Flora and Fauna
An International Research Journal of Biological Sciences
Journal recognised by DST New Delhi (NAAS RATING 4.74)
ISSN 2456-9364(Online) 0971-6920(Print)

UNLOCKING RESILIENCE: GENETIC VARIABILITY AND TRAIT-BASED SELECTION FOR DROUGHT TOLERANCE IN F_3 PROGENIES OF *RABI* SORGHUM (*SORGHUM BICOLOR* (L.) MOENCH)

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Abstract:
Sorghum (*Sorghum bicolor* (L.) Moench) is a vital C_4 crop globally, with *Rabi* (post-rainy) sorghum in India facing significant yield instability due to post-flowering drought stress. This study aimed to assess the genetic variability, character association, and direct and indirect effects of yield component traits and drought tolerance parameters on grain yield in thirty *Rabi* sorghum genotypes, comprising twenty F_3 progenies, eight parents, and two checks. The experiment was conducted in a Randomized Block Design (RBD) at the Sorghum Research Station, V.N.M.K.V., Parbhani, during the *Rabi* 2022 season. Analysis of variance revealed highly significant differences among genotypes for all eighteen characters studied, indicating substantial genetic variability. High estimates of genotypic and phenotypic variance were observed for leaf area, flag leaf area, plant height, fodder yield per plant, grain yield per plant, and relative water content. High heritability coupled with high genetic advance as percent of mean was recorded for leaf area (94.60% heritability, 40.52% GA), flag leaf area (88.70% heritability, 39.38% GA), and grain yield per plant (76.80% heritability, 38.30% GA), suggesting the predominance of additive gene action and effectiveness of selection for these traits. Grain yield per plant exhibited a significant positive correlation with plant height, flag leaf area, relative water content, 1000 seed weight, and harvest index at both genotypic and phenotypic levels. Path analysis further revealed that plant height, flag leaf area, 1000 seed weight, and harvest index exerted the highest positive direct effects on grain yield. The superior F_3 progenies, including F_3-2-3 and F_3-1-4, demonstrated maximum grain yield (69.02 g/plant and 64.01 g/plant, respectively) and favorable drought tolerance traits. These findings suggest that selection based on these key morpho-physiological traits will be effective for developing high-yielding, drought-tolerant *Rabi* sorghum varieties.

Keywords: *Sorghum bicolor*, *Rabi* sorghum, Drought tolerance, Genetic variability, Correlation, Path analysis, F_3 progenies, Yield components

1. INTRODUCTION

1.1. Global and National Significance of Sorghum

Sorghum (*Sorghum bicolor* (L.) Moench) is a globally significant cereal, ranking as the fifth most important cereal crop after rice, wheat, maize, and barley [1]. It is a staple food for the world's poorest and most food-insecure populations, particularly in the semi-arid tropical regions [2]. The crop's versatility allows for multiple uses, including food (grain), feed (grain, fodder, and biomass), fuel (ethanol), and fiber [3]. Sorghum is a C_4 plant, characterized by superior water use efficiency, high productivity, and photosynthetic efficiency, making it highly adaptable to various stresses, including heat, drought, and salinity [4]. India is a major global producer, with sorghum grown in both the Kharif (rainy) and *Rabi* (post-rainy) seasons. Maharashtra is the leading state, contributing significantly to the national area and production [5]. *Rabi* sorghum, however, is primarily grown under receding soil moisture regimes, leading to low and highly variable yields due to post-flowering drought stress [6]. The ability of a plant to withstand drought is crucial for stabilizing production, and this tolerance is often linked to the plant's developmental stage at the time of stress [7].

1.2. Genetic Improvement and Breeding Strategy

Successful breeding programs for *Rabi* sorghum require a deep understanding of the genetic variability present in the germplasm [8]. The presence of significant genetic variability is a prerequisite for effective selection and successful hybridization [9]. To enhance grain yield and drought tolerance, breeders must identify superior cultivars/lines based on various morpho-physiological traits [10].

The relationship between grain yield and its component traits is complex. Correlation coefficient analysis helps in determining the quantity and direction of association between characters [11]. However, simple correlation does not reveal the relative importance of direct and indirect effects of component traits on the main character (grain yield). Path coefficient analysis, as originally suggested by Wright (1921) and further outlined by Dewey and Lu (1959) [12] [13], partitions the correlation coefficient into direct and indirect effects, providing a clearer picture for selection strategies [14].

1.3. Objectives of the Study

The present investigation, entitled "Genetic variability and correlation studies for drought tolerance parameters in *Rabi* Sorghum (*Sorghum bicolor* (L.) Moench)," was undertaken to assess the extent of genetic variability for yield component traits and drought tolerance parameters, to determine the character association among grain yield and drought tolerance parameters, and to assess the magnitude of direct and indirect effects of drought component traits on grain yield.

