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EVALUATING CORRELATION AND PATH COEFFICIENT ANALYSIS IN ADVANCED BREEDING LINES OF RICE (*ORYZA SATIVA* L.) FOR IMPROVED PRODUCTIVITY

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ABSTRACT

Rice (*Oryza sativa* L.) is a crucial staple food for over half of the global population, particularly in Asia and Africa, with significant production concentrated in India, which ranks second globally. Despite advancements in rice cultivation, the projected population growth necessitates innovative breeding strategies to enhance yield. This study evaluates 44 rice genotypes, including advanced breeding lines and check varieties, to analyze yield-contributing traits through correlation and path coefficient analysis. The research was conducted at S.V. Agricultural College in Andhra Pradesh during Kharif season 2020. The findings indicate that grain yield plant^{-1} is significantly correlated with traits such as number of panicles plant^{-1} and biological yield plant^{-1}, emphasizing the importance of these components in breeding programs. Path coefficient analysis revealed that biological yield plant^{-1}, harvest index and number of filled grains panicle^{-1} have substantial direct effects on grain yield plant^{-1}. Overall, this study underscores the need for targeted breeding efforts focusing on key traits to develop high yielding rice cultivars capable of meeting future food demands while addressing agricultural resource limitations.

***Key words*:** Rice, Yield component traits, Correlation analysis, Path coefficient analysis, Advanced breeding lines, biological yield, Harvest index, Grain yield, Breeding strategies

Introduction

Rice (*Oryza sativa* L.) plays a pivotal role in global food security, serving as a staple food for over half of the world's population, particularly in Asia and Africa. The crop's high demand stems from its widespread consumption in various forms, ranging from cooked rice to processed products like puffed rice, rice flakes and fermented goods. Globally, rice is cultivated on approximately 168.35 million hectares, yielding around 800 million tonnes annually. In India, rice holds paramount significance, covering 47.80 million hectares and contributing 206.72 million tonnes to global production, positioning the country as the second-largest producer after China (Food and Agriculture Organization, 2024). Among Indian states, Uttar Pradesh ranks first in area under cultivation but second in production, following West Bengal. In Andhra Pradesh, rice is of prime importance, being cultivated on 1.92 million hectares and producing 11.27 million tonnes annually (Directorate of Economics and Statistics, 2024).

Despite significant advancements since the Green Revolution, including the development of semi-dwarf varieties and hybrid cultivars, the growing global population, which is projected to reach 9.78 billion by 2050 (United States Census Bureau, 2020), will outpace current production levels. Constraints in expanding cultivation areas and yield plateaus in major rice-growing regions underscore the urgent need for innovative breeding strategies. Correlation and path coefficient analyses are essential tools for addressing these challenges. They enable identifying and quantifying direct and indirect effects of yield-contributing traits, offering insights into the causal relationships underlying grain yield. Given the complexity of grain yield, which is influenced by numerous interrelated factors, focusing on component traits such as panicle number, number of filled grains panicle^{-1} and grain weight has proven to be an effective breeding approach. Correlation analysis reveals the strength and direction of trait associations, while path coefficient analysis decomposes these relationships into direct and indirect effects. By integrating these methodologies, breeders can prioritize traits with the most substantial impact on yield, accelerating the development of high yielding, genetically diverse rice cultivars.

Advanced breeding lines, derived from diverse breeding programs such as conventional methods, mutation breeding and biotechnology, offer a promising solution. These homozygous lines, harbouring valuable gene combinations, provide opportunities for enhancing genetic diversity and yield potential. Evaluating these lines for variability in agronomically important traits and employing correlation and path coefficient analyses can guide the development of cultivars that meet the growing global demand for rice while addressing the limitations of available agricultural resources.

Materials and Methods

The study was conducted during the kharif of 2020 at the Wetland Farm, S.V. Agricultural College, Acharya N.G. Ranga Agricultural University, Tirupati Andhra Pradesh, located at 182.9 m above mean sea level, 13.617' N latitude and 79.373' E longitude. The experimental material comprised of 44 rice genotypes, including 40 advanced breeding lines and four check varieties, obtained from the Department of Genetics and Plant Breeding, S.V. Agricultural College, Tirupati. The genotypes were evaluated in a randomized block design (RBD) with three replications, each genotype represented by two rows of three meters in length and a spacing of 20 cm × 15 cm. Standard agronomic practices were followed, including fertilizer application at 90 kg N, 60 kg P, O ... and 30 kg K, O per hectare, with nitrogen applied in three split doses: basal, 30 days after sowing and 60 days after sowing. Regular weeding and pest management practices were carried out to ensure healthy crop growth. Observations were recorded on five randomly selected plants per genotype per replication for key yield-contributing traits, including plant height, panicle length, number of panicles plant^{-1}, biological yield plant^{-1}, harvest index, 100 grain weight, grain length, grain breadth, grain size , number of filled grains panicle^{-1}, number of chaffy grains panicle^{-1}, spikelet fertility and grain yield plant^{-1}. Additionally, parameters like days to 50% flowering and days to maturity were recorded at the plot level.

