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ASSOCIATION ANALYSIS AND PATH COEFFICIENT STUDIES FOR GRAIN YIELD IMPROVEMENT IN BREAD WHEAT (*Triticum aestivum* L.)

Rhea Hanjabam¹, Akhoury Ayush^{2*}, Naven Kumar Meena³, Sayakumari Thingbaijam¹ and Shivam Rathi⁴

¹Department of Agriculture, School of Agriculture, Forestry and Fisheries, Jigyasa University, Dehradun, Uttarakhand, India.

²Department of Genetics and Plant Breeding, GBPUAT, Pantnagar, Uttarakhand-263145, India.

³Department of Genetics and Plant Breeding, Maharana Pratap University of Agriculture and Technology, Udaipur -313 001, Rajasthan, India.

⁴YP-2, ICAR-Indian Institute of Farming System Research, Modipuram Meerut, U.P., India.

*Corresponding author E-mail : akhouryayush@gmail.com

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ABSTRACT

Understanding the association among yield and its component traits is essential for developing efficient selection strategies in wheat breeding programmes. The present investigation was conducted during the *Rabi* season of 2023–24 at the Crop Research Centre, Jigyasa University, Dehradun, Uttarakhand, to study character association and path coefficient analysis in thirty wheat (*Triticum aestivum* L.) genotypes. The experiment was laid out in a Randomized Block Design with three replications. Observations were recorded on fifteen quantitative traits, including phenological, morphological and yield-related characters. Genotypic and phenotypic correlation coefficients were estimated following the method of Al-Jibouri *et al.* (1958), while path coefficient analysis was performed according to Dewey and Lu (1959) using Grain yield per plant as the dependent variable. Correlation analysis revealed that Grain yield per plant exhibited significant positive association with flag leaf area, spike length per plant and 1000-Grain weight, indicating the importance of these traits in determining grain productivity. Genotypic correlations were generally higher than phenotypic correlations, suggesting a strong inherent genetic association among the characters studied. Path coefficient analysis indicated that 1000-Grain weight (0.654), flag leaf area (0.401) and plant height (0.319) exerted substantial positive direct effects on Grain yield at the genotypic level, whereas grain filling period (1.775), days to 50% flowering (1.035) and 1000-Grain weight (0.671) showed the highest positive direct effects at the phenotypic level. The findings suggest that flag leaf area, spike length per plant and 1000-Grain weight are the most important traits influencing grain yield and should be considered as reliable selection criteria for the development of high-yielding wheat cultivars.

Key words : Bread wheat, Character association, Path coefficient analysis, Grain yield, Yield components, *Triticum aestivum* L.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and serves as a staple food for nearly 35% of the global population. It contributes substantially to global food and nutritional security by providing carbohydrates, proteins, vitamins, minerals and dietary fibre. Globally, wheat is cultivated on more than 220 million hectares with an annual production exceeding 780 million tonnes. In India, wheat occupies a pivotal position among food grain crops and is the second most important cereal after rice, contributing significantly to

national food security and agricultural economy (FAO, 2024; Shewry and Hey, 2015).

The increasing demand for wheat due to rapid population growth, urbanization and changing dietary preferences necessitates continuous improvement in grain productivity. However, wheat production is increasingly challenged by climate change, shrinking arable land, emerging pests and diseases, and degradation of natural resources. Under such circumstances, the development of high-yielding and climate-resilient wheat cultivars remains one of the major objectives of contemporary

breeding programmes (Zhang *et al.*, 2023; Wang *et al.*, 2023).

Grain yield is a highly complex quantitative trait controlled by numerous genes and strongly influenced by environmental factors. Consequently, direct selection for grain yield is often less effective because the observed phenotype represents the combined effects of genotype, environment and genotype $\times$ environment interactions. Therefore, breeders frequently rely on yield-contributing traits and their interrelationships to formulate efficient selection strategies (Falconer and Mackay, 1996). Understanding the association among various agronomic traits and grain yield is essential for identifying characters that can be used as indirect selection criteria in breeding programmes.

Correlation analysis is an important biometrical tool that measures the magnitude and direction of association among traits. It provides valuable information regarding the extent to which changes in one trait are accompanied by changes in another and helps breeders identify characters that are positively associated with grain yield. Positive associations among yield components facilitate simultaneous improvement of multiple traits, whereas negative associations may limit breeding progress due to antagonistic relationships (Al-Jibouri *et al.*, 1958). Several investigators have reported significant positive correlations of grain yield with productive tillers per plant, grains per spike, spike length, thousand-grain weight, biological yield and harvest index in bread wheat (Bhushan *et al.*, 2013; Kumar *et al.*, 2020; Poudel *et al.*, 2021).

Although, correlation analysis is useful for identifying associated traits, it does not reveal the actual contribution of individual characters toward grain yield because the observed correlation may result from indirect effects through other related traits. Consequently, selection decisions based solely on correlation coefficients may be misleading. To overcome this limitation, Wright (1921) developed path coefficient analysis, which was subsequently adapted to plant breeding by Dewey and Lu (1959). Path analysis partitions correlation coefficients into direct and indirect effects and provides a more precise understanding of cause-and-effect relationships among traits. This approach enables breeders to identify those characters that exert the greatest direct influence on grain yield and therefore should receive priority during selection.

