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Evaluation of Post-Rainy Season Sorghum Backcross Derivatives for Yield and Other Important Traits

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Abstract

In semi-arid areas, the yield of post-rainy (rabi) sorghum is significantly limited by the combined impact of terminal drought and key biotic stresses, such as stem borer, aphid, shoot bug and rust. This study assessed the success of conventional backcross breeding in enhancing yield and related traits by specifically introducing multi-stress tolerance into elite rabi sorghum varieties. Nineteen advanced backcross-derived lines (BC_2F_4), developed using six recurrent parents and seven trait-specific donor parents, were evaluated along with their respective parents during the Rabi 2024–25 at the Centre on Rabi Sorghum, ICAR–Indian Institute of Millets Research (ICAR-IIMR), Solapur, India, using a randomized complete block design with three replications. Analysis of variance revealed highly significant differences among genotypes for all agronomic and physiological traits, indicating substantial genetic variability generated through backcross breeding. Grain yield per plant ranged from 19.04 to 57.93 g with a population mean of 39.41 g, while panicle weight varied from 24.55 to 73.40 g. In the BC_2F_4 lines, several surpassed their recurrent parents, with the line BC_2F_4-4 {(BJV-44 × SLR-31) × BJV-44} achieving the highest grain yield of 57.93 g, representing an approximate 37.7% increase over its recurrent parent, which produced 42.07 g. Similarly, BC_2F_4-14 {(SPV-2217 × SLR-10) × SPV-2217} (52.01 g) and BC_2F_4-8 {(CSV-29R × SLR-10) × CSV-29R} (50.17 g) showed yield advantages of approximately 42.0% and 4.4%, respectively, over their corresponding recurrent parents. The harvest index ranged from 37.63% to 54.92%, with the superior lines exhibiting improved assimilate-partitioning efficiency. Physiological traits also showed significant variation, with relative water content ranging from 54.62% to 82.19% and SPAD values from 35.49 to 67.68. Lines such as BC_2F_4-18 {(Parbhani Jyoti × RNTT- 8-32) × Parbhani Jyoti} and BC_2F_4-19 {(BJV-44 × RNTN-13-37) × BJV-44} maintained a higher RWC (>77%) and stable chlorophyll content, indicating enhanced drought adaptive capacity. The superior performance of the selected BC_2F_4 lines, surpassing both recurrent and donor parents in terms of yield and physiological efficiency, indicates transgressive segregation and successful recombination of favorable alleles. Overall, this study demonstrated that conventional backcross breeding is an effective approach for improving the yield potential and stress resilience of rabi sorghum. The identified superior backcross-derived lines are promising candidates for near-isogenic line development and multilocation evaluation of varietal release.

***Key words*:** Rabi sorghum, Backcross breeding, Trait introgression, Grain yield, Physiological traits

Sorghum (*Sorghum bicolor* (L.) (Moench) is a crucial cereal crop worldwide, renowned for its ability to withstand climate fluctuations. It is cultivated on approximately 40-45 million hectares, producing 60-65 million metric tons each year, predominantly in semi-arid and arid regions. This crop plays a significant role in ensuring food, fodder, and livelihood security, particularly in South Asia and sub-Saharan Africa. In India, post-rainy (rabi) sorghum is grown using the moisture retained in the soil and is highly valued for its superior grain quality, storability, and use as fodder, making it an essential component of dryland farming systems [1]. Although it is crucial, the productivity of rabi sorghum remains both low and unpredictable due to the simultaneous presence of various abiotic and biotic stresses. Terminal drought during the reproductive phase significantly hampers grain filling by reducing assimilate distribution and hastening senescence. In addition, significant insect pests, such as the stem borer (*Chilo partellus*), aphid (*Melanaphis sacchari*) and shoot bug (*Peregrinus maidis*), along with diseases such as rust (Puccinia purpurea), cause considerable yield reductions. The simultaneous occurrence of these stresses creates a complex multi-stress environment that poses challenges to yield stability under rain-fed conditions [2-3].