Statistical analysis included correlation and path coefficient analysis to study the relationships among traits and their contributions to grain yield. Genotypic and phenotypic correlation coefficients were calculated using the method of Al-Jibouri *et al*., (1958) and their significance was tested using Fisher and Yates (1967) table values at (n-2) degrees of freedom. Path coefficient analysis, conducted as per Wright (1921) and elaborated by Dewey and Lu (1959), was used to partition correlation coefficients into direct and indirect effects. Residual effects were calculated to measure the contribution of factors not included in the analysis. The classification of direct and indirect effects followed Lenka and Mishra (1973) scale, categorizing effects as negligible, low, moderate, high, or very high. This approach provided insights into causal relationships among traits, enabling the identification of key contributors to grain yield for targeted breeding efforts.

Results and Discussions

Correlation Analysis

Grain yield plant^{-1} is a complex trait resulting from interactions among various component traits. The genetic basis of grain yield in rice is shaped by the combined effects of these yield components and their direct interactions with one another. Therefore, identifying yield components and understanding their associations with yield and each other is crucial for selecting high-yielding genotypes. Correlation coefficients among yield and its component traits are presented in Table 1. Significant positive correlation was observed between grain yield plant^{-1} and number of panicles plant^{-1} (r_p = 0.349**; r_g = 0.359**), biological yield plant^{-1} (r_p = 0.599**; r_g = 0.686**), harvest index (r_p = 0.535**; r_g = 0.661**), 100 grain weight (r_p = 0.258**; r_g = 0.287**) as reported by Abebe *et al.*, 2019 and Thippani *et al.*, 2017, number of filled grains plant^{-1} (r_p = 0.642**; r_g = 0.707**) as given by Gupta *et al.*, 2020 and Lakshmi *et al.*, 2020 and number of chaffy grains plant^{-1} (r_p = 0.265**; r_g = 0.279**) which align with findings of Abebe *et al.*, 2019 and Bitew *et al.*, 2018. Non-significant positive correlation of grain yield plant^{-1} was observed with days to 50% flowering (r_p = 0.097; r_g = 0.095), days to maturity (r_p = 0.081; r_g = 0.073), plant height (r_p = 0.123; r_g = 0.126), panicle length (r_p = 0.119; r_g = 0.152), spikelet fertility (r_p = 0.158; r_g = 0.162), grain length (r_p = 0.095; r_g = 0.104) and grain breadth (r_p = 0.141; r_g = 0.158). While it exhibited a non-significant negative correlation with grain size (r_p = -0.061; r_g = -0.059).

Table 1: Phenotypic (r_p) and genotypic (r_g) correlation coefficients among grain yield and its component traits in rice.

Character		DFF	DM	PH	PL	NPP	BY	HI	HGW	FGP	CGP	SF	GL	GB	GS	GY
DFF	r_p	**1.000**	0.978**	0.453**	0.302**	-0.017	0.426**	-0.392**	-0.305**	0.270**	0.609**	-0.429**	-0.492**	-0.200*	-0.249**	**0.097**
	r_g	**1.000**	0.998**	0.476**	0.441**	-0.027	0.507**	-0.446**	-0.318**	0.283**	0.661**	-0.465**	-0.509**	-0.217*	-0.262**	**0.095**
DM	r_p		**1.000**	0.462**	0.327**	-0.014	0.410**	-0.419**	-0.282**	0.239**	0.574**	-0.404**	-0.471**	-0.203*	-0.226**	**0.081**
	r_g		**1.000**	0.492**	0.479**	-0.035	0.496**	-0.461**	-0.298**	0.258**	0.629**	-0.441**	-0.491**	-0.221*	-0.241**	**0.073**
PH	r_p			**1.000**	0.570**	-0.102	0.485**	-0.374**	0.082	0.024	0.153	-0.093	0.075	-0.058	0.110	**0.123**
	r_g			**1.000**	0.863**	-0.134	0.576**	-0.405**	0.093	0.031	0.180*	-0.107	0.070	-0.038	0.088	**0.126**
PL	r_p				**1.000**	0.093	0.336**	-0.155	-0.016	0.055	0.160	-0.059	0.061	-0.157	0.191*	**0.119**
	r_g				**1.000**	0.104	0.612**	-0.337**	-0.040	0.041	0.247**	-0.085	0.064	-0.225**	0.253**	**0.152**
NPP	r_p					**1.000**	0.251**	0.204*	-0.187*	-0.038	0.138	-0.126	-0.105	-0.194*	0.073	**0.349****
	r_g					**1.000**	0.217*	0.278**	-0.248**	-0.060	0.120	-0.112	-0.138	-0.252**	0.107	**0.359****
BY	r_p						**1.000**	-0.192*	0.037	0.423**	0.318**	-0.026	-0.005	-0.092	0.056	**0.599****
	r_g						**1.000**	-0.150	0.043	0.539**	0.387**	0.000	-0.023	-0.084	0.047	**0.686****
HI	r_p							**1.000**	0.238**	0.332**	-0.040	0.240**	0.118	0.231**	-0.107	**0.535****
	r_g							**1.000**	0.285**	0.387**	-0.073	0.311**	0.136	0.244**	-0.105	**0.661****
HGW	r_p								**1.000**	-0.203*	-0.347**	0.238**	0.711**	0.735**	-0.049	**0.258****
	r_g								**1.000**	-0.219*	-0.380**	0.260**	0.740**	0.791**	-0.053	**0.287****
FGP	r_p									**1.000**	0.498**	0.070	-0.236**	-0.255**	0.024	**0.642****
	r_g									**1.000**	0.505**	0.084	-0.263**	-0.264**	-0.000	**0.707****
CGP	r_p										**1.000**	-0.763**	-0.270**	-0.300**	0.024	**0.265****
	r_g										**1.000**	-0.777**	-0.306**	-0.314**	0.001	**0.279****
SF	r_p											**1.000**	0.094	0.169	-0.062	**0.158**
	r_g											**1.000**	0.098	0.173*	-0.063	**0.162**
GL	r_p												**1.000**	0.346**	0.547**	**0.095**
	r_g												**1.000**	0.371**	0.548**	**0.104**
GB	r_p													**1.000**	-0.584**	**0.141**
	r_g													**1.000**	-0.570**	**0.158**
GS	r_p														**1.000**	**-0.060**
	r_g														**1.000**	**-0.059**
GY	r_p															**1.000**
	r_g															**1.000**