Numerous studies have demonstrated the effectiveness of path coefficient analysis in wheat improvement programmes. Chaudhary *et al.* (2022) reported that test weight, productive tillers per plant and

spike length exhibited substantial direct effects on grain yield and could be effectively utilized in selection programmes. Similarly, Chauhan *et al.* (2023) observed that grains per spike, test weight and biological yield contributed significantly toward grain yield through direct and indirect effects. Saini *et al.* (2024) also reported positive associations between grain yield and spike length, flag leaf area and thousand-grain weight and emphasized the usefulness of path coefficient analysis in identifying superior selection criteria.

Recent investigations have highlighted the importance of flag leaf area, spike architecture and grain weight traits in determining wheat productivity under diverse agro-climatic conditions. Poudel *et al.* (2021) demonstrated that grain weight and spike-related traits were among the most reliable indicators of yield performance across multiple environments. Likewise, Patil *et al.* (2024) emphasized that association studies combined with path coefficient analysis provide a powerful approach for identifying key yield determinants and improving selection efficiency in wheat breeding programmes.

Despite substantial progress in wheat breeding, the magnitude and direction of trait associations often vary with genetic background and environmental conditions. Therefore, evaluation of locally adapted wheat germplasm remains essential for identifying stable and effective selection criteria. Information regarding direct and indirect effects of yield-related traits under the agro-climatic conditions of Uttarakhand is limited. Consequently, the present investigation was undertaken to study character association and path coefficient analysis among yield and yield-contributing traits in thirty wheat genotypes. The findings are expected to provide useful information for identifying key selection parameters and accelerating genetic improvement for grain yield in bread wheat.

Materials and Methods

The present investigation was conducted during the Rabi season of 2023–24 at the Crop Research Centre, Department of Agriculture, Jigyasa University (formerly Himgiri Zee University), Dehradun, Uttarakhand, India. The experimental farm is situated at approximately 30.31° N latitude and 78.03° E longitude with an altitude of about 650 m above mean sea level. The region is characterized by a subtropical climate with cool winters and moderate temperatures during the wheat growing season, which are conducive for wheat cultivation. The experimental material comprised thirty diverse wheat (*Triticum aestivum* L.) genotypes obtained from different breeding programmes and germplasm collections. The genotypes included CML-104, CML-108, CML-111, CML-112,

CML-113, CML-134, CML-135, CML-136, CML-137, CML-138, CML-139, CML-140, CML-144, CML-198, CML-133, HP-333, HP-2002, PBW-173, PBW-502, PBW-1-Zn, PBW-550, W-75, W-2967, WH-711, HUW-468, GW-322, HI-8759, LOK-1, DBW-303 and RAJ-4238.

The experiment was laid out in a Randomized Block Design (RBD) with three replications following the standard procedure described by Gomez and Gomez (1984). Each genotype was grown in a separate plot with a row-to-row spacing of 23 cm and plant-to-plant spacing of 10 cm. The crop was sown on 13 December 2023 following the recommended package of practices for wheat cultivation in the region. A fertilizer dose of 120:60:40 kg N:P₂O₅:K₂O ha⁻¹ was applied. Nitrogen was supplied in split applications, whereas phosphorus and potassium were applied as basal doses at sowing. Standard agronomic practices including irrigation, weed management and plant protection measures were adopted uniformly throughout the crop growth period to minimize environmental variation among treatments. Observations were recorded on five randomly selected competitive plants from each genotype in each replication for fifteen quantitative traits, namely days to emergence, days to 50% booting, days to 50% heading, days to 50% flowering, days to maturity, grain filling period, productive tillers per plant, plant height (cm), flag leaf area (cm²), peduncle length (cm), spike weight per plant (g), spike length per plant (cm), number of grains per spike, 1000-Grain weight (g) and Grain yield per plant (g). Phenological observations were recorded on a plot basis, whereas morphological and yield-related observations were recorded from selected plants and averaged for statistical analysis. Analysis of variance (ANOVA) was performed according to the procedure outlined by Gomez and Gomez (1984) to determine the significance of differences among genotypes. Genotypic and phenotypic correlation coefficients among different traits were estimated following the method proposed by Al-Jibouri *et al.* (1958). Correlation analysis was used to assess the magnitude and direction of association among grain yield and its component characters.

The genotypic correlation coefficient was estimated as:

$$R(g_{xy}) = \frac{\text{Covg}(xy)}{\sqrt{\sigma^2_{gx} \times \sigma^2_{gy}}}$$

where, Covg(xy) is the genotypic covariance between traits x and y, and σ^2_{gx} and σ^2_{gy} represent the genotypic variances of the respective traits.

Similarly, phenotypic correlation coefficients were estimated using phenotypic variance and covariance components.

