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Estimation of path coefficient analysis for yield and its contributing traits in wheat (*Triticum aestivum* L.)

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Abstract
Path coefficient analysis is a powerful tool for understanding the direct and indirect contributions of yield-contributing traits. This study aimed to find the relationships among key agronomic and quality traits and their influence on grain yield per plant. Genotypic and phenotypic path analyses were conducted to determine the relative importance of traits such as number of grains per ear, productive tillers, biological yield, 1000-grain weight, spikelets per spike, and harvest index. The analysis revealed that biological yield per plant, number of productive tillers, and number of grains per ear had strong direct effects on grain yield, while other traits like spikelets per spike and harvest index exerted considerable indirect effects through their association with major yield components. Traits such as days to heading, plant height, protein content, and gluten content showed low or negligible direct effects, indicating their limited direct contribution to grain yield. These findings provide valuable information for wheat breeding programs, facilitating the selection of traits that can effectively improve yield potential and stability.

Keywords: Breeding, direct and indirect effects, grain yield, path coefficient analysis, wheat, yield-contributing traits

Introduction
Wheat (*Triticum aestivum* L.) is one of the most important staple crops worldwide, providing nearly 20% of the total dietary calories and protein consumed by humans (FAO, 2021) [7]. wheat serves as a vital source of energy, essential nutrients, and minerals such as iron, zinc, magnesium, and phosphorus (Healthline, 2021; IntechOpen, 2022) [12, 13]. As the world population continues to grow, projected to reach nearly 10 billion by 2050, the demand for wheat will rise substantially, not only as a calorie source but also for its role in food security and nutrition (FAO, 2021) [7]. India is the second-largest producer of wheat in the world. According to the USDA Foreign Agricultural Service (FAS), India's wheat production for the marketing year (MY) 2025-26 is forecast at a record 115 million metric tons (MMT), up from 113.29 MMT in 2023-24, with an estimated area of 32.6 million hectares under wheat cultivation (USDA, 2024; Milling MEA, 2024) [18, 16]. The average national productivity stands at approximately 3.54 tonnes per hectare, though yields vary significantly across states, with Punjab and Haryana achieving higher than the national average. Despite record harvests, India's wheat yield still lags behind other major producers such as the United States and China, largely due to challenges like heat stress, declining soil fertility, and water scarcity (USDA, 2024) [18]. Wheat is a staple crop with complex yield-determining traits, making it highly valuable for path coefficient analysis. This method enables breeders to distinguish between direct and indirect effects of multiple traits on grain yield, which simple correlation cannot reveal (Dewey and Lu, 1959) [5]. Traits with strong direct effects, such as number of grains per ear, productive tillers, and biological yield per plant, can be prioritized in selection programs to enhance yield (Gaur, 2025) [9].
Therefore, the primary goal of most wheat breeding programs worldwide is to develop high-yielding varieties. These programs aim to create diverse genetic materials containing a high repetative of superior yield genotypes. To identify the best genotypes with desirable traits for future breeding efforts and to select an appropriate selection index that enhances the success

of breeding programs, it is essential to conduct studies that analyse variance and examine the relationships among different traits through path analysis between yield and its components. Path coefficient analysis was used by plant breeders to help identify traits that could be useful as a selection criterion for improving crop yield. Path coefficient analysis separates correlation coefficients into direct and indirect effects among related traits. When two traits are genetically correlated, selecting for one can cause a corresponding change in the other. Path analysis parameters quantify both the direct influence of an independent variable on a dependent variable and its indirect influence through other independent variables (Hadi *et al.*, 2018) [10]. It has been proposed that yield components have either direct or indirect effects on grain yield. Consequently, path coefficient analysis is most common statistical method to determine the magnitude of these direct and indirect effects of various traits on a target characteristic, typically grain yield. To achieve the objectives of breeding programs, it is crucial to analyze the relationship between yield and its components, as well as the direct and indirect contributions of yield components to overall grain yield.

Materials and Methods

Plant materials

This experiment was conducted at Nawabganj Farm of C.S. Azad University of Agriculture and Technology, Kanpur-208002 (U.P.) during *Rabi*, 2023-24 and *Rabi*, 2024-25 to determine the most appropriate traits to improve the yield of wheat grains and count them as selection criteria through studying and analyzing the path coefficient in the genotypic and phenotypic. A randomized complete block design with three replications was used, which included ten varieties of bread wheat (PBW852, HD3386, PBW826, HD3388, K0607, DBW187, DBW 316, K1317, PBW833, PBW 835), The characters studied were, total number of tillers, number of productive tillers, area of flag leaf, biological yield, number of seeds per spike, thousand grain weight, and the harvest index as an selection index to improve grain yield. Planting was carried out at a spacing of 20 cm × 10 cm.