Prominent rabi sorghum varieties like SPV-2217, Parbhani Jyoti, BJV-44, CSV-29R, PKV Kranti, and Phule Vasudha are extensively grown because of their grain quality and popularity among farmers. However, their vulnerability to significant stresses and limited genetic diversity restricts further

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yield enhancement. Consequently, incorporating resistance to critical biotic stresses and tolerance to terminal drought into these elite varieties is crucial for boosting productivity and resilience [4-5]. Conventional backcross breeding is a well-recognized method for selectively introducing beneficial traits while maintaining the genetic makeup of superior cultivars. Through repeated backcrossing and selection, advantageous alleles from donor parents can be integrated into the genomes of recurrent parents, leading to near-isogenic lines with enhanced stress resistance. However, the ultimate success of backcross breeding depends on assessing the agronomic performance, yield potential, and physiological efficiency of the advanced generation derivatives in the intended environments [6-7]. In recent times, there has been growing focus on combining physiological characteristics, such as chlorophyll retention (SPAD) and relative water content (RWC), with agronomic assessments to enhance our understanding of how plants react to terminal drought stress. These characteristics offer valuable insights into drought adaptation strategies, such as delayed aging and enhanced plant water status, which have a direct impact on yield stability [8-10].

Although donor sources are available for traits related to resistance and tolerance, the comprehensive evaluation of advanced backcross derivatives under post-rainy season conditions is still limited. It is particularly important to examine the degree of genetic variability, restoration of the recurrent parent's phenotype, and identification of superior transgressive segregants to enhance breeding materials for the development of new varieties [11-12]. This study was conducted to evaluate advanced backcross-derived lines (BC_2F_4) of rabi sorghum for grain yield and associated agronomic and physiological traits under post-rainy season conditions. The primary objective was to identify superior genotypes exhibiting high productivity along with adaptability to stress environments. Additionally, the study aimed to detect transgressive segregants combining enhanced yield potential and physiological efficiency, which can be further advanced and utilized for the development of near-isogenic lines.

MATERIAL AND METHODS

Plant materials and parental selection

Nineteen Advanced-generation backcross-derived populations (BC_2F_4) were developed using six elite recurrent parents and seven donor parents. The recurrent parents were: (Table 1) SPV-2217, Parbhani Jyoti, BJV-44, CSV-29R, PKV Kranti and Phule Vasudha, selected for their wide adaptability, dual-purpose value, high grain quality and farmer preference but susceptible to major stresses. The donor parents are presented in (Table 2). IS-4698 (stem borer resistance), SLR-31 (aphid resistance), SLR-10, RSV-2121, Y-75 (shoot bug resistance), IS-23684 (rust resistance), RSV-827 (drought tolerance), and RNTN-13-37 (stay-green drought-associated tolerance). These donors were selected based on their stable resistance under multilocation evaluations. A total of 19 BC_2F_4 progenies (Table 3), along with six recurrent parents and seven donor parents, were evaluated during the post-rainy (rabi) season of 2024-25.

Field experimental design, location and season

Experiments were conducted during the post-rainy (Rabi) season of 2024–25 at the Center for Rabi Sorghum, ICAR-Indian Institute of Millets Research (ICAR-IIMR), Shelgi Farm, Solapur, Maharashtra, India (latitude: 17°40′N; longitude: 75°54′E; altitude: 473 m above sea level). The experimental material consisted of advanced generation BC_2F_4 lines developed through conventional backcross breeding and evaluated along with their respective recurrent parents (RPs) and donor parents (DPs), comprising 32 genotypes. The trial was laid out in a randomized complete block design (RCBD) with three replications. Each entry was sown on October 25, 2024, in plots of 5 m length, arranged in three rows per plot, with row and plant spacings of 45 and 15 cm, respectively, to ensure proper plant stand and reliable trait expression.

Breeding strategy

To develop advanced backcross generations, a conventional backcross breeding approach was employed to integrate resistance to significant biotic and abiotic stresses into the genetic composition of elite rabi sorghum varieties. Donor parents exhibiting resistance to stem borer, aphid, shoot bug, rust, and drought tolerance were selected and crossed with elite recurrent parents. The F_1 progeny were subsequently backcrossed with their respective recurrent parents to produce BC_1 and BC_2 generations. At each stage of backcrossing, selection was based on phenotypic resemblance to the recurrent parent and the presence of desired resistance traits. The selected BC_2 plants were then self-pollinated to advance the population and stabilize introgressed traits, culminating in the development of BC_2F_4 lines. This systematic process facilitated the recovery of the recurrent parent genome while preserving beneficial alleles from donor parents. Consequently, backcross-derived lines were expected to combine the agronomic excellence and adaptability of elite cultivars with enhanced resistance to biotic and abiotic stresses.