Path coefficient analysis was carried out according to the method developed by Wright (1921) and later adapted for plant breeding studies by Dewey and Lu (1959). Grain yield per plant was considered the dependent variable, while all other characters were treated as independent variables. The correlation coefficients were partitioned into direct and indirect effects to determine the relative contribution of individual traits toward grain yield. Traits exhibiting high positive direct effects along with significant positive correlations with grain yield were considered important selection criteria. The residual effect was also estimated to determine the proportion of variability in grain yield not explained by the characters included in the path coefficient analysis. All statistical analyses were performed using standard biometrical procedures for quantitative genetic studies. Genotypic and phenotypic variance-covariance matrices were used for the estimation of correlation coefficients and path coefficients.

Results and Discussion

Genotypic Correlation analysis

Correlation analysis provides valuable information regarding the degree and direction of association among different traits and helps breeders identify suitable selection criteria for crop improvement. In the present investigation, genotypic correlation coefficients were generally higher than the corresponding phenotypic correlation coefficients, indicating that the associations among characters were predominantly governed by genetic factors and were less influenced by environmental conditions. Similar observations were reported by Kumar *et al.* (2020), Poudel *et al.* (2021), Chauhan *et al.* (2023) and Saini *et al.* (2024) in bread wheat.

Grain yield per plant exhibited significant and positive genotypic association with flag leaf area (0.419), 1000-Grain weight (0.395) and spike length per plant (0.358). The positive association of flag leaf area with grain yield may be attributed to its role in photosynthetic assimilation and translocation of assimilates towards developing grains. Likewise, the positive relationship between thousand-Grain weight and grain yield indicates the importance of grain size and grain filling efficiency in determining final productivity. Similar positive associations of grain yield with test weight, spike length and flag leaf area have been reported by Bhushan *et al.* (2013), Kumar *et al.* (2020), Poudel *et al.* (2021) and Saini *et al.* (2024).

Table 1 : Genotypic Correlations among the fifteen characters of Wheat. (*Triticum aestivum* L).

Characters	Days to Emergence	Days to 50 % booting	Days to 50 % heading	Days to 50 % flowering	Days to maturity	Grain Filling period	Productive tillers per plant	Plant height	Flag Leaf area	Peduncle length	Spike weight per plant	Spike Length per plant	Grain per Spike	1000 seeds weight	Grain Yield per plant
Days to Emergence	1.0000	0.466**	0.838**	0.558**	0.008	-0.259	0.473**	0.344*	-0.200	0.133	-0.211	0.719**	0.674**	-0.244	-0.100
Days to 50% booting		1.0000	0.794**	-0.448**	0.229	0.382*	0.621**	0.316*	0.766**	0.570**	0.037	0.442**	0.461**	0.285	0.014
Days to 50% heading			1.0000	-0.1493	0.001	0.013	0.188	0.452**	0.155	0.318*	0.275	0.695**	0.274	0.429*	0.160
Days to 50% Flowering				1.0000	0.711**	0.340*	-0.633**	0.387*	0.349*	-0.201	0.216	0.813**	0.328*	0.329*	0.278
Days to Maturity					1.0000	0.957**	0.106	0.081	0.335*	0.042	0.024	0.156	0.196	0.263	0.279
Grain Filling Period						1.000	0.380*	0.047	0.517**	0.087	0.041	0.422*	0.317*	0.408*	0.228
Productive Tillers per Plant							1.0000	0.001	0.331*	-0.487**	0.102	-0.062	-0.284	0.327*	0.033
Plant height								1.0000	0.112	0.059	0.268	0.271	0.115	0.148	0.188
Flag leaf Area									1.0000	0.577**	0.010	0.314*	0.037	0.012	0.419*
Peduncle Length										1.0000	0.049	-0.073	0.051	0.142	0.003
Spike weight per Plant											1.0000	0.173	0.271	0.107	0.073
Spike length per plant												1.0000	0.707**	0.514**	0.358*
Grain per Spike													1.0000	0.130	0.009
1000 grain Weight														1.0000	0.395*

(F-tab value at (0.05 level of significance and 0.01 level of significance are 0.306 and 0.423, respectively). *, **significant at 5% and 1% per cent, respectively.

Among the inter-character associations, thousand-Grain weight showed significant positive correlation with spike length per plant (0.514), days to 50% heading (0.429), grain filling period (0.408), days to 50% flowering (0.329) and productive tillers per plant (0.327). These relationships suggest that improvement in spike architecture and grain filling duration may indirectly contribute to enhancement of grain weight. Similar findings were reported by Chaudhary *et al.* (2022) and Patil *et al.* (2024), who observed positive associations among grain weight, spike traits and grain yield in wheat. The number of grains per spike exhibited significant positive correlations with spike length per plant (0.707), days to emergence (0.674), days to 50% booting (0.461), days to 50% flowering (0.328) and grain filling period (0.317). The strong positive association between grains per spike and spike length indicates that longer spikes tend to accommodate more grains, ultimately contributing to yield improvement. Similar results were reported by Bhushan *et al.* (2013), Chauhan *et al.* (2023) and Saini *et al.* (2024).