Plan of Lay out

Final trial was conducted in Randomized Block Design (RBD) with three replications during *Rabi* season 2024-25 comprising of 100 lines (10 parents + 45 F1 and 45 F2) at Nawabganj farm of C.S. Azad University, Kanpur. Each parent and F1 were grown in single row plot, while F2 had double row plot.

Details of Layout

Experimental Design	:	Randomized Block Design (RBD)
Replication	:	Three
Spacing	:	20 cm x 10 cm
Treatment	:	100 lines (10 parents + 45 F_1 and 45 F_2)

Results

Path coefficient analysis reveals the direct and indirect influences of various traits on grain yield in bread wheat, offering important guidance for selection in breeding programs. The path coefficients based on genotypic and phenotypic data from the F_1 and F_2 generations, using grain yield per plant as the main (dependent) variable, are explained below.

Genotypic path coefficient analysis in F_1 and F_2 generation

The estimated direct and indirect genotypic path coefficients of each trait toward grain yield in F_1 and F_2 generation presented in Table 3a and 3b (F_1 and F_2) are as follows:

1. Days to 50% heading

Days to 50% heading showed a non-significant relationship with grain yield per plant in both F1 (r = -0.1379) and F2 (r = 0.0408) generations. The direct effect was low positive in F1 (0.1187) and low negative in F2 (-0.16986). Most indirect effects were small, except a very high positive effect through gluten content in F2 (1.05178). Negative indirect effects were observed via days to maturity in F1 (-0.19873) and through number of spikelets per spike (-0.19705), number of grains per spike (-0.20486), number of productive tillers per plant (-0.25588), and harvest index (-0.34261) in F2.

2. Days to maturity

The correlation between days to maturity and grain yield per plant was negative and non-significant in both F1 (r = -0.1298) and F2 (r = -0.0593) generations. In F1, the direct effect of days to maturity on grain yield per plant was negative (-0.30372). Positive indirect effects were low or negligible, while negative indirect effects were also low or negligible. In F2, the direct effect was positive (0.10502), and positive indirect effects included harvest index (1.43502, very high), number of spikelets per spike (0.77281, high).

3. Plant height (cm)

The correlation between plant height and grain yield per plant was positive and non-significant in both F1 (r = 0.0842) and F2 (r = 0.0877) generations. In F1, the direct effect of plant height on grain yield per plant was positive (0.06593) and in F2, the direct effect was positive (0.4917), and positive indirect effects included harvest index (1.15933, very high) and number of spikelets per spike (0.3061), while the remaining positive indirect effects were low or negligible.

4. Total No. of tillers per plant

There was a positive and significant (at 1 percent level of significance) relationship between number of tillers per plant and grain yield per plant in both F1 (r = 0.8037) and F2 (r = 0.7681) generations. In F1, the direct effect of number of tillers per plant on grain yield per plant was negative (-0.12812). In F2, the direct effect was strongly positive (2.08842). Positive indirect effects included biological yield per plant (2.78972, very high) and number of productive tillers per plant (2.48721, very high), while others were low or negligible.

5. Productive tillers/plant

In F1, the direct effect of number of productive tillers per plant on grain yield per plant was positive (0.5381). Positive indirect effects were biological yield per plant (0.57162, high), harvest index (0.14772, low), 1000-grain weight (0.13043, low), and number of spikelets per spike (0.12771, low), while other positive indirect effects were low or

negligible. Negative indirect effects were all low or negligible. In F2, the direct effect was strongly positive (2.46997).

6. Number of spikelets/spike

Positive and significant (at 1 percent level of significance) correlation was observed between number of spikelets per spike and grain yield per plant in both F1 (r = 0.6713) and F2 (r = 0.5749) generations. In F1, the direct effect of number of spikelets per spike on grain yield per plant was positive (0.20226). In F2, the direct effect was positive (0.935). Negative indirect effects included number of grains per spike (-1.66, very high), harvest index (-2.29, very high), 1000-grain weight (-0.65, high), and the remaining negative effects were low or negligible.