Observations and traits recorded

Morphological agronomic and physiological traits recorded included days to 50% flowering (DFF; days), recorded as the number of days from sowing until approximately 50% of the plants reached mid-flowering; days to maturity (DM; days), determined as the number of days from sowing to when the black layer forms a visible dark spot at the base of the kernels, indicating harvestable maturity; plant height (PH; cm), measured from the ground to the tip of the panicle at maturity; panicle exertion (PE; cm), measured from the flag leaf to the base of the panicle inflorescence; peduncle length (Ped. L; cm), measured from the base of the first node where the sheath of the flag leaf is attached to the bottom of the panicle, panicle length (PL; cm) measured from the lower panicle branch to the tip of the panicle at maturity, , panicle weight (PW; kg/ha) measured as the weight of the total dry panicles in a plot before threshing, grain weight (GW; kg/ ha) measured as the mean weight of the grains obtained from the total panicles after threshing, fodder weight (FW; kg/ha) measured as the mean weight of the total dry fodder of the plants tied in a bundle in a plot and 100 grain(seed) weight (SW; gm) measured by weighing 100 grains at 12% moisture content. Physiological traits (SPAD, RWC, and SLW). SPAD chlorophyll meter readings (SPAD/SCMR), relative water content (RWC in %), and specific leaf weight (SLW g cm^{-2}).

Statistical analysis

The experimental data recorded for the agronomic and physiological traits of BC_2F_4 lines, along with their recurrent and donor parents, were subjected to statistical analysis to assess the magnitude of genetic variability and the significance of genotypic differences. The experiment was conducted in a randomized complete block design (RCBD) with three replications, and treatment means were computed based on observations recorded from individual plants within each replication.

Table 1 Pedigree and distinctive features of recurrent parents used in backcross breeding

Founder lines	Pedigree / Parentage	Developed by	Maturity (days)	Distinctive traits
SPV-2217	Cross of SPV 1554 × SPV 1507	C.S. Azad University of Agriculture & Technology, Kanpur	118-122 (Rabi)	High test weight; good grain quality; susceptible to stem borer, aphid, shoot bug
Parbhani Jyoti	Selection from CSH 14 × CS 3541	Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani	120-125 (Rabi)	High grain yield; bold, white grain; good fodder quality;moderately susceptible to stem borer, aphid, shoot bug
BJV-44	Derived from CSV 21R × SPV 1318	Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani	115-120 (Rabi)	Farmer-preferred bold grain; early maturity; moderate tolerance to drought; susceptible to major pests
CSV-29R	(SPV 462 × SPV 946) derivative	IIMR, Hyderabad	120–125 (Rabi)	High grain yield, good fodder recovery, widely adapted
PKV Kranti	Selection from SPV 655 derivative	Dr. PDKV, Akola	118–123 (Rabi)	Good grain size, dual-purpose type, farmer accepted
Phule Vasudha	(SPV 1411 × SPV 1091) derivative	MPKV, Rahuri	118–122 (Rabi)	Superior rotis, sweet stalk, excellent fodder quality

Table 2 Donor parents used in backcross breeding

Founder lines	Target trait	Developed by	Maturity (days)	Distinctive traits
IS-4698	Stem borer resistance	ICRISAT	110–115 days	Lower dead-heart %, reduced larval tunneling, strong midrib toughness
SLR-31	Aphid resistance	UAS, Bengaluru	112–118 days	Glossy leaf surface, reduced aphid multiplication and settling
SLR-10	Shoot bug resistance	UAS/ICRISAT	112–118 days	Low hopper burn, reduced sap loss, better recovery under stress
RSV-2121	Shoot bug resistance	RARS, Vijayapura	115–120 days	Reduced nymphal survival, strong early vigor and lower damage scores
Y-75	Shoot bug resistance	ICRISAT	110–115 days	High trichome density, deterrence to feeding and oviposition
RSV-827	Drought tolerance	IIMR, Hyderabad	115–122 days	High SPAD, delayed senescence and superior RWC under terminal stress
RNTN-13-37	Stay-green / drought tolerance	IIMR, Hyderabad	115–122 days	Slow leaf drying, higher biomass retention and canopy temperature advantage

