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RESEARCH

Latitudinal Adaptation of Flowering Response to Photoperiod and Temperature in the World Collection of Sorghum Landraces

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ABSTRACT

Knowledge of photoperiod and temperature sensitivity of landraces is required to understand their latitudinal pattern of adaptation and to identify insensitive germplasm for crop improvement. Photoperiod and temperature sensitivity of 20,710 sorghum [*Sorghum bicolor* (L.) Moench] landraces was assessed under long-day rainy and short-day post-rainy seasons. The results revealed 1697 landraces to be photoperiod and temperature insensitive (PTINS), 18,766 to be photoperiod sensitive and temperature insensitive (PSTINS), and 247 to be photoperiod and temperature sensitive (PTS). Lower latitudes (0.00–25.00°) were important regions for sorghum landraces. The mean number of days to 50% flowering (DFL) was equal in both the seasons for PTINS landraces. The mean DFL was high (98 d) for PSTINS and low (63 d) for PTS in the rainy season in the entire set of landraces. The DFL in all three groups—PTINS, PSTINS, and PTS—decreased with increase in latitude. The mean cumulative growing degree days were higher for PTINS (1153°C d) and PSTINS (1587°C d) in the rainy season than in the post-rainy season (866°C d in PTINS, 905°C d in PSTINS) but were similar in both the seasons for PTS (~1040°C d). Insensitive landraces were found in higher proportions at 0.00 to 25.00° N and 15.00 to 35.00° S than at other latitudes. Evaluation of these insensitive sources for stress tolerance, and for agronomic and seed quality traits is suggested to identify parents to develop high-yielding, nutrient-dense, and climate-resilient sorghum cultivars.

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Abbreviations: CGDD, cumulative growing degree days; DFL, days to 50% flowering; GDD, growing degree days; PSTINS, photoperiod sensitive and temperature insensitive; PTINS, photoperiod and temperature insensitive; PTS, photoperiod and temperature sensitive.

SORGHUM [*Sorghum bicolor* (L.) Moench] is an important and widely adapted cereal crop grown mostly for food, fodder, and feed in both temperate and tropical regions between 40° N and 40° S of the equator (Doggett, 1988). It is a major crop in Africa; its production area encompasses West Africa, south of the Sahara, Sudan, Ethiopia, and Somalia. During 2016, globally, sorghum was grown on an estimated area of 44.77 million ha, with a production of 63.93 million tons (FAOSTAT, 2016), with Sudan (9.2 million ha), Nigeria (5.8 million ha), India (5.7 million ha), Niger (3.6 million ha), the United States (2.5 million ha), and Mexico (1.5 million ha) being the major sorghum-growing countries. Sorghum production was estimated at 12.20 million tons in the United States, 6.94 million tons in Nigeria, 6.46 million tons in Sudan, 5.01 million tons in Mexico, 4.41 million tons in India, and 1.81 million tons in Niger (FAOSTAT, 2016).

Climate change poses one of the biggest threats to food production worldwide (Villanueva et al., 2017). It is likely to adversely affect food security in many regions of the world (Dar and Gowda, 2013). Sultan et al. (2013) predicted sorghum yield losses of up to 41% in West Africa, a major sorghum-growing

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region in Africa, as a result of climate change. A central element of the sustainable agricultural development concept and the climate-smart-agriculture approach is the use of agricultural biodiversity at the genetic, species, and ecosystem levels for increasing productivity, adaptability, and resilience of agricultural production systems (Villanueva et al., 2017). Sorghum, which originated near the equator in northeastern Africa, is a short-day crop and exhibits substantial sensitivity to both photoperiod and temperature (Miller, 1982). Germplasm with reduced sensitivity or insensitivity broadens the area of adaptation of the crop, leading to sustainable production. Exploiting large germplasm databases to stratify landraces for their response to photoperiod and temperature and identifying climate-resilient sources are essential to combat climate change. Temperature sensitivity refers to the response of plants to both below- and above-optimum temperatures for various traits and stages across diverse crop seasons. Plant development is more closely related to the temperature or heat units accumulated up to a given stage than to time alone. Temperature affects the plant's rate of development throughout the life cycle, whereas photoperiod affects the duration of the inductive phase (Roberts and Summerfield, 1987). Prasad et al. (2006) reported that reproductive processes were more sensitive to high temperature than vegetative processes. Photoperiod sensitivity refers to the response of plants to daylength for flowering across diverse seasons. The critical or optimum daylength for flowering in sorghum has been reported to be 12 h 20 min (Pennington, 2011). In photoperiod sensitive cultivars, the effects of photoperiod are substantial and are the major determinant of flowering time (Craufurd and Wheeler, 2009). Insensitive plants initiate flowering, irrespective of temperature and daylength, after attaining an overall developmental stage. Crop improvement for specific locations in a wide range of latitudes is possible only when knowledge of temperature and photoperiod responses of the parental material is available. Several studies have reported on the association of latitude with response of genotypes to climate-related traits (Curtis, 1968; Roberts and Summerfield, 1987; Roberts et al., 1996; Craufurd et al., 1999; Upadhyaya et al., 2012).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has assembled, from 93 countries, 41,023 sorghum accessions, including landraces, breeding material, advanced cultivars, and wild relatives. Sorghum landraces collected from different latitudes ranging from 0.00 to 43.67° N and from 0.00 to 33.88° S have not been characterized for their response to photoperiod and temperature. It is difficult to predict plant response to photoperiod and temperature on the basis of calendar days because temperatures can vary greatly from year to year and season to season. Use of cumulative growing degree days (CGDD) and number of days for any developmental stage in a crop season is a simple and relatively accurate way to predict response of landraces to photoperiod and temperature (Gerik et al., 2003). The availability of climate data for evaluation and collection sites and GIS have opened up avenues in understanding the latitudinal distribution of genotypic sensitivity to photoperiod and temperature. Studies on latitudinal adaptation of photoperiod and temperature sensitivity of landraces in large collections are useful in identifying insensitive sources, particularly under climate change scenarios. The current study was undertaken to assess the latitudinal adaptation of flowering response to photoperiod and temperature in the world collection of sorghum landraces (20,710) assembled at the ICRISAT genebank, India, and to classify them into photoperiod and temperature insensitive and sensitive groups on the basis of their requirement of calendar days and CGDD for flowering during rainy and post-rainy seasons at ICRISAT, Patancheru, India.