7. Spike length

In F1, the direct effect of spike length on grain yield per plant was negative (-0.024). Positive indirect effects were low or negligible except for biological yield per plant (0.164, low) and days to maturity (0.103, low), while negative indirect effects were low or negligible. In F2, the direct effect was negative (-0.227). Positive indirect effects included gluten content (1.579, very high), number of tillers per plant (1.031, very high), number of productive tillers per plant (0.951, moderate), biological yield per plant (0.816, moderate), and canopy temperature (0.131, low).

8. Number of grains/ear

In F1, the direct effect of number of grains per spike on grain yield per plant was positive (0.68). Positive indirect effects included biological yield per plant (0.417, high), number of spikelets per spike (0.155, low), and harvest index (0.146, low), while the remaining positive indirect effects were low or negligible. In F2, the direct effect was positive (1.662). Positive indirect effects included number of tillers per plant (3.375, very high), biological yield per plant (2.682, very high), number of productive tillers per plant (2.368, very high).

9. Biological yield/plant (g)

In F1, the direct effect of biological yield per plant on grain yield per plant was positive (0.559). Positive indirect effects included 1000-grain weight (0.119, low), harvest index (0.119, low), and number of spikelets per spike (0.109, low), while the remaining positive indirect effects were low or negligible. In F2, the direct effect was strongly positive (1.570). Positive indirect effects included number of tillers per plant (1.195, very high) and number of productive tillers per plant (1.385, very high), while other positive indirect effects were low or negligible.

10. 1000-grain weight (g)

There was a positive and significant (at 1 percent level of significance) relationship between 1000-grain weight and grain yield per plant in both F1 (r = 0.8682) and F2 (r = 0.6052) generations. In F1, the direct effect of 1000-grain weight on grain yield per plant was positive (0.133). In F2, the direct effect was positive (-1.252). Positive indirect effects included number of tillers per plant (2.454, very high), number of productive tillers per plant (2.348, very high), biological yield per plant (2.238, very high), and gluten content (0.667, high), while other positive indirect effects were low or negligible.

11. Harvest index

There was a positive and significant (at 1 percent level of significance) relationship between harvest index and grain yield per plant in both F1 (r = 0.633) and F2 (r = 0.447) generations. In F1, the direct effect of harvest index on grain yield per plant was positive (0.206). In F2, the direct effect was positive (1.309). Positive indirect effects included biological yield per plant (2.603, very high), number of tillers per plant (2.589, very high), number of productive tillers per plant (2.404, very high).

12. Protein content

Positive and non-significant correlation was observed between protein content and grain yield per plant in both F1 (r = 0.083) and F2 (r = 0.034) generations. In F1, the direct effect of protein content on grain yield per plant was negative (-0.037). In F2, the direct effect was positive (0.095). Positive indirect effects included biological yield per plant (0.622, high) and harvest index (0.550, high), while other positive indirect effects were low or negligible.

13. Gluten content

In F1, the direct effect of gluten content on grain yield per plant was positive (0.049). Positive indirect effects were all low or negligible. Negative indirect effects were also low or negligible. In F2, the direct effect was negative (-1.674). Positive indirect effects included number of spikelets per spike (1.700, very high), harvest index (0.869, high), and number of grains per spike (0.570, moderate).

14. Canopy temperature depression (°C)

In F1, the direct effect of canopy temperature on grain yield per plant was positive (0.120). Positive indirect effects included biological yield per plant (0.319, high), while the remaining positive indirect effects were low or negligible. Negative indirect effects were all low or negligible. In F2, the direct effect was negative (-0.136). Positive indirect effects included harvest index (1.930, very high) and number of spikelets per spike (0.602, moderate).

Table 3a: Genotypic path analysis among 15 characters of F_1s generation in wheat.