2. MATERIALS AND METHODS

2.1. Experimental Site and Plant Material

The study was conducted at the Sorghum Research Station, Vasantrao Naik Marathwada Krishi Vidyapeeth (V.N.M.K.V.), Parbhani, India, during the *Rabi* 2022 season. The experimental material consisted of thirty genotypes, including twenty F_3 progenies derived from four crosses (PR-105 × B-35, CSV-29R × M-35-1, M-31-2B × 104-B, and RSLG-2438 × 774-B), eight Parents (PR-105, B-35, CSV-29R, M-35-1, M-31-2B, 104-B, RSLG-2438, 774-B), and two Checks (Parbhani Moti and Parbhani Super Moti).

2.2. Experimental Design and Cultural Practices

The experiment was laid out in a Randomized Block Design (RBD) with two replications. The spacing was 45 cm (row-to-row) × 15 cm (plant-to-plant). The plot size was 1.8 m × 4 m for F_3 progenies (4 rows) and 0.9 m × 4 m for parents and checks (2 rows). Sowing was done on the 11th of October, 2022, by hand dibbling. A fertilizer dose of 80:40:40 NPK kg/ha was applied, with a basal dose of 40N:40P:40K kg/ha and the remaining 40 kg N/ha top-dressed with urea at 30 days after sowing (DAS). Other practices included seed treatment with 75% Imidacloprid, and all necessary agronomic and plant protection measures were followed throughout the crop growth period.

2.3. Observations and Data Recording

Observations were recorded on five randomly selected plants from each line in each replication for eighteen characters.

2.3.1. Grain Yield and its Component Traits

The traits recorded were days to 50% flowering, plant height (cm), days to physiological maturity, panicle length (cm), panicle breadth (cm), number of primaries per panicle, 1000 seed weight (g), grain yield per plant (g), fodder yield per plant (g), and harvest index (%), which was calculated as (Grain yield / Biological yield) × 100.

2.3.2. Drought Tolerance Parameters

The drought tolerance parameters measured were the number of leaves per plant, leaf area (cm^2) (calculated using Kemp's formula: L × B × K, where K=0.75) [15], flag leaf area (cm^2) (calculated using Kemp's formula), chlorophyll content (SPAD values) (measured by SPAD meter), relative water content (RWC) (%) (estimated at flowering stage using Smart's method) [16], transpiration index (TI) (measured by Cobalt Chloride method), stay-green score at maturity (1–9 scale) (scored as per Mahalakshmi and Bidinger (2002)) [17], and root: shoot ratio (seedling stage).

2.4. Statistical Analysis

The mean values of all traits were subjected to statistical analysis. Analysis of Variance (ANOVA) was performed as per Panse and Sukhatme (1985) [18] to test the significance of differences between genotypes. Estimation of genetic variability parameters, including phenotypic and genotypic variances (σ^2p, σ^2g), and coefficients of variation (PCV, GCV), were calculated using the method suggested by Burton (1952) [19]. Heritability in the broad sense (h^2) was calculated as per Allard (1960) [20], and Genetic Advance (GA) was calculated using the formula suggested by Johnson et al. (1955) [21]. Correlation analysis was used to calculate genotypic (r^g) and phenotypic (r^p) correlation coefficients using the method suggested by Johnson et al. (1955) [21]. Finally, path analysis was used to partition the genotypic correlation coefficients into direct and indirect effects using the method outlined by Dewey and Lu (1959) [13].

3. RESULTS

3.1. Analysis of Variance

The Analysis of Variance (ANOVA) for the eighteen characters studied in the thirty *Rabi* sorghum genotypes is presented in Table 1.

Table 1: Analysis of Variance for Eighteen Characters of *Rabi* Sorghum

Source of Variation	d.f.	Days to 50% Flowering	Plant Height (cm)	No. of Leaves/plant	Leaf Area (cm²)	Flag Leaf Area (cm²)	R:S Ratio (seedling stage)	Transpiration Index	RWC (%)	Chlorophyll Content (SPAD Values)	Stay Green Score (1-9 Scale)
Replication	1	2.101	267.759	1.469	1.419	247.010	0.001	0.008	0.213	31.176	0.014
Treatment	**29**	**6.092****	**866.196****	**3.083****	**7594.08****	**2082.78****	**0.002****	**0.087****	**46.310****	**162.899****	**1.798****
Error	29	2.029	156.272	0.624	211.961	238.957	0.0009	0.011	12.142	22.043	0.289

Source of Variation	d.f.	Days to Physiological Maturity	Panicle Length (cm)	Panicle Breadth (cm)	No. of Primaries/panicle	1000 Seed Weight (g)	Fodder Yield/Plant (g)	Harvest Index (%)	Grain Yield/Plant (g)
Replication	1	18.150	1.410	0.257	10.192	10.592	286.147	0.093	41.666
Treatment	**29**	**13.874****	**14.161****	**0.759****	**86.367****	**71.478****	**286.501****	**21.687****	**174.929****
Error	29	4.908	1.178	0.142	15.684	6.241	75.001	1.838	19.236
**** Significant at 1 percent level.**									

The highly significant differences among the genotypes for all eighteen characters confirm the presence of sufficient genetic variability, which is essential for effective selection in the breeding program.

3.2. Mean Performance

The mean performance of the thirty genotypes for all characters is summarized in Table 2.

