DEVELOPMENT OF STRESS TOLERANT VERSIONS OF POPULAR RABI SORGHUM VARIETIES USING BACKCROSS BREEDING APPROACH

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ABSTRACT
Rabi sorghum (Sorghum bicolor (L.) Moench) is an important food and fodder crop cultivated under the post-rainy season in the semi-arid regions of India, where productivity is frequently constrained by major biotic and abiotic stresses. The present investigation aimed to develop stress-tolerant versions of popular rabi sorghum cultivars through conventional backcross breeding by introgressing resistance to stem borer, aphid, shoot bug, rust and terminal drought, and to evaluate advanced BC_2F_4 backcross-derived lines for agronomic performance, physiological efficiency and stress tolerance. Nineteen BC_2F_4 backcross-derived lines, developed using six elite recurrent parents and seven trait-specific donor parents, were evaluated during Rabi 2024–25 at the Centre on Rabi Sorghum, ICAR–Indian Institute of Millets Research, Solapur, in a randomized complete block design with three replications. Advanced backcross-derived lines were further screened for stem borer resistance across four hotspot locations, rust resistance under natural epiphytotic conditions and terminal drought tolerance using a gravimetric lysimeter facility at ICAR–IIMR, Hyderabad. Significant genetic variability was observed among the BC_2F_4 lines for agronomic and physiological traits. Field evaluation identified BC2F4-4 {(BJV-44 × SLR-31) × BJV-44} as the best-performing genotype, recording the highest grain yield (57.93 g plant^{-1}), panicle weight (73.40 g), harvest index (54.92%) and SPAD value (67.68). Likewise, BC2F4-14 {(SPV-2217 × SLR-10) × SPV-2217} and BC2F4-15 {(CSV-29R × SLR-10) × CSV-29R} exhibited superior grain yield and desirable agronomic performance, whereas BC2F4-18 {(Parbhani Jyoti × RNTN-13-37) × Parbhani Jyoti}, BC2F4-12 {(SPV-2217 × RSV-2121) × SPV-2217} and BC2F4-19 {(BJV-44 × RNTN-13-37) × BJV-44} showed improved physiological performance with higher relative water content and chlorophyll retention. Multi-environment screening further validated the breeding programme, with S24007RV and S24005RV exhibiting superior stem borer resistance, S24009RV and S24010RV expressing stable rust resistance, and S24003RV recording the highest transpiration efficiency (10.84), total water use (13.24 kg plant^{-1}) and grain yield under drought stress (70.25 g plant^{-1}). The study demonstrated that conventional backcross breeding effectively combined superior agronomic performance with resistance to major biotic and abiotic stresses, resulting in elite BC_2F_4 introgression lines that constitute valuable genetic resources for developing high-yielding, climate-resilient rabi sorghum cultivars adapted to post-rainy season environments.

KEYWORDS: Rabi sorghum, Backcross breeding, Stress tolerant, Multi-location screening, Lysimeter phenotyping

INTRODUCTION
Sorghum (Sorghum bicolor (L.) Moench) is the fifth most important cereal crop globally and serves as a major source of food, feed and fodder for millions of people in the semi-arid tropics. In India, post-rainy (rabi) sorghum is highly valued for its superior grain quality, fodder yield and adaptation to residual soil moisture conditions. However, the productivity of elite rabi cultivars remains constrained by multiple biotic and abiotic stresses, which substantially reduce grain yield and production stability under rainfed environments (Paterson et al., 2009; Rakshit et al., 2014; Dahlberg et al., 2011). Among the major production constraints, stem borer (Chilo partellus), aphid (Melanaphis sacchari), shoot bug (Peregrinus maidis) and rust (Puccinia purpurea) are economically important pests and diseases affecting rabi sorghum cultivation. Stem borer infestation during the early vegetative stage causes dead-heart formation, while aphid and shoot bug reduce photosynthetic efficiency through sap feeding. Rust infection accelerates

premature leaf senescence, reducing grain filling and fodder quality. In addition, terminal drought during the reproductive stage remains one of the most important yield-limiting factors in post-rainy sorghum production. The combined occurrence of these stresses poses a major challenge to the development of stable, high-yielding cultivars for semi-arid regions (Sharma et al., 2003; Sharma et al., 2010; Borrell et al., 2014). Host plant resistance is widely recognized as the most economical and environmentally sustainable approach for managing insect pests, diseases and drought stress. Considerable progress has been made in identifying resistant donor sources for stem borer, aphid, shoot bug, rust and drought tolerance in sorghum germplasm. However, these donor lines generally possess poor agronomic performance and limited farmer acceptance. Conversely, popular rabi cultivars such as Parbhani Jyoti, BJV-44, CSV-29R, SPV-2217, PKV Kranti and Phule Vasudha possess excellent grain quality, adaptation and yield potential but remain susceptible to one or more of these stresses (Reddy et al., 2009; Rakshit et al., 2021). Conventional backcross breeding is an effective strategy for improving established cultivars by introgressing one or more desirable traits from donor parents while recovering the superior genetic background of elite recurrent parents. This approach has been successfully employed in several cereal crops to improve resistance against insect pests, diseases and abiotic stresses without compromising agronomic performance. In sorghum, backcross breeding has been widely utilized for transferring stay-green, drought tolerance and disease resistance traits into adapted genetic backgrounds, thereby generating improved cultivars with enhanced resilience to environmental stresses (Knoll and Ejeta, 2008; Jordan et al., 2012; Mace et al., 2013). Advanced backcross-derived populations also provide valuable genetic resources for developing near-isogenic lines (NILs), which facilitate precise phenotypic evaluation and genetic dissection of target traits. NILs are extensively used in quantitative trait locus (QTL) mapping, gene validation and marker-assisted breeding because they differ primarily at the introgressed genomic region while retaining the recurrent parent genome. Development of such populations through repeated backcrossing followed by rigorous phenotypic selection provides an effective bridge between conventional breeding and modern molecular improvement programmes (Hospital, 2005; Collard and Mackill, 2008).