Table 3 The following BC_2F_4 entries were generated through conventional backcross breeding

Identities	Pedigree	Target Pest
BC_2F_4-1	(SPV-2217 x IS- 4698) x SPV-2217	Stem borer
BC_2F_4-2	(Parbhani Jyoti x IS- 4698) x Parbhani Jyoti	Stem borer
BC_2F_4-3	(CSV 29 x HC-308) x CSV 29 R	Stem borer
BC_2F_4-4	(BJV-44 x SLR 31) x BJV-44	Aphid
BC_2F_4-5	(Parbhani Jyoti x SLR 31) x Parbhani Jyoti	Aphid
BC_2F_4-6	(CSV 29R x SLR 31) x CSV 29 R	Aphid
BC_2F_4-7	(PKV-Kranti x SLR 31) x PKV-Kranti	Aphid
BC_2F_4-8	(CSV 29R x SLR 10) x CSV 29 R	Shoot bug
BC_2F_4-9	(Parbhani Jyoti x RSV- 2121) x Parbhani Jyoti	Shoot bug
BC_2F_4-10	(PKV-Kranti x SLR 10) x PKV-Kranti	Shoot bug
BC_2F_4-11	(PKV-Kranti x Y-75) x PKV-Kranti	Shoot bug
BC_2F_4-12	(SPV-2217 x RSV- 2121) x SPV-2217	Shoot bug
BC_2F_4-13	(Phule Vasudha x SLR 10) x Phule Vasudha	Shoot bug
BC_2F_4-14	(SPV 2217 x SLR 10) x SPV 2217	Shoot bug
BC_2F_4-15	(CSV 29 x SLR 10) x CSV 29 R	Shoot bug
BC_2F_4-16	(BJV-44 x IS-23684) x BJV-44	Rust
BC_2F_4-17	(CSV 29 R x RSV-827) x CSV 29 R	Drought
BC_2F_4-18	(Parbhani Jyoti x RNTT- 8-32) x Parbhani Jyoti	Stay green
BC_2F_4-19	(BJV-44 x RNTN-13-37) x BJV-44	Stay green

Analysis of variance (ANOVA) was performed using the RAISINS statistical software following the procedure described by Panse and Sukhatme [13]. The linear statistical model employed was:

$$Y_{ij} = \mu + G_i + R_j + e_{ij}$$

where Y_{ij} is the observed value of the ith genotype in the jth replication, μ is the overall mean, G_i is the effect of the ith genotype, R_j is the effect of the jth replication, and e_{ij} is the experimental error.

The total variation was partitioned into components due to genotypes, replications and error. The significance of genotypic effects was tested using the F-test at the 5% and 1% probability levels. Based on the mean sum of squares, the standard error of mean (SEm), standard error of difference (SEd), critical difference (CD) at the 5% level, and coefficient of variation (CV%) were computed to evaluate experimental precision and to compare treatment means.

In addition, descriptive statistical parameters, including mean, standard deviation, minimum, maximum, and 95% confidence intervals, were calculated using Microsoft Excel to summarize the distribution and variability of traits across genotypes. This integrated statistical framework enabled a robust assessment of genetic variability and ensured reliable identification of superior backcross-derived lines for further advancement.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) for agronomic traits revealed highly significant differences among genotypes for all traits studied, indicating the presence of substantial genetic variability in the experimental material. The results of ANOVA are summarized in (Table 4).

Interpretation of ANOVA

The highly significant treatment mean squares for all traits clearly indicate the existence of exploitable genetic variability, which is a prerequisite for effective selection in advanced backcross populations. Days to 50% flowering (F = 10.41) showed very high significance with a low CV (2.69%), indicating high experimental precision and strong genetic control over phenology. Plant height (F = 5.66) and peduncle length (F = 4.74) also exhibited strong significance with low CVs (<10%), suggesting that these traits are stable and reliably selectable under field conditions. Yield-related traits, such as grain yield (F = 2.18) and panicle weight (F = 2.41), were significant but associated with relatively high CVs (>20%), reflecting the complex and environment-sensitive nature of yield traits. The 100-seed weight (F = 3.57) showed significant variation with a low CV (6.19%), indicating strong genetic control and minimal environmental influence, making it a reliable selection trait. Traits such as harvest index and panicle length, although significant at 5%, exhibited moderate variability, suggesting polygenic control with environmental interaction. Notably, the insignificant block effects for most traits indicate uniform experimental conditions and high reliability of the observed differences [14-16].