Traits	DFF	DTM	PHT	TN	NOPT	NOS	SL	GPE	BW	TW	HI	PC	GC	CT	GYPP
DFF	0.119	-0.199	0.019	0.007	-0.011	0.035	0.005	-0.182	-0.054	0.006	-0.043	-0.001	-0.012	-0.009	-0.1379 NS
DTM	0.078	-0.304	0.022	0.018	0.003	-0.010	0.008	-0.006	-0.005	0.013	-0.004	0.010	-0.005	0.052	-0.1298 NS
PHT	0.035	-0.101	0.066	0.020	0.004	-0.035	0.008	0.001	0.095	-0.006	-0.109	0.022	0.003	0.081	0.0842 NS
TN	-0.007	0.043	-0.010	-0.128	0.046	0.165	-0.006	0.060	0.396	0.095	0.179	-0.013	-0.022	0.005	0.8037 **
NOPT	-0.023	-0.015	0.005	-0.110	0.538	0.128	-0.007	0.057	0.572	0.130	0.148	-0.001	-0.023	0.077	0.9313 **
NOS	0.021	0.015	-0.011	-0.105	0.034	0.202	-0.009	0.052	0.301	0.085	0.141	-0.019	-0.018	-0.016	0.6713 **
SL	-0.023	0.103	-0.023	-0.032	0.016	0.079	-0.024	0.016	0.164	0.049	0.086	-0.024	0.004	-0.040	0.3515 *
GPE	0.000	0.026	0.001	-0.114	0.046	0.155	-0.006	0.675	0.417	0.097	0.146	-0.005	-0.009	0.009	0.8307 **
BW	-0.011	0.003	0.011	-0.091	0.055	0.109	-0.007	0.050	0.559	0.119	0.119	-0.002	-0.022	0.068	0.9198 **
TW	0.005	-0.031	-0.003	-0.092	0.053	0.129	-0.009	0.049	0.500	0.133	0.126	-0.005	-0.016	0.028	0.8682 **
HI	-0.025	0.007	-0.035	-0.111	0.039	0.138	-0.010	0.048	0.323	0.081	0.206	-0.009	-0.004	-0.014	0.633 **
PC	0.003	0.084	-0.039	-0.043	0.002	0.105	-0.015	0.008	0.031	0.017	0.049	-0.037	-0.011	-0.070	0.0834 NS
GC	-0.030	0.029	0.004	0.057	-0.025	-0.074	-0.002	-0.013	-0.255	-0.044	-0.017	0.009	0.049	-0.005	-0.3153 *
CT	-0.009	-0.131	0.045	-0.005	0.035	-0.028	0.008	0.005	0.319	0.031	-0.025	0.022	-0.002	0.120	0.3838 **

DFF = Days to 50% heading, DTM = Days to maturity, PHT = Plant height (cm), TN = Number of tillers/plant, NOPT = Number of productive tillers/plant, NOS = Number of spikelets/ear, SL = Spike length (cm), GPE = Number of grains/ear, BW = Biological yield/plant (g), TW = 1000-grain weight (g), HI = Harvest index (%), PC = Protein content (%), GC = Gluten content (%), CT = Canopy Temperature, GYPP = Grain yield/plant (g).
Resi-0.03846
*, ** significant at 5% and 1% level, respectively.

Table 3b: Genotypic path analysis among 15 characters of F_2s generation in wheat.

Trait	DFF	DTM	PHT	TN	NOPT	NOS	SL	GPE	BW	TW	HI	PC	GC	CT	GYPP
DFF	-0.170	0.036	0.025	-0.156	-0.256	-0.197	0.026	-0.205	0.074	0.000	-0.343	-0.009	1.052	0.163	0.0408 NS
DTM	-0.058	0.105	0.105	-0.905	-0.681	0.773	0.086	0.528	-0.608	0.109	1.435	0.023	-0.691	-0.279	-0.0593 NS
PHT	-0.009	0.022	0.492	-0.188	-0.261	0.306	0.053	-0.018	-0.360	0.128	1.159	0.019	-1.147	-0.111	0.0877 NS
TN	0.006	-0.023	-0.023	2.088	2.487	-3.016	-0.057	-2.197	2.790	-0.752	-2.729	0.006	0.159	0.027	0.7681 **
NOPT	0.013	-0.021	-0.037	2.931	2.470	-2.442	-0.062	-1.816	2.454	-0.848	-2.985	0.009	-0.307	0.184	0.5417 **
NOS	-0.009	-0.021	-0.038	3.133	2.154	0.935	-0.081	-1.662	2.075	-0.655	-2.293	-0.006	1.587	0.327	0.5749 **
SL	0.019	-0.040	-0.115	1.031	0.951	-1.401	-0.227	-0.695	0.816	-0.608	-1.387	-0.019	1.579	0.131	0.0335 NS
GPE	-0.013	-0.021	0.003	3.375	2.368	-1.458	-0.059	1.662	2.682	-0.836	-1.461	0.004	0.786	0.064	0.7723 **
BW	-0.003	-0.018	-0.050	1.195	1.385	-0.288	-0.052	-1.999	1.570	-0.785	-0.141	0.017	0.009	-0.014	0.8258 **
TW	0.000	-0.009	-0.050	2.454	2.348	-2.059	-0.110	-1.777	2.238	1.252	-0.258	0.003	0.667	0.412	0.6052 **
HI	-0.014	-0.035	-0.132	2.589	2.404	-2.094	-0.073	-1.520	2.603	-0.656	1.309	-0.012	0.741	0.956	0.4473 **
PC	0.015	0.025	0.097	0.273	0.319	0.264	0.046	-0.106	0.622	-0.035	0.550	0.095	-1.787	-0.345	0.0336 NS
GC	0.049	0.020	0.154	-0.177	0.290	1.700	0.098	0.570	-0.009	0.227	0.869	0.046	-1.674	-0.278	-0.1159 NS
CT	0.013	0.014	0.025	-0.053	-0.299	0.602	0.014	0.080	0.024	0.242	1.930	0.015	-0.478	-0.136	-0.007 NS