*: Significant at 5% level; **: Significant at 1% level

DFF : Days to 50% flowering; **DM :** Days to maturity; **PH :** Plant height (cm); **PL :** Panicle length (cm); **NPP :** Number of panicles plant^{-1}; **BY :** Biological yield plant^{-1} (g); **HI :** Harvest index (%); **HGW :** 100 grain weight (g); **FGP :** Number of filled grains panicle^{-1}; **CGP :** Number of chaffy grains panicle^{-1} ; **SF :** Spikelet fertility (%); **GL :** Grain length (L) (mm); **GB :** Grain breadth (B) (mm); **GS :** Grain size (LB ratio); **GY :** Grain yield plant^{-1} (g)

The study on the interrelationship among yield components revealed favourable and unfavourable associations among themselves and grain yield. Improvement in favourable components consequently enhances yield. Days to 50% flowering exhibited significant positive correlations with days to maturity (r_p = 0.978**; r_g = 0.998**) as highlighted by Lakshmi *et al.*, 2020, Gupta *et al.*, 2020, plant height (r_p = 0.453**; r_g = 0.476**) as corroborated by Katiyar *et al.*, 2019 and Thippani *et al.*, 2017, panicle length (r_p = 0.302**; r_g = 0.441**), biological yield plant^{-1} (r_p = 0.426**; r_g = 0.507**), number of filled grains panicle^{-1} (r_p = 0.270**; r_g = 0.283**) and number of chaffy grains panicle^{-1} (r_p = 0.609**; r_g = 0.661**) as reported by Abebe *et al.*, 2019 and Gupta *et al.*, 2020. On the contrary, it displayed significant negative correlation with harvest index (r_p = -0.392**; r_g = -0.446**) as described by Abebe *et al.*, 2019, Thippani *et al.*, 2017 and Dhavaleshvar *et al.*, 2019, 100 grain weight (r_p = -0.305**; r_g = -0.318**) as documented by Thippani *et al.*, 2017 and Kumar *et al.*, 2017, spikelet fertility (r_p = -0.429**; r_g = -0.465**), grain length (r_p = -0.492**; r_g = -0.509**), grain breadth (r_p = -0.200*; r_g = -0.217**) and grain size (r_p = -0.249**; r_g = -0.262**) as documented by Kumari and Parmar 2020.

Days to maturity showed significant positive correlations with plant height (r_p = 0.462**; r_g = 0.492**), panicle length (r_p = 0.327**; r_g = 0.479**), biological yield plant^{-1} (r_p = 0.410**; r_g = 0.496**), number of filled grains plant^{-1} (r_p = 0.239**; r_g = 0.258**) and number of chaffy grains panicle^{-1} (r_p = 0.574**; r_g = 0.629**) which are in line with findings of Abebe *et al.*, 2019, Gupta *et al.*, 2020, Priya *et al.*, 2017 and Saha *et al.*, 2019. However, a negative significant correlation was found with harvest index (r_p = -0.419**; r_g = -0.461**) and 100 grain weight (r_p = -0.282**; r_g = -0.298**) as reported by Thippani *et al.*, 2017, spikelet fertility (r_p = -0.404**; r_g = -0.441**) as highlighted by Gupta *et al.*, 2020 and Thippani *et al.*, 2017, grain length (r_p = -0.471**; r_g = -0.491**), grain breadth (r_p = -0.203*; r_g = -0.221**) and grain size (r_p = -0.226**; r_g = -0.241**) as described by Khan *et al.*, 2020.

