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Correlation and path analysis studies for yield and yield contributing traits in M_3 population of *rabi* sorghum (*Sorghum bicolor* (L.) Moench)

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Abstract
This study investigates the induction of desirable variability in sorghum [*Sorghum bicolor* (L.) Moench] through electron beam irradiation to enhance seed yield and its components. The experiment, titled "Genetic Variability and Correlation Studies for Morphophysiological Traits in M_3 Generation of Mutagenized Population of *Rabi* Sorghum," aims to evaluate variability, heritability, and correlations among traits in mutagenized populations. Rabi parental material TSG-98 (Muguthi) was subjected to electron beam doses (100 Gy, 200 Gy, 300 Gy, 400 Gy, and 500 Gy), resulting in 60 M_3 generation mutants. Evaluated traits included days to flowering, plant height, and various yield components. Significant genetic variability was observed, with irradiated treatments outperforming controls in several traits. High heritability was noted for grain yield and associated traits, with correlation studies revealing positive associations between grain yield and plant height, panicle length, and fodder yield. Path analysis indicated direct positive effects of multiple traits on grain yield.

Keywords: *Rabi* sorghum, mutagens, genetic variability, electron beam, irradiation, M_3 generation, heritability, path analysis, phenotypic variance, genotypic variance, correlation studies, fodder yield

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is predominantly cultivated in the USA, China, India and Africa for both human consumption and livestock feed. In 2024-2025, the production of sorghum projected to be 63.64 million metric tons worldwide. Nigeria leads the world in total production (12%) with 6.40 million metric worldwide tones, followed by the Brazil, Mexico and Ethiopia. India is the third largest producers tons sorghum worldwide, with 4.40 million metric tons cultivated in 4.10 millon hectares in 2023-2024. In contrast, 4.20 million metric tons (1st advance estimates) of sorghum were produced in 3.80 million hectares in Kharif 2024-2025. (Anonymous, 2023") [1].

In India, the major sorghum growing states are Maharashtra, Karnataka and Rajasthan which contributes nearly 93 percent of area and production. Remaining area is distributed in states of Tamil Nadu, Gujarat and Madhya Pradesh. Sorghum is grown state wise in India as Maharashtra ranks first in area 16.00 lakh hectares and annual production 14.04 lakh tons and productivity is 878 kg/ha, Karnataka ranks second with an annual production 7.06 lakh tons and productivity is 1204 kg/ha, Rajasthan ranks third with area 5.09 lakh hectares and annual production 5 27 lakh tons and productivity is 1036 kg/ha, area of cultivation in Uttar pradesh is 2.89 lakh hectares, with an annual production 4.62 lakh tons and productivity is 1600 kg/ha, Andhra pradesh ranks fifth with an area 0.84 lakh hectares and an annual production 2.93 lakh tons. (Anonymous, 2023") [1].

A shorter rainy season and accompanying growth season have been observed in recent years as a result of climate change. In this scenario, water deficits lead to an inevitable shift in cropping patterns toward drought-tolerant food crops. Sorghum is one of the most drought-tolerant grain crops, making it an ideal choice for production in low rainfall areas. The primary issue with sorghum cultivation is its lower productivity compared to other cereals particularly in *rabi* sorghum since 1990. The introduction of a high-yielding cultivar with a shorter duration could significantly enhance the potential for sorghum cultivation under moisture stress conditions, thereby expanding its use in challenging environments in the future.

Sorghum is a significant feed and food crop that is utilized worldwide to nourish millions of animals that provide milk and meat for human consumption. In many different industries, it is also utilized as an industrial raw material. In India, flour is used to make "*Bhakri*" after the grains have been ground. It is also consumed in modest amounts as popped and parched grain. In most parts of the world, sorghum serves as the staple food for both humans and animals. Its fodder is composed of about 50% digestible components, 2.5% fat, 8% protein and 45% nitrogen-free extract. People in some countries consume sorghum grains. A number of parameters including test weight, panicle length and number of grains per panicle affect sorghum grain yield. Collectively, these elements raise the yield.

Sorghum is a key green fodder crop, and despite India having the largest cattle population, the grain production is insufficient to meet their needs. In 2002, there was a significant shortfall of 45 million tonnes of fodder, with green fodder accounting for 66.5% and dry fodder for 25.9%. The main reason for low fodder production is a shortage of seeds. Some fodder sorghum varieties, such as CO (FS) 29 from TNAU, face issues with seed cracking, which reduces yields. In this context, increasing variability through induced mutation could enhance the potential for sorghum improvement.

In India, the productivity of *rabi* sorghum is very low and highly variable from year to year, primarily due to post-flowering drought. Despite this, *rabi* sorghum is highly valued for its excellent grain quality. The crop is typically affected by water stress at both pre-flowering and post-flowering stages, with the most adverse effects on yield occurring during these periods (Kebede *et al.* 2001) [15]. Drought tolerance is defined as the relative yield of a genotype compared with other genotypes subjected to the same drought stress (Hall, 2004) [9]. This tolerance depends on the plant developmental stage at the onset of stress, which can occur during early vegetative growth, panicle development and post flowering and the period between grain filling and physiological maturity. Drought tolerance in sorghum is a complex trait influenced by numerous genes that contribute to various aspects of tolerance (Tesfamichael *et al.* 2015) [25]. In the future, advancements in genetic research and breeding could lead to the development of sorghum varieties with enhanced drought tolerance, potentially improving yield stability and quality under variable climatic conditions.