DFF = Days to 50% heading, DTM = Days to maturity, PHT = Plant height (cm), TN = Number of tillers/plant, NOPT = Number of productive tillers/plant, NOS = Number of spikelets/ear, SL = Spike length (cm), GPE = Number of grains/ear, BW = Biological yield/plant (g), TW = 1000-grain weight (g), HI = Harvest index (%), PC = Protein content (%), GC = Gluten content (%), CT = Canopy Temperature, GYPP = Grain yield/plant (g).
Resi-0.03360
*, ** significant at 5% and 1% level, respectively

Phenotypic path coefficient analysis in F_1 and F_2 generation

The estimated direct and indirect phenotypic path coefficients of each trait toward grain yield in F_1 and F_2 generation presented in Table 3c-3d (F_1 and F_2) are as follows:

1. Days to 50% heading

The correlation between days to 50% heading and grain yield per plant was negative and non-significant in F1 (r = -0.126) and positive and non-significant in F2 (r = 0.049). In F1, the direct effect of days to 50% heading on grain yield per plant was negative (-0.112). In F2, the direct effect was negative (-0.021). Positive indirect effects included grains per spike (0.033, low) and spike length (0.017, low), while protein content (0.5, negligible) was negligible. Negative indirect effects included gluten content (-0.3, negligible) and thousand-grain weight (-0.4, low).

2. Days to maturity

The correlation between days to maturity and grain yield per plant was negative and non-significant in F1 (r = -0.118) and F2 (r = -0.053). In F1, the direct effect of days to maturity on grain yield per plant was negative (-0.094). In F2, the direct effect was positive (0.037). Positive indirect effects included spike length (0.055, low) and plant height (0.016, low), while gluten content (0.002, negligible) was negligible.

3. Plant height (cm)

The correlation between plant height and grain yield per plant was positive and non-significant in both F1 (r = 0.063) and F2 (r = 0.099). In F1, the direct effect of plant height on grain yield per plant was positive (0.068). In F2, the direct effect was positive (0.084). Positive indirect effects included spike length (0.041, low), while traits such as harvest index and gluten content were low or negligible.

4. Total No. of tillers per plant
The correlation between number of tillers per plant and grain yield per plant was positive and significant in F1 (r = 0.623) and F2 (r = 0.568). In F1, the direct effect of number of tillers per plant on grain yield per plant was positive (0.156). In F2, the direct effect was positive (0.187). Positive indirect effects included grains per spike (0.258, moderate) and biological yield per plant (0.106, low), while gluten content was negligible. Negative indirect effects included spike length (-0.032, low) and number of productive tillers per plant (-0.043, low), among others.

5. Productive tillers/plant
The correlation between number of productive tillers per plant and grain yield per plant was positive and significant in F1 (r = 0.665) and F2 (r = 0.422). In F1, the direct effect of number of productive tillers per plant on grain yield per plant was positive (0.039). In F2, the direct effect was negative (-0.078). Positive indirect effects included grains per spike (0.244, moderate) and number of tillers per plant (0.104, low), while gluten content was negligible. Negative indirect effects included harvest index (-0.018, low) and spike length (-0.036, low).

6. Number of spikelet/spike
In F1 Positive indirect effects included biological yield per plant (0.106, low) and number of tillers per plant (0.095, low), while spike length was negligible. Negative indirect effects included plant height (-0.008, low) and canopy temperature (-0.018, low). In F2, the direct effect was positive (0.151). Positive indirect effects included grains per spike (0.221, moderate) and number of tillers per plant (0.087, low), while protein content was negligible.