Although resistant donor sources for stem borer, aphid, shoot bug, rust and drought tolerance are available, relatively few studies have attempted to introgress these traits into multiple popular rabi sorghum cultivars through a common backcross breeding programme followed by comprehensive evaluation under natural hotspot, epiphytotic and managed drought environments. Furthermore, information on the performance of advanced BC_2F_4 backcross-derived populations for simultaneous agronomic recovery and stress tolerance remains limited. Therefore, identification of superior introgression lines possessing stable resistance together with high yield potential is essential for accelerating the development of climate-resilient rabi sorghum cultivars.

Accordingly, the present investigation was undertaken (i) to introgress stem borer, aphid, shoot bug, rust and drought tolerance traits into the genetic background of popular rabi sorghum cultivars through conventional backcross breeding, and (ii) to evaluate advanced BC_2F_4 backcross-derived populations under field, hotspot and managed stress environments to identify superior lines with enhanced stress tolerance and desirable agronomic performance for use in future sorghum improvement programmes.

MATERIAL AND METHODS

Plant Materials and Parental Selection: Nineteen Advanced-generation backcross-derived populations (BC2F4) 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 BC2F4 entries (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

The field experiment was conducted at the Centre on Rabi Sorghum, ICAR–Indian Institute of Millets Research (ICAR–IIMR), Regional Centre, Shelgi Farm, Solapur, Maharashtra, India (17°40′N, 75°54′E; 473 m above sea level) during the Rabi 2024–25 season. Thirty-two genotypes (19 BC_2F_4 lines, six recurrent parents and seven donor parents) were evaluated in a randomized complete block design (RCBD) with three replications. Each genotype was sown on 25 October 2024 in plots comprising three rows of 5 m length with a spacing of 45 cm × 15 cm. Recommended agronomic practices for rabi sorghum cultivation were followed throughout the crop growth period.

Breeding Strategy: A conventional backcross breeding approach was employed to develop stress-tolerant versions of elite rabi sorghum cultivars by introgressing resistance to major biotic (stem borer, aphid, shoot bug and rust) and abiotic (terminal drought) stresses into high-yielding recurrent parent backgrounds. Six elite rabi sorghum cultivars were used as recurrent parents, while trait-specific donor parents possessing resistance to the target stresses served as resistance sources. Initially, each recurrent parent was crossed with its respective donor parent to produce F_1 hybrids.

The F_1 plants were subsequently backcrossed twice with the recurrent parent to generate BC_1F_1 and BC_2F_1 populations. At each backcross generation, plants exhibiting maximum phenotypic resemblance to the recurrent parent together with expression of the target resistance trait were selected. Selected BC_2F_1 plants were self-pollinated and advanced through pedigree selection from BC_2F_2 to BC_2F_4 to stabilize the introgressed traits while recovering the recurrent parent genome. The advanced BC_2F_4 backcross-derived lines were subsequently evaluated for agronomic performance and stress tolerance. The same breeding strategy was followed for all nineteen backcross combinations involving stem borer, aphid, shoot bug, rust and drought tolerance, with differences only in the recurrent parent, donor parent and target trait. The breeding scheme illustrated in Figure 1 represents the development of the stem borer-resistant cross Parbhani Jyoti × IS-4698, and an identical approach was adopted for the remaining backcross populations.

Table no. 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 no. 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 BC2F4 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