Mutation breeding is a very rapid technique for improving a variety of crops and is acknowledged as one of the forces influencing evolution in order to influence choices for quantitatively inherited traits, breeders need genetic variation. Mutation breeding is one alternative stratergy for increasing genetic variability. It is frequently employed to remediate defects in a cultivar that possesses a number of advantageous agronomic traits. A wide range of physical mutagens including electron beams, x-rays, thermal neutrons, fast neutrons, ultraviolet radiation and beta radiation can affect plant growth and development. Of these, gamma rays are particularly well-known for their ability to cause cytological, physiological and morphological changes in somatic and germ line cells. There are numerous publications describing the use of gamma radiation by breeders to enhance yield and qualities that contribute to yield by producing genetic variability in quantitative features. High power linear electron accelerators with energies ranging from 500 keV and 10 MeV have become more significant recently for many kinds of uses. Similar to X-ray facilities, the accelerators function via a switch-on/off mechanism. It generates electron beams that are useful for high-throughput material irradiation. An effective method for increasing yield and improving quality traits is to expose plants to electron beam radiation, which also induces genetic diversity.

Artificial mutagenesis offers the potential to induce desired qualities that may be absent or not found naturally in crops, while mutation induction is a proven method for creating variation within a crop variety. Through induced mutations, targeted recombination can be achieved in a relatively short time without significantly impacting the yield and quality of currently popular varieties. Defect rectification in sorghum varieties for their improvement has been achieved through mutagenesis (Bhatnagar and Tiwari, 1992) [4]. There are two types of mutations *i.e.* spontaneous (Natural) and artificial (induced). Due to the very low frequency of natural mutations, induced mutations are utilized to create genetic variability for both qualitative and quantitative traits.

Mutation inductions were greatly aided by the identification of a broad spectrum of chemical mutagens after Auerbach and Robson's (1946) [30] research, which also revealed that X-rays were a potent physical mutagen (Muller, 1927) [19]. The identification of base-specific mutagens such as hydroxylamine and ethyl methane sulphonate has reignited interest in chemical mutagenesis. Unlike gamma rays, which act randomly, these chemical mutagens react selectively with a certain base of DNA.

The presence of a link between contributing features is described by correlation coefficients. A system of correlation as the indirect linkage of the character increase is not an easy system to explain. When determining characters association with yield is having a direct or indirect effect on yield or is a result of an indirect effect through other features, Wright's (1921) [27] route coefficient technique can be useful.

Materials and Methods

The present study was conducted during rabi 2023-24 at the Department of Genetics and Plant Breeding, VNMKV, Parbhani, using 60 M_3 mutant lines derived from five gamma radiation treatments (100 Gy, 200 Gy, 300 Gy, 400 Gy, 500 Gy) along with one control and three checks (CSV-29R, Parbhani Moti, and Parbhani Supermoti). The M_3 mutant lines were developed from a single sorghum genotype, TSG-98 (Muguthi) provided by the Bhabha Atomic Research Centre (BARC), Mumbai and their salient features of this genotype TSG-98 are shown in Table 1. The field experiment was laid out in a randomized block design (RBD) with two replications. Each plot consisted of two rows with spacing of 45 cm × 15 cm and a plot size of 0.9 m × 4 m. Sowing was done manually through hand dibbling, and a fertilizer dose of 80 kg N, 40 kg P, and 40 kg K per hectare was applied. Quantitative traits such as days to 50% flowering, plant height, days to maturity, and yield parameters were recorded on five randomly selected plants from each treatment. Additionally, drought tolerance parameters like relative water content and chlorophyll content (SPAD values) were measured. Statistical analysis including analysis of variance (ANOVA), variability, heritability, genetic advance, correlation, and path coefficient analysis was performed following standard procedures.

Table 1: The salient features of the genotype TSG-98

Sr. No.	Features	TSG-98 (Muguthi)
1.	Year of release	1969 (UAS Dharwad)
2.	Notification date	2/2/1976
3.	Pedigree	Selection from 5-4-1
4.	Yield	18-20 q/ha
5.	100 Seed weight	3.75-4.0 g
6.	Seed color	Pearl yellow
7.	Days to flower	60-70 days
8.	Days to maturity	110-120 days
9.	Plant height	220-240 cm
10.	Panicle length	20-22 cm
11.	Panicle width	5-7 cm
12.	Season adapted	*Rabi*

Results and Discussion

Correlation coefficient analysis

Correlation coefficient is a statistical measure, which denotes the degree and magnitude of association between any two casually related variables. This association is due to pleiotropic gene action or linkage or more likely both. In plant breeding correlation coefficient analysis measures the mutual relationship between two characters and it determines character association for improvement yield and other economic characters. Since the association pattern among yield components help to select the superior genotypes from divergent population based on more than one interrelated characters. Thus information on the degree and magnitude of association between characters is of prime important for the breeder to initiate any selection plan. In the present investigation the estimates of genotypic correlation was higher than those of phenotypic correlation for most of the traits. These higher genotypic values whenever observed were contributed to the relative stability of the genotypes. Thus trait with higher genetic correlation may throw light on validity of selection for those traits. Correlation studies revealed that, genotypic and phenotypic coefficients among fourteen yield and yield attributing characters are presented in Table 2. The correlation studies in the present investigation revealed that grain yield per plant recorded positive and significant correlation with plant height (G=0.227*, P=0.373**), panicle length (G=0.227*, P=0.444**), panicle width (G=0.286**, P=0.522**), 100 seed weight (G=0.530**, P= 0.655**), fodder yield per plant (G=0.572**, P=0.677**) at both genotypic and phenotypic level, respectively and it showed negative significant correlation with with days to maturity (G=0.333**, P=0.226**), relative water content (G= -0.475**, P= -0.340**). Similar results were reported by Gedifew (2012) [8], Jain and Patel (2014) [11], Zinzala *et al.* (2018) [29], The results revealed that any positive increase in these traits will accelerate the yield potential of rabi sorghum. So, these traits should be attract for selection in rabi sorghum breeding programmes. The positive and significant correlations between yield and yield components in were also reported by Jeyaprakash *et al.* (1997) [12], Veerbhadiran and Kennedy (2001) [26], Prabhakar (2001) [22], Kole *et al.* (2010) [17], Mahajan *et al.* (2011) [18], Dhutmal *et al.* (2014) [7], Khandelwal *et al.* (2015) [16], Jimmy *et al.* (2017) [13], Prasad and Sridhar *et al.* (2019) [23], Shivprasad *et al.* (2019) [24], Patil *et al.* (2022) [21], Patil *et al.* (2023) [22] and Karpe *et al.* (2023) [14].