MATERIALS AND METHODS

The Collection

Passport information and characterization data of the sorghum collection used in this study were updated for georeferenced data using electronic atlas and GIS software. Data on days to 50% flowering (DFL) during rainy and post-rainy seasons were retrieved from the ICRISAT sorghum germplasm characterization database (http://genebank.icrisat.org/). Depending on the availability of georeferenced data and flowering data for rainy and post-rainy seasons, a total of 20,710 landraces that originated from 37 countries were selected for the present study.

Characterization of Germplasm

Sorghum germplasm were characterized during rainy (June–November) and post-rainy (October–March) seasons in vertisols, in batches of 500 to 1000 at ICRISAT, Patancheru (17°51′ N, 78°27′ E, 545 m asl) from 1977 to 2014, as and when new germplasm entries were received at the ICRISAT genebank. These two different seasonal conditions are typical to the semiarid regions (Reddy et al., 2004). Every year, landraces were sown on 20 June (±2 d) and harvested in October or November during the rainy season, whereas in the post-rainy season, the accessions were sown on 15 October (±2 d) and harvested in March of the subsequent year. For a given location, strict photoperiodic control causes flowering to occur at a specific time of the year, independent of the date of germination, which can be highly variable (Dow El-Madina and Hall, 1986). About 100 seeds of each accession were sown in a 4-m-long row, with an inter-row spacing of 75 cm. After 2 wk, the stand was thinned, leaving ~10 cm of distance between plants to accommodate ~40 plants in a row. Fertilizer was applied at the rate of 80 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1} in both the seasons. Every year, landraces were sown in an augmented design using systematic checks (IS 2205, a promising landrace, and released cultivars IS 18758 and IS 33844) repeated after every block of 20 test accessions. Seeds were sown at a uniform depth using a four-cone planter in all years of evaluation to minimize the variation in seedling emergence, which affects germination and growing degree days (GDD) for flowering. Need-based irrigation was provided in rainy and post-rainy seasons. Weeds, pests, and diseases were controlled as needed to raise a good crop.

As part of sorghum germplasm characterization, observations were recorded on 11 qualitative and eight quantitative traits, including DFL. The observations on DFL were recorded on a plot basis during both rainy and post-rainy seasons. Emergence of anthers in 50% plants in a plot (accession) was recorded as DFL, following the descriptors for sorghum (IBPGR and ICRISAT, 1993). At ICRISAT, crop specialists (biochemists, pathologists, entomologists, and physiologists) evaluated germplasm accessions during 1974 to 2014 for seed quality traits and for the reaction of landraces to abiotic and biotic stresses and identified promising sources. Data from all such evaluations were added to the sorghum germplasm characterization database. The weather data, such as monthly mean (across the past 42 yr) daylength, minimum and maximum temperatures, and rainfall for ICRISAT, Patancheru, were retrieved from http://icrisat-intranet/nrmp/agroclimatology/weather.asp. Daylength varied from 13.20 (on 29 June) to 11.10 h (on 1 December) during the rainy season and from 11.10 (on 1 December) to 12.00 h (on 17 March) during the post-rainy season. During the rainy season, the monthly mean minimum temperature varied from 23.7 (in June) to 15.9°C (in November) and the monthly mean maximum temperature ranged from 34.4°C (in June) to 28.9°C (in November). During the post-rainy season, monthly mean minimum temperature ranged from 19.5 (in October) to 12.9°C (in December), and the mean maximum temperature ranged from 28.1 (in December) to 35.2°C (in March). The mean annual rainfall was 889 mm. The number of GDD or heat units is commonly used to predict plant growth stages. The GDD were estimated using the data on DFL and daily minimum and maximum atmospheric temperature and the base temperature for sorghum. The GDD were computed using the equation GDD = [(daily maximum temperature + daily minimum temperature)/2] − 10°C, the base temperature for sorghum.

Gerik et al. (2003) reported 10°C as the base temperature for sorghum. The GDD per calendar day varied from 18.29 (on 20 June) to 10.30°C d (on 9 December) in the rainy season and from 9.78 (on 27 December) to 16.94°C d (on 15 March) in the post-rainy season. The CGDD was computed as follows: CGDD = the sum of all daily GDD from the effective date of sowing to the date of 50% flowering.

The differences in DFL and CGDD requirement during long-day rainy and short-day post-rainy seasons were used to classify landraces as sensitive or insensitive to photoperiod and temperature, respectively. Thus, when the difference between DFL in rainy and post-rainy seasons was equivalent to ± two calendar days, the landraces were classified as photoperiod insensitive and the rest were classified as photoperiod sensitive. In the case of temperature, when the difference in CGDD requirements in the rainy and post-rainy seasons was equivalent to ± two calendar days (−34 to + 34°C d), the landraces were classified as temperature sensitive and the remaining landraces on both sides (+ and −) were classified as temperature insensitive. This procedure resulted in three groups of landraces (photoperiod and temperature insensitive [PTINS], photoperiod sensitive and temperature insensitive [PSTINS], and photoperiod and temperature sensitive [PTS]) and served as a preliminary tool to stratify the large number (20,710) of sorghum landraces for their sensitivity to photoperiod and temperature.