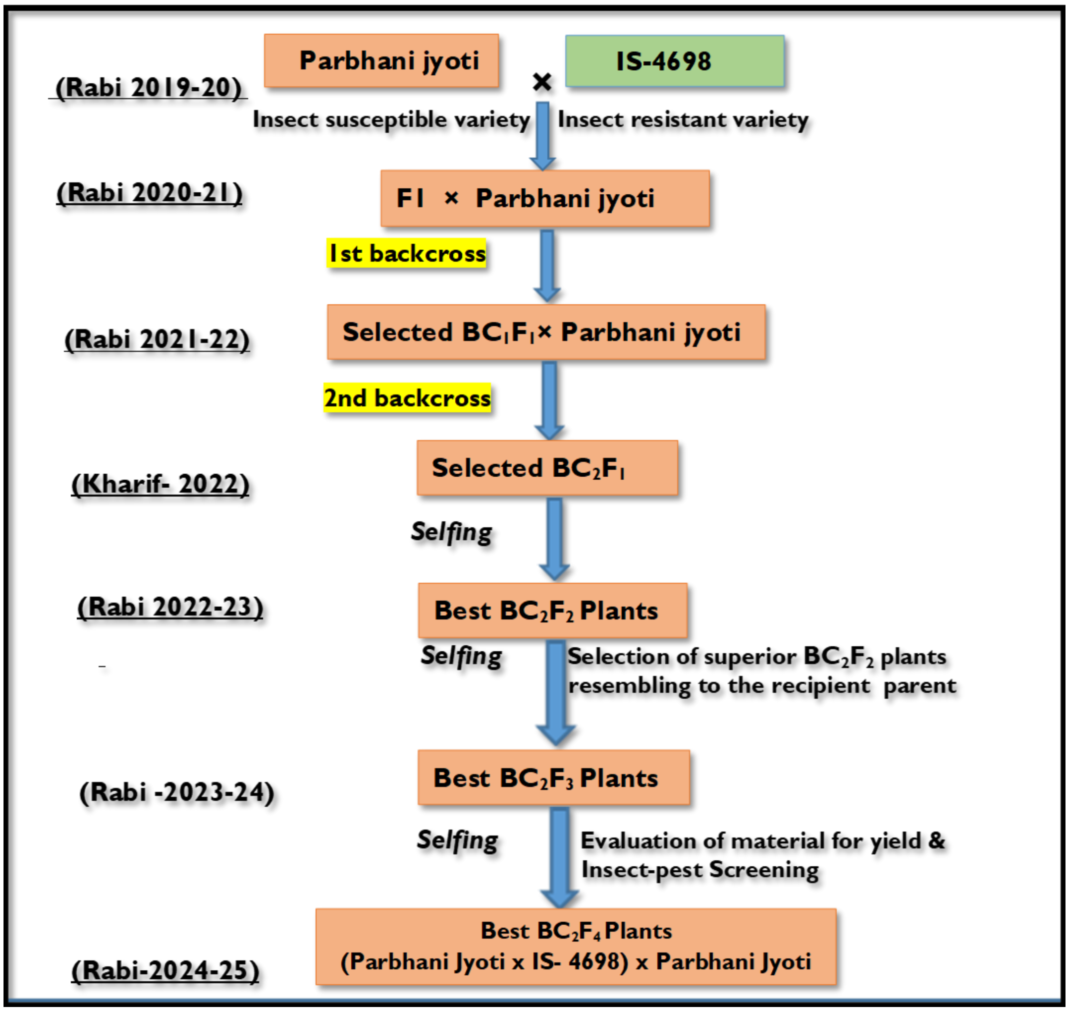


Figure 1. Breeding scheme used for the development of stem borer-resistant backcross lines for the cross Parbhani Jyoti × IS-4698. Similar pattern was followed for other crosses BJV-44 × SLR 31(Aphid) SPV-2217 × RSV-2121(Shoot bug), BJV-44 × IS-23684 (for rust resistance) and CSV-29R × RSV-827 (for drought tolerance).

Screening for Biotic and Abiotic Stresses

Stem borer screening: Advanced BC_2F_4 backcross-derived lines along with recurrent and donor parents were evaluated for stem borer (Chilo partellus) resistance under natural hotspot conditions during Rabi 2024–25 at Solapur, Rahuri, Parbhani and Vijayapura. Dead-heart incidence was recorded at 21–28 days after emergence, and stem borer damage was expressed as:

$$\text{Dead heart (\%)} = \frac{\text{Number of dead-heart plants}}{\text{Total number of plants}} \times 100$$

Lower dead-heart percentage indicated higher resistance.

Rust screening: Rust resistance was evaluated under natural epiphytotic conditions during Rabi 2024–25 at Dharwad, Rahuri, Parbhani and Solapur. Disease severity was recorded at the dough stage using a 1–9 disease rating scale, where 1–3 = resistant, 4–6 = moderately susceptible, and 7–9 = susceptible. Lower disease scores indicated stable resistance to Puccinia purpurea.

Lysimeter-based drought screening: Drought tolerance of selected BC_2F_4 lines was evaluated during Rabi 2024–25 at ICAR–IIMR, Hyderabad using a PVC-based gravimetric lysimeter under well-watered (WW) and water-stressed (WS) conditions. Terminal drought stress was imposed by withholding irrigation after crop establishment (35–45 DAS). Daily lysimeter weight measurements were used to estimate transpiration rate (TR), transpiration efficiency (TE), total water use (TWU), shoot biomass, harvest index (HI) and grain yield. Grain yield under drought stress was interpreted using the relationship: All observations were recorded up to physiological maturity following the standard gravimetric lysimeter methodology described by Blum (1988) and Ludlow and Muchow (1990).

Figure 2. Lysimeter-based drought phenotyping facility at ICAR–Indian Institute of Millets Research (IIMR), Hyderabad, showing the rain-out shelter and gravimetric PVC lysimeter system used to evaluate BC_2F_4 backcross-derived sorghum lines under well-watered and terminal drought stress conditions. The facility was used to measure transpiration rate, transpiration efficiency, total water use, biomass accumulation, harvest index and grain yield.

Observations and Traits Recorded

Morphological agronomic and physiological traits recorded included days to 50% flowering (DFF; days), 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

Experimental data were subjected to analysis of variance (ANOVA) using RAISINS statistical software following the procedure described by Panse and Sukhatme (1967) for a randomized complete block design. Genotypic means were compared using the critical difference (CD) test at the 5% probability level. Standard error of mean (SEm), standard error of difference (SEd) and coefficient of variation (CV%) were estimated for all measured traits. Descriptive statistics were used to summarize drought-related physiological parameters recorded under lysimeter conditions.

RESULTS AND DISCUSSION

Table 4. Analysis of variance (ANOVA) for agronomic traits and physiological traits in BC2F4 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
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)*

Analysis of variance (ANOVA) for agronomic and physiological traits

Analysis of variance (ANOVA) revealed significant differences among the BC_2F_4 backcross-derived lines, recurrent parents and donor parents for most agronomic and physiological traits, indicating the presence of substantial genetic variability for effective selection (Table 4). Highly significant ($P \leq 0.01$) treatment effects were observed for days to 50% flowering (F = 10.41), plant height (F = 5.66), panicle exertion (F = 2.83), peduncle length (F = 4.74), panicle weight (F = 2.41), grain yield per plant (F = 2.18), 100-seed weight (F = 3.57), SPAD (F = 7.32) and relative water content (RWC) (F = 6.97), whereas panicle length (F = 1.67) and harvest index (F = 1.79) were significant at the 5% level. In contrast, specific leaf weight (SLW) did not differ significantly among the genotypes (F = 0.98), suggesting limited genetic variation for this trait under the experimental conditions. The low coefficient of variation for days to 50% flowering (2.69%), 100-seed weight (6.19%), plant height (8.55%) and RWC (6.04%) indicated high experimental precision, while relatively higher CV values for grain yield (24.44%) and panicle weight (23.15%) reflected the greater environmental influence on these complex quantitative traits. Overall, the significant treatment effects for most agronomic and physiological traits confirmed the existence of adequate genetic variability among the experimental materials, providing considerable scope for selecting superior BC_2F_4 backcross-derived lines with improved agronomic performance and stress adaptation.