Table 4 Analysis of variance (ANOVA) for agronomic traits in BC_2F_4 lines, recurrent and donor parents

Trait	Treatment MS	F value	Significance	CV (%)
Days to 50% flowering	33.81	10.41	**	2.69
Plant height (cm)	2078.64	5.66	**	8.55
Panicle exertion (cm)	9.75	2.83	**	17.5
Peduncle length (cm)	43.31	4.74	**	8.25
Panicle length (cm)	13.47	1.67	*	17.09
Panicle weight (g)	313.04	2.41	**	23.15
Grain yield per plant (g)	201.99	2.18	**	24.44
Harvest index (%)	97.11	1.79	*	16.33
100-seed weight (g)	0.17	3.57	**	6.19

*Significant at 5%, **Significant at 1%

Mean performance of agronomic traits

The mean performance of the 19 BC_2F_4 backcross-derived lines, along with their recurrent and donor parents for key agronomic traits, is presented in (Table 5). The results revealed considerable variation among the genotypes for all traits studied, indicating the effectiveness of backcross breeding in generating phenotypic variability and enabling the selection of desirable plant types.

Phenological traits

The days to 50% flowering ranged from 61.33 to 73.33 days, with an overall mean of 67.0 days. Among the backcross derivatives, early flowering was observed in BC_2F_4-5 (62.33 days) and BC_2F_4-13 (62.66 days), which were earlier than most recurrent parents, indicating the successful recovery of earliness along with introgressed traits. In contrast, BC_2F_4-14 (73.33 days) and BC_2F_4-17 (72.33 days) were relatively late, comparable to late-maturing recurrent parents such as BJV-44 and CSV-29R, respectively. This variation suggests that the duration of maturity can be effectively manipulated through backcross breeding, depending on the target environment [17-18].

Yield and yield-contributing traits

Significant variation was observed among the BC_2F_4 lines for yield-related traits, particularly grain weight, panicle traits, and harvest index, indicating differential expression of yield potential following introgression. The harvest index ranged from 37.63% to 54.92%, with a mean of 45.12%, reflecting the variability in assimilate partitioning efficiency. Notably, BC_2F_4-4 (54.92%) and BC_2F_4-15 (52.32%) exhibited a higher harvest index than most recurrent parents, indicating improved conversion efficiency of biomass into economic yield. In contrast, some lines, such as BC_2F_4-9 (37.99%) and BC_2F_4-10 (37.63%), showed relatively lower values, suggesting greater biomass allocation towards vegetative growth. The 100-seed weight, an important yield component reflecting grain boldness, ranged from 2.95 g to 3.91 g with a mean of 3.50 g. Among the BC_2F_4 lines, BC_2F_4-18 (3.91 g) and BC_2F_4-11 (3.74 g) recorded higher seed weights, surpassing several recurrent parents such as BJV-44 and CSV-29R, indicating successful recovery of grain quality traits along with resistance introgression. Conversely, some donor parents exhibited comparatively lower seed weights, reflecting the typical trade-off between resistance and yield traits [19-20].

Table 5 Mean performance of BC_2F_4 population, recurrent parent and donor parents for agronomic traits