Table 2: Genotypic correlation coefficient for fourteen characters studied in rabi sorghum.

Characters		Days to 50% Flowering	Plant height	Days to maturity	Primaries per panicle	Grains per primary	Panicle length	Panicle width	100 seed weight	Fodder yield Per plant	RWC	SPAD	leaf area	Flag Leaf area	Grain Yield Per plant
Days to 50% flowering	G	1.000	-0.2100*	0.2664**	0.9515**	-0.8929**	-0.9567**	-0.9123**	-0.0553	-0.8041**	0.0074	-0.5184**	-0.2931**	-0.1725*	-0.1047
	P	1.000	0.1924*	0.5044**	0.7224**	-0.2433**	-0.2790**	-0.1283	0.2762**	0.0285	-0.1078	-0.3161**	0.0914	0.1916*	0.2177**
Plant height (cm)	G		1.000	-0.5514**	0.1483*	-0.1640*	-0.2566**	0.0827	-0.1286	0.1661	0.2315**	0.2530**	-0.3069**	-0.1233	0.2267*
	P		1.000	0.1617	0.1693	0.1475	0.1112	0.3337**	0.1972*	0.4336**	0.0145	0.1652	0.0715	0.1353	0.3733*
Days to maturity	G			1.000	0.2639**	-0.5536**	-0.7993**	-0.8976**	-0.6446**	-0.6100**	0.1893**	-0.3117**	-0.6867**	-0.2533**	-0.3339**
	P			1.000	0.2439**	0.0907	-0.0519	0.0481	0.2033*	0.2319**	-0.0964	-0.1945*	0.0414	0.1745*	0.2264*
Primaries per panicle (Nos.)	G				1.000	-0.6939**	-0.7340**	-0.3907**	0.3120**	-0.2833	0.0753	-0.4213**	-0.0828	-0.0388	0.1327
	P				1.000	-0.4719**	-0.5090**	-0.1887*	0.2884**	-0.1058	0.0276	-0.3676**	0.0157	0.0232	0.1864*
Grains per primary (Nos.)	G					1.000	0.3956**	0.1232	-0.3023**	0.2731	-0.2326**	0.2418**	-0.0072	-0.0864	0.0339
	P					1.000	0.4360**	0.3232**	0.1454	0.4545**	-0.2278**	0.1471	0.2680**	0.1214	0.2775*
Panicle length (cm)	G						1.000	0.3150**	-0.0651	0.2727**	-0.1630	0.2367**	0.1379	-0.1626	0.2277*
	P						1.000	0.5192**	0.3507**	0.5063**	-0.2510**	0.1566	0.3663**	0.1432	0.4449**
Panicle width (cm)	G							1.000	0.0313	0.3799**	0.0059	0.1868*	-0.1510	-0.2303**	0.2869**
	P							1.000	0.4556**	0.6004**	-0.1989*	0.1270	0.2565**	0.1778*	0.5223**
100-seed weight (g)	G								1.000	-0.1170	-0.3849**	-0.1759*	-0.2187*	-0.1452	0.5309**
	P								1.000	0.3910**	-0.2724**	-0.1551	0.2799**	0.2494**	0.6552**
Fodder yield/ plant (g)	G									1.000	-0.1795*	0.2214*	-0.1316	-0.1332	0.5722**
	P									1.000	-0.2074*	0.1288	0.2970**	0.2505**	0.6775**
RWC	G										1.000	-0.0271	-0.1747*	0.0688	-0.4758**
	P										1.000	-0.0017	-0.2105*	-0.0828	-0.3405**
SPAD	G											1.000	-0.1798*	-0.1994*	0.0167
	P											1.000	-0.1150	-0.1295	0.0020
Leaf area (cm^2)	G												1.000	-0.2520**	-0.0876
	P												1.000	0.0926	0.2855**
Flag leaf area (cm^2)	G													1.000	-0.0501
	P													1.000	0.2228*