Table 5. Mean performance of BC2F4 Population, Recurrent parent and Donor Parents for Agronomic traits and physiological traits

Identity	DF(50%)	Plant Height (cm)	Panicle Exertion(cm)	Peduncle length (cm)	Panicle Length (cm)	PW/Plt (g)	GW/Plt(g)	FodderWt/plt (g)	100 Seed Wt(g)	Harvest index(%)	SPAD(SCMR)	RWC(%)	SLW(g cm⁻²)
BC2F4-1	69.00	222.67	11.27	37.20	15.13	46.00	37.89	38.55	3.52	47.73	54.69	64.80	0.12
BC2F4-2	66.00	219.33	12.73	37.40	15.83	50.32	42.38	42.07	3.59	48.84	62.88	64.20	0.10

BC2F4-3	64.00	228.00	14.27	37.53	16.37	44.56	36.93	29.37	3.45	51.70	48.03	76.19	0.38
BC2F4-4	69.33	250.67	10.40	35.67	18.17	73.40	57.93	32.38	3.45	54.92	67.68	69.87	0.13
BC2F4-5	62.33	213.67	10.67	35.13	14.90	49.57	41.31	43.48	3.68	44.29	40.72	70.05	0.12
BC2F4-6	67.00	236.67	11.27	34.67	17.10	56.22	45.72	33.46	3.46	50.00	44.74	68.63	0.11
BC2F4-7	63.33	230.33	10.40	35.00	15.33	52.28	42.48	43.85	3.55	43.84	49.09	73.34	0.20
BC2F4-8	68.67	227.67	7.73	32.27	16.67	50.67	41.33	35.40	3.50	48.31	43.70	75.92	0.10
BC2F4-9	65.33	233.87	10.47	35.87	15.80	47.50	39.23	58.72	3.63	37.99	35.49	69.40	0.10
BC2F4-10	66.67	237.33	11.13	38.27	16.87	49.94	40.44	58.69	3.37	37.63	61.94	69.84	0.10
BC2F4-11	64.67	243.00	11.20	37.67	16.27	54.67	46.08	37.37	3.74	50.06	37.90	68.90	0.10
BC2F4-12	66.00	244.33	9.00	37.47	16.97	45.39	37.23	47.90	3.72	39.71	41.11	81.93	0.11
BC2F4-13	62.67	231.00	8.93	32.60	16.30	40.73	33.35	33.33	3.58	45.14	35.52	73.82	0.11
BC2F4-14	73.33	223.33	8.07	36.33	16.87	66.04	52.01	45.27	3.45	46.12	54.51	70.05	0.11
BC2F4-15	70.67	235.40	10.60	40.00	18.47	60.25	50.17	35.89	3.45	52.32	45.06	74.94	0.12
BC2F4-16	70.00	250.67	12.67	41.40	19.03	58.05	45.67	39.93	3.14	46.37	42.14	74.13	0.12
BC2F4-17	72.33	257.00	11.80	40.27	18.17	60.33	46.90	36.34	3.06	48.51	38.26	72.46	0.11
BC2F4-18	67.33	228.33	11.60	38.53	14.87	44.94	37.48	45.52	3.91	41.72	51.33	82.19	0.13
BC2F4-19	69.00	244.07	12.80	40.33	19.27	58.94	47.53	39.81	3.49	48.14	51.28	77.96	0.13
RP-20	70.00	228.67	9.27	37.67	16.17	47.70	36.64	35.11	3.79	44.09	66.13	75.60	0.13
RP-21	68.00	231.07	11.07	39.20	15.90	45.82	34.52	44.53	3.78	38.64	52.49	75.70	0.12

RP-22	72.33	266.67	11.60	41.67	19.13	56.27	42.07	38.38	3.26	43.47	53.19	72.03	0.14
RP-23	71.33	248.33	9.67	38.00	19.27	62.80	48.07	38.39	3.09	47.09	41.42	74.21	0.12
RP-24	65.33	224.67	9.47	37.33	18.00	41.29	33.18	37.83	3.63	41.94	46.88	93.45	0.14
RP-25	63.33	220.67	9.93	37.47	16.83	40.49	32.62	35.46	3.70	41.98	47.60	65.23	0.13
DP-26	64.33	203.67	7.93	31.00	13.50	40.39	33.08	28.32	3.47	47.48	43.92	63.96	0.12
DP-27	64.00	187.00	8.67	36.13	13.37	27.42	21.13	50.49	3.83	26.77	54.33	68.57	0.09
DP-28	62.33	139.73	12.67	36.73	15.87	43.21	31.82	25.96	3.27	45.84	48.97	74.36	0.11
DP-29	64.67	180.33	9.73	30.07	21.50	38.06	30.38	31.59	3.35	46.36	52.93	71.79	0.12
DP-30	68.00	185.33	6.53	23.20	9.93	47.10	35.58	25.20	2.95	51.02	46.79	70.61	0.12
DP-31	71.33	224.33	12.87	37.40	17.50	51.02	40.88	33.69	3.76	50.02	42.38	73.82	0.11
DP-32	61.33	177.33	13.13	42.87	16.83	24.55	19.04	30.39	3.31	35.78	45.04	54.62	0.07
Mean	67.00	224.22	10.61	36.64	16.63	49.25	39.41	38.52	3.50	45.12	48.38	72.27	0.23
Standard Deviation	3.36	26.32	1.80	3.80	2.12	10.21	8.21	8.11	0.24	5.69	8.30	6.65	0.66
Minimum	61.33	139.73	6.53	23.20	9.93	24.55	19.04	25.20	2.95	26.77	35.49	54.62	0.07
Maximum	73.33	266.67	14.27	42.87	21.50	73.40	57.93	58.72	3.91	54.92	67.68	93.45	3.85
Confidence Level(95.0%)	1.21	9.49	0.65	1.37	0.76	3.68	2.96	2.93	0.09	2.05	2.99	2.40	0.24