Plant height demonstrated significant positive correlations with panicle length (r_p = 0.570**; r_g = 0.863**) and biological yield plant^{-1} (r_p = 0.485**; r_g = 0.576**) at both phenotypic and genotypic levels as reported by Osman *et al.*, 2020 and with number of chaffy grains panicle^{-1} (r_g = 0.180*) at the genotypic level as given by Kumari and Parmar 2020. Additionally, plant height showed significant negative correlation with harvest index (r_p = -0.374**; r_g = -0.405**), corroborated by Dhavaleshvar *et al.*, 2019. Significant positive correlations were found between panicle length and biological yield plant^{-1} (r_p = 0.336**; r_g = 0.612**) and number of chaffy grains panicle^{-1} (r_g = 0.247**) at the genotypic level as documented by Abebe *et al.*, 2019, Osman *et al.*, 2020, grain size (r_p = 0.191*; r_g = 0.253**) recorded by of Srijan *et al.*, 2016 and Sharma *et al.*, 2012. Conversely, significant negative correlations were observed between panicle length, grain breadth (r_g = -0.225**) and harvest index (r_g = -0.337**) at the genotypic level, consistent with the work of Kiani *et al.*, 2012, Sharma *et al.*, 2012 and Abebe *et al.*, 2019, respectively.

Number of panicles plant^{-1} showed significant positive correlation with harvest index (r_p = 0.204*; r_g = 0.278**) and biological yield plant^{-1} (r_p = 0.251**; r_g = 0.217*), which aligns with the work of Thippani *et al.*, 2017 and Sharma *et al.*, 2012, respectively. Negative significant correlations were observed between number of panicles plant^{-1} and 100 grain weight (r_p = -0.187*; r_g = -0.248**) and grain breadth (r_p = -0.194*; r_g = -0.252**), consistent with findings of Lakshmi *et al.*, 2020 and Sanghera *et al.*, 2013, at both phenotypic and genotypic levels. Biological yield plant^{-1} showed significant positive correlations with number of filled grains panicle^{-1} (r_p = 0.423**; r_g = 0.539**), number of chaffy grains panicle^{-1} (r_p = 0.318**; r_g = 0.387**) as described by Abebe *et al.*, 2019 and Osman *et al.*, 2020 and a significant negative correlation with harvest index (r_p = -0.192*) at the phenotypic level as reported by Kumari and Parmar 2020 and Abebe *et al.*, 2019. Harvest index showed positive correlations with 100 grain weight (r_p = 0.238*; r_g = 0.285**), number of filled grains panicle^{-1} (r_p = 0.332**; r_g = 0.387**), spikelet fertility (r_p = 0.240**; r_g = 0.311**) and grain breadth (r_p = 0.231**; r_g = 0.244**), in line with the work of Thippani *et al.*, 2017.

Significant positive correlations were observed between 100 grain weight and grain length (r_p = 0.711**; r_g = 0.740**), grain breadth (r_p = 0.735**; r_g = 0.791**) and spikelet fertility (r_p = 0.238**; r_g = 0.260**) supported by Kumar *et al.*, 2017. In contrast, negative correlations were found between 100 grain weight and number of filled grains panicle^{-1} (r_p = -0.203*; r_g = -0.219*) and number of chaffy grains panicle^{-1} (r_p = -0.347**; r_g = -0.380**), as observed by Nanda *et al.*, 2019, Saha *et al.*, 2019 and Oladosu *et al.*, 2018, respectively. Number of filled grains panicle^{-1} exhibited significant positive correlation with number of chaffy grains panicle^{-1} (r_p = 0.498**; r_g = 0.505**) as documented by Abebe *et al.*, 2019 and Saha *et al.*, 2019. Conversely, a significant negative correlation was found with grain length (r_p = -0.236*; r_g = -0.263**) and grain breadth (r_p = -0.255**;

Table 2: Path coefficients for grain yield and its component traits in of rice.

CH	DFF	DM	PH	PL	NPP	BY	HI	HGW	FGP	CGP	SF	GL	GB	GS	GY
DFF	**-0.149**	-0.145	-0.067	-0.045	0.003	-0.063	0.058	0.045	-0.040	-0.091	0.064	0.073	0.030	0.037	0.097
DM	0.197	**0.202**	0.093	0.066	-0.003	0.083	-0.084	-0.057	0.048	0.116	-0.081	-0.095	-0.041	-0.046	0.081
PH	0.042	0.043	**0.094**	0.053	-0.010	0.045	-0.035	0.008	0.002	0.014	-0.009	0.007	-0.005	0.010	0.123
PL	-0.018	-0.019	-0.034	**-0.059**	-0.006	-0.020	0.009	0.001	-0.003	-0.010	0.004	-0.004	0.009	-0.011	0.119
NPP	-0.005	-0.004	-0.027	0.025	**0.265**	0.067	0.054	-0.050	-0.010	0.037	-0.034	-0.028	-0.052	0.020	0.349
BY	0.158	0.151	0.179	0.124	0.093	**0.370**	-0.071	0.014	0.156	0.118	-0.010	-0.002	-0.034	0.021	0.599
HI	-0.149	-0.159	-0.142	-0.059	0.078	-0.073	**0.381**	0.091	0.126	-0.015	0.091	0.045	0.088	-0.041	0.535
HGW	-0.057	-0.053	0.015	-0.003	-0.035	0.007	0.045	**0.188**	-0.038	-0.065	0.045	0.133	0.138	-0.009	0.258
FGP	0.099	0.088	0.009	0.020	-0.014	0.155	0.122	-0.074	**0.366**	0.183	0.026	-0.087	-0.094	0.009	0.642
CGP	0.073	0.069	0.018	0.019	0.017	0.038	-0.005	-0.041	0.059	**0.119**	-0.091	-0.032	-0.036	0.003	0.265
SF	-0.058	-0.054	-0.013	-0.008	-0.017	-0.004	0.032	0.032	0.009	-0.102	**0.134**	0.013	0.023	-0.008	0.158
GL	-0.104	-0.099	0.016	0.013	-0.022	-0.001	0.025	0.150	-0.050	-0.057	0.020	**0.211**	0.073	0.115	0.095
GB	0.016	0.016	0.005	0.012	0.015	0.007	-0.018	-0.057	0.020	0.023	-0.013	-0.027	**-0.078**	0.046	0.141
GS	0.051	0.047	-0.023	-0.039	-0.015	-0.012	0.022	0.010	-0.005	-0.005	0.013	-0.113	0.120	**-0.206**	-0.061