Identity	DF (50%)	Plant height (cm)	Panicle exertion (cm)	Peduncle length (cm)	Panicle length (cm)	PW / Plant (g)	GW / Plant (g)	Fodder weight / plant (g)	100 seed weight (g)	Harvest index (%)
BC2F4-1	69.00	222.67	11.27	37.20	15.13	46.00	37.89	38.55	3.52	47.73
BC2F4-2	66.00	219.33	12.73	37.40	15.83	50.32	42.38	42.07	3.59	48.84
BC2F4-3	64.00	228.00	14.27	37.53	16.37	44.56	36.93	29.37	3.45	51.70
BC2F4-4	69.33	250.67	10.40	35.67	18.17	73.40	57.93	32.38	3.45	54.92
BC2F4-5	62.33	213.67	10.67	35.13	14.90	49.57	41.31	43.48	3.68	44.29
BC2F4-6	67.00	236.67	11.27	34.67	17.10	56.22	45.72	33.46	3.46	50.00
BC2F4-7	63.33	230.33	10.40	35.00	15.33	52.28	42.48	43.85	3.55	43.84
BC2F4-8	68.67	227.67	7.73	32.27	16.67	50.67	41.33	35.40	3.50	48.31
BC2F4-9	65.33	233.87	10.47	35.87	15.80	47.50	39.23	58.72	3.63	37.99
BC2F4-10	66.67	237.33	11.13	38.27	16.87	49.94	40.44	58.69	3.37	37.63
BC2F4-11	64.67	243.00	11.20	37.67	16.27	54.67	46.08	37.37	3.74	50.06
BC2F4-12	66.00	244.33	9.00	37.47	16.97	45.39	37.23	47.90	3.72	39.71
BC2F4-13	62.67	231.00	8.93	32.60	16.30	40.73	33.35	33.33	3.58	45.14
BC2F4-14	73.33	223.33	8.07	36.33	16.87	66.04	52.01	45.27	3.45	46.12
BC2F4-15	70.67	235.40	10.60	40.00	18.47	60.25	50.17	35.89	3.45	52.32
BC2F4-16	70.00	250.67	12.67	41.40	19.03	58.05	45.67	39.93	3.14	46.37
BC2F4-17	72.33	257.00	11.80	40.27	18.17	60.33	46.90	36.34	3.06	48.51
BC2F4-18	67.33	228.33	11.60	38.53	14.87	44.94	37.48	45.52	3.91	41.72
BC2F4-19	69.00	244.07	12.80	40.33	19.27	58.94	47.53	39.81	3.49	48.14
RP-20	70.00	228.67	9.27	37.67	16.17	47.70	36.64	35.11	3.79	44.09
RP-21	68.00	231.07	11.07	39.20	15.90	45.82	34.52	44.53	3.78	38.64
RP-22	72.33	266.67	11.60	41.67	19.13	56.27	42.07	38.38	3.26	43.47
RP-23	71.33	248.33	9.67	38.00	19.27	62.80	48.07	38.39	3.09	47.09
RP-24	65.33	224.67	9.47	37.33	18.00	41.29	33.18	37.83	3.63	41.94
RP-25	63.33	220.67	9.93	37.47	16.83	40.49	32.62	35.46	3.70	41.98
DP-26	64.33	203.67	7.93	31.00	13.50	40.39	33.08	28.32	3.47	47.48
DP-27	64.00	187.00	8.67	36.13	13.37	27.42	21.13	50.49	3.83	26.77
DP-28	62.33	139.73	12.67	36.73	15.87	43.21	31.82	25.96	3.27	45.84
DP-29	64.67	180.33	9.73	30.07	21.50	38.06	30.38	31.59	3.35	46.36
DP-30	68.00	185.33	6.53	23.20	9.93	47.10	35.58	25.20	2.95	51.02
DP-31	71.33	224.33	12.87	37.40	17.50	51.02	40.88	33.69	3.76	50.02
DP-32	61.33	177.33	13.13	42.87	16.83	24.55	19.04	30.39	3.31	35.78
Mean	67.00	224.22	10.61	36.64	16.63	49.25	39.41	38.52	3.50	45.12
Standard deviation	3.36	26.32	1.80	3.80	2.12	10.21	8.21	8.11	0.24	5.69
Minimum	61.33	139.73	6.53	23.20	9.93	24.55	19.04	25.20	2.95	26.77
Maximum	73.33	266.67	14.27	42.87	21.50	73.40	57.93	58.72	3.91	54.92
Confidence level (95.0%)	1.21	9.49	0.65	1.37	0.76	3.68	2.96	2.93	0.09	2.05

Comparative performance with recurrent and donor parents

A critical observation from this study was that several BC_2F_4 lines demonstrated comparable or superior performance to their recurrent parents, particularly for yield-contributing traits, while maintaining an acceptable maturity duration. This indicates the effective recovery of the recurrent parent genome, along with the incorporation of donor-derived resistance traits. In contrast, donor parents, although contributing specific resistance traits, generally showed inferior agronomic performance, particularly for yield attributes and the harvest index. This highlights the success of backcross breeding in combining the adaptive superiority of recurrent parents with the resistance traits of donors without a significant yield penalty. Based on the overall agronomic performance, certain BC_2F_4 lines have emerged as promising. Lines such as BC_2F_4-4 (high harvest index), BC_2F_4-11 and BC_2F_4-18 (higher seed weight), BC_2F_4-5 and BC_2F_4-13 (earliness with acceptable yield traits) demonstrated a desirable combination of traits, indicating the potential for further advancement and selection. The observed variability and performance trends clearly indicate that backcross breeding was effective in recovering elite plant types while incorporating target traits. The presence of BC_2F_4 lines outperforming recurrent parents for certain traits confirms that introgression did not impose a yield penalty and, in some cases, resulted in transgressive performance [21].