Significant negative genotypic associations were observed between productive tillers per plant and peduncle length (-0.487), productive tillers per plant and days to 50% flowering (-0.633) and days to 50% booting and days to 50% flowering (-0.448). Such antagonistic relationships indicate that simultaneous improvement of these traits through direct selection may be difficult. Similar negative associations among phenological and yield-related traits have also been documented by Kumar *et al.* (2020) and Patil *et al.* (2024). The positive association of Grain yield with flag leaf area, spike length and thousand-Grain weight suggests that these characters may serve as reliable indirect selection criteria in wheat breeding programmes. Therefore, greater emphasis should be placed on these traits while selecting superior genotypes for yield improvement.

Phenotypic Correlation analysis

Phenotypic correlation coefficients represent the combined effects of genetic and environmental factors on trait expression and therefore provide a practical measure of association among characters under field conditions. In the present investigation, the magnitude of phenotypic correlations was generally lower than the corresponding genotypic correlations, indicating that environmental factors partially masked the inherent genetic relationships among traits. Similar observations were reported by Poudel *et al.* (2021), Chauhan *et al.* (2023) and Saini *et al.* (2024), who observed stronger genotypic associations than phenotypic associations in bread wheat.

Grain yield per plant exhibited significant and positive phenotypic correlation with flag leaf area (0.419) and spike length per plant (0.358). The positive association of flag leaf area with grain yield highlights the importance of photosynthetic efficiency in determining productivity. A larger flag leaf contributes significantly to assimilate production during grain filling and thereby enhances grain development. Similarly, longer spikes generally accommodate a greater number of spikelet and grains, resulting in improved yield potential. Comparable findings have been reported by Bhushan *et al.* (2013), Kumar *et al.* (2020), Chaudhary *et al.* (2022) and Saini *et al.* (2024). Thousand-Grain weight exhibited significant positive association with spike length per plant (0.417), grain filling period (0.316) and days to 50% heading (0.307). These relationships indicate that genotypes with longer grain filling duration and well-developed spike architecture tend to produce heavier grains. Similar positive correlations between test weight and spike-related traits were reported by Poudel *et al.* (2021) and Patil *et al.* (2024), suggesting that these characters collectively contribute to improved grain productivity.

Spike length per plant showed positive and significant correlation with grains per spike (0.564), days to 50% heading (0.400) and days to 50% flowering (0.345). The strong association between spike length and grains per spike indicates that spike morphology plays a crucial role in determining sink capacity and grain production. Similar observations have been documented by Bhushan *et al.* (2013), Chauhan *et al.* (2023) and Saini *et al.* (2024). A significant negative phenotypic correlation was observed between days to emergence and spike length per plant (-0.408), while flag leaf area exhibited a negative association with peduncle length (-0.329). These negative relationships suggest that improvement in one character may adversely affect the other and therefore require careful consideration during selection. Similar antagonistic associations among morphological traits have been reported by Kumar *et al.* (2020) and Chaudhary *et al.* (2022). Overall, the phenotypic correlation analysis revealed that flag leaf area, spike length per plant and thousand-Grain weight are important yield-associated traits. The consistency of positive associations observed at both genotypic and phenotypic levels suggests that these characters may be effectively utilized as indirect selection criteria for grain yield improvement in bread wheat breeding programmes.

Path Coefficient analysis

Genotypic Path Coefficient analysis

Correlation alone does not reveal the true contribution of individual traits towards yield. Therefore, path

Table 2 : Phenotypic Correlations among the fifteen characters of Wheat. (*Triticum aestivum* L.).

Characters	Days to Emergence	Days to 50 % booting	Days to 50 % heading	Days to 50 % flowering	Days to maturity	Grain Filling period	Productive tillers per plant	Plant height	Flag Leaf area	Peduncle length	Spike weight per plant	Spike Length per plant	Grain per Spike	1000 seeds weight	Grain Yield per plant
Days to Emergence	1.0000	0.292	0.510**	0.102	0.018	-0.057	0.374*	-0.231	0.123	-0.020	-0.086	-0.408*	0.407*	-0.155	-0.100
Days to 50% booting		1.0000	0.445*	-0.257	0.076	0.182	0.319*	0.181	0.435*	0.209	0.031	0.140	0.254	0.190	0.014
Days to 50% heading			1.0000	-0.017	-0.032	0.032	0.237	0.368*	0.110	0.209	0.210	0.400*	0.200	0.307*	-0.160
Days to 50% flowering				1.0000	0.363*	0.109	0.290	0.251	0.209	-0.084	0.203	0.345*	0.241	0.184	-0.278
Days to maturity					1.0000	0.877**	0.034	0.070	0.307*	0.051	0.027	0.045	0.179	0.220	-0.279
Grain filling period						1.000	0.211	0.042	0.426*	0.075	0.074	0.215	0.297	0.316*	-0.228
Productive Tillers per plant							1.0000	0.008	0.350*	0.084	-0.012	0.131	0.304*	0.263	0.033
Plant height								1.0000	0.108	0.013	0.259	0.227	0.112	0.136	0.188
Flag leaf Area									1.0000	-0.329*	0.013	0.235	0.036	0.007	0.419*
Peduncle length										1.0000	0.027	-0.141	0.041	0.030	0.003
Spike weight per Plant											1.0000	0.122	0.263	0.111	0.073
Spike length per Plant												1.0000	0.564**	0.417*	0.358*
Grain per Spike													1.0000	0.123	0.100
1000 grain weight														1.0000	0.014

(F-tab value at 0.05 level of significance and 0.01 level of significance are 0.306 and 0.423, respectively).