Characterization data, recorded across several years, reflected genetic differences among the landraces (Upadhyaya et al., 2007). Range and mean DFL and CGDD requirements for flowering in the rainy and post-rainy seasons were estimated for the entire set (20,710; i.e., landraces from northern and southern hemispheres and from different latitudes within a hemisphere). Similarly, range and mean DFL and CGDD were estimated for PTINS, PSTINS, and PTS landraces. Frequencies were estimated for each group of landraces in the entire collection, in the northern and southern hemispheres, and for latitudinal ranges within each hemisphere. Landraces requiring the lowest and highest DFL and CGDD for flowering during the rainy and post-rainy seasons were identified. Climate data, such as monthly mean (across the past 30 yr) minimum and maximum temperatures, rainfall, and daylength for collection sites of all landraces, were retrieved from http://www.worldclim.org/current (accessed in February 2017). The high-resolution (1 km) interpolated climate surfaces are a useful source of data for studying the spatial relationship between environmental variables and the vegetation existing at that location. Monthly climate variables were extracted from WorldClim (http://www.worldclim.org/, accessed in June 2011; Hijmans et al., 2005) surfaces for each landrace using the spatial analyst extension in ArcGIS software (ESRI, 2016), and analyzed. Irrespective of hemisphere, the lowest and highest mean daylength; minimum, maximum, and mean temperatures; and mean annual rainfall were estimated for each latitude range. The total and the three groups of landraces (PTINS, PSTINS, and PTS) were plotted on world map using ArcGIS to show their geographical distribution.

RESULTS AND DISCUSSION

Sensitivity of Landraces to Photoperiod and Temperature

The differences in DFL and CGDD requirements during long-day rainy seasons and short-day post-rainy seasons were used to classify landraces into three groups: PTINS (1697 accessions), PSTINS (18,766 accessions), and PTS (247 accessions) (Fig. 1, Table 1). The difference in DFL between rainy and post-rainy seasons for PTINS landraces was within 2 d and adapted to both long-day rainy and short-day post-rainy seasons. The PTS landraces flowered early in the rainy season compared with the post-rainy season and showed similar CGDD requirement (±34°C d). The PSTINS landraces showed different adaptation patterns relative to DFL and CGDD requirement for flowering and were, therefore, further divided into three subgroups. The landraces that took fewer days and CGDD for flowering in the rainy season than in the post-rainy (213 landraces) were grouped into Subgroup 1. The landraces that took fewer days and more CGDD in the rainy season