*, ** shows significance at 0.05 and 0.01 levels of probability, respectively

G- Genotypic correlation coefficient; P- Phenotypic correlation coefficient

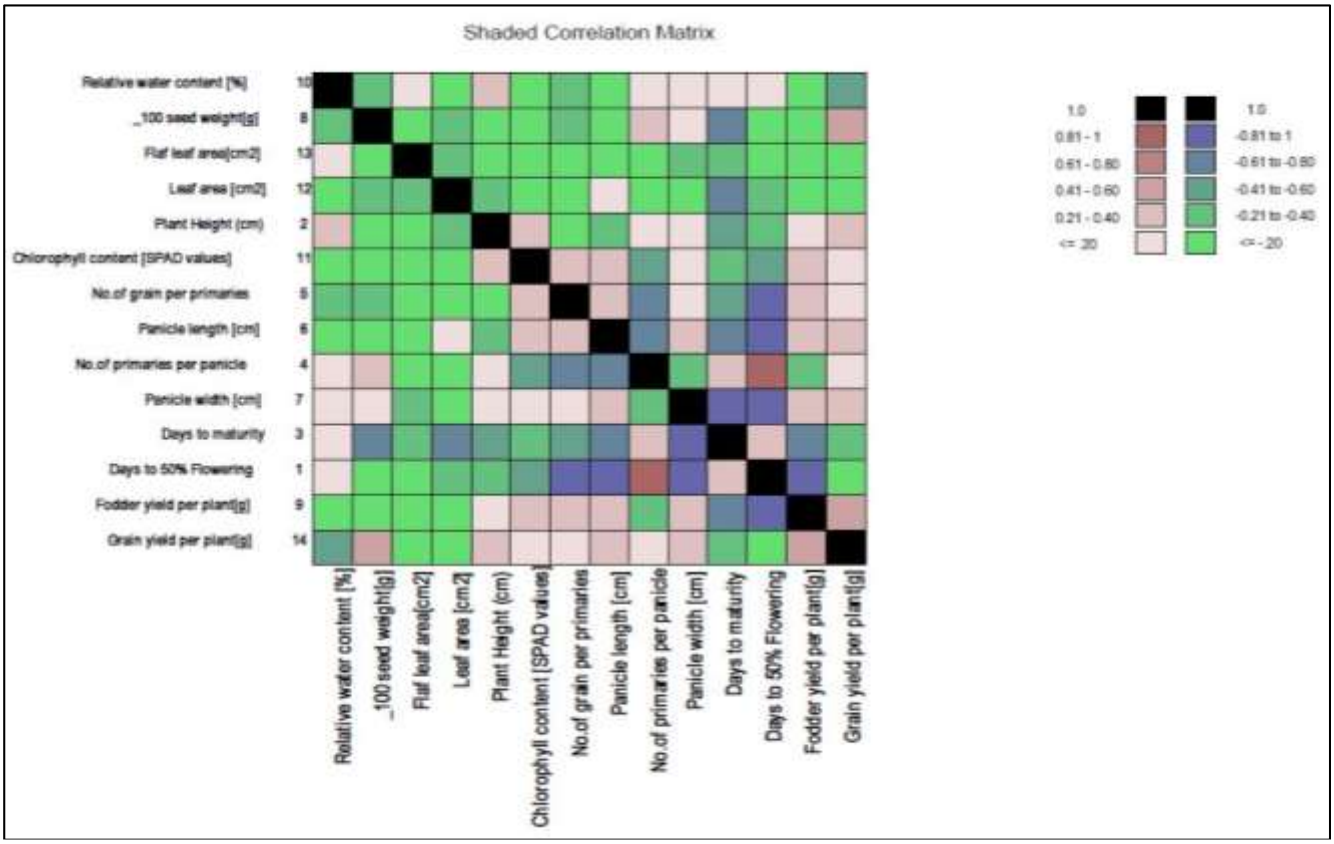

Fig 1: Genotypical shaded correlation matrix

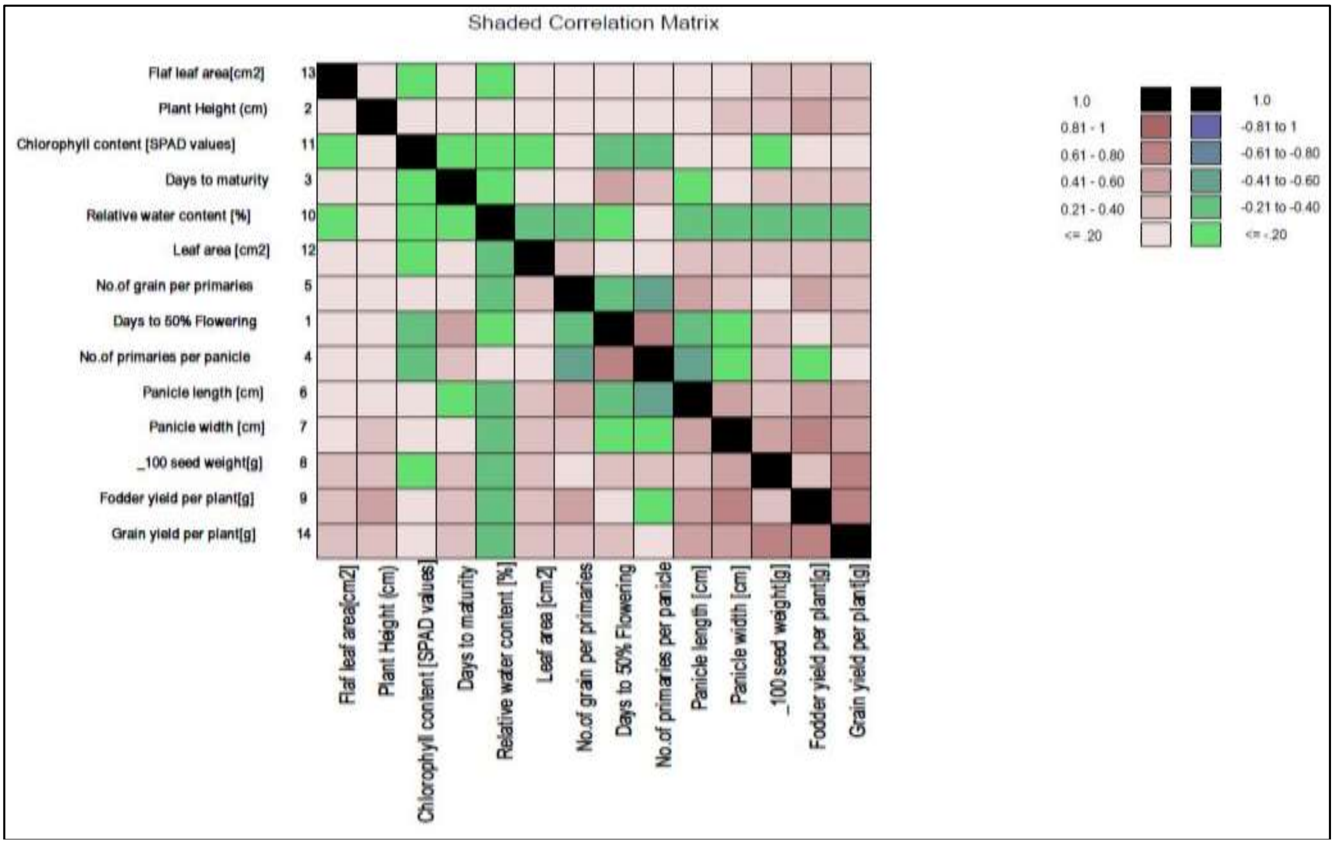

Fig 2: Phenotypical shaded correlation matrix

Table 3: Phenotypic correlation coefficient for fourteen characters studied in *rabi* sorghum.

Characters		Days to 50% Flowering	Plant height	Days to maturity	Primaries per panicle	Grains per primary	Panicle length	Panicle width	100 seed weight	Fodder yield per plant	RWC	SPAD	leaf area	Flag Leaf area	Grain Yield per plant
Days to 50% flowering	G	-0.4107	0.0862	-0.1094	-0.3908	0.3667	0.3929	0.3747	0.0227	0.3302	-0.0030	0.2129	0.1204	0.0708	-0.1047
	P	-0.0358	-0.0069	-0.0181	-0.0259	0.0087	0.0100	0.0046	-0.0099	-0.0010	0.0039	0.0113	-0.0033	-0.0069	0.2177
Plant height (cm)	G	-0.0307	0.1462	-0.0806	0.0217	-0.0240	-0.0375	0.0121	-0.0188	0.0243	0.0338	0.0370	-0.0449	-0.0180	0.2267
	P	0.0085	0.0443	0.0072	0.0075	0.0065	0.0049	0.0148	0.0087	0.0192	0.0006	0.0073	0.0032	0.0060	0.3733
Days to maturity	G	0.0011	-0.0023	0.0042	0.0011	-0.0023	-0.0034	-0.0038	-0.0027	-0.0026	0.0008	-0.0013	-0.0029	-0.0011	-0.3339
	P	0.0053	0.0017	0.0105	0.0026	0.0010	-0.0005	0.0005	0.0021	0.0024	-0.0010	-0.0020	0.0004	0.0018	0.2264
Primaries per panicle (Nos.)	G	0.6650	0.1036	0.1844	0.6988	-0.4849	-0.5130	-0.2730	0.2180	-0.1980	0.0526	-0.2944	-0.0578	-0.0271	0.1327
	P	0.2437	0.0571	0.0823	0.3373	-0.1592	-0.1717	-0.0636	0.0973	-0.0357	0.0093	-0.1240	0.0053	0.0078	0.1820
Grains per primary (Nos.)	G	0.0799	0.0147	0.0495	0.0621	0.0895	-0.0354	-0.0110	0.0270	-0.0244	0.0208	-0.0216	0.0006	0.0077	0.0339
	P	-0.0154	0.0093	0.0057	-0.0299	0.0633	0.0276	0.0205	0.0092	0.0288	-0.0144	0.0093	0.0170	0.0077	0.2775