Mean performance of BC2F4 population, recurrent parents and donor parents for agronomic and physiological traits

The mean performance of nineteen BC_2F_4 backcross-derived lines together with six recurrent parents and seven donor parents for agronomic and physiological traits is presented in Table 5. Considerable variation was observed among the genotypes for all the traits studied, indicating the effectiveness of the conventional backcross breeding programme in generating genetic variability while recovering the desirable characteristics of the recurrent parents. The experimental population recorded an overall mean of 67.00 days to 50% flowering, 224.22 cm plant height, 49.25 g panicle weight, 39.41 g grain yield per plant, 3.50 g hundred-seed weight, 45.12% harvest index, 48.38 SPAD value, 72.27% relative water content (RWC) and 0.23 g cm^{-2} specific leaf weight (SLW). Among the agronomic traits, days to 50% flowering ranged from 61.33 to 73.33 days, with BC_2F_4-5 (62.33 days) and BC_2F_4-13 (62.67 days) flowering earliest, whereas BC_2F_4-14 (73.33 days) and BC_2F_4-17 (72.33 days) were comparatively late flowering. Plant height varied from 139.73 to 266.67 cm, with BC_2F_4-17 (257.00 cm), BC_2F_4-4 (250.67 cm) and BC_2F_4-16 (250.67 cm) being among the tallest backcross-derived lines. Grain yield per plant exhibited substantial variation, ranging from 19.04 to 57.93 g, with BC_2F_4-4 recording the highest grain yield (57.93 g $plant^{-1}$), followed by BC_2F_4-14 (52.01 g $plant^{-1}$) and BC_2F_4-15 (50.17 g $plant^{-1}$). These superior yielding lines also possessed desirable panicle characteristics and harvest index, demonstrating the successful recovery of the elite recurrent parent background without compromising productivity. Panicle weight ranged from 24.55 to 73.40 g, with BC_2F_4-4 producing the heaviest panicles (73.40 g). Harvest index varied from 26.77 to 54.92%, and the highest values among the BC_2F_4 lines were recorded in BC_2F_4-4 (54.92%) and BC_2F_4-15 (52.32%), indicating greater assimilate partitioning towards grain production. Hundred-seed weight ranged from 2.95 to 3.91 g, with BC_2F_4-18 (3.91 g), BC_2F_4-11 (3.74 g) and BC_2F_4-5 (3.68 g) producing comparatively bolder grains than several recurrent parents. Considerable variation was also observed for physiological traits associated with plant performance under post-rainy season conditions. SPAD chlorophyll content ranged from 35.49 to 67.68, with BC_2F_4-4 (67.68), BC_2F_4-2 (62.88) and BC_2F_4-10 (61.94) recording the highest values, suggesting improved chlorophyll retention and delayed leaf senescence. Relative water content ranged from 54.62 to 93.45%, with BC_2F_4-18 (82.19%), BC_2F_4-12 (81.93%) and BC_2F_4-19 (77.96%) maintaining comparatively higher leaf water status. Specific leaf weight varied from 0.07 to 0.38 g cm^{-2}, with BC_2F_4-3 (0.38 g cm^{-2}), BC_2F_4-7 (0.20 g cm^{-2}) and BC_2F_4-18/BC_2F_4-19 (0.13 g cm^{-2}) exhibiting relatively higher values, reflecting improved leaf structural characteristics. Comparison of the advanced backcross-derived lines with their recurrent and donor parents revealed that several BC_2F_4 lines equalled or surpassed the recurrent parents for important agronomic and physiological traits while maintaining desirable maturity duration. In particular, BC_2F_4-4 {(BJV-44 × SLR-31) × BJV-44} emerged as the most promising line, recording the highest grain yield, panicle weight, harvest index and SPAD chlorophyll content. Similarly, BC_2F_4-14 {(SPV-2217 × SLR-10) × SPV-2217} and BC_2F_4-15 {(CSV-29R × SLR-10) × CSV-29R} consistently exhibited superior grain yield, favourable harvest index and desirable agronomic performance, indicating effective recovery of the recurrent parent phenotype together with favourable donor alleles. Although BC_2F_4-12, BC_2F_4-17, BC_2F_4-18 and BC_2F_4-19 maintained comparatively higher relative water content and favourable physiological attributes, their drought adaptation was further validated under controlled lysimeter evaluation. In contrast, donor parents generally expressed the target stress-resistance traits but exhibited comparatively lower grain yield and harvest index, confirming their primary role as sources of stress tolerance rather than agronomically superior cultivars. Overall, the superior performance of several BC_2F_4 backcross-derived lines demonstrates that conventional backcross breeding effectively combined improved agronomic performance with enhanced physiological efficiency, providing elite breeding materials for the development of high-yielding and multiple stress-tolerant rabi sorghum cultivars.

Screening for Drought Tolerance: Lysimeter-Based Drought Screening (ICAR–IIMR, Hyderabad)

Table 6 Performance of back cross derived lines for key water use traits contributing to drought stress tolerance

S.N	Identity	Transpiration Rate (g/day /plant)		Transpiration efficiency (g/day /plant)		Total water use (kg/plant)		Shoot biomass (g /plant)		Harvest Index (g /plant)		Grain Yield (g /plant)	
		WW	WS	WW	WS	WW	WS	WW	WS	WW	WS	WW	WS
Back-cross derived lines													
1	S24001RV	122.47	106.97	8.65	9.60	16.45	12.05	170.10	138.13	0.50	0.45	80.58	60.81
2	S24002RV	125.21	108.50	8.51	9.92	16.21	11.45	172.58	139.45	0.53	0.44	82.34	61.75
3	S24003RV	129.57	110.15	8.68	10.84	17.82	13.24	189.82	154.14	0.55	0.48	88.30	70.25
4	S24004RV	123.57	106.60	8.21	9.75	17.46	12.36	186.14	151.57	0.54	0.47	87.02	68.87
	R-1 (CSV 29R)	110.47	98.97	7.20	8.60	14.04	10.35	152.10	135.13	0.45	0.41	70.58	50.81