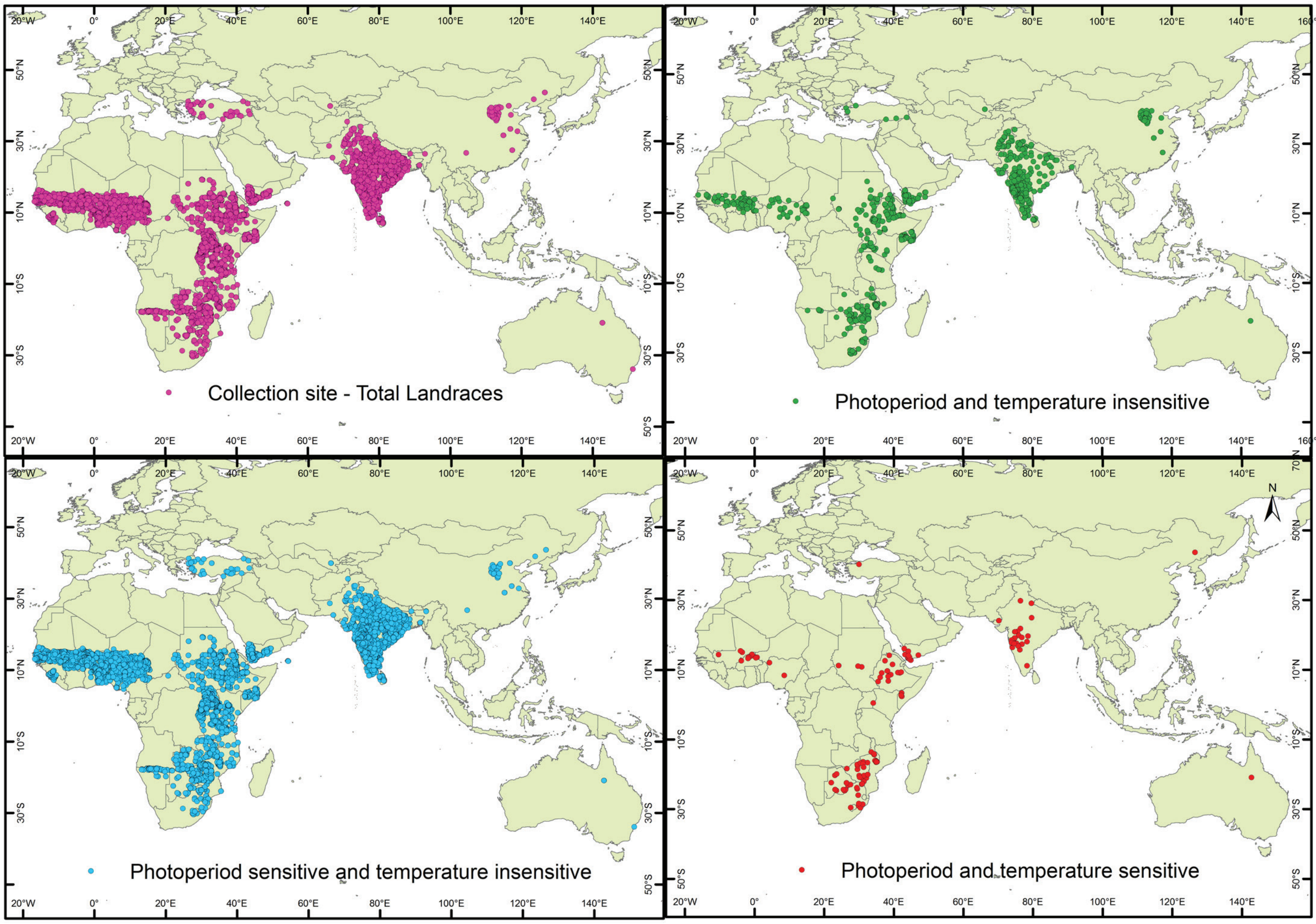

Fig. 1. Latitudinal distribution of total (20,710), photoperiod and temperature insensitive, photoperiod sensitive and temperature insensitive, and photoperiod and temperature sensitive landraces of sorghum conserved at the ICRISAT genebank, India.

than in the post-rainy (2789 landraces) were grouped into Subgroup 2, and the landraces that took more days and more CGDD in the rainy season than in the post-rainy (15,764 accessions) were grouped into Subgroup 3 (data not shown). Subgrouping of PSTINS landraces indicated their selective adaptation either to rainy season (Subgroup 1 and 2 landraces) or post-rainy season (Subgroup 3 landraces). Interestingly, the northern hemisphere was found to be an important source of Subgroup 2 (74.8%) and 3 (84.7%) landraces, whereas the southern hemisphere was an important source of Subgroup 1 landraces (81.7%).

Adaptation Pattern of Landraces

The analysis of passport data of sorghum landraces conserved at the ICRISAT genebank revealed that the collection was from latitudes ranging from 0.00 to 43.67° N and from 0.00 to 33.88° S (Table 1). The northern hemisphere was found to be an important source, contributing 81.5% of total landraces compared with the southern hemisphere (18.5%). Lower latitudes (0.00–25.00°) on either side of the equator contributed 92% of landraces, whereas the higher latitudes contributed only 8% of landraces. The higher frequency of landraces between the Tropic of Cancer and the Tropic of Capricorn (0.00–23.00° latitudes) could be attributed to the adaptation of sorghum to the prevailing equatorial climate characterized by ~12-h daylength and a steady and narrow range of annual temperatures and optimal precipitation at collection sites. On the other hand, because of longer days, below-optimal temperature, and low rainfall, the frequency of landraces decreased with the increase in latitude.

Frequency distribution for photoperiod and temperature sensitivity revealed that there were 8.2% PTINS, 90.6% PSTINS, and 1.2% PTS landraces in the collection. The northern hemisphere was found to be an important source for PTINS (76.1%) and PSTINS (82.5%) landraces, whereas the southern hemisphere was an important source for PTS landraces (58.3%). Within the collection from the northern hemisphere, 7.7% were PTINS, 91.7% were PSTINS, and 0.6% were PTS (Table 1). Within the southern hemisphere, 10.6% were PTINS, 85.7% were PSTINS, and 3.8% were PTS landraces (Table 1). The highest frequency of PTINS, PSTINS, and PTS landraces was from 10.00 to 15.00° N, whereas the highest frequency

Table 1. Frequency distribution of photoperiod and temperature sensitive and insensitive sorghum landraces adapted in different latitude ranges.

Latitude range	No. of landraces	Frequency of sensitive and insensitive landraces within the sensitive group			Frequency of sensitive and insensitive landraces within the latitude group		
		Photoperiod and temperature insensitive	Photoperiod sensitive and temperature insensitive	Photoperiod and temperature sensitive	Photoperiod and temperature insensitive	Photoperiod sensitive and temperature insensitive	Photoperiod and temperature sensitive
degrees		%					
Total collection	20,710	1,697 (8.2)†	18,766 (90.6)	247 (1.2)			
Northern hemisphere	16,873 (81.5)	1291 (76.1)	15,479 (82.5)	103 (41.7)	7.7	91.7	0.6
0–5	1,418	84 (6.5)	1,321 (8.5)	13 (12.6)	5.9	93.2	0.9
5–10	3,581	224 (17.4)	3,343 (21.6)	14 (13.6)	6.3	93.4	0.4
10–15	6,181	426 (33.0)	5,715 (36.9)	40 (38.8)	6.9	92.5	0.6
15–20	3,108	318 (24.6)	2,766 (17.9)	24 (23.3)	10.2	89.0	0.8
20–25	1,558	49 (3.8)	1,501 (9.7)	8 (7.8)	3.1	96.3	0.5
25–30	721	72 (5.6)	647 (4.2)	2 (1.9)	10.0	89.7	0.3
30–35	123	37 (2.9)	86 (0.6)	0 (0)	30.1	69.9	0.0
35–40	164	79 (6.1)	85 (0.5)	0 (0)	48.2	51.8	0.0
40–45	19	2 (0.2)	15 (0.1)	2 (1.9)	10.5	78.9	10.5
Southern hemisphere	3,837 (18.5)	406 (23.9)	3,287 (17.5)	144 (58.3)	10.6	85.7	3.8
0–5	1,052	13 (3.2)	1,039 (31.6)	0 (0)	1.2	98.8	0.0
5–10	204	4 (1.0)	200 (6.1)	0 (0)	2.0	98.0	0.0
10–15	305	8 (2.0)	294 (8.9)	3 (2.1)	2.6	96.4	1.0
15–20	1,027	115 (28.3)	889 (27.0)	23 (16.0)	11.2	86.6	2.2
20–25	622	79 (19.5)	486 (14.8)	57 (39.6)	12.7	78.1	9.2
25–30	483	135 (33.3)	287 (8.7)	61 (42.4)	28.0	59.4	12.6
30–35	144	52 (12.8)	92 (2.8)	0 (0)	36.1	63.9	0.0