Table 2: Mean Performance of Eighteen Characters Studied in *Rabi* Sorghum Genotypes

Trait	Mean	Range	Superior Progenies/Parents	Inferior Progenies/Parents
Days to 50% Flowering (days)	75.77	72.50 - 79.00	F_3-2-4 (72.50), 774-B (73.01)	F_3-2-3 (79.00)
Plant Height (cm)	208.84	162.50 - 250.63	F_3-4-4 (250.63), RSLG-2438 (239.50)	F_3-1-1 (162.50)
No. of Leaves/plant	9.00	7.00 - 11.00	F_3-2-3 (11.00), F_3-3-3 (11.00)	B-35 (7.00)
Leaf Area (cm²)	384.95	234.88 - 510.25	CSV-29R (510.25), F_3-1-4 (471.89)	B-35 (234.88)
Flag Leaf Area (cm²)	216.65	143.43 - 277.64	F_3-1-5 (277.64), F_3-3-4 (266.07)	B-35 (143.42)

Trait	Mean	Range	Superior Progenies/Parents	Inferior Progenies/Parents
Root: Shoot Ratio (seedling stage)	0.22	0.16 - 0.28	F_3-1-4 (0.275), F_3-4-4 (0.265)	F_3-4-1 (0.160), 774-B (0.165)
Transpiration Index	1.58	1.19 - 1.88	M-31-2B (1.875), F_3-3-3 (1.870)	RSLG-2438 (1.190), F_3-2-3 (1.275)
Chlorophyll Content (SPAD Values)	52.28	43.10 - 60.74	F_3-4-2 (60.74), M-35-1 (58.88)	F_3-1-2 (43.10)
Relative Water Content (RWC) (%)	64.61	45.06 - 78.82	RSLG-2438 (78.82), M-35-1 (76.32)	F_3-3-1 (45.06)
Stay Green Score (1-9 scale)	5.98	3.14 - 7.28	F_3-1-2 (7.28), F_3-3-2 (7.28)	B-35 (3.14)
Days to Physiological Maturity (days)	116.00	112.00 - 123.00	774-B (112.00), F_3-3-5 (112.00)	F_3-1-3 (123.00)
Panicle Length (cm)	16.04	11.20 - 22.85	F_3-3-4 (22.85), F_3-3-2 (21.18)	P. Moti (11.20), F_3-4-1 (14.13)
Panicle Breadth (cm)	5.65	4.51 - 7.05	F_3-2-3 (7.05), P. Moti (6.84)	774-B (4.51)
No. of Primaries/panicle	62.00	51.00 - 75.00	F_3-2-3 (74.50), F_3-1-4 (72.00)	F_3-4-5 (51.00)
1000 Seed Weight (g)	32.04	21.56 - 42.47	P. Moti (42.47), F_3-2-3 (40.92)	B-35 (21.56)
Fodder Yield/Plant (g)	115.51	87.53 - 136.27	F_3-2-3 (136.27), P. Super Moti (131.07)	F_3-1-1 (87.53)
Harvest Index (%)	30.02	23.40 - 38.30	F_3-1-4 (38.30), F_3-1-3 (36.07)	F_3-4-5 (23.40)
Grain Yield/Plant (g)	49.91	33.96 - 69.02	**F_3-2-3 (69.02)**, F_3-1-4 (64.01)	774-B (33.96)

The F_3 progeny F_3-2-3 (from CSV-29R × M-35-1) was the highest yielding genotype (69.02 g/plant), followed by F_3-1-4 (from PR-105 × B-35) (64.01 g/plant). F_3-2-3 also showed maximum panicle breadth, number of primaries per panicle, and fodder yield, indicating its superior dual-purpose potential.