	D-1 (RSV 827)	121.47	105.97	7.90	9.60	16.04	11.35	169.10	137.13	0.48	0.45	78.58	52.81

Lysimeter-based drought screening

Significant genotypic variation was observed among the backcross-derived lines for water-use traits, biomass production and grain yield under terminal drought stress (Table 6). Under water-stressed (WS) conditions, all genotypes exhibited reduced transpiration rate; however, the BC_2F_4 lines maintained higher values than the recurrent parent, CSV-29R. Among the evaluated entries, S24003RV recorded the highest transpiration rate (110.15 g day^{-1} plant^{-1}), transpiration efficiency (10.84), total water use (13.24 kg plant^{-1}) and shoot biomass (154.14 g plant^{-1}), followed by S24002RV and S24004RV. In contrast, CSV-29R recorded the lowest values for transpiration rate (98.97 g day^{-1} plant^{-1}), transpiration efficiency (8.60), total water use (10.35 kg plant^{-1}) and shoot biomass (135.13 g plant^{-1}). Grain yield under drought stress also differed markedly among the genotypes. S24003RV produced the highest grain yield (70.25 g plant^{-1}), followed by S24004RV (68.87 g plant^{-1}), whereas the recurrent parent CSV-29R and donor parent RSV-827 recorded 50.81 and 52.81 g plant^{-1}, respectively. Similarly, S24003RV maintained the highest harvest index (0.48) under water stress, indicating superior partitioning of assimilates towards grain production.

Performance across field and controlled environments

The drought-tolerant backcross-derived line (CSV-29R × RSV-827) × CSV-29R (S24003RV) consistently exhibited superior performance under both field and lysimeter evaluations. The line combined improved agronomic performance with higher transpiration efficiency, greater water extraction, increased biomass accumulation and superior grain yield under terminal drought stress, demonstrating successful introgression of drought-tolerance traits into the elite recurrent parent background.

Screening for Stem Borer Resistance:

Stem Borer Resistance Screening Under Multi-Location Epiphytotic Conditions (Rabi 2024–25)

Table 7 Performance of back cross derived lines for Stem borer resistance

S. N	Identity	Stem borer (% Dead Hearts)				
		Vijjayapura	Rahuri	Solapur	Parbhani	Mean
1	S24005RV	2.8	2.6	2.42	2.5	2.58
2	S24006RV	3.02	2.8	2.9	2.8	2.88
3	S24007RV	2.42	2.5	2.38	2.4	2.425
4	S24008RV	3.5	2.8	2.1	2	2.6
	R-2 (Parbhani Jyoti)	6.2	5.8	8	7	6.75
	D-2 (IS 4698)	4	3.9	4.6	4.2	4.175
	Susceptible check - Swarna	17.1	18	16.5	15.6	16.8
	Resistant check – IS 2205	4.5	4.2	4	4.3	4.25

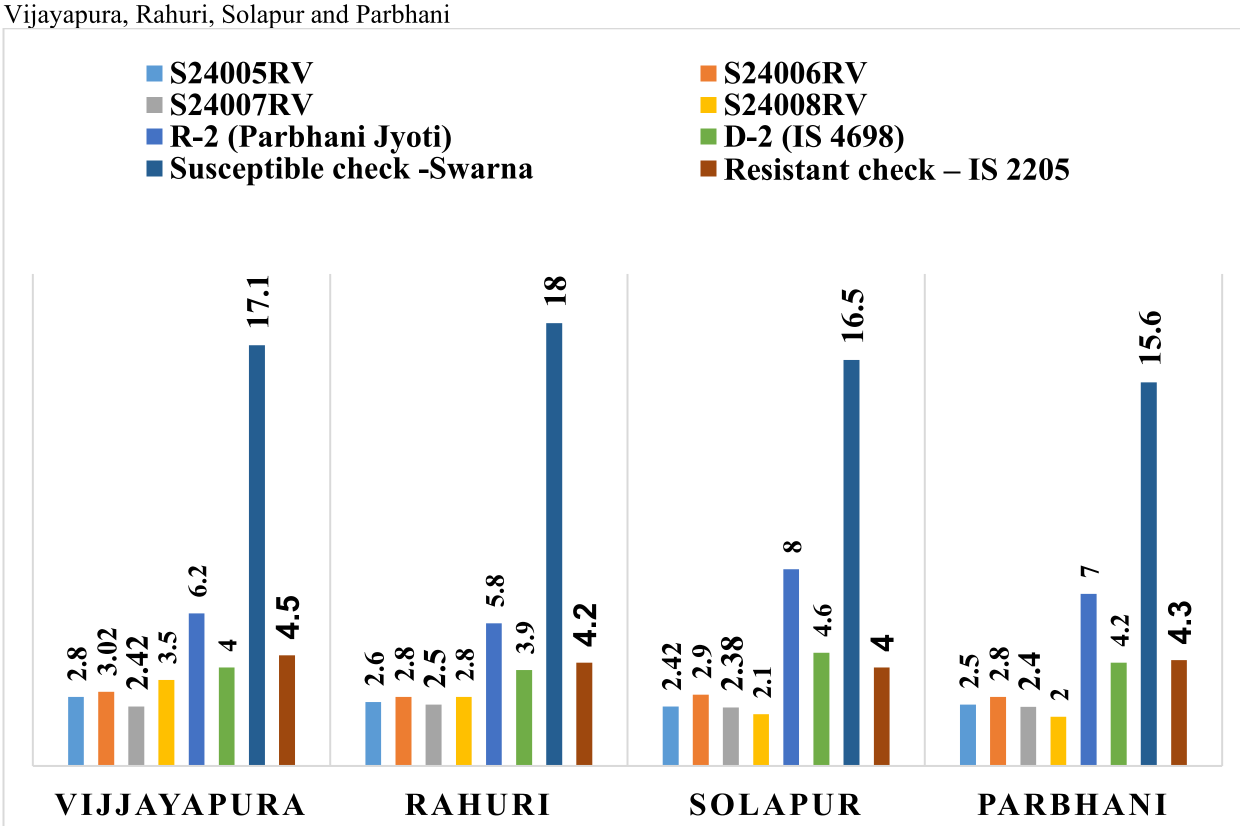
Screening Methodology: Evaluations were carried out at multi-location hotspots (Solapur, Rahuri, Parbhani, and Vijayapura) by recording dead heart percentages.