† Values in parentheses are the frequency of landraces (%).

of PSTINS landraces was from 0.00 to 5.00° S, and PTINS and PTS landraces were from 25.00 to 30.00° S. None of the landraces from 30.00 to 40.00° N, 0.00 to 10.00° S, and 30.00 to 35.00° S were PTS. Frequency of all three groups of landraces decreased in the northern hemisphere, whereas the frequency of landraces in different latitudes in the southern hemisphere did not show any clear pattern. The PTINS landraces were in high frequency at 0.00 to 20.00° N and 15.00 to 30.00° S. Sanon et al. (2014) reported negative association between photoperiod sensitivity and latitude of origin. Craufurd et al. (1999) reported a strong relationship between photoperiod sensitivity and the latitude of sorghum collection sites. A similar association was observed in soybean [*Glycine max* (L.) Merr.], a short-day plant (Roberts et al., 1996), and a reverse relationship was observed in lentil (*Lens culinaris* Medik.), a long-day plant (Erskine et al., 1990).

Sorghum adapted to near-optimum climate at lower latitudes flowered late in the long-day rainy season as compared with the short-day post-rainy season at Patancheru (17°51′ N, 78°27′ E), resulting in a high frequency of PTINS, PSTINS, and PTS landraces from lower latitudes in northern hemisphere. The daylength was optimum (12 h, 20 min) at lower latitudes where more landraces had evolved (Pennington, 2011). Maiti (1996) reported that the mean optimum temperature range for sorghum was 21 to 35°C for seed germination, 26 to 34°C for vegetative growth and development, and 25 to 28°C for reproductive growth. Roberts and Summerfield (1987) reported the evolution of landraces or crops showing response to short days in the tropics around the equator and of crops with long-day responses in latitudes >30.00°.

The sorghum adapted to low temperature and low and inconsistent rainfall at higher latitudes is expected to flower late, but because of near-optimum minimum (15.9–23.7°C) and maximum (28.9–34.4°C) temperatures and shorter days at Patancheru than at collection sites, some accessions might have flowered early in the rainy season than in the post-rainy season, resulting in a high frequency of insensitive sources at lower latitudes (Hijmans et al., 2002; Upadhyaya et al., 2012). Generally, landraces from tropical regions (lower latitudes) are short-day plants that exhibit high photoperiod sensitivity if grown outside of the tropics, whereas landraces from temperate regions (higher latitudes) are long-day plants that exhibit less sensitivity to photoperiod if grown in the tropics (Erskine et al., 1990; Roberts et al., 1996). These landraces might have developed insensitivity because of their alternate exposure to short and long photoperiods, as well as to low and high temperatures during a long period of time (Upadhyaya et al., 2012). Pennington (2011) reported that landraces exposed to low temperatures for a longer period were less sensitive to cold. The insensitive landraces are not affected by varying climate and can adapt in all latitudes. Roberts et al. (1996) reported that sorghum landraces originating in higher latitudes (>25.00°) were less photoperiod sensitive than those from lower latitudes (<25.00°).

Distribution of Days to 50% Flowering and Cumulative Growing Degree Days

The collection studied represented wide variations for DFL during the rainy season (33–180 d) and the post-rainy season (36–154 d) (Table 2). The variation for flowering can be attributed to the latitude of landraces' origin and associated environmental factors, such as daylength, minimum and maximum temperatures, radiation, rainfall, CGDD requirement, and sensitivity of landraces to photoperiod and temperature for flowering (Curtis, 1968; Bidinger and Rai, 1989; Craufurd et al., 1999). The number of days and CGDD requirement for flowering of sorghum landraces varied between seasons, hemispheres, and latitudes within hemispheres.

The number of days and CGDD required to trigger flowering is species and cultivar specific, and short-day plants flower rapidly as daylength decreases (Major, 1980). Sorghum, being a quantitative short-day species, flowers at all photoperiods, but earlier under short days (Shinde et al., 2013). Therefore, the range and mean DFL and CGDD requirements of sorghum landraces were lower during the short-day post-rainy season when compared with the long-day rainy season in the collections from both the hemispheres (Table 2) (Major, 1980; Alagarswamy et al., 1998; Craufurd et al., 1999). Ong and Everard (1979) also reported that each short day resulted in a 1.4-d reduction in anthesis in pearl millet [*Pennisetum glaucum* (L.) R. Br.], which is also a short-day plant.

The ranges of DFL (33–180 d in rainy and 36–154 d in post-rainy seasons) and CGDD (567.9–2679.2°C d in rainy and 489.8–1952.6°C d in post-rainy seasons) requirements in landraces from the northern hemisphere were higher than those from the southern hemisphere in both seasons. The mean DFL and CGDD requirements in the post-rainy season were higher in landraces from the southern hemisphere than those from the northern hemisphere (Table 2). These results could be attributed to the differences in hemispheres relative to the proportion of land and water, and associated climatic parameters. The northern hemisphere has 80% land and 20% ocean, whereas the southern hemisphere has 40% land and 60% ocean. Water is a good conductor of heat, and most of the radiation absorbed is stored in the deeper waters in the southern hemisphere. Land surfaces, on the other hand, conduct heat poorly; therefore, most of the absorbed radiation heats up the land surface and associated vegetation in the northern hemisphere. In addition to the vast majority of the earth's land mass, high levels of manmade pollution also contribute to the higher temperature in the northern hemisphere. Crops adapted to such warm conditions in the northern hemisphere require additional CGDD for flowering.