*, **significant at 5% and 1% per cent, respectively.

coefficient analysis was performed to partition the correlation coefficients into direct and indirect effects using Grain yield per plant as the dependent variable.

Among all characters, 1000-Grain weight exerted the highest positive direct effect (0.654) on Grain yield per plant, followed by flag leaf area (0.401), plant height (0.319), days to maturity (0.250), days to 50% heading (0.220), peduncle length (0.153) and days to emergence (0.129). The positive direct effects of these traits indicate that direct selection for these characters would be effective in improving grain yield. In contrast, grain filling period (-0.401), days to 50% flowering (-0.197), productive tillers per plant (-0.149) and grains per spike (-0.080) exhibited negative direct effects on Grain yield. Although some of these traits showed positive correlations with yield, their contribution was primarily through indirect effects mediated via other characters. The residual effect (0.6723) indicated that additional characters not included in the present study also contributed to Grain yield expression.

Genotypic Path Coefficient analysis

Correlation analysis provides information regarding the degree of association among traits; however, it does not distinguish between direct and indirect contributions of individual characters towards grain yield. Therefore, genotypic path coefficient analysis was performed to partition the correlation coefficients into direct and indirect effects and identify the most influential yield-contributing traits. The method proposed by Dewey and Lu (1959) is widely used in plant breeding programmes for understanding cause-and-effect relationships among quantitative traits.

In the present study, 1000-Grain weight exhibited the highest positive direct effect (0.654) on Grain yield per plant, followed by flag leaf area (0.401), plant height (0.319), days to maturity (0.250), days to 50% heading (0.220), peduncle length (0.153) and days to emergence (0.129). The high positive direct effect of 1000-Grain weight indicates that this trait contributes substantially towards grain yield and may be considered one of the most important selection criteria in wheat breeding programmes. Similar findings have been reported by Bhushan *et al.* (2013), Kumar *et al.* (2020), Chaudhary *et al.* (2022) and Saini *et al.* (2024), who identified test weight as a major determinant of grain yield in bread wheat. Flag leaf area exerted the second highest positive direct effect on Grain yield. The positive contribution of flag leaf area may be attributed to its role as the principal photosynthetic source during grain filling. Larger flag leaf area enhances assimilate production and translocation to

developing grains, thereby improving grain yield. Similar observations have been reported by Poudel *et al.* (2021), Chauhan *et al.* (2023) and Patil *et al.* (2024), who emphasized the importance of flag leaf characteristics in wheat productivity.

Plant height also exhibited a substantial positive direct effect on grain yield. The positive contribution of plant height suggests that taller genotypes may possess greater biomass production and improved assimilate partitioning capacity. Similar positive direct effects of plant height on grain yield have been reported by Kumar *et al.* (2020) and Saini *et al.* (2024). In contrast, grain filling period (-0.401), days to 50% flowering (-0.197), productive tillers per plant (-0.149) and grains per spike (-0.080) exhibited negative direct effects on Grain yield. Although, some of these characters showed positive correlation with yield, their contribution was primarily through indirect effects via other traits. This observation highlights the importance of path coefficient analysis because correlation alone may sometimes provide misleading conclusions regarding the actual contribution of a trait to yield. Similar findings were reported by Dewey and Lu (1959), Chaudhary *et al.* (2022) and Chauhan *et al.* (2023).

The positive indirect contribution of 1000-Grain weight through spike length, grain filling period and productive tillers per plant further strengthened its overall association with Grain yield. Likewise, flag leaf area contributed positively through its association with plant height and Grain weight, indicating the interconnected nature of yield-related traits. Such indirect effects suggest that simultaneous improvement of these characters may result in greater genetic gains. The residual effect at the genotypic level was estimated as 0.6723, indicating that the characters included in the present investigation explained a substantial proportion of the variability in Grain yield. However, the residual value also suggests that additional physiological, biochemical or environmental factors not considered in the study may influence grain yield expression. Similar residual effects have been reported in wheat by Kumar *et al.* (2020), Poudel *et al.* (2021) and Saini *et al.* (2024). Based on the magnitude of direct effects and overall association with grain yield, 1000-Grain weight, flag leaf area, plant height and days to maturity emerged as the most important characters influencing grain yield at the genotypic level. Therefore, these traits may be effectively utilized as selection criteria for developing high-yielding wheat genotypes.

Phenotypic Path Coefficient analysis

Phenotypic path coefficient analysis was performed to estimate the direct and indirect effects of various

Table 3 : Genotypic direct and indirect effects of different characters on Grain yield per plant of wheat (*Triticum aestivum* L.).

