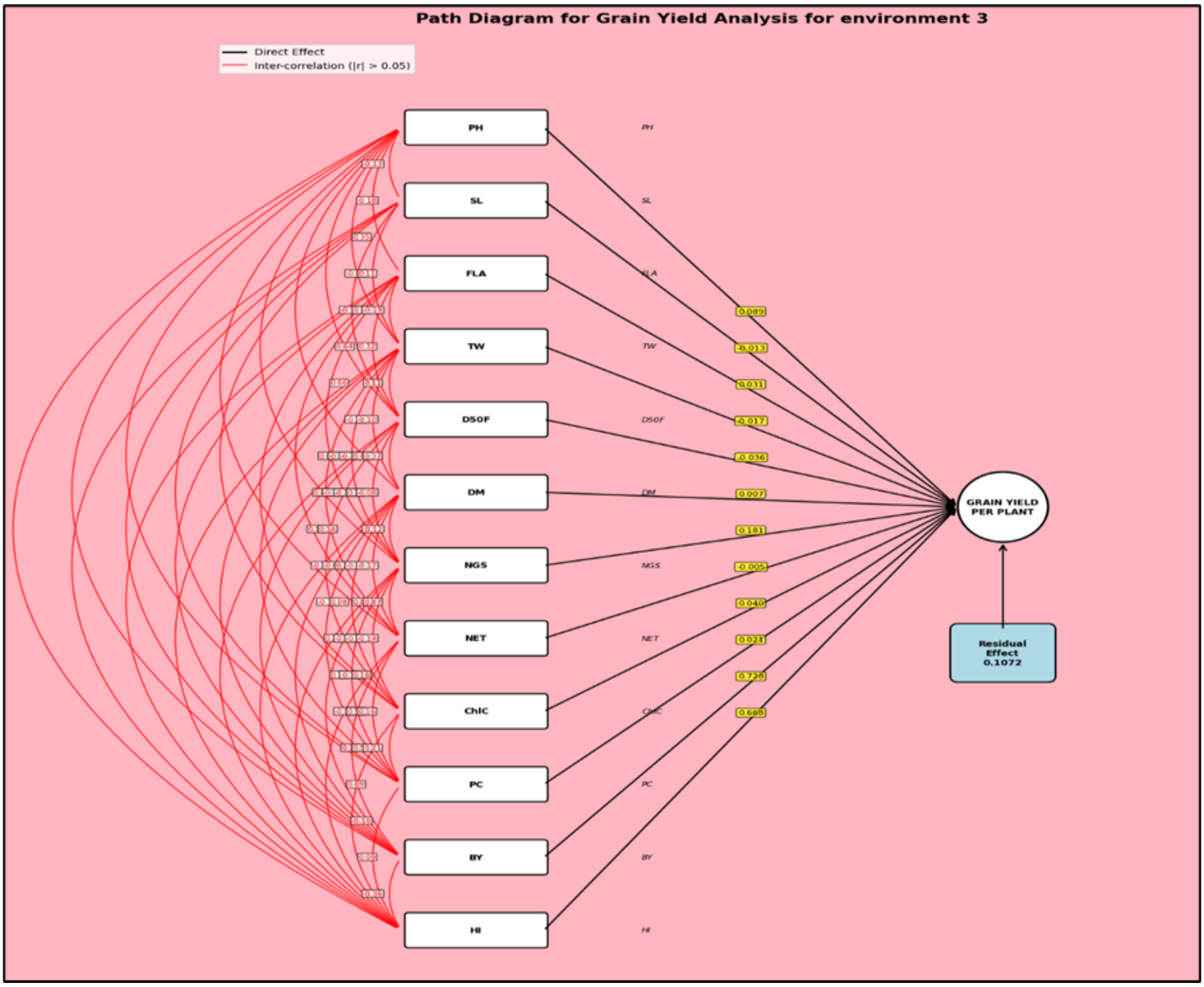

Fig. 6. Phenotypic path diagram depicting direct and indirect effects of twelve characters in wheat genotypes under very late sown environment (E3). PH-plant height, SL-spike length, FLA-flag leaf area, TW- 1000-seed weight, D50F- days to 50 % flowering, NGS- number of grains per spike, NET-number of effective tillers/plant, Chlc- chlorophyll content %, PC- protein content %, BY- biological yield, HI- harvest index and GYP- grain yield per plant.