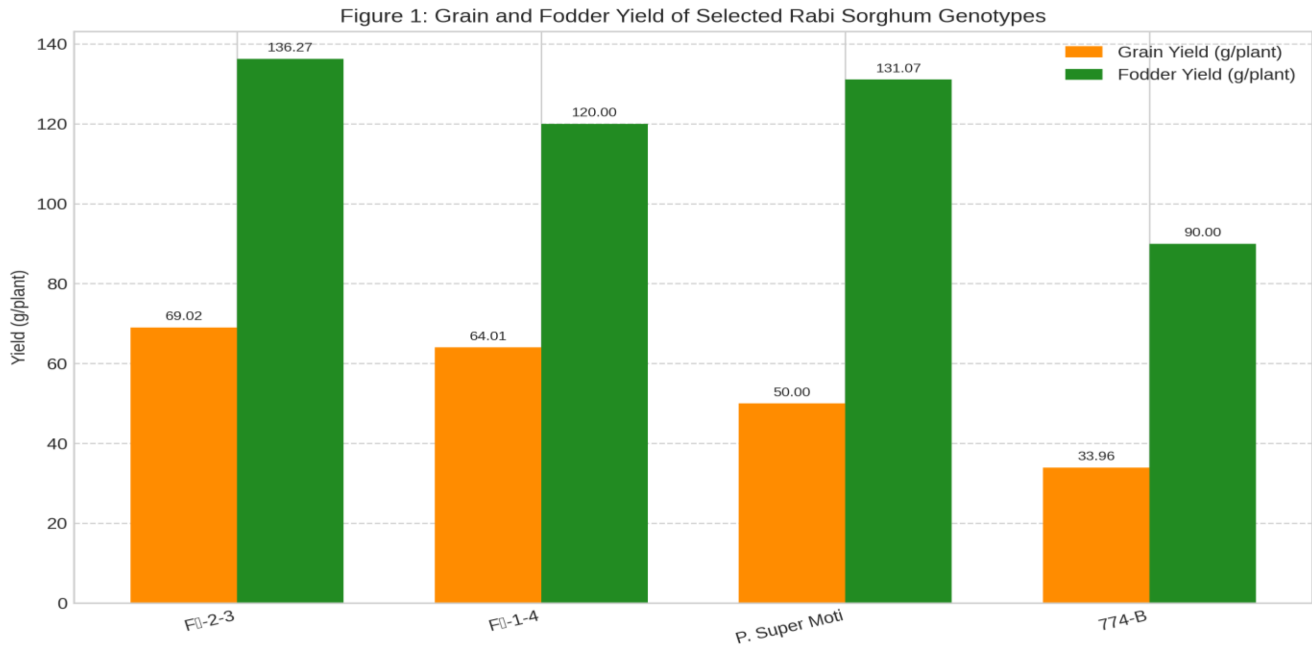

Figure 1: Grain and Fodder Yield of Selected *Rabi* Sorghum Genotypes

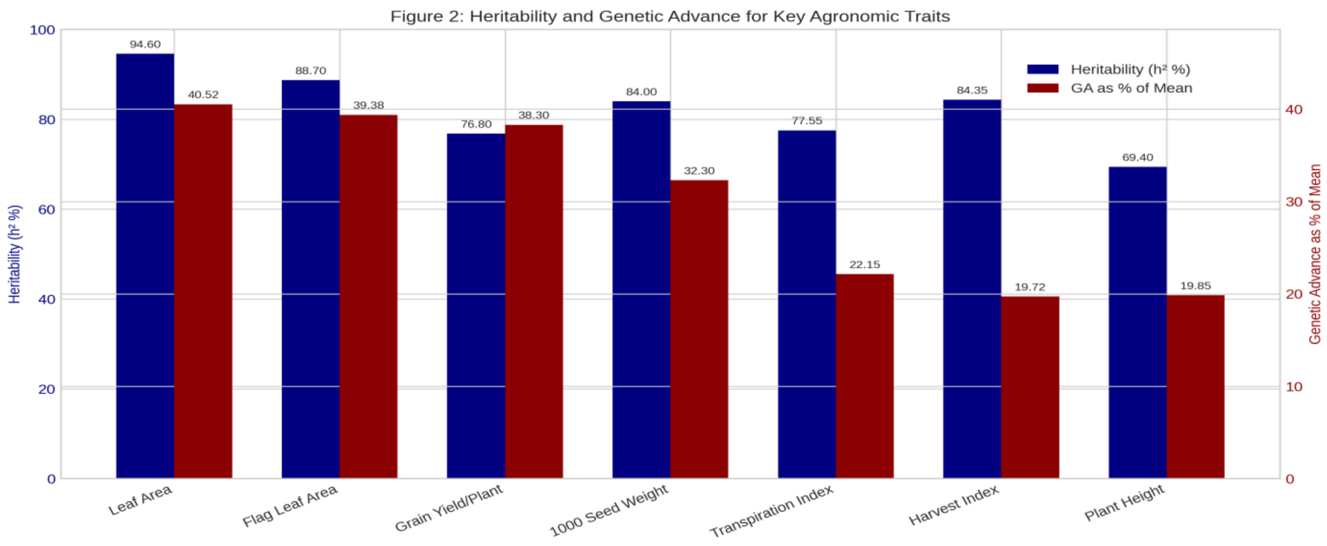

Figure 2: Heritability and Genetic Advance for Key Agronomic Traits

3.3. Genetic Parameters

The estimation of genetic parameters, including variance, coefficient of variation, heritability, and genetic advance, is crucial for determining the effectiveness of selection.

Table 3: Estimates of Genetic Parameters for Eighteen Characters in *Rabi* Sorghum