Stem borer resistance under field conditions: Significant variation was observed among the BC_2F_4 backcross-derived lines, parents and checks for stem borer incidence across the four hotspot locations (Vijayapura, Rahuri, Solapur and

Parbhani) (Table 7). The susceptible check, Swarna, consistently recorded the highest dead-heart incidence (15.6–18.0%), whereas the resistant check, IS 2205, and the donor parent IS 4698 exhibited low dead-heart percentages (approximately 4.0–4.6%), confirming the effectiveness of the screening environments. The BC_2F_4 lines exhibited significantly lower dead-heart incidence than the recurrent parent Parbhani Jyoti across all locations. Dead-heart percentages in the backcross-derived lines ranged from 2.42 to 3.50% at Vijayapura, 2.50 to 2.80% at Rahuri, 2.10 to 2.90% at Solapur and 2.00 to 2.80% at Parbhani. Among the evaluated entries, S24007RV and S24008RV consistently recorded the lowest dead-heart percentages across locations, indicating stable stem borer resistance.

The mean performance across environments demonstrated that the BC_2F_4 lines maintained lower dead-heart incidence than both the recurrent parent and the donor parent, suggesting successful introgression and stabilization of stem borer resistance in the elite genetic background. The consistent performance across diverse environments further indicated the stability of resistance in the advanced backcross-derived lines, making S24007RV and S24008RV promising candidates for utilization in rabi sorghum improvement programmes.

Figure 3. Multi-location evaluation of BC_2F_4 backcross-derived lines for stem borer resistance (dead heart %) across Vijayapura, Rahuri, Solapur and Parbhani



Screening for Rust: Rust Resistance: Multi-location Epiphytotic Screening for Rust Resistance

Table 8 Performance of back cross derived lines for rust resistance

S. N	Identity	Rust (1-9 scale))				
		Vijjayapura	**Rahuri**	**Solapur**	**Dharwad**	**Mean**
1	S24009RV	2	2	3	2	2.25
2	S24010RV	2	3	3	2	2.5
3	S24011RV	3	2	2	2	2.25
4	S24012RV	3	2	3	2	2.5
	R-3 (BJV 44)	7	6	8	6	6.75

	D-3 (IS 23684)	3	2	3	3	2.75

Rust resistance under multi-location field conditions: The BC_2F_4 backcross-derived lines exhibited significant variation for rust resistance across the four hotspot locations (Vijayapura, Rahuri, Solapur and Dharwad) under natural epiphytotic conditions (Table 8). The recurrent parent BJV 44 consistently recorded higher rust scores (6–8), indicating susceptibility, whereas the donor parent IS 23684 maintained low disease scores (2–3), confirming its resistance. The BC_2F_4 lines (S24009RV, S24010RV, S24011RV and S24012RV) consistently recorded lower rust severity (2–3) across all locations, demonstrating stable resistance under varying disease pressure. At Solapur, where rust incidence was comparatively higher, the backcross-derived lines maintained low disease scores, while the recurrent parent exhibited maximum disease severity. The mean rust scores of the BC_2F_4 lines (2.2–2.6) were comparable to the donor parent and substantially lower than the recurrent parent, indicating successful introgression of rust resistance into the elite genetic background. The consistent expression of resistance across locations suggests the stability of the introgressed resistance and identifies the BC_2F_4 lines as promising genetic resources for the development of rust-resistant rabi sorghum cultivars.

Overall performance of BC_2F_4 backcross-derived lines under biotic and abiotic stress screening

Overall, multi-location evaluation for stem borer and rust resistance, together with lysimeter-based drought screening, demonstrated the effectiveness of the backcross breeding programme in improving popular rabi sorghum cultivars for multiple stress tolerance. The BC_2F_4 lines exhibited significantly lower stem borer damage and rust severity than their respective recurrent parents while maintaining superior drought-adaptive traits, including higher transpiration efficiency, biomass accumulation and grain yield under terminal drought stress. Among the evaluated entries, S24007RV and S24008RV showed stable resistance to stem borer, S24009RV–S24012RV expressed consistent rust resistance across locations, and S24003RV emerged as the most drought-tolerant line under lysimeter conditions. These results confirm the successful introgression and stable expression of target stress-tolerance traits in the elite recurrent parent backgrounds, identifying the advanced backcross-derived lines as promising genetic resources for the development of climate-resilient rabi sorghum cultivars.