Discussion

The evaluation of genetic variability across three sowing environments provided critical insights into the stability and adaptability of key agronomic traits in bread wheat. A consistent trend was observed where phenotypic variances exceeded genotypic variances, confirming the influence of the environment. However, the relatively narrow gap for traits such as 1000-seed weight, days to maturity and number of grains per spike suggests that these are largely governed by genetic factors and thus remain dependable targets for selection. Similar patterns have been reported in earlier wheat studies, where traits with a small difference between phenotypic and genotypic variances were identified as more stable under variable conditions (17-19).

Heritability estimates, combined with genetic advance, further clarified the mode of genetic control. Traits such as grain yield per plant, number of grains per spike and effective tillers exhibited high heritability with substantial genetic advance, indicating additive gene action (20-21). This suggests that direct selection can be highly effective in improving these traits (22-24). In contrast, traits such as days to maturity and protein content, while highly heritable, showed moderate genetic advance, implying the role of non-additive effects like dominance or epistasis. These findings align with earlier reports (25, 26). However, our results emphasize that under very late sowing, even traits like flag leaf area and spike length expressed both high heritability and genetic advance, highlighting their importance as selection indices in stressed environments.

Correlation analysis across environments revealed that biological yield, effective tillers and grains per spike consistently showed strong positive associations with grain yield, establishing them as the most reliable determinants of productivity across sowing conditions (27-30). Plant height also maintained a positive influence, with its contribution becoming more pronounced under late and very late sowing, reflecting its role in sustaining canopy photosynthesis and assimilate transport under stress. Harvest index and 1000-seed weight contributed positively in all environments, but their importance increased under delayed sowing, highlighting the need for efficient biomass partitioning and grain filling when growth duration is shortened by terminal heat stress. By contrast, spike length exhibited weak or inconsistent correlations, confirming its minor role in yield determination. These results demonstrate that wheat yield stability depends on a balance between biomass production, assimilate partitioning and reproductive efficiency and that the key contributing traits remain effective even under adverse environments (31-34).

Path coefficient analysis provided further resolution of cause -effect relationships. Traits such as number of effective tillers, grains per spike and plant height consistently exerted high positive direct effects on grain yield (35-37). The physiological basis of these effects is clear: more tillers increase sink capacity, higher spike fertility enhances grain number and taller plants facilitate greater biomass accumulation. Under very late sowing, grains per spike and biomass retained their direct influence, demonstrating their resilience under stress. Conversely, traits like delayed maturity and excessive vegetative growth exerted negative effects, suggesting that under heat stress, early adaptability and efficient resource partitioning are more beneficial than prolonged vegetative phases (38-40).

From a breeding perspective, the comparative synthesis across environments highlights a clear distinction between stable traits (effective tillers, grains per spike, 1000-seed weight and biomass), which can be targeted universally and environment-specific traits (flag leaf area, spike length, days to maturity), which may only be advantageous under particular sowing conditions (41). This distinction is particularly relevant for climate-resilient breeding, where stability across environments is crucial for developing widely adaptable varieties, while targeted selection for environment-specific traits can enhance local adaptation (42).

Overall, the study demonstrates that selection for effective tillers, grain number and seed weight offers the strongest potential for yield improvement across environments. Incorporating these traits into breeding programs can help develop wheat varieties that are not only high yielding but also resilient to climate variability and late sowing stress, thus contributing to sustainable production under changing agro-climatic scenarios.

Conclusion

This study demonstrates that wheat possesses sufficient genetic variability to support yield improvement across different sowing environments. Key traits such as effective tillers, plant height, grains per spike and 1000-seed weight consistently emerged as reliable indicators of yield potential. Their stability across environments and genetic control by additive effects make them strong candidates for selection in breeding programs. Importantly, targeting these traits can accelerate the development of wheat varieties that are both high yielding and resilient to late sowing and climate-related stresses. Future breeding efforts should integrate these traits into selection indices and combine them with molecular tools to enhance the efficiency of developing climate-smart wheat varieties.

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Authors' contributions

SKM carried out the experiment, took observations and analyzed the data. SSS, NV and SKT guided the research by formulating the research concept. PKB participated in the design of the study and performed the statistical analysis. AKA, DKM, RK and MKP contributed by imposing the experiment and helped edit, summarise and revise the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish or preparation of the manuscript.

Ethical issues: None

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