Panicle length (cm)	G	-0.3197	-0.0857	-0.2671	-0.2452	0.1322	0.3341	0.1052	-0.0218	0.0911	-0.0545	0.0791	0.0461	-0.0543	0.2277
	P	-0.0659	0.0263	-0.0123	-0.1202	0.1029	0.2361	0.1226	0.0828	0.1195	-0.0593	0.0370	0.0865	0.0338	0.4449
Panicle width (cm)	G	0.0409	-0.0037	0.0403	0.0175	-0.0055	-0.0141	0.0448	-0.0014	-0.0170	-0.0003	-0.0084	0.0068	0.0103	0.2869
	P	-0.0054	0.0142	0.0020	-0.0080	0.0137	0.0220	0.0424	0.0193	0.0255	-0.0084	0.0054	0.0109	0.0075	0.5223
100-seed weight (g)	G	-0.0053	-0.0124	-0.0623	0.0301	-0.0292	-0.0063	0.0030	0.0966	-0.0113	-0.0372	-0.0170	-0.0211	-0.0140	0.5309
	P	0.0772	0.0551	0.0568	0.0806	0.0407	0.0980	0.1274	0.2796	0.1093	-0.0761	-0.0434	0.0783	0.0697	0.6552
Fodder yield/ plant (g)	G	-0.2288	0.0473	-0.1736	-0.0806	0.0777	0.0776	0.1081	-0.0333	0.2845	-0.0511	0.0630	-0.0374	-0.0379	0.5722
	P	0.0112	0.1708	0.0914	-0.0417	0.1790	0.1994	0.2365	0.1540	0.3939	-0.0817	0.0507	0.1170	0.0987	0.6775
RWC	G	-0.0035	-0.1097	-0.0897	-0.0357	0.1102	0.0772	-0.0028	0.1823	0.0851	-0.4738	0.0129	0.0828	-0.0326	-0.4758
	P	0.0134	-0.0018	0.0120	-0.0034	0.0283	0.0312	0.0247	0.0338	0.0258	-0.1242	0.0002	0.0261	0.0103	-0.3405
SPAD	G	0.0444	-0.0217	0.0267	0.0361	-0.0207	-0.0203	-0.0160	0.0151	-0.0190	0.0023	-0.0857	0.0154	0.0171	0.0167
	P	-0.0139	0.0073	-0.0085	-0.0161	0.0065	0.0069	0.0056	-0.0068	0.0057	-0.0001	0.0439	-0.0051	-0.0057	0.0020
Leaf area (cm^2)	G	0.0589	0.0617	0.1380	0.0166	0.0015	-0.0277	0.0303	0.0439	0.0264	0.0351	0.0361	-0.2009	0.0506	-0.0876
	P	-0.0046	-0.0036	-0.0021	-0.0008	-0.0135	-0.0185	-0.0130	-0.0141	-0.0150	0.0106	0.0058	-0.0505	-0.0047	0.2855
Flag leaf area (cm^2)	G	0.0037	0.0027	0.0055	0.0008	0.0019	0.0035	0.0050	0.0031	0.0029	-0.0015	0.0043	0.0055	-0.0217	-0.0501
	P	-0.0006	-0.0004	-0.0006	-0.0001	-0.0004	-0.0005	-0.0006	-0.0008	-0.0008	0.0003	0.0004	-0.0003	-0.0033	0.2228