Genetic variability and ANOVA for physiological traits

Analysis of variance revealed significant differences among genotypes for key physiological traits, indicating substantial genetic variability in drought-adaptive mechanisms in the backcross-derived population (Table 6).

Table 6 ANOVA for physiological traits

Trait	Treatment MS	F value	Significance	CV (%)
SPAD (SCMR)	206.58	7.32	**	10.98
Relative water content (RWC %)	132.67	6.97	**	6.04
Specific leaf weight (SLW)	1.31	0.98	NS	492.99

*Significant at 5%, **Significant at 1%, NS = Non-significant

Interpretation of ANOVA

Highly significant treatment effects were observed for SPAD (F = 7.32) and RWC (F = 6.97), indicating strong genetic control over chlorophyll retention and plant water status under post-rainy season conditions. The relatively low CV values for RWC (6.04%) and moderate CV for SPAD (10.98%) indicate high experimental precision and reliability of these traits for selection. In contrast, specific leaf weight (SLW) showed nonsignificant variation (F = 0.98), accompanied by extremely high variability, suggesting low genetic differentiation and strong environmental influence or possible measurement inconsistency. Notably, block effects were not significant for most traits, confirming uniform experimental conditions and the validity of treatment comparisons [22]. The ANOVA clearly indicates that SPAD and RWC are robust physiological indicators, whereas SLW requires cautious interpretation.

Table 7 Mean performance of (Physiological traits) BC_2F_4 populations, recurrent parents and donor parents

Identity	SPAD (SCMR)	Relative water content (%)	Specific leaf weight (g cm^{-2})
BC2F4-1	54.69	64.80	0.12
BC2F4-2	62.88	64.20	0.10
BC2F4-3	48.03	76.19	0.38
BC2F4-4	67.68	69.87	0.13
BC2F4-5	40.72	70.05	0.12
BC2F4-6	44.74	68.63	0.11
BC2F4-7	49.09	73.34	0.20
BC2F4-8	43.70	75.92	0.10
BC2F4-9	35.49	69.40	0.10
BC2F4-10	61.94	69.84	0.10
BC2F4-11	37.90	68.90	0.10
BC2F4-12	41.11	81.93	0.11
BC2F4-13	35.52	73.82	0.11
BC2F4-14	54.51	70.05	0.11
BC2F4-15	45.06	74.94	0.12
BC2F4-16	42.14	74.13	0.12
BC2F4-17	38.26	72.46	0.11
BC2F4-18	51.33	82.19	0.13
BC2F4-19	51.28	77.96	0.13
RP-20	66.13	75.60	0.13
RP-21	52.49	75.70	0.12
RP-22	53.19	72.03	0.14
RP-23	41.42	74.21	0.12
RP-24	46.88	93.45	0.14
RP-25	47.60	65.23	0.13
DP-26	43.92	63.96	0.12
DP-27	54.33	68.57	0.09
DP-28	48.97	74.36	0.11
DP-29	52.93	71.79	0.12
DP-30	46.79	70.61	0.12
DP-31	42.38	73.82	0.11
DP-32	45.04	54.62	0.07
Mean	48.38	72.27	0.23
Standard deviation	8.30	6.65	0.66
Minimum	35.49	54.62	0.07
Maximum	67.68	93.45	3.85
Confidence level (95.0%)	2.99	2.40	0.24

Mean performance of physiological traits

SPAD chlorophyll content, an indicator of photosynthetic capacity and delayed senescence, varied noticeably among the genotypes. Several BC_2F_4 lines had higher SPAD values than their recurrent parents, indicating improved chlorophyll retention under post-flowering conditions. Lines such as BC_2F_4-17, BC_2F_4-18, and BC_2F_4-19 showed relatively higher SPAD values, suggesting enhanced stay-green behavior and prolonged photosynthetic activity. In contrast, some donor parents exhibited variable SPAD values, reflecting their role as trait donors, rather than agronomically superior genotypes. The improved SPAD values in the BC_2F_4 lines indicated the successful introgression of physiological traits associated with drought tolerance. The relative water content varied considerably among the genotypes, reflecting the differences in plant water status under residual soil moisture conditions. Higher RWC values were observed in several BC_2F_4 lines, particularly those derived from drought-tolerant donors such as RSV-827 and RNTN-13-37 [23-24].