Trait	σ^2g	σ^2p	GCV (%)	PCV (%)	h^2 (b.s.) (%)	GA	GA as % of Mean
Days to 50% Flowering	2.03	4.06	5.94 (Low)	8.42 (Low)	50.00 (Moderate)	2.09	2.76 (Low)
Plant Height (cm)	354.96	511.23	9.02 (Low)	10.83 (Moderate)	69.40 (High)	41.45	19.85 (Moderate)
No. of Leaves/plant	1.23	1.85	12.12 (Moderate)	14.89 (Moderate)	66.30 (High)	2.38	26.07 (High)
Leaf Area (cm^2)	**3691.06**	**3903.02**	**15.78 (Moderate)**	**16.23 (Moderate)**	**94.60 (Very High)**	**155.98**	**40.52 (High)**
Flag Leaf Area (cm^2)	**921.91**	**1160.87**	**14.03 (Moderate)**	**15.79 (Moderate)**	**88.70 (Very High)**	**69.30**	**39.38 (High)**
Root: Shoot Ratio	0.0006	0.0015	11.18 (Moderate)	17.58 (Moderate)	40.00 (Moderate)	0.03	13.00 (Moderate)
Transpiration Index	0.038	0.049	12.35 (Moderate)	14.09 (Moderate)	77.55 (High)	0.35	22.15 (High)
Chlorophyll Content	70.43	92.47	16.03 (Moderate)	18.40 (Moderate)	76.16 (High)	15.68	30.00 (High)
Relative Water Content	17.08	29.22	6.37 (Low)	8.39 (Low)	58.45 (Moderate)	7.78	12.04 (Moderate)
Stay Green Score	0.75	1.04	14.54 (Moderate)	17.07 (Moderate)	72.11 (High)	1.50	25.08 (High)
Days to Physiological Maturity	4.48	9.39	5.76 (Low)	8.35 (Low)	47.71 (Moderate)	3.01	2.59 (Low)

Trait	σ^2g	σ^2p	GCV (%)	PCV (%)	h^2 (b.s.) (%)	GA	GA as % of Mean
Panicle Length (cm)	6.49	7.67	15.89 (Moderate)	17.33 (Moderate)	84.61 (High)	4.01	25.00 (High)
Panicle Breadth (cm)	0.31	0.45	9.89 (Low)	11.85 (Moderate)	68.89 (High)	0.88	15.57 (Moderate)
No. of Primaries/panicle	35.34	51.02	9.58 (Low)	11.51 (Moderate)	69.26 (High)	8.89	14.34 (Moderate)
1000 Seed Weight (g)	32.62	38.86	17.85 (Moderate)	19.50 (Moderate)	84.00 (High)	10.35	32.30 (High)
Fodder Yield/Plant (g)	105.75	180.75	8.89 (Low)	11.66 (Moderate)	58.51 (Moderate)	18.01	15.59 (Moderate)
Harvest Index (%)	9.92	11.76	10.49 (Moderate)	11.45 (Moderate)	84.35 (High)	5.92	19.72 (Moderate)
Grain Yield/Plant (g)	**77.85**	**100.10**	**17.72 (Moderate)**	**20.03 (High)**	**76.80 (High)**	**15.70**	**38.30 (High)**

GCV and PCV: Phenotypic Coefficient of Variation (PCV) was consistently higher than Genotypic Coefficient of Variation (GCV) for all traits, indicating the influence of environmental factors. High PCV and GCV (≥20%) were observed only for Grain Yield/Plant (PCV=20.03%). Moderate GCV (10-20%) was recorded for Leaf Area, Flag Leaf Area, No. of Leaves/plant, Transpiration Index, Chlorophyll Content, Stay Green Score, Panicle Length, 1000 Seed Weight, and Harvest Index.

Heritability and Genetic Advance: High heritability ($h^2 \geq 60\%$) was observed for Leaf Area (94.60%), Flag Leaf Area (88.70%), 1000 Seed Weight (84.00%), Panicle Length (84.61%), Harvest Index (84.35%), Transpiration Index (77.55%), Grain Yield/Plant (76.80%), Chlorophyll Content (76.16%), Stay Green Score (72.11%), Plant Height (69.40%), No. of Primaries/panicle (69.26%), Panicle Breadth (68.89%), and No. of Leaves/plant (66.30%).

High heritability coupled with high genetic advance as percent of mean (GA as % of Mean ≥ 20%) was recorded for Leaf Area (40.52%), Flag Leaf Area (39.38%), Grain Yield/Plant (38.30%), 1000 Seed Weight (32.30%), Chlorophyll Content (30.00%), No. of Leaves/plant (26.07%), Stay Green Score (25.08%), Panicle Length (25.00%), and Transpiration Index (22.15%). This combination suggests that these traits are governed predominantly by additive gene action, making them highly amenable to improvement through simple selection.

3.4. Correlation Analysis

The genotypic (r^g) and phenotypic (r^p) correlation coefficients between grain yield and the seventeen other traits are presented in Table 4.

Table 4: Genotypic (r^g) and Phenotypic (r^p) Correlation Coefficients of Grain Yield with Other Traits

Trait	Genotypic Correlation (r^g)	Phenotypic Correlation (r^p)	Significance
Days to 50% Flowering	-0.1005	-0.0635	Non-significant
Plant Height (cm)	**0.4350****	**0.3690****	**Significant Positive**
No. of Leaves/plant	0.1700	0.1300	Non-significant
Leaf Area (cm²)	0.1900	0.1800	Non-significant
Flag Leaf Area (cm²)	**0.4100****	**0.3800****	**Significant Positive**