The range and mean DFL and CGDD requirements of landraces for flowering decreased with the increase in latitude in both hemispheres (Table 2). The relatively higher

Table 2. Range and mean of days to 50% flowering and cumulative growing degree days for sorghum landraces from different latitudes, evaluated during rainy and post-rainy seasons at ICRISAT, India.

		Days to 50% flowering				Cumulative growing degree days			
	No. of	Rainy		Post-rainy		Rainy		Post-rainy	
Latitude range	accessions	Range	Mean	Range	Mean	Range	Mean	Range	Mean
degrees		d				°C d			
Total collection	20,710	33–180	96.0	36–154	74.0	567.9–2,679.2	1,545.0	489.8–1,952.6	903.7
Northern hemisphere	16,873	33–180	97.0	36–154	73.0	567.9–2,679.2	1,562.6	489.8–1,952.6	893.8
0–5	1,418	46–165	103.0	49–154	78.0	773.6–2,517.9	1,662.5	640.6–1,952.5	949.1
5–10	3,581	42–170	109.0	40–120	79.0	711.0–2,573.7	1,752.0	537.8–1,433.2	954.5
10–15	6,181	44–172	96.0	37–139	73.0	742.5–2,594.5	1,555.7	501.9–1,708.5	890.0
15–20	3,108	46–180	90.0	36–114	73.0	773.6–2,679.2	1,451.8	489.8–1,353.8	891.4
20–25	1,558	48–154	94.0	44–105	66.0	804.8–2,390.5	1,527.5	584.0–1,242.9	818.0
25–30	721	33–140	78.0	42–100	59.0	567.9–2,213.6	1,272.6	561.1–1,182.7	751.2
30–35	123	46–144	65.0	46–79	58.0	773.6–2,265.9	1,067.4	607.0–954.5	733.1
35–40	164	47–80	59.0	50–83	60.0	789.3–1,304.4	969.1	651.8–985.8	754.2
40–45	19	41–66	58.0	50–83	67.0	695.1–1,085.7	959.9	651.8–985.8	834.5
Southern hemisphere	3,837	48–162	90.4	46–149	77.9	804.8–2,484.2	1,465.0	607.0–1,869.2	947.2
0–5	1,052	48–162	115.0	53–149	84.0	804.8–2,484.2	1,849.6	685.1–1,869.2	1,013.7
5–10	204	82–159	129.0	66–135	97.0	1,335.6–2,449.8	2,052.9	820.5–1,648.0	1,155.5
10–15	305	61–145	120.0	54–114	88.0	1,007.8–2,279.1	1,927.6	695.5–1,353.8	1,055.6
15–20	1,027	52–152	80.0	46–127	74.0	867.0–2,366.4	1,298.6	606.9–1,531.1	905.3
20–25	622	50–119	67.0	46–120	73.0	836.0–1,918.7	1,109.0	607.0–1,433.2	893.8
25–30	483	53–128	63.0	48–119	70.0	882.4–2,050.3	1,040.3	629.3–1,419.7	863.4
30–35	144	53–69	61.0	55–72	59.0	882.4–1,133.0	1,000.9	705.9–881.9	748.2

DFL and CGDD requirements of landraces from latitudes between the Tropic of Cancer and the Tropic of Capricorn (0.00–23.00° latitudes) can be attributed to the prevailing equatorial climate. The angle of the sun is almost 90° at the equator. The sunlight received at the equator is most concentrated because of this angle, which makes tropical regions relatively hotter than subtropical and temperate regions. Hence, the landraces adapted to higher temperatures in lower latitudes require more CGDD for flowering. The angle of the sun decreases as the latitude increases. In higher latitudes, the climate is temperate and areas will be colder than at the equator, because the sun shines at a "slanted" angle, and the light rays spread out across a larger area and heat up the earth's surface at a slower speed. Therefore, the CGDD requirement of landraces adapted to higher latitudes was lower compared with those adapted to lower latitudes.

Range and mean DFL were almost equal in both rainy and post-rainy seasons for PTINS landraces from both hemispheres and latitudes within hemispheres, whereas the range and mean DFL were higher for PSTINS than for PTS in the rainy season, in all latitudes across the hemispheres (Table 3). Range and mean DFL in PTINS and PSTINS landraces decreased with increase in latitude. The pattern was not clear for PTS landraces. Small deviations in pattern might be attributed to the sowing date, fluctuations in climate at evaluation location, and the adaptation of sorghum.

The range and mean CGDD requirement for flowering were higher for PSTINS landraces than for PTINS and PTS landraces (Table 4). The mean CGDD requirement was similar in the hemispheres for all three groups of landraces both in the rainy and post-rainy seasons; however, CGDD requirement was relatively high in lower latitudes and decreased with increase in latitude. Range of variation for CGDD requirement was lower in PTS landraces than in PTINS and PSTINS landraces. When compared with the post-rainy season, mean CGDD requirement was relatively high in all latitudes for PTINS and PSTINS landraces in the rainy season and almost equal for PTS landraces in the rainy and the post-rainy season. Differences in DFL and near-equal CGDD in the rainy and the post-rainy seasons indicated the photoperiod and temperature sensitivity of PTS landraces.