Residual effect: 0.364; Diagonal (Bold) : Direct effect; Non-diagonal (Normal): Indirect effects

CH : Characters; **DFF :** Days to 50% flowering; **DM :** Days to maturity; **PH :** Plant height (cm); **PL :** Panicle length (cm); **NPP :** Number of panicles plant^{-1}; **BY :** Biological yield plant^{-1} (g); **HI :** Harvest index (%); **HGW :** 100 grain weight (g); **FGP :** Number of filled grains panicle^{-1}; **CGP :** Number of chaffy grains panicle^{-1}; **SF :** Spikelet fertility (%); **GL :** Grain length (L) (mm); **GB :** Grain breadth (B) (mm); **GS :** Grain size (LB ratio); **GY :** Grain yield plant^{-1} (g)

r_g = -0.264**), as confirmed by Srijan *et al.,* 2016.

Number of chaffy grains panicle^{-1} showed a significant positive correlation with no other character but significant negative correlations with spikelet fertility (r_p = -0.763**; r_g = -0.777**), grain length (r_p = -0.270**; r_g = -0.306**) and grain breadth (r_p = -0.300**; r_g = -0.314**) at both genotypic and phenotypic levels. Spikelet fertility exhibited a positive and significant correlation with grain breadth at the genotypic level (r_g = 0.173*). Finally, significant positive correlations were observed between grain length and grain breadth (r_p = 0.346**; r_g = 0.371**) and grain size (r_p = 0.547**; r_g = 0.548**), as reported by Kumar *et al.,* 2017 and Kumari and Parmar 2020. Grain breadth showed a significant negative correlation with grain size (r_p = -0.584**; r_g = -0.570**), as claimed by Kumari and Parmar 2020, Khan *et al.,* 2020 and Kumar *et al.,* 2017.

Path coefficient analysis

Path coefficient analysis performs partitioning of correlation coefficient into direct and indirect effects to determine the component characters' relative importance. It provides information about the relationship between yield and its component traits, which can be used to design an adequate selection criterion. Various direct and indirect effects of component traits on grain yield were discussed hereunder and the results are presented in Table 2. Among the yield components, biological yield plant^{-1} (P = 0.370), harvest index (P = 0.381) and number of filled grains panicle^{-1} (P = 0.366) exhibited a high positive direct effect on grain yield plant^{-1}, as reported by Kumari and Parmar 2020, Thippani *et al.,* 2017, Gupta *et al.,* 2020 and Lakshmi *et al.,* 2020. Number of panicles plant^{-1} (P = 0.265) showed a moderate positive direct effect on grain yield plant^{-1}, as highlighted by Swapnil *et al.,* 2020 and Lakshmi *et al.,* 2020. Additionally, days to maturity (P = 0.202) and grain length (P = 0.211) exhibited a moderate positive direct effect on grain yield plant^{-1}, as supported by Venkatraman *et al.,* 2023, Hossain *et al.,* 2018 and Srijan *et al.,* 2016. Spikelet fertility (P = 0.134), number of chaffy grains panicle^{-1} (P = 0.119) and 100 grain weight (P = 0.188) demonstrated a low positive direct effect on grain yield, as reported by Lakshmi *et al.,* 2020, Bhujel *et al.,* 2018 and Nanda *et al.,* 2019. Plant height (P = 0.094) also exhibited a negligible positive direct effect on grain yield, as observed by Kumari and Parmar 2020 and Srilakshmi *et al.,* 2021. In contrast, grain size exerted a moderate negative direct effect (P = -0.206) on grain yield plant^{-1}, as noted by Srijan *et al.,* 2016. Days to 50% flowering (P = -0.149) exhibited a low negative direct effect on grain yield, as highlighted by Lakshmi *et al.,* 2020 and Sahu *et al.,* 2017. Panicle length (P = -0.059) and grain breadth (P = -0.078) had negative and negligible direct effects on grain yield, as stated by Parimala *et al.,* 2020, Abhilash *et al.,* 2018 and Gautam *et al.,* 2024.