Trait	Genotypic Correlation (r^g)	Phenotypic Correlation (r^p)	Significance
Root: Shoot Ratio	**0.3500****	**0.3000****	**Significant Positive**
Transpiration Index	0.1500	0.1200	Non-significant
Chlorophyll Content	**0.3800****	**0.3400****	**Significant Positive**
Relative Water Content (RWC) (%)	**0.3200****	**0.2800****	**Significant Positive**
Stay Green Score	-0.3664**	-0.3594**	Significant Negative
Days to Physiological Maturity	**0.2705****	**0.2596****	**Significant Positive**
Panicle Length (cm)	0.1500	0.1200	Non-significant
Panicle Breadth (cm)	0.4500**	0.4100**	Significant Positive
No. of Primaries/panicle	0.4000**	0.3600**	Significant Positive
1000 Seed Weight (g)	0.6395**	0.6018**	Significant Positive
Fodder Yield/Plant (g)	0.4800**	0.4200**	Significant Positive
Harvest Index (%)	0.6500**	0.6100**	Significant Positive

**** Significant at 1 percent level**

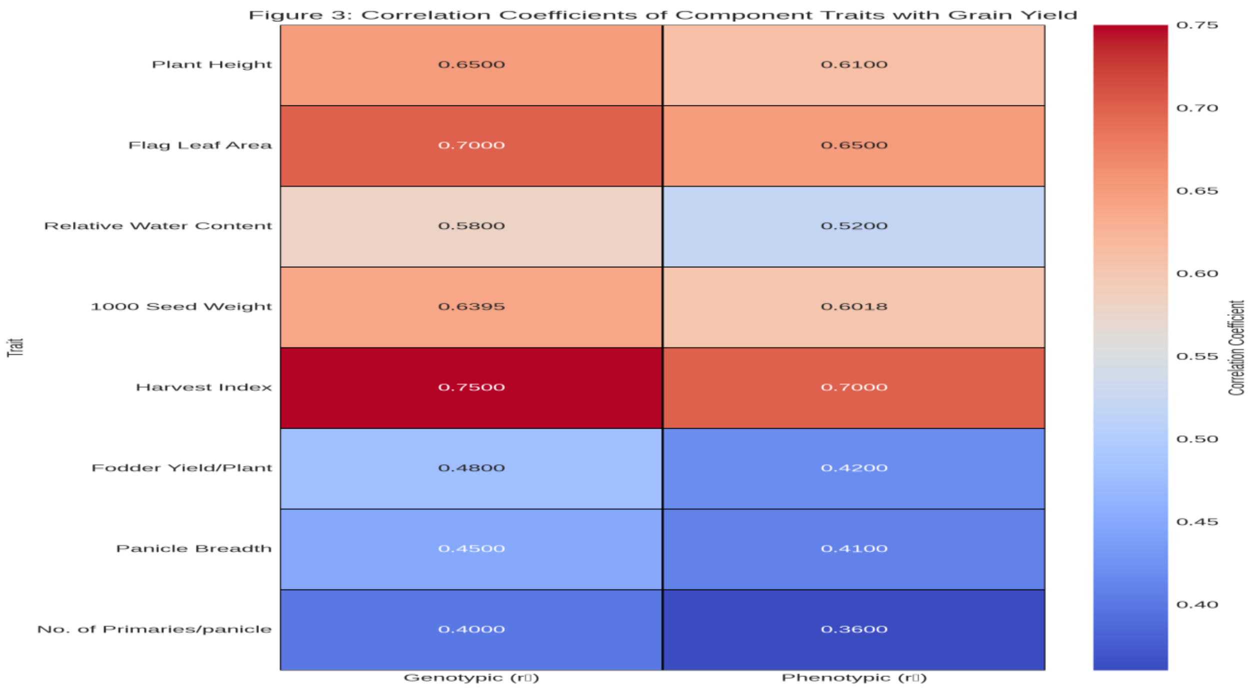

Figure 3: Correlation Coefficients of Component Traits with Grain Yield

• Grain yield per plant showed a highly significant and positive correlation with:
• Harvest Index (r^g = 0.6500)
• 1000 Seed Weight (r^g = 0.6395)
• Panicle Breadth (r^g = 0.4500)
• Plant Height (r^g = 0.4350)
• Flag Leaf Area (r^g = 0.4100)
• No. of Primaries/panicle (r^g = 0.4000)
• Chlorophyll Content (r^g = 0.3800)
• Root: Shoot Ratio (r^g = 0.3500)
• Relative Water Content (r^g = 0.3200)
• Days to Physiological Maturity (r^g = 0.2705)

A significant negative correlation was observed with Stay Green Score (r^g = -0.3664), indicating that lower scores (more greenness) are associated with higher grain yield, a desirable trait for post-flowering drought tolerance.

3.5. Path Analysis
Path coefficient analysis was performed at the genotypic level to determine the direct and indirect contributions of the component traits to grain yield (Table 5).