Residual effect (genotypic) = 0.561 Residual effect (phenotypic) = 0.552

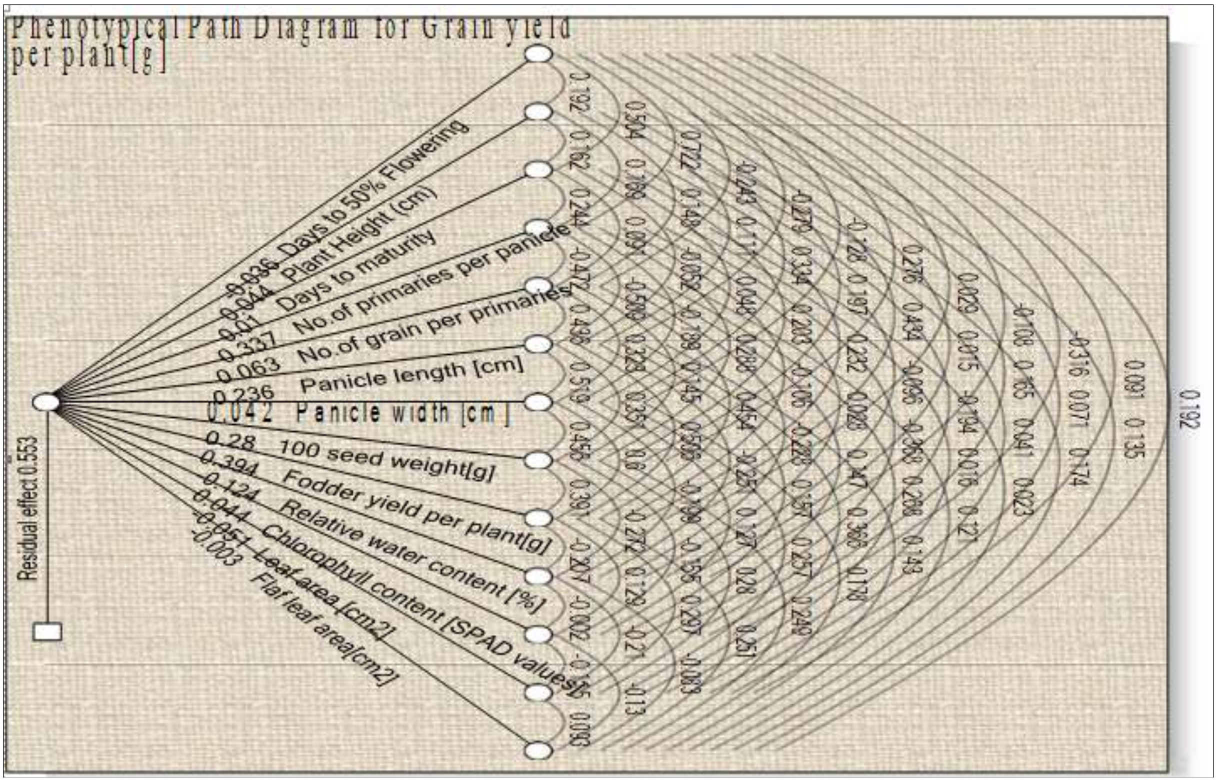

Fig 3: Phenotypical path Diagram

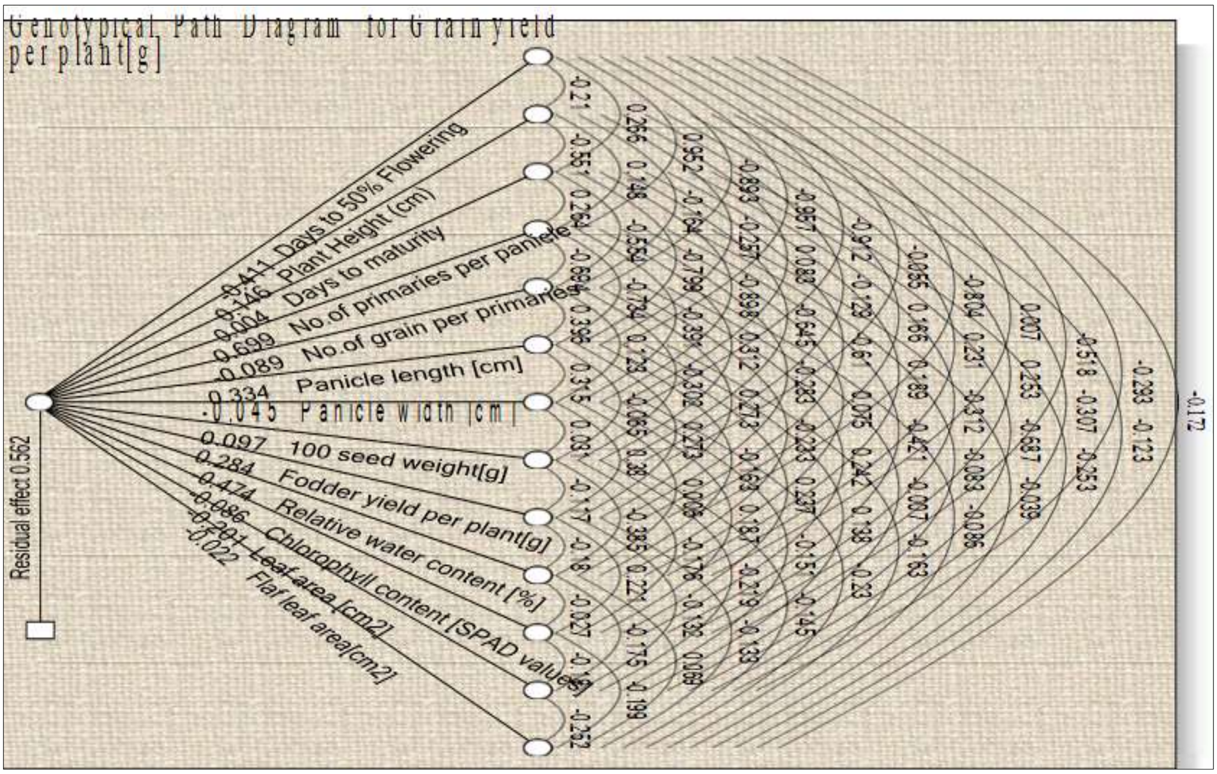

Fig 4: Genonotypical path Diagram

Path coefficient analysis

Path coefficient analysis Table 3. revealed that Most of the characters had shows positive and direct effects on grain yield per plant i.e. Plant height (G= 0.1462, P= 0.0443), Days to physiological maturity (G=0.0042, P=0.0105), no. of primarie per panicle (G=0.6988, P=0.3373), Panicle length (G=0.3341, P=0.2361), 100 Seed weight (G=0.0966, P=0.2796), Fodder yield per plant (G=0.2845, P=0.3939) at genotypic and phenotypic level. A Similar trend was also observed by earlier worker, Jeyaprakash *et al.* (1997) [12], Jain and Patel (2014) [11], Khandelwal *et al.* (2015) [16], Zinzala *et al.* (2018) [29], Shivprasad *et al.* (2019) [24], Prasad and Sridhar (2019) [23] and Patil *et al.* Chavhan *et al.* (2022) [21], Patil *et al.* (2023) [20], Except days to 50 percent flowering (G=-0.4107, P=-0.0358), no. of grain per primarie (G=-0.0895, P=0.0633), leaf area (G=-0.2009, P=-0.0505), flag leaf area (G=-0.0217, P=-0.0033) shows negative direct effect on grain yield per plant. Similar results were reported by Iyaner *et al.* (2001) [10], Veerabadhiran and Kennedy (2001) [26], Ali *et al.* (2011) [3], Khandelwal *et al.* (2015) [16], Prasad and Sridhar (2019) [23], Karpe *et al.* (2023) [14] also observed similar results. The results of path analysis indicated that days to 50% flowering and 100 seed weight showed highest positive direct effects along with positive significant correlation with grain yield at both genotypic and phenotypic level in the present material under study. Thus, the present study indicated that the days to 50% flowering, plant height and 100-seed weight are important characters in deciding the grain yield per plant in the present material under study. Hence these characters may be considered as suitable selection indices in sorghum breeding programmes in the present investigation. Residual effect was negligible at genotypic (0.56) and phenotypic (0.52) level. Hence most of the yield and yield contributing character included in the study.