7. Spike length
In F1, the direct effect of spike length on grain yield per plant was positive (0.029). Positive indirect effects included biological yield per plant (0.067, low) and thousand-grain weight (0.046, low), while number of productive tillers per plant was negligible. In F2, the direct effect was negative (-0.186). Positive indirect effects included grains per spike (0.099, low) and number of spikelets per spike (0.047, low), while days to 50% heading was negligible.

8. Number of grains/ear
In F1, the direct effect of grains per spike on grain yield per plant was positive (0.112). Positive indirect effects included biological yield per plant (0.167, low) and number of tillers per plant (0.110, low), while days to maturity was negligible. In F2, the direct effect was positive (0.463). Positive indirect effects included biological yield per plant (0.113, low), number of tillers per plant (0.104, low), and number of spikelets per spike (0.072, low), while canopy temperature was negligible.

9. Biological yield/plant (g)
In F1, the direct effect of biological yield per plant on grain yield per plant was positive (0.277). Positive indirect effects included thousand-grain weight (0.117, low), number of tillers per plant (0.080, low), and number of grains per spike (0.068, low), while spike length was negligible. The negative indirect effect was via protein content negligible. In F2, the direct effect was positive (0.218).

10. 1000-grain weight (g)
In F1, the direct effect of thousand-grain weight on grain yield per plant was positive (0.170). Positive indirect effects included biological yield per plant (0.191, low), number of tillers per plant (0.073, low), and grains per spike (0.069, low), while spike length was negligible. Negative indirect effects were via plant height and days to maturity both were negligible. In F2, the direct effect was positive (0.145). Positive indirect effects included biological yield per plant (0.198, moderate) and number of tillers per plant (0.109, low). Negative indirect effects included spike length (-0.056, low) and number of grains per spike (-0.035, low).

11. Harvest index
In F1, the direct effect of HI on GYPP was positive (0.088). Positive indirect effects included number of tillers per plant (0.068, low) and number of spikelets per spike (0.061, low). In F2, the direct effect was positive (-0.048). Positive indirect effects included grains per spike (0.181, moderate), biological yield per plant (0.070, low), and number of tillers per plant (0.055, low), while plant height was negligible. Negative indirect effects included spike length (-0.037, low) and number of productive tillers (-0.029, low).

12. Protein content
The correlation between protein content PC and grain yield per plant was negative and non-significant in both F1 (r = -0.021) and F2 (r = 0.016). In F1, the direct effect of PC on GYPP was negative (-0.088). In F2, the direct effect was negative (-0.070). Positive indirect effects included spike length (0.029, low) and biological yield (0.014, low), while thousand-grain weight (0.002, negligible) was negligible. Negative indirect effects included number of productive tillers (-0.006, low) and number of spikelets per spike (-0.008, low).

13. Gluten content
In F1, the direct effect of GC was negative (-0.077). Negative indirect effects included number of tillers (-0.011, low) and biological yield (-0.089, moderate). In F2, the direct effect was positive (0.031). Positive indirect effects included spike length (0.034, low) and plant height (0.013, low), while productive tillers was negligible. Negative indirect effects included thousand grain weight (-0.021, low), biological yield (-0.022, low), and number of tillers (-0.031, low).

14. Canopy temperature depression (°C)
In F1, the direct effect of CT was positive (0.127). In F2, the direct effect was negative (-0.003). Positive indirect effects included biological yield (0.012, low), spike length (0.010, low), and harvest index (0.010, low), while productive tillers was negligible.

Discussion
Path coefficient analysis showed the relative direct and indirect contributions of traits to rice grain yield. Unlike simple correlation, it clarifies cause-and-effect relationships (Dewey and Lu, 1959) [5]. Traits with high direct effects are reliable for selection, while those with high indirect effects influence yield through other traits. Genotypic and phenotypic path coefficient analyses highlighted the relative contributions of traits to grain yield per plant (GYPP) in wheat, showing the influence of genetic versus

environmental factors, with genotypic coefficients being more reliable (Baye *et al.*, 2020) [1]. Genotypic analysis revealed that number of grains per ear had strong positive direct effects and significant indirect effects via biological yield, spikelets per spike, harvest index, productive tillers, and gluten content in both F_1 and F_2 generations, consistent with Gaur (2025) [9] and Harijan *et al.* (2021) [11]. Biological yield per plant showed the highest direct effect, with additional indirect contributions through tiller traits, confirming its key role as observed by Vida *et al.* (2006) [3] and Carvalho *et al.* (2017) [2]. Thousand-grain weight had moderate to strong indirect effects via biological yield and tillers, despite a negative direct effect in F_2. Harvest index showed moderate direct and strong indirect effects in F_2 through biological yield, tillers, and canopy temperature (Laala *et al.*, 2018) [14].