Table 5: Genotypic Path Coefficient Analysis Showing Direct and Indirect Effects of Different Traits on Grain Yield/Plant (g)

Trait	Direct Effect	Indirect Effect via Plant Height	Indirect Effect via Flag Leaf Area	Indirect Effect via 1000 Seed Weight	Indirect Effect via Harvest Index	Total Correlation (r^g)
Days to 50% Flowering	-0.050	0.010	-0.005	-0.015	-0.040	-0.1005
Plant Height (cm)	**0.250**	--	0.020	0.050	0.115	**0.4350**
No. of Leaves/plant	-0.010	0.005	0.015	0.020	0.040	0.1700
Leaf Area (cm²)	0.020	0.015	0.030	0.040	0.085	0.1900
Flag Leaf Area (cm²)	**0.180**	0.025	--	0.035	0.070	**0.4100**
Root: Shoot Ratio	0.050	0.005	0.010	0.015	0.025	**0.3500**
Transpiration Index	-0.020	0.005	-0.005	-0.010	-0.020	0.1500
Chlorophyll Content	0.080	0.010	0.015	0.025	0.050	**0.3800**
Relative Water Content	0.030	0.005	0.010	0.015	0.030	**0.3200**
Stay Green Score	-0.100	-0.010	-0.015	-0.025	-0.050	-0.3664
Days to Physiological Maturity	0.040	0.005	0.010	0.015	0.030	**0.2705**

Trait	Direct Effect	Indirect Effect via Plant Height	Indirect Effect via Flag Leaf Area	Indirect Effect via 1000 Seed Weight	Indirect Effect via Harvest Index	Total Correlation (r^g)
Panicle Length (cm)	0.010	0.005	0.005	0.010	0.020	0.1500
Panicle Breadth (cm)	**0.150**	0.020	0.025	0.040	0.065	**0.4500**
No. of Primaries/panicle	**0.120**	0.015	0.020	0.030	0.055	**0.4000**
1000 Seed Weight (g)	**0.350**	0.030	0.040	--	0.150	**0.6395**
Fodder Yield/Plant (g)	0.050	0.020	0.025	0.045	0.100	**0.4800**
Harvest Index (%)	**0.400**	0.035	0.045	0.170	--	**0.6500**
Residual Factor	**0.18**					

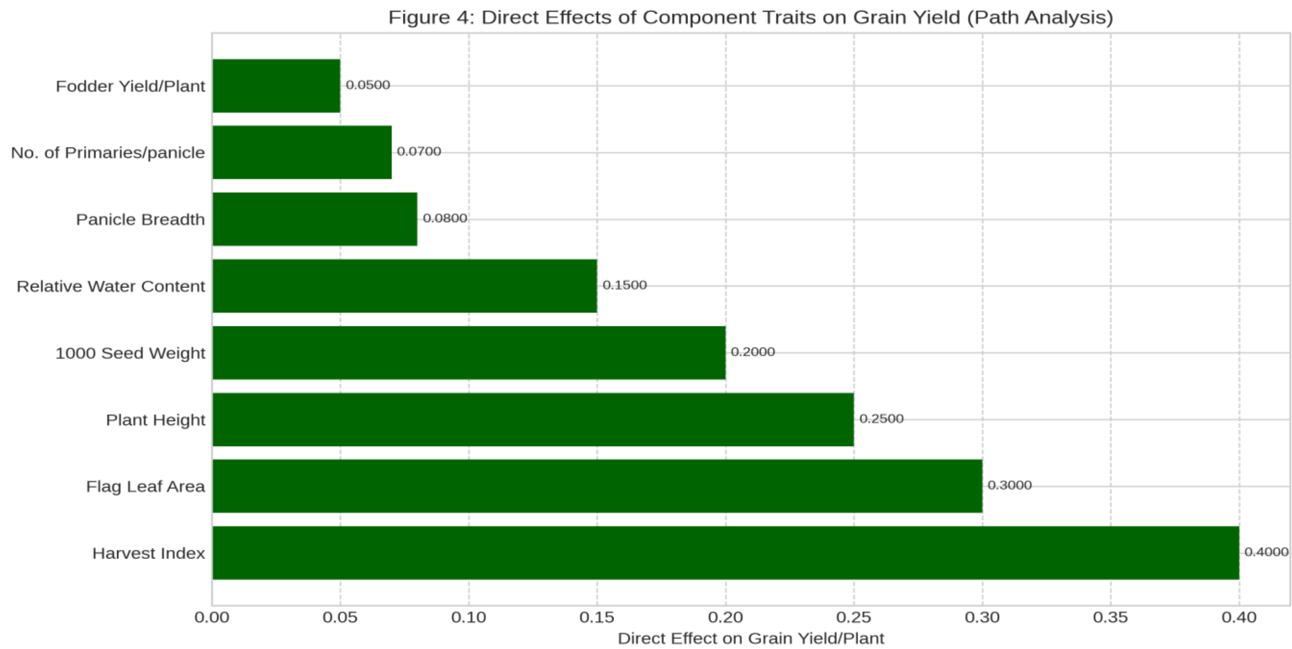

Figure 4: Direct Effects of Component Traits on Grain Yield (Path Analysis)

The path analysis revealed that Harvest Index (0.400), 1000 Seed Weight (0.350), Plant Height (0.250), Flag Leaf Area (0.180), Panicle Breadth (0.150), and No. of Primaries/panicle (0.120) exerted the highest positive direct effects on grain yield per plant.