Association of Latitude, Climate at Collection Sites, and Photoperiod and Temperature Sensitivity

Across hemispheres, lower daylength and temperatures (minimum, maximum, and mean), and annual rainfall at collection sites, as well as the frequency of

Table 3. Range and mean of days to 50% flowering for insensitive and sensitive sorghum landraces from different hemispheres and latitude ranges.

Latitude range	Photoperiod and temperature insensitive					Photoperiod sensitive and temperature insensitive					Photoperiod and temperature sensitive				
	No. of accessions	Rainy		Post-rainy		No. of accessions	Rainy		Post-rainy		No. of accessions	Rainy		Post-rainy	
		Range	Mean	Range	Mean		Range	Mean	Range	Mean		Range	Mean	Range	Mean
degrees		d					d					d			
Total landraces	1,697	45–137	70.0	45–135	70.0	18,766	33–180	98.0	36–154	74.0	247	41–93	63.0	53–127	86.0
Northern hemisphere	1,291	45–137	71.0	45–135	71.0	1,5479	33–180	99.0	36–154	73.0	103	41–91	61.0	53–124	84.0
0–5	84	65–137	76.0	64–135	77.0	1,321	46–165	105.2	49–154	78.0	13	56–71	67.5	79–100	93.5
5–10	224	53–105	79.1	51–103	79.0	3,343	43–170	112.0	40–120	79.0	14	42–65	52.6	57–93	71.5
10–15	426	48–128	72.6	47–127	72.4	5,715	45–172	98.3	37–139	72.5	40	44–91	61.6	57–124	83.0
15–20	318	47–101	71.4	48–102	71.4	2,766	46–180	91.8	36–114	72.9	24	52–77	65.0	69–104	88.8
20–25	49	50–105	68.8	50–105	69.1	1,501	48–154	95.2	44–100	65.6	8	50–68	60.0	67–92	80.9
25–30	72	45–75	56.8	45–75	56.7	647	33–140	80.4	42–100	59.6	2	53–57	55.0	72–79	75.5
30–35	37	48–70	55.7	47–71	55.8	86	46–144	68.7	46–79	58.4	0	NA†	NA	NA	NA
35–40	79	52–65	57.2	54–63	57.1	85	47–80	59.8	50–83	62.0	0	NA	NA	NA	NA
40–45	2	66–66	62.5	66–66	61.5	15	47–65	58.3	50–83	68.3	2	61–61	51.0	81–81	67.0
Southern hemisphere	406	52–134	67.0	51–135	68.0	3,287	48–162	94.0	46–149	79.0	144	50–93	64.0	68–127	88.0
0–5	13	65–128	91.0	65–130	91.0	1,039	48–162	115.0	53–149	84.0	0	NA	NA	NA	NA
5–10	4	94–134	120.0	93–135	119.7	200	82–159	129.0	66–132	97.0	0	NA	NA	NA	NA
10–15	8	68–108	83.5	70–108	83.6	294	61–145	121.7	54–114	88.3	3	75–83	79.7	104–114	109.3
15–20	115	58–107	71.0	57–107	71.0	889	52–152	80.8	46–127	73.5	23	58–93	78.0	79–127	107.4
20–25	79	52–105	67.8	51–105	68.1	486	50–119	68.1	46–118	72.4	57	50–90	62.0	68–120	84.0
25–30	135	56–80	62.9	56–80	63.1	287	53–128	64.0	48–119	71.0	61	53–73	61.0	72–99	83.0
30–35	52	53–64	58.0	55–63	58.0	92	56–69	62.0	55–72	59.0	0	NA	NA	NA	NA

† NA, not applicable.

PSTINS landraces, decreased with the increase in latitude (Table 5). On the other hand, the PTINS landraces were distributed across all latitudes, but their frequency was high at 10 to 20° latitudes, and that of PTS landraces was higher at 20 to 30° latitudes than at other latitudes. Several investigators have found that the latitude range of 10 to 25° on either side of the equator was characterized by relatively higher annual mean minimum (9.6–24.4°C) and maximum (25.6–37.9°C) temperatures and rainfall (718–877 mm) at the collection sites compared with higher latitudes (30.00–45.00°) (Roberts and Summerfield, 1987; Erskine et al., 1990; Craufurd et al., 1999). Collection sites at latitudes of 35.00 to 40.00° recorded the lowest mean minimum (−10.3°C), maximum (1.9°C), and mean (−4.2°C) temperatures and rainfall (490 mm), indicating the association of longer days with cooler climate. Folliard et al. (2004) reported the reduction in time to panicle initiation in sorghum from 54 to 22 d because of a 2-min variation in daylength. Goldsworthy (1984) reported sensitivity of sorghum to even small changes (<15 min) in daylength originated near the equator. Kassam and Andrews (1976) reported that strong photoperiod sensitivity was characteristic of West African (lower latitudes) sorghum germplasm, which allows it to flower nearly at the same time irrespective of sowing time. The observed small deviations in DFL and CGDD requirements in different latitudes and in the patterns of response to temperature and photoperiod in the present study can be attributed to the inherent early or late flowering of landraces, elevations, date of sowings, soils, etc., at the collection sites in different latitudes, soils, and climates at the evaluation location. These results are in agreement with those reported by Roberts et al. (1996).