Phenotypic path analysis confirmed positive correlations of grains per ear, biological yield, 1000-grain weight, and harvest index with GYPP in both generations, with moderate direct and generally low indirect effects. Total tillers and productive tillers showed variable direct effects, with strong positive indirect effects via biological yield and productive tillers, consistent with Elhani *et al.* (2007) [6] and Li *et al.* (2022) [15]. Spikelets per spike had moderate direct effects and positive indirect contributions, while spike length had weak negative effects with limited indirect contributions.

Days to heading and maturity, plant height, and protein content had non-significant correlations with yield and low direct effects, with indirect effects mostly negligible (Baye *et al.*, 2020; Muhammad *et al.*, 2024) [1, 17]. Gluten content was negatively correlated with yield (significant in F_1, non-significant in F_2), while canopy temperature showed positive effects in F_1 and negative, non-significant effects in F_2. Indirect contributions of these traits via biological yield, harvest index, and tillers were minimal, in line with Gahtyari *et al.* (2022) [8] and Dewan *et al.* (2024) [4].

Overall, number of grains per ear, biological yield, tiller traits, harvest index, and 1000-grain weight were the most influential for yield improvement, whereas other traits had limited direct or indirect effects.

Table 3c: Phenotypic path analysis among 15 characters of F_1s generation in wheat.

Trait	DFF	DTM	PHT	TN	NOPT	NOS	SL	GPE	BW	TW	HI	PC	GC	CT	GYPP
DFF	-0.1116	-0.0532	0.0174	0.2180	-0.2304	0.0257	-0.2431	0.3834	-0.1619	0.0997	-0.3374	-0.8079	0.0168	-0.7352	-0.1259 NS
DTM	-0.0635	-0.0935	0.0203	-0.0202	0.0006	-0.7434	-0.0085	-0.0086	-0.2380	0.0105	-0.0040	0.0190	0.0069	0.0329	-0.1179 NS
PHT	-0.0287	-0.0280	0.0678	-0.0173	0.0022	-0.0185	-0.0075	0.0036	0.2629	-0.0058	-0.0165	0.0333	-0.0042	0.0561	0.063 NS
TN	-0.0002	0.0121	-0.0075	0.1560	0.0201	0.0914	0.0051	0.0794	0.1429	0.0790	0.0382	-0.0113	0.0259	-0.0076	0.6234 **
NOPT	0.0087	-0.0015	0.0039	0.0806	0.0388	0.0579	0.0043	0.0680	0.2132	0.1061	0.0376	-0.0004	0.0217	0.0264	0.6653 **
NOS	-0.0192	0.0046	-0.0084	0.0950	0.0150	0.1499	0.0078	0.0702	0.1060	0.0630	0.0356	-0.0278	0.0235	-0.0183	0.497 **
SL	0.0166	0.0275	-0.0175	0.0274	0.0057	0.0406	0.0289	0.0223	0.0667	0.0456	0.0183	-0.0309	-0.0068	-0.0179	0.2266 **
GPE	-0.0038	0.0072	0.0021	0.1103	0.0235	0.0938	0.0057	0.1121	0.1667	0.1049	0.0468	-0.0056	0.0121	0.0014	0.6773 **
BW	0.0065	0.0008	0.0064	0.0804	0.0299	0.0574	0.0070	0.0675	0.2768	0.1168	0.0062	-0.0012	0.0249	0.0352	0.7146 **
TW	-0.0066	-0.0058	-0.0023	0.0726	0.0243	0.0557	0.0078	0.0693	0.1906	0.1696	0.0310	-0.0059	0.0187	0.0055	0.6244 **
HI	0.0043	0.0042	-0.0127	0.0678	0.0166	0.0608	0.0060	0.0597	0.0196	0.0599	0.0879	-0.0067	0.0051	-0.0109	0.3616 **
PC	-0.0010	0.0202	-0.0257	0.0200	0.0002	0.0474	0.0102	0.0072	0.0038	0.0114	0.0067	-0.0878	0.0140	-0.0469	-0.0205 NS
GC	0.0244	0.0084	0.0037	-0.0524	-0.0109	-0.0457	0.0026	-0.0175	-0.0893	-0.0413	-0.0059	0.0159	-0.0771	-0.0049	-0.2899 **
CT	0.0065	-0.0243	0.0300	-0.0093	0.0081	-0.0217	-0.0041	0.0012	0.0769	0.0073	-0.0076	0.0326	0.0030	0.1265	0.225 **