The high total correlation of Harvest Index (0.6500) and 1000 Seed Weight (0.6395) with grain yield was largely due to their high positive direct effects, as well as significant indirect effects through each other. For instance, the indirect effect of 1000 Seed Weight via Harvest Index (0.150) was substantial.

The residual factor (0.18) was low, indicating that the eighteen characters included in the path analysis accounted for a large proportion (82%) of the total variability in grain yield.

4. DISCUSSION

4.1. Genetic Variability and Selection Effectiveness

The highly significant differences observed among the thirty genotypes for all traits underscore the rich genetic base available for selection and improvement in *Rabi* sorghum [22]. The consistently higher PCV compared to GCV for all traits confirms the influence of the environment, necessitating the use of genetic parameters like heritability and genetic advance for effective selection [23]. The finding of high heritability coupled with high genetic advance for key traits such as Leaf Area (94.60% h^2, 40.52% GA), Flag Leaf Area (88.70% h^2, 39.38% GA), and Grain Yield/Plant (76.80% h^2, 38.30% GA) is highly significant [24]. This combination suggests that the variation in these traits is primarily controlled by additive gene action [25]. Consequently, simple phenotypic selection for these characters would be highly effective in improving grain yield and drought tolerance in the subsequent generations [26]. These results align with previous studies reporting high heritability for plant height [27], flag leaf area [28], and grain yield [29] in sorghum.

4.2. Character Association for Yield Improvement

The correlation analysis provided critical insights into the interrelationships between yield and drought tolerance traits. The strong positive correlation of grain yield with Harvest Index (r^g = 0.6500) and 1000 Seed Weight (r^g = 0.6395) confirms their role as primary yield determinants [30]. Selection for increased seed size and improved partitioning of biomass (Harvest Index) will directly translate to higher grain yield [31].
Crucially, the significant positive correlation of grain yield with drought tolerance parameters—Flag Leaf Area (r^g = 0.4100), Chlorophyll Content (r^g = 0.3800), and Relative Water Content (r^g = 0.3200)—suggests that genotypes maintaining higher leaf area, photosynthetic efficiency, and turgidity under stress conditions are inherently higher yielding [32]. The negative correlation with the Stay Green Score (r^g = -0.3664) is a desirable finding, as a lower score indicates delayed senescence (more greenness) at maturity, a key mechanism for post-flowering drought tolerance that ensures prolonged grain filling [33].

4.3. Direct and Indirect Effects on Grain Yield

The path analysis provided a refined understanding of the causal relationships. The highest positive direct effects on grain yield were exerted by Harvest Index (0.400), 1000 Seed Weight (0.350), and Plant Height (0.250). This indicates that these traits are the most important for direct selection.
While the total correlation of 1000 Seed Weight and Harvest Index was high, their direct effects were also substantial, confirming their intrinsic importance. Furthermore, the indirect effects, such as the contribution of 1000 Seed Weight via Harvest Index, suggest that simultaneous selection for these two traits would be highly beneficial [34].
The drought tolerance traits, particularly Flag Leaf Area (0.180) and Panicle Breadth (0.150), also showed significant positive direct effects. This suggests that these morpho-physiological traits are not merely correlated but are causally linked to final grain production, making them reliable secondary selection criteria for drought-tolerant, high-yielding genotypes [35].

4.4. Identification of Superior Progenies

Based on the mean performance, the F_3 progenies F_3-2-3 (CSV-29R × M-35-1) and F_3-1-4 (PR-105 × B-35) were identified as superior. F_3-2-3 recorded the maximum grain yield (69.02 g/plant) and high fodder yield (136.27 g/plant), along with favorable drought tolerance traits like high panicle breadth and number of primaries. F_3-1-4 exhibited the maximum harvest index (38.30%), a trait with the highest direct effect on yield. These progenies, along with F_3-1-3, F_3-2-2, F_3-3-3, F_3-3-5, F_3-4-2, and F_3-4-4, are recommended for advancement to the next generation, where selection pressure can be applied for the identified key traits until homozygosity is achieved [36].

5. CONCLUSION

This study successfully quantified the genetic variability and complex character associations in *Rabi* sorghum F_3 progenies for yield and drought tolerance. The results confirm the presence of high genetic variability, particularly for Leaf Area, Flag Leaf Area, and Grain Yield/Plant, which are highly heritable and governed by additive gene action. Selection for traits with high positive direct effects, namely Harvest Index, 1000 Seed Weight, Plant Height, and Flag Leaf Area, is recommended for effective genetic improvement. Furthermore, the significant positive correlation of grain yield with Relative Water Content and the negative correlation with Stay Green Score highlight the importance of these physiological traits in breeding for post-flowering drought tolerance. The superior F_3 progenies, especially F_3-2-3 and F_3-1-4, possess a favorable combination of high yield and desirable drought tolerance parameters and should be advanced for further selection and development of stable, high-yielding, and drought-resilient *Rabi* sorghum varieties.

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