Characters	Days to emerge- nce	Days to 50 % Booting	Days to 50 % heading	Days to 50 % flowering	Days to maturity	Grain filling period	Productive tillers per plant	Plant height	Flag leaf area	Peduncle length	Spike weight per plant	Spike length per plant	Grain per Spike	1000 seeds weight
Days to Emergence	0.129	0.060	0.108	0.072	0.001	-0.033	0.061	-0.044	-0.026	0.017	-0.027	-0.093	-0.087	-0.031
Days to 50% booting	-0.008	-0.018	-0.014	0.008	-0.004	-0.007	-0.011	0.005	0.014	-0.010	0.007	0.008	0.008	-0.005
Days to 50% heading	0.184	0.175	0.220	-0.032	0.003	0.003	0.041	-0.099	-0.034	0.070	-0.060	-0.153	-0.060	-0.094
Days to 50% Flower	-0.110	0.088	0.029	-0.197	-0.140	-0.067	0.125	0.076	-0.068	0.039	0.042	0.160	0.064	0.064
Days to Maturity	0.002	0.057	0.004	0.178	0.250	0.240	0.026	-0.020	-0.084	0.010	0.006	0.039	0.049	0.066
Grain filling Period	0.104	-0.153	-0.005	-0.136	-0.384	-0.401	-0.152	-0.019	0.207	-0.035	-0.016	-0.169	-0.127	-0.164
Tillers per Plant	-0.071	-0.093	-0.028	0.095	-0.015	-0.057	-0.149	-0.002	0.049	0.073	-0.015	0.009	0.042	-0.049
Plant height	-0.110	-0.101	-0.144	-0.123	-0.026	0.015	0.005	0.319	0.036	0.019	0.086	0.086	0.036	-0.047
Flag leaf area	-0.080	-0.307	-0.062	0.140	-0.134	-0.207	-0.133	0.045	0.401	-0.231	-0.004	0.126	0.015	-0.005
Peduncle Length	0.020	0.087	0.048	-0.031	0.006	0.013	-0.074	0.009	-0.088	0.153	-0.007	-0.013	0.007	-0.021
Spike weight per plant	-0.001	-0.003	-0.002	-0.002	0.002	0.004	0.009	0.002	-0.001	-0.004	0.009	0.001	0.002	0.001
Spike length per plant	-0.053	-0.033	-0.051	-0.060	0.011	0.031	-0.004	0.020	0.023	-0.005	0.012	0.074	0.052	0.038
Grains per spike	0.054	0.037	0.022	0.026	-0.015	-0.025	0.022	-0.009	-0.003	-0.004	-0.021	-0.056	-0.080	-0.010
1000 grain weight	-0.160	0.186	-0.280	-0.215	0.172	0.267	0.214	-0.096	-0.008	-0.092	0.070	0.336	0.085	0.654
Grain yield per plant	-0.100	-0.014	-0.160	-0.278	-0.279	-0.228	-0.033	0.188	0.419	0.003	0.073	0.358	0.009	0.395
Partial R ²	-0.013	0.003	-0.035	0.055	-0.069	0.091	0.005	0.060	0.168	0.005	0.007	0.026	-0.008	0.258

R Square = 0.5481, Residual effect = 0.6723

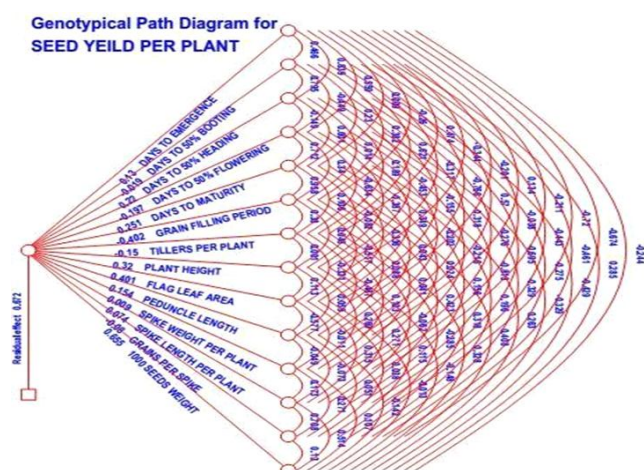


Fig. 1 : Genotypic direct and indirect effects of different characters on Grain yield per plant of Wheat (*Triticum aestivum* L).

characters on Grain yield per plant under field conditions. Unlike genotypic path analysis, phenotypic path coefficients reflect the combined influence of genetic and environmental factors on trait expression and therefore provide a practical assessment of trait contribution under actual growing conditions. Path analysis is particularly useful in identifying traits that exert substantial direct effects on yield and can therefore serve as reliable selection criteria in breeding programmes (Dewey and Lu, 1959).

In the present investigation, grain filling period exhibited the highest positive direct effect (1.775) on Grain yield per plant, followed by days to 50% flowering (1.035), 1000-Grain weight (0.671), plant height (0.353), days to 50% heading (0.304), productive tillers per plant (0.264), days to emergence (0.184), spike length per plant (0.180), flag leaf area (0.158), spike weight per plant (0.149) and peduncle length (0.120). The substantial positive direct effect of grain filling period suggests that a longer duration for assimilate accumulation and translocation contributes significantly towards grain development and final yield. Similar findings have been reported by Kumar *et al.* (2020), Poudel *et al.* (2021) and Saini *et al.* (2024), who emphasized the importance of grain filling duration in determining wheat productivity.