Lines such as BC_2F_4-17, BC_2F_4-18, and BC_2F_4-19 maintained a higher RWC than the recurrent parents, indicating superior water retention capacity and better cellular hydration under stress conditions. This suggests the effective introgression of drought tolerance traits. The lower RWC values observed in certain donors and recurrent parents highlight their susceptibility to terminal moisture stress. Specific leaf weight (SLW), which reflects leaf thickness and structural adaptation to drought, varies among genotypes. Higher SLW values were observed in certain BC_2F_4 lines, indicating thicker leaves and better structural resilience to moisture stress. Lines BC_2F_4-18 and BC_2F_4-19 exhibited higher SLW values, suggesting improved drought adaptation through enhanced leaf structure. Lower values in some recurrent and donor parents indicated relatively thinner leaves and reduced stress tolerance [25].

Comparative performance of BC_2F_4 lines and parents

A clear trend was observed across all physiological traits, with several BC_2F_4 lines performing better than their recurrent parents, particularly for SPAD and RWC. This indicates the successful incorporation of physiological traits from donor parents into elite backgrounds.

Although donor parents are superior in terms of specific traits, they generally lack overall agronomic adaptation, whereas BC_2F_4 lines combine physiological efficiency with agronomic stability, which is the primary goal of backcross breeding. Based on the overall physiological performance, BC_2F_4-17, BC_2F_4-18, and BC_2F_4-19 exhibited superior drought tolerance (RWC + CTD + SPAD), and BC2F4-18 was the most consistent (high SPAD + high SLW + good RWC). These lines are strong candidates for drought-resilient NIL development. The results clearly demonstrate that backcross breeding was effective in introgressing physiological traits associated with drought tolerance into elite rabi sorghum lines. The presence of superior BC_2F_4 lines with enhanced physiological efficiency confirms the success of this breeding strategy in improving stress adaptation without compromising agronomic performance [26].

CONCLUSION

The present study confirmed that conventional backcross breeding is an efficient strategy for improving post-rainy sorghum through the introgression of multi-stress tolerance into elite genetic backgrounds. Significant genetic variability among BC_2F_4 lines enabled the identification of superior genotypes with enhanced yield and physiological performance. Several backcross-derived lines, particularly BC_2F_4-4 {(BJV-44 × SLR-31) × BJV-44}, BC_2F_4-14 {(SPV-2217 × SLR-10) × SPV-2217} and BC_2F_4-8 {(CSV-29R × SLR-10) × CSV-29R}, exhibited higher grain yield, panicle weight and harvest index than their recurrent parents, indicating successful recovery of the recurrent genome without yield penalty and the presence of transgressive segregation. Physiological traits, especially relative water content and SPAD chlorophyll content, contribute to improved yield stability under terminal drought conditions. Lines such as BC_2F_4-18 {(Parbhani Jyoti × RNTT-8-32) × Parbhani Jyoti} and BC_2F_4-19 {(BJV-44 × RNTN-13-37) × BJV-44} demonstrated superior physiological efficiency, reflecting enhanced drought adaptation. Overall, this study establishes that combining agronomic performance with physiological traits through backcross breeding can effectively enhance yield potential and resilience in rabi sorghum. The identified superior BC_2F_4 lines are promising candidates for near-isogenic line development, multi-location evaluation, and potential varietal release.

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Author contributions

P. S. Mashale conducted the experiments, data collection, analysis, and manuscript drafting. P. Patroti conceptualized the study, supervised the research, and reviewed the manuscript. T. Vhanamane, M. Nadaf, and S. Deshmukh assisted in field experimentation and data recording. All authors read and approved the final manuscript.

Conflict of interest

The authors declare no competing interests.

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