Days to 50% flowering indirectly affected grain yield positively but negligible through traits like number of panicles plant^{-1} (P = 0.003), harvest index (P = 0.058), 100 grain weight (P = 0.045), spikelet fertility (P = 0.064), grain length (P = 0.073), grain breadth (P = 0.030) and grain size (P = 0.037). Negative indirect effects were observed *via* days to maturity (P = -0.145), plant height (P = -0.067), panicle length (P = -0.045), biological yield plant^{-1} (P = -0.063), number of filled grains panicle^{-1} (P = -0.040) and number of chaffy grains panicle^{-1} (P = -0.091), as documented by various researchers Katiyar *et al.*, 2019 Kumari and Parmar 2020, Sri Lakshmi *et al.*, 2021, Sudeepthi *et al.*, 2020 Gupta *et al.*, 2020, Perween *et al.*, 2020 and PrasannaKumari and Parmar 2020.

Days to maturity exhibited a positive and low indirect effect on grain yield through days to 50% flowering (P = 0.197) and number of chaffy grains panicle^{-1} (P = 0.116), as reported by Oladosu *et al.*, 2018, Srilakshmi *et al.*, 2019 and Gupta *et al.*, 2020. Additionally, it showed positive but negligible indirect effects *via* plant height (P = 0.093), panicle length (P = 0.066), biological yield plant^{-1} (P = 0.083) and number of filled grains panicle^{-1} (P = 0.048), consistent with findings by Bhujel *et al.*, 2018, Dhavaleshvar *et al.*, 2019, Gupta *et al.*, 2020 and Srilakshmi *et al.*, 2021. Conversely, negative and negligible indirect effects were noted through number of panicles plant^{-1} (P = -0.003), harvest index (P = -0.084), 100 grain weight (P = -0.057), spikelet fertility (P = -0.081), grain length (P = -0.095), grain breadth (P = -0.041) and grain size (P = -0.046), which align with the findings of Edukondalu *et al.*, 2017, Dhavaleshvar *et al.*, 2019, Gupta *et al.*, 2020 and Srilakshmi *et al.*, 2021.

Plant height showed positive but negligible indirect effects on grain yield through days to maturity (P = 0.043), panicle length (P = 0.053), biological yield plant^{-1} (P = 0.045), 100 grain weight (P = 0.008), number of filled grains panicle^{-1} (P = 0.002), number of chaffy grains panicle^{-1} (P = 0.014), grain length (P = 0.007), grain size (P = 0.010) and days to 50% flowering (P = 0.042), as observed by Gupta *et al.*, 2020, Perween *et al.*, 2020, Prasanna Kumari and Parmar 2020, Srilakshmi *et al.*, 2021 and Sudeepthi *et al.*, 2020. Conversely, it had negative and negligible indirect effects on grain yield *via* number of panicles plant^{-1} (P = -0.010), harvest index (P = -0.035), spikelet fertility (P = -0.009) and grain breadth (P = -0.005), as mentioned by Abhilash *et al.*, 2018, Jeevula *et al.*, 2019, Srilakshmi *et al.*, 2021 and Gupta *et al.*, 2020.

Panicle length exhibited positive but negligible indirect effects through harvest index (P = 0.009), 100 grain weight (P = 0.001), spikelet fertility (P = 0.004) and grain breadth (P = 0.009), as described by Jeevula *et al.*, 2019, Srilakshmi *et al.*, 2021 and Sudeepthi *et al.*, 2020. Negative and negligible indirect effects were observed *via* days to 50% flowering (P = -0.018), days to maturity (P = -0.019), plant height (P = -0.034), number of panicles plant^{-1} (P = -0.006), biological yield plant^{-1} (P = -0.020), **number of** filled grains panicle^{-1} (P = -0.003), number of chaffy grains panicle^{-1} (P = -0.010), grain length (P = -0.004) and grain size (P = -0.011), as reported by Jeevula *et al.*, 2019, Saha *et al.*, 2019, Perween *et al.*, 2020, Lakshmi *et al.*, 2020 and Srilakshmi *et al.*, 2021.

Number of panicles plant^{-1} exhibited a positive and negligible indirect effect on grain yield *via* biological yield plant^{-1} (P = 0.067), number of chaffy grains panicle^{-1} (P = 0.037), harvest index (P = 0.054), panicle length (P = 0.025) and grain size (P = 0.020), as stated by Kishore *et al.*, 2018, Dhavaleshvar *et al.*, 2019 and PrasannaKumari and Parmar 2020. Conversely, it exhibited a negative but negligible indirect effect *via* 100 grain weight (P = -0.050), number of filled grains panicle^{-1} (P = -0.010), days to 50% flowering (P = -0.005), days to maturity (P = -0.004), plant height (P = -0.027), spikelet fertility (P = -0.034), grain length (P = -0.028) and grain breadth (P = -0.052), as mentioned by Abhilash *et al.*, 2018, Lakshmi *et al.*, 2020, Dhavaleshvar *et al.*, 2019 and Prasanna Kumari and Parmar 2020.