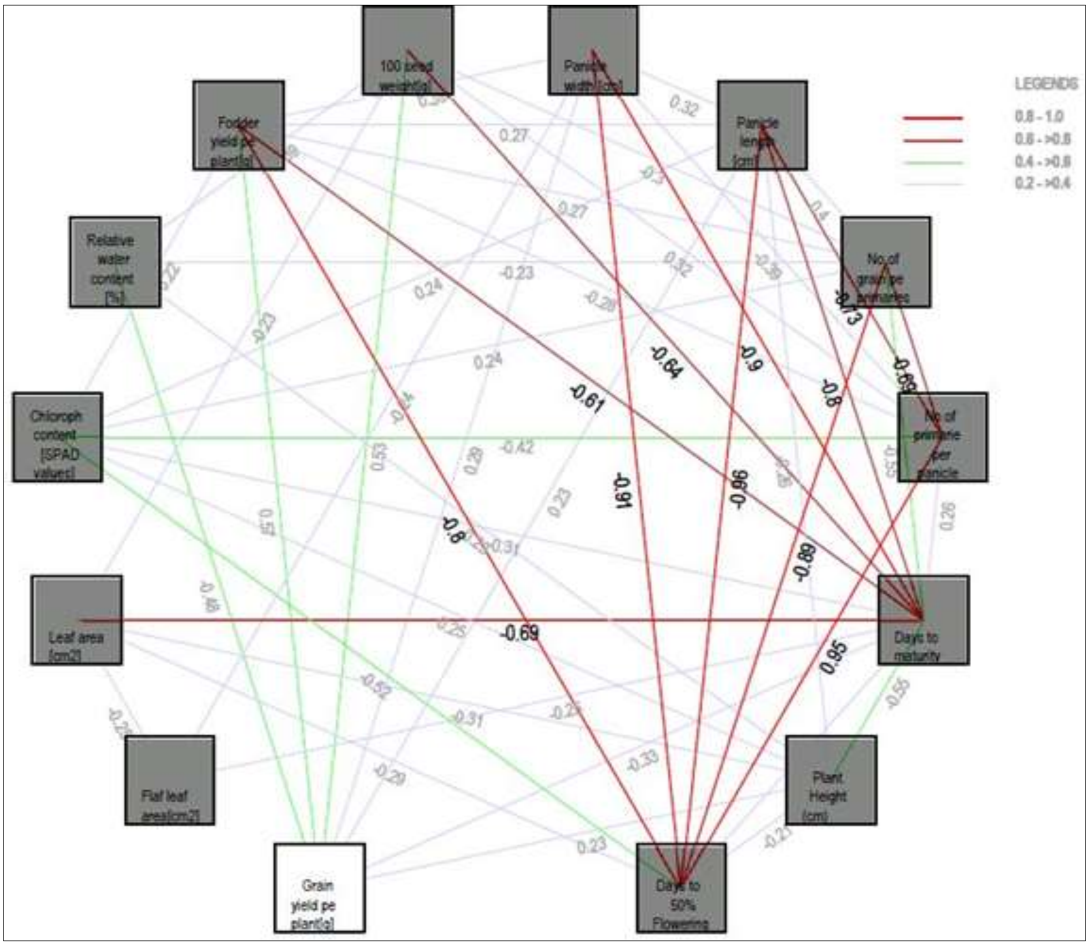

Fig 5: Genotypical correlation

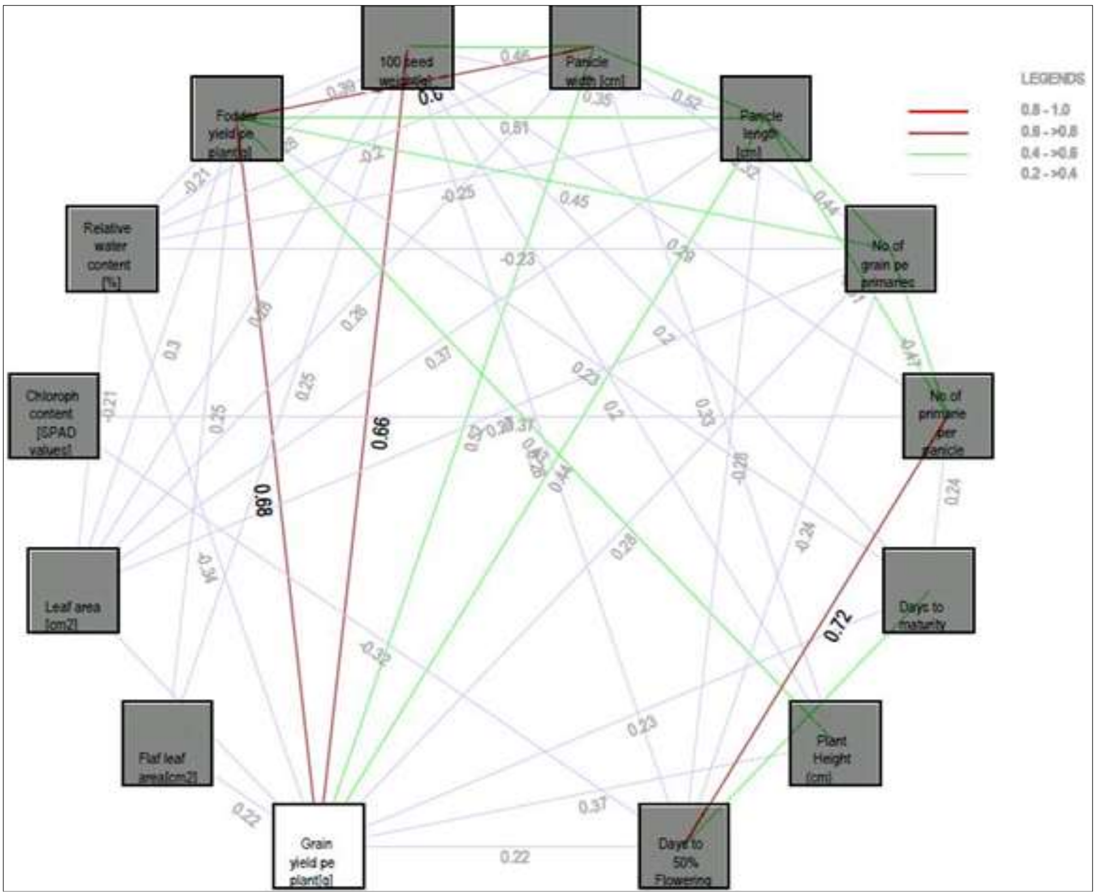

Fig 6: Phenotypical correlation

Conclusion

The present study highlights the significant role of specific phenotypic traits in influencing grain yield in sorghum. The analysis revealed that phenotypic correlation coefficients were consistently higher than genotypic coefficients across all character pairs, suggesting that environmental factors have a minimal impact on trait expression. Notably, traits such as panicle length, panicle width, number of primaries per panicle, fodder yield per plant, and 100-seed weight emerged as critical for indirect selection to enhance grain yield.

Additionally, the positive and significant correlations observed between grain yield per plant and traits like plant height, panicle length, panicle width, 100-seed weight, and fodder yield further underline the importance of these traits in breeding strategies. The moderate residual effect indicates that while these traits are vital, there may still be environmental components influencing grain yield, warranting careful consideration in future breeding plans.

Path coefficient analysis further confirmed that plant height, number of primaries per panicle, number of grains per primary, panicle length, panicle width, 100-seed weight, fodder yield, and chlorophyll content have direct positive effects on grain yield per plant at both genotypic and phenotypic levels. Therefore, breeding programs should prioritize these traits to optimize grain yield in sorghum effectively, balancing both genetic potential and environmental considerations.

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