CONCLUSION

The present investigation demonstrated that conventional backcross breeding is an effective strategy for developing stress-tolerant versions of popular rabi sorghum cultivars while maintaining superior agronomic performance. Significant genetic variability among the BC_2F_4 backcross-derived lines confirmed the successful introgression of desirable alleles for yield, physiological efficiency and stress tolerance. Field evaluation identified BC2F4-4 {(BJV-44 × SLR-31) × BJV-44}, BC2F4-14 {(SPV-2217 × SLR-10) × SPV-2217} and BC2F4-15 {(CSV-29R × SLR-10) × CSV-29R} as superior lines for grain yield, harvest index and overall agronomic performance, whereas BC2F4-18 {(Parbhani Jyoti × RNTN-13-37) × Parbhani Jyoti}, BC_2F_4-12 {(SPV-2217 × RSV-2121) × SPV-2217} and BC2F4-19 {(BJV-44 × RNTN-13-37) × BJV-44} exhibited superior physiological performance associated with drought adaptation. Multi-environment screening further validated the breeding approach, with S24003RV exhibiting superior drought tolerance under lysimeter conditions, S24007RV and S24005RV showing stable stem borer resistance, and S24009RV–S24012RV expressing consistent rust resistance across hotspot locations. Overall, the study demonstrated that conventional backcross breeding can successfully pyramid multiple stress-tolerance traits into elite rabi sorghum backgrounds without compromising productivity. The superior BC2F4- introgression lines identified in this study represent valuable genetic resources for near-isogenic line development, multi-location evaluation and future cultivar improvement aimed at developing high-yielding, climate-resilient rabi sorghum cultivars.

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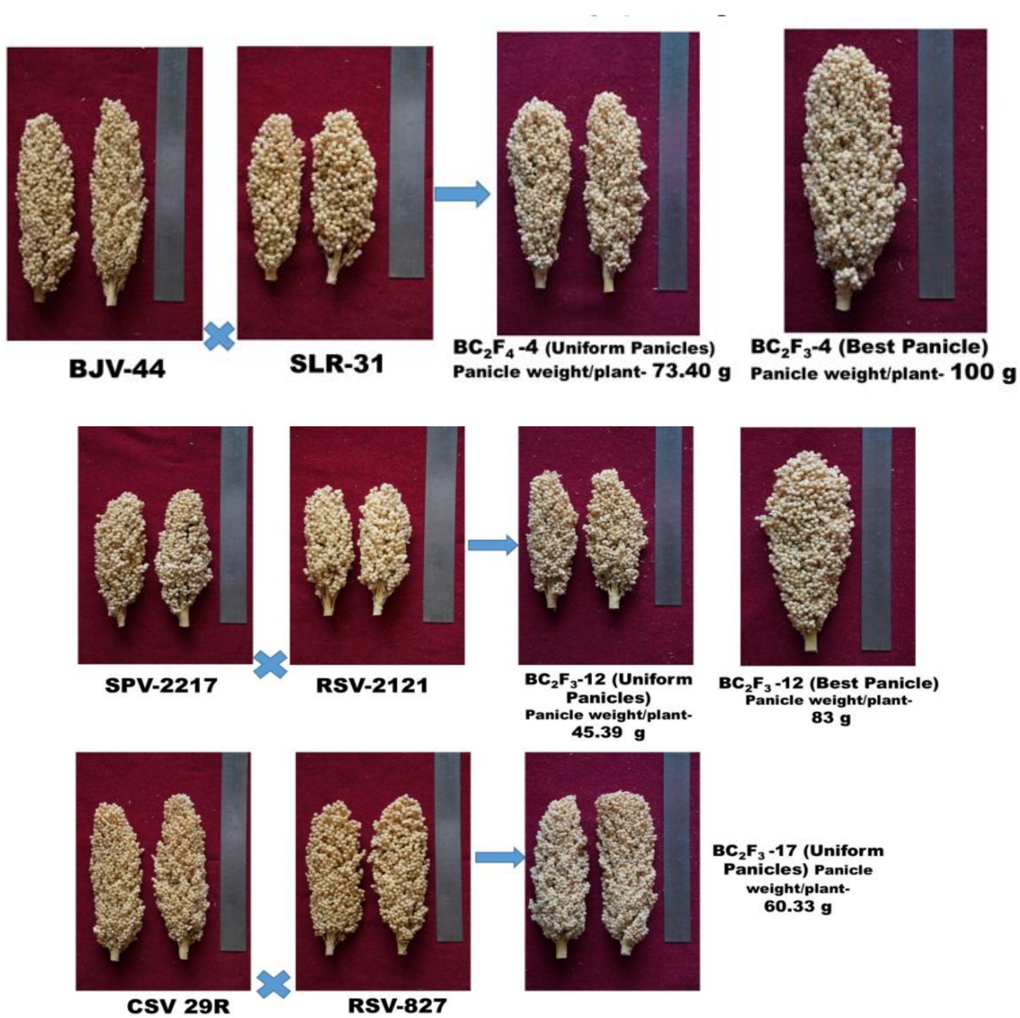

Figure 4. Panicle morphology of recurrent parents, donor parents and representative BC_2F_4 backcross-derived lines developed through conventional backcross breeding for introgression of stem borer, aphid, shoot bug and drought tolerance in rabi sorghum.

The backcross derivative (SPV-2217 × IS-4698) × SPV-2217 produced uniform, compact panicles with a panicle weight of approximately 46 g, while the superior selected plant attained 53 g. Similarly, the aphid-resistant derivative (BJV-44 × SLR-31) × BJV-44 exhibited excellent panicle uniformity with an average panicle weight of 73.40 g, and the best selected plant recorded 100 g, demonstrating considerable improvement over the parental lines. Likewise, the shoot bug-resistant derivative (SPV-2217 × RSV-2121) × SPV-2217 produced uniform panicles with an average panicle weight of 45.39 g, whereas the best selected plant recorded 83 g. The drought-tolerant derivative (CSV-29R × RSV-827) × CSV-29R also exhibited uniform panicle development with an average panicle weight of 60.33 g, indicating successful recovery of desirable agronomic characteristics along with stress tolerance. Overall, the visual uniformity and improved panicle characteristics observed among the selected BC_2F_4 lines confirm the effectiveness of conventional backcross breeding in recovering the recurrent parent phenotype while successfully introgressing resistance to stem borer, aphid, shoot bug and terminal drought. These elite backcross-derived lines represent promising breeding materials for the development of climate-resilient, high-yielding rabi sorghum cultivars.