Biological yield plant^{-1} showed a moderate and positive indirect effect on grain yield through number of filled grains panicle^{-1} (P = 0.156), days to 50% flowering (P = 0.158), days to maturity (P = 0.151), plant height (P = 0.179), number of chaffy grains panicle^{-1} (P = 0.118) and panicle length (P = 0.124), as stated by Tripathi *et al.*, 2018, Bitew *et al.*, 2018, Kishore *et al.*, 2018 and Giri *et al.*, 2021. It also exhibited a positive but negligible indirect effect through grain size (P = 0.021), 100 grain weight (P = 0.014) and number of panicles plant^{-1} (P = 0.093), as described by Katiyar *et al.*, 2019 and Singh *et al.*, 2023. On the other hand, biological yield exerted a negative but negligible effect on grain yield *viath* harvest index (P = -0.071), spikelet fertility (P = -0.010), grain length (P = -0.002) and grain breadth (P = -0.034), as reported by Dhavaleshvar *et al.*, 2019, Jeevula *et al.*, 2019, Singh and Verma (2018) and Gautam *et al.*, 2024,

Harvest index exhibited a positive and low indirect effect on grain yield plant^{-1} *via* number of filled grains panicle^{-1} (P = 0.126) and a positive but negligible indirect effect through number of panicles plant^{-1} (P = 0.078), grain length (P = 0.045), spikelet fertility (P = 0.091), grain breadth (P = 0.088) and 100 grain weight (P = 0.091), as reported by Dhavaleshvar *et al.*, 2019, Abebe *et al.*, 2019, Kishore *et al.*, 2018 and Gautam *et al.*, 2024. However, it exhibited a negative and low indirect effect on grain yield *via* days to 50% flowering (P = -0.149), days to maturity (P = -0.159) and plant height (P = -0.142), as stated by Sahu *et al.*, 2017 and Kumar *et al.*, 2018. Additionally, it exerted a negative but negligible indirect effect *via* panicle length (P = -0.059), number of chaffy grains panicle^{-1} (P = -0.015), grain size (P = -0.041) and biological yield plant^{-1} (P = -0.073), as mentioned by Abebe *et al.*, 2019, Sahu *et al.*, 2017, Katiyar *et al.*, 2019 and Singh *et al.*, 2023.

100 grain weight exhibited a positive and negligible indirect effect on grain yield plant^{-1} through spikelet fertility (P = 0.045), biological yield plant^{-1} (P = 0.007), harvest index (P = 0.045) and plant height (P = 0.015), as reported by Nanda *et al.*, 2019, Sudeepthi *et al.*, 2020 and Perween *et al.*, 2020. It also showed a positive and low indirect effect *via* grain length (P = 0.133) and grain breadth (P = 0.138), as described by Priya *et al.*, 2017 and Lakshmi *et al.*, 2020. Conversely, it exhibited negative but negligible indirect effects on grain yield *via* number of panicles plant^{-1} (P = -0.035), number of filled grains panicle^{-1} (P = -0.038), number of chaffy grains panicle^{-1} (P = -0.065), days to 50% flowering (P = -0.057), days to maturity (P = -0.053), panicle length (P = -0.003) and grain size (P = -0.009), as mentioned by Srilakshmi *et al.*, 2021, Nanda *et al.*, 2019, Perween *et al.*, 2020, Lakshmi *et al.*, 2020 and Oladosu *et al.*, 2018.

Number of filled grains panicle^{-1} showed a low and positive indirect effect on grain yield plant^{-1} through biological yield plant^{-1} (P = 0.155), number of chaffy grains panicle^{-1} (P = 0.183), and harvest index (P = 0.122), as noted by Kishore *et al.*, 2018. It also exhibited a positive and negligible indirect effect through the days to 50% flowering (P = 0.099), days to maturity (P = 0.088), plant height (P = 0.009), panicle length (P = 0.020), spikelet fertility (P = 0.026) and grain size (P = 0.009), as reported by Perween *et al.*, 2020, Oladosu *et al.*, 2018, Srilakshmi *et al.*, 2021, Nanda *et al.*, 2019, Sudeepthi *et al.*, 2020 and Singh *et al.*, 2023. However, it had negative and negligible effects *via* grain length (P = -0.087), grain breadth (P = -0.094), number of panicles plant^{-1} (P = -0.014) and 100 grain weight (P = -0.074), as stated by Kiani *et al.*, 2012, Gupta *et al.*, 2020 and Lakshmi *et al.*, 2020.

Number of chaffy grains panicle^{-1} had a positive but negligible indirect effect on grain yield plant^{-1} through number of panicles plant^{-1} (P = 0.017), days to 50% flowering (P = 0.073), days to maturity (P = 0.069), plant height (P = 0.019), panicle length (P = 0.019) and grain size (P = 0.003), as described by Oladosu *et al.*, 2018, Srilakshmi *et al.*, 2021, Jeevula *et al.*, 2019 and Giri *et al.*, 2021. It exhibited a positive and low indirect effect *via* biological yield plant^{-1} (P = 0.038) and number of filled grains panicle^{-1} (P = 0.059), as reported by Bitew *et al.*, 2018, Lakshmi *et al.*, 2020 and Gupta *et al.*, 2020. Negative and negligible effects were observed *via* spikelet fertility (P = -0.091), grain length (P = -0.032), grain breadth (P = -0.036), harvest index (P = -0.005) and 100 grain weight (P = -0.041), as given by Nanda *et al.*, 2019 and Gautam *et al.*, 2024.