The positive direct effect of days to 50% flowering indicates that genotypes with an optimum flowering duration may achieve better synchronization between vegetative growth and grain development, thereby enhancing yield potential. Similar observations were reported by Chauhan *et al.* (2023) and Patil *et al.* (2024), who identified phenological traits as important contributors to grain yield under specific environmental conditions. Thousand-Grain weight exhibited a strong positive direct

effect (0.671) on grain yield, confirming its importance as one of the major yield determinants. The consistency of positive direct effects at both genotypic and phenotypic levels indicates that this trait is relatively stable across environments and can be effectively utilized as a selection criterion. Similar results were reported by Bhushan *et al.* (2013), Chaudhary *et al.* (2022), Chauhan *et al.* (2023) and Saini *et al.* (2024).

Plant height and spike length per plant also exerted positive direct effects on grain yield. These findings suggest that genotypes possessing favourable plant architecture and well-developed spikes have greater potential for biomass accumulation and grain production. Similar positive direct effects of plant height and spike-related traits on grain yield have been documented by Kumar *et al.* (2020), Poudel *et al.* (2021) and Patil *et al.* (2024). Conversely, days to maturity (-2.242), grains per spike (-0.118) and days to 50% booting (-0.051) exhibited negative direct effects on Grain yield. Although, some of these traits displayed positive correlations with grain yield, their direct contribution was negative, indicating that their positive association with yield was mainly mediated through indirect effects via other characters. This observation further highlights the importance of path coefficient analysis in distinguishing true cause-and-effect relationships from simple associations. Similar findings were reported by Dewey and Lu (1959), Chaudhary *et al.* (2022) and Chauhan *et al.* (2023).

Several traits contributed indirectly to grain yield through their influence on major yield determinants. For instance, grain filling period and spike length enhanced yield indirectly through their association with thousand-Grain weight and flag leaf area. Likewise, productive tillers per plant contributed indirectly through spike-related traits and grain weight. Such interrelationships indicate that simultaneous selection for multiple complementary traits may result in greater improvement in grain yield than selection based on a single character. The residual effect at the phenotypic level was estimated as 0.7180, suggesting that although the characters included in the present investigation accounted for a substantial proportion of yield variation, other physiological, environmental and genetic factors also contributed to grain yield expression. Similar residual effects have been reported in several wheat studies, indicating the complex nature of grain yield as a quantitative trait (Poudel *et al.*, 2021; Saini *et al.*, 2024).

Overall, the phenotypic path coefficient analysis identified grain filling period, days to 50% flowering, thousand-Grain weight, plant height and spike length per

Table 4 : Phenotypic direct and indirect effects of different characters on Grain yield per plant of wheat (*Triticum aestivum* L).

Characters	Days to emerge- nce	Days to 50 % Booting	Days to 50 % heading	Days to 50 % flowering	Days to maturity	Grain filling period	Productive tillers per plant	Plant height	Flag leaf area	Peduncle length	Spike weight per plant	Spike length per plant	Grain per Spike	1000 seeds weight
Days to emergence	0.184	0.054	0.094	0.018	0.003	-0.010	-0.069	-0.042	-0.022	-0.003	-0.016	-0.075	-0.075	-0.028
Days to 50% Booting	-0.01	-0.051	-0.023	0.013	-0.004	-0.009	0.016	0.009	0.022	-0.010	0.001	0.007	0.013	-0.009
Days to 50% heading	0.154	0.134	0.302	-0.005	-0.009	-0.009	-0.071	-0.111	-0.033	0.063	-0.063	-0.121	-0.060	-0.093
Days to 50% flower	0.105	-0.266	-0.018	1.035	0.376	-0.113	0.300	-0.260	0.217	-0.087	-0.210	-0.357	-0.249	-0.190
Days to maturity	-0.041	-0.171	0.072	-0.815	-2.242	-1.966	0.078	0.159	0.690	-0.115	-0.061	-0.101	-0.401	-0.495
Grain filling Period	-0.102	0.323	-0.057	-0.194	1.557	1.775	-0.375	0.076	-0.757	0.134	0.132	0.382	0.528	0.561
Tillers per plant	-0.098	-0.084	-0.062	0.076	-0.009	-0.055	0.264	0.002	0.092	0.022	-0.003	0.034	0.080	-0.069
Plant height	-0.082	-0.064	-0.130	-0.089	-0.025	0.015	0.002	0.353	0.038	0.004	0.091	0.080	0.039	-0.048
Flag leaf area	-0.019	-0.069	-0.017	0.033	-0.048	-0.067	0.055	0.017	0.158	-0.052	-0.002	0.037	0.005	-0.001
Peduncle length	-0.002	0.025	0.025	-0.010	0.006	0.009	0.010	0.001	-0.039	0.120	-0.003	-0.017	0.005	-0.003
Spike weight per plant	-0.012	-0.004	-0.031	-0.030	0.004	0.011	-0.001	0.038	-0.001	-0.004	0.149	0.018	0.039	0.016
Spike length per plant	-0.073	-0.025	-0.072	-0.062	0.008	0.038	0.023	0.041	0.042	-0.025	0.022	0.180	0.101	0.075
Grains per Spike	0.048	0.030	0.023	0.028	-0.021	-0.035	-0.036	-0.013	-0.004	-0.004	-0.031	-0.066	-0.118	-0.014
1000 grain weight	-0.104	0.127	-0.206	-0.123	0.148	0.212	-0.176	-0.091	-0.005	-0.020	0.074	0.280	0.082	0.671
Grain yield per plant	-0.059	-0.041	-0.102	-0.124	-0.255	-0.206	0.020	0.179	0.397	0.020	0.080	0.282	-0.009	0.369
Partial R ²	-0.011	0.002	-0.031	-0.129	0.573	-0.366	0.005	0.063	0.062	0.004	0.012	0.051	0.001	0.248