DFF = Days to 50% heading, DTM = Days to maturity, PHT = Plant height (cm), TN = Number of tillers/plant, NOPT = Number of productive tillers/plant, NOS = Number of spikelets/ear, SL = Spike length (cm), GPE = Number of grains/ear, BW = Biological yield/plant (g), TW = 1000-grain weight (g), HI = Harvest index (%), PC = Protein content (%), GC = Gluten content (%), CT = Canopy Temperature, GYPP = Grain yield/plant (g).

Resi-0.07332

*, ** significant at 5% and 1% level, respectively.

Table 3d: Phenotypic path analysis among 15 characters of F_2s generation in wheat.

Trait	DFF	DTM	PHT	TN	NOPT	NOS	SL	GPE	BW	TW	HI	PC	GC	CT	GYPP
DFF	-0.021	0.011	0.005	-0.007	0.368	0.111	0.017	0.033	-0.004	-0.004	0.004	0.005	-0.337	0.20769	0.0491 NS
DTM	-0.006	0.037	0.016	-0.037	0.011	-0.022	0.055	-0.065	-0.029	-0.013	0.011	-0.012	0.002	-0.00033	-0.0532 NS
PHT	-0.001	0.007	0.084	-0.006	0.006	-0.009	0.041	0.005	-0.016	-0.011	0.007	-0.012	0.005	-0.00012	0.0991 NS
TN	0.001	-0.007	-0.003	0.187	-0.043	0.070	-0.032	0.258	0.106	0.048	-0.014	-0.003	0.000	-0.00003	0.5675 **
NOPT	0.001	-0.005	-0.006	0.104	-0.078	0.060	-0.036	0.244	0.094	0.066	-0.018	-0.005	0.002	0.03280	0.4221 **
NOS	-0.002	-0.005	-0.005	0.087	-0.031	0.151	-0.058	0.221	0.074	0.039	-0.013	0.004	-0.007	0.00035	0.4557 **
SL	0.002	-0.011	-0.018	0.032	-0.015	0.047	-0.186	0.099	0.031	0.044	-0.010	0.011	-0.006	0.00014	0.0205 NS
GPE	-0.001	-0.005	0.001	0.104	-0.041	0.072	-0.040	0.463	0.113	0.062	-0.019	-0.002	-0.004	0.00007	0.7031 **
BW	0.000	-0.005	-0.006	0.091	-0.034	0.051	-0.027	0.240	0.218	0.073	-0.015	-0.005	-0.003	-0.00014	0.5788 **
TW	0.001	-0.003	-0.006	0.061	-0.035	0.040	-0.056	0.198	0.109	0.145	-0.015	-0.001	-0.004	-0.01021	0.433 **
HI	0.002	-0.008	-0.013	0.055	-0.029	0.040	-0.037	0.181	0.070	0.045	0.048	0.002	-0.002	0.51834	0.2569 **
PC	0.001	0.006	0.014	0.009	-0.006	-0.008	0.029	0.010	0.015	0.002	0.001	-0.070	0.012	-0.00036	0.0158 NS
GC	0.002	0.003	0.013	0.002	-0.004	-0.032	0.034	-0.056	-0.022	-0.020	0.003	-0.026	0.031	-0.00014	-0.0725 NS
CT	0.002	0.005	0.004	0.002	0.001	-0.021	0.010	-0.013	0.012	0.001	0.010	-0.010	0.002	-0.00257	0.0016 NS

DFF = Days to 50% heading, DTM = Days to maturity, PHT = Plant height (cm), TN = Number of tillers/plant, NOPT = Number of productive tillers/plant, NOS = Number of spikelets/ear, SL = Spike length (cm), GPE = Number of grains/ear, BW = Biological yield/plant (g), TW = 1000-grain weight (g), HI = Harvest index (%), PC = Protein content (%), GC = Gluten content (%), CT = Canopy Temperature, GYPP = Grain yield/plant (g).

Resi-0.04091

*, ** significant at 5% and 1% level, respectively

Conclusion

Path coefficient analysis revealed that biological yield, number of grains per ear, and productive tillers had the strongest direct effects on grain yield, while thousand-grain weight and harvest index contributed indirectly. Quality traits like protein and gluten content, and canopy temperature depression showed weak associations with yield, indicating limited selection value.

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