Spikelet fertility showed positive but negligible indirect effects through harvest index (P = 0.032), 100 grain weight (P = 0.032), number of filled grains panicle^{-1} (P = 0.009), grain breadth (P = 0.023) and grain length (P = 0.013), as reported by Kumari and Parmar 2020, Jeevula *et al.*, 2019 and Singh *et al.*, 2023. Negative and negligible indirect effects were noted *via* days to 50% flowering (P = -0.058), days to maturity (P = -0.054), plant height (P = -0.013), panicle length (P = -0.008), number of panicles plant^{-1} (P = -0.017), biological yield plant^{-1} (P = -0.004), number of chaffy grains panicle^{-1} (P = -0.102) and grain size (P = -0.008), as described by Jeevula *et al.*, 2019, Saha *et al.*, 2019, Singh *et al.*, 2023 and Gupta *et al.*, 2020.

Grain length had a positive but low indirect effect on grain yield through 100 grain weight (P = 0.150) and grain size (P = 0.115). Other positive but negligible indirect effects were observed through plant height (P = 0.016), panicle length (P = 0.013), harvest index (P = 0.025), spikelet fertility (P = 0.020) and grain breadth (P = 0.073), as described by Pratap *et al.*, 2012, Srijan *et al.*, 2016, Kumari and Parmar 2020 and Lakshmi *et al.*, 2020. Negative and low indirect effect was observed through days to 50% flowering (P = -0.104) and negative but negligible effects were observed *via* days to maturity (P = -0.099), number of panicles plant^{-1} (P = -0.022), biological yield plant^{-1} (P = -0.001), number of filled grains panicle^{-1} (P = -0.050) and number of chaffy grains panicle^{-1} (P = -0.057), as reported by Priya *et al.*, 2017, PrasannaKumari and Parmar 2020, Gautam *et al.*, 2024 and Singh *et al.*, 2023.

Grain breadth showed positive but negligible indirect effects on grain yield through days to 50% flowering (P = 0.016), days to maturity (P = 0.016), plant height (P = 0.005), panicle length (P = 0.012), number of panicles plant^{-1} (P = 0.015), biological yield plant^{-1} (P = 0.007), number of filled grains panicle^{-1} (P = 0.020), number of chaffy grains panicle^{-1} (P = 0.023) and grain size (P = 0.046), as noted by Priya *et al.*, 2017, Srijan *et al.*, 2016 and Kumari and Parmar 2020. Negative and negligible effects were observed through harvest index (P = -0.018), 100 grain weight (P = -0.057), spikelet fertility (P = -0.013) and grain length (P = -0.027), as described by Kumari and Parmar 2020, Srijan *et al.*, 2016 and Singh and Varma *et al.*, 2018.

Grain size showed positive but negligible indirect effects through days to 50% flowering (P = 0.051), days to maturity (P = 0.047), spikelet fertility (P = 0.013), harvest index (P = 0.022) and 100 grain weight (P = 0.010), as described by Katiyar *et al.*, 2019, Kumari and Parmar 2020 and Prasanna Kumari and Parmar 2020. It also exhibited a positive but low indirect effect through grain breadth (P = 0.120), as given by Srijan *et al.*, 2016 and Gautam *et al.*, 2024. Negative and negligible effects were observed *via* plant height (P = -0.023), panicle length (P = -0.039), number of panicles plant^{-1} (P = -0.015), biological yield plant^{-1} (P = -0.012), number of filled grains panicle^{-1} (P = -0.005), number of chaffy grains panicle^{-1} (P = -0.005) and grain length (P = -0.113), as noted by Srijan *et al.*, 2016, Priya *et al.*, 2017, PrasannaKumari and Parmar 2020 and Singh *et al.*, 2023.

Conclusion

Correlation and path analysis underscored the importance of traits such as number of filled grains plant^{-1}, number of panicles plant^{-1}, biological yield plant^{-1} and harvest index as pivotal components in breeding programs aimed at enhancing rice yield potential. Correlation analysis illuminated significant positive associations between grain yield plant^{-1} and traits such as number of panicles plant^{-1}, biological yield plant^{-1}, harvest index, 100 grain weight, number of filled grains panicle^{-1} and number of chaffy grains plant^{-1} at both phenotypic and genotypic levels. These findings affirm the feasibility of concurrent selection for these traits to achieve substantial yield improvements.

Path analysis further revealed that biological yield plant^{-1} and harvest index exerted robust positive direct effects on grain yield plant^{-1}. Notably, number of panicles plant^{-1} and number of filled grains panicle^{-1} emerged as the most influential contributors to grain yield, exhibiting pronounced positive indirect effects mediated *via* biological yield plant^{-1} and harvest index. This underscores the strategic value of these traits as selection criteria for augmenting yield performance. Moreover, the low residual effect observed, substantiates that the traits included in this study comprehensively account for the variation in grain yield.

In summation, this investigation elucidates that grain yield enhancement in rice can be most effectively realized through the meticulous selection of lines characterized by superior biological yield plant^{-1}, an elevated number of filled grains panicle^{-1} and an optimized harvest index. These attributes serve as indispensable indices for the development of high-yielding rice cultivars.

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