R Square = 0.4845, Residual effect = 0.7180

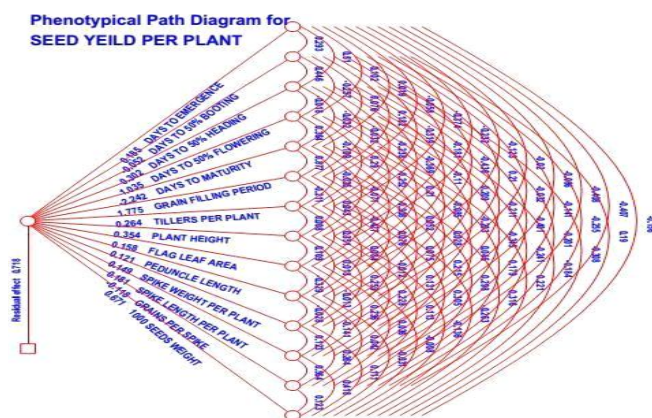


Fig. 2 : Phenotypic direct and indirect effects of different characters on Grain yield per plant of wheat (*Triticum aestivum* L).

plant as the most influential traits contributing directly to grain yield. Therefore, these characters should receive due emphasis in breeding programmes aimed at improving grain productivity in bread wheat.

Breeding implications

The results of the present investigation provide valuable insights for wheat improvement programmes aimed at enhancing grain yield through indirect selection. Correlation analysis revealed that flag leaf area, spike length per plant and 1000-Grain weight were positively associated with Grain yield per plant, indicating their potential utility as reliable selection criteria. Furthermore, path coefficient analysis demonstrated that 1000-Grain weight, flag leaf area and plant height exerted substantial positive direct effects on grain yield at the genotypic level, whereas grain filling period, days to 50% flowering and 1000-Grain weight contributed positively at the phenotypic level. The consistency of positive associations and direct effects observed for 1000-Grain weight and flag leaf area suggests that these traits are comparatively stable and less influenced by environmental fluctuations. Therefore, selection strategies focusing on increased grain weight, improved flag leaf development and favourable spike architecture are likely to enhance grain productivity. The identified traits may be effectively incorporated into breeding programmes for the development of high-yielding wheat cultivars adapted to the agro-climatic conditions of Uttarakhand and similar wheat-growing regions. In addition, genotypes possessing superior performance for these traits may serve as valuable parental lines in future hybridization and selection programmes.

Conclusion

The present study revealed significant associations among yield and yield-related traits in wheat germplasm, indicating the usefulness of correlation and path coefficient

analyses in identifying effective selection criteria for grain yield improvement. Genotypic correlations were generally higher than phenotypic correlations, suggesting that the observed associations were primarily governed by genetic factors with comparatively lower environmental influence. Grain yield per plant exhibited significant and positive associations with flag leaf area, 1000-Grain weight and spike length per plant, indicating that these traits contribute substantially to yield improvement and can be effectively utilized in selection programmes. The positive correlations observed among important yield-contributing traits further suggest the possibility of simultaneous improvement of multiple characters through selection.

Path coefficient analysis provided deeper insights into the direct and indirect contributions of various traits towards Grain yield. At the genotypic level, 1000-Grain weight, flag leaf area, plant height, days to maturity and days to 50% heading exerted substantial positive direct effects on grain yield. Similarly, phenotypic path analysis revealed strong positive direct effects of grain filling period, days to 50% flowering, 1000-Grain weight, plant height and spike length per plant on Grain yield. These findings indicate that correlation alone may not adequately explain the true contribution of individual traits and highlight the importance of path coefficient analysis in breeding programmes. Considering both correlation and path coefficient analyses, flag leaf area, spike length per plant and 1000-Grain weight emerged as the most important yield-determining traits. Therefore, these characters should be given due emphasis while formulating selection strategies aimed at developing high-yielding wheat cultivars. The results generated in the present investigation provide valuable information for wheat breeders and may serve as a useful basis for future crop improvement programmes.

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