Promising Sources Identified

Photoperiod and temperature insensitivity, combined with agronomic and nutritional traits and abiotic and biotic stress resistance, is very useful in crop improvement programs. Information available in the ICRISAT sorghum germplasm characterization database for resistance to important abiotic and biotic stresses and agronomic and nutritional traits revealed several landraces as promising sources for important traits (Table 6). Among the PSTINS landraces, IS 6335, a *caudatum* from India with the lowest DFL (33 d) and CGDD (567.9°C d) requirements in the rainy season, and IS 29142, a *durra-caudatum* from Yemen with the

Table 4. Range and mean of cumulative growing degree days for insensitive and sensitive sorghum landraces from different hemispheres and latitude ranges.

Latitude range	Photoperiod and temperature insensitive				Photoperiod sensitive and temperature insensitive				Photoperiod and temperature sensitive			
	Rainy		Post-rainy		Rainy		Post-rainy		Rainy		Post-rainy	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Degrees	°C d											
Total landraces	787.5–2173.1	1153.0	595.6–1648.0	865.7	567.9–2679.2	1586.6	489.8–1952.6	905.4	695.1–1509.8	1040.5	685.1–1531.1	1035.0
Northern hemisphere	787.5–2173.1	1167.3	595.6–1648.0	874.6	567.9–2679.2	1599.2	489.8–1952.6	894.7	695.1–1478.2	1014.9	685.1–1488.1	1005.9
0–5	1069.9–2173.1	1245.6	800.7–1648.0	935.4	773.0–2517.9	1694.5	640.7–1952.6	948.4	929.0–1163.7	1108.8	954.5–1182.7	1109.8
5–10	882.4–1701.2	1289.8	663.0–1219.2	954.5	726.7–2573.7	1786.6	537.8–1433.2	954.8	710.9–1070.0	877.1	726.8–1103.1	877.0
10–15	804.8–2050.3	1190.1	618.3–1531.1	889.5	773.6–2594.5	1586.8	501.9–1708.5	889.3	742.5–1478.2	1016.9	726.8–1488.1	1005.3
15–20	789.3–1637.8	1169.8	629.3–1207.1	875.6	773.6–2679.2	1487.5	489.8–1353.8	891.8	867.0–1257.4	1070.8	851.0–1231.2	1058.7
20–25	651.8–1712.0	1129.5	651.8–1242.9	853.0	804.8–2390.5	1543.4	584.0–1182.7	816.0	836.0–1117.3	991.9	830.5–1092.0	973.3
25–30	787.5–1226.1	942.3	595.6–911.7	723.0	567.9–2213.6	1310.5	561.1–1182.7	753.9	882.4–944.6	913.5	881.9–954.5	918.2
30–35	804.8–1148.4	925.1	618.3–871.7	714.1	773.6–2265.9	1128.7	607.0–954.5	741.3	NA†	NA	NA	NA
35–40	867.0–1070.0	948.6	695.5–790.6	727.9	789.3–1304.4	988.1	651.8–985.8	778.6	NA	NA	NA	NA
40–45	1085.7–1085.7	1030.9	820.5–820.5	773.6	789.3–1069.9	964.9	651.8–985.8	843.2	1007.8–1007.8	851.4	975.7–975.7	830.4
Southern hemisphere	867.0–2132.8	1107.4	663.0–1648.0	837.5	804.8–2484.2	1527.4	607.0–1869.2	956.0	836.0–1509.8	1058.9	840.7–1531.1	1055.8
0–5	1070.0–2050.3	1476.5	810.5–1574.4	1092.8	804.8–2484.2	1854.2	685.1–1869.2	1012.7	NA	NA	NA	NA
5–10	1525.7–2132.8	1925.5	1103.1–1648.0	1442.6	1335.6–2449.8	2055.4	820.5–1603.3	1149.7	NA	NA	NA	NA
10–15	1117.3–1748.3	1359.9	861.3–1278.9	1005.4	1007.8–2279.1	1949.5	695.5–1353.8	1054.5	1226.1–1351.2	1299.1	1231.2–1353.8	1296.1
15–20	960.3–1732.6	1159.9	726.8–1266.7	870.7	867.0–2366.4	1317.3	606.9–1531.1	900.2	960.3–1509.8	1273.3	954.5–1531.1	1278.7
20–25	867.0–1701.2	1114.6	663.0–1242.9	842.7	836.0–1918.7	1119.0	607.0–1406.4	888.1	836.0–1462.4	1015.5	840.7–1433.2	1013.5
25–30	929.0–1304.4	1037.6	716.2–965.3	790.5	882.4–2050.3	1048.7	629.3–1419.7	868.8	882.4–1194.7	1006.8	881.9–1170.7	999.6
30–35	882.4–1054.5	968.0	705.9–790.6	742.1	929.0–1133.0	1019.5	705.9–881.9	751.6	NA	NA	NA	NA

† NA, not applicable.

Table 5. Climate and frequency distribution of insensitive and sensitive landraces in different latitudes.

Climatic factor and landrace group	Latitude range								
	0–5°	5–10°	10–15°	15–20°	20–25°	25–30°	30–35°	35–40°	40–45°
Daylength (h)									
Lower	12.0	11.6	11.4	11.1	10.8	10.4	10.1	9.5	9.2
Higher	12.1	12.6	12.8	13.2	13.5	13.8	14.1	14.8	15.1
Minimum temperature (°C)									
Lowest	15.5	13.6	13.7	13.0	9.6	6.0	1.9	–10.3	–6.0
Highest	17.6	17.9	21.8	22.8	24.4	22.7	18.9	18.1	16.7
Maximum temperature (°C)									
Lowest	27.3	25.7	28.3	26.9	25.6	20.9	15.3	1.9	2.7
Highest	31.2	31.6	36.3	36.0	37.9	35.1	32.1	30.4	28.2
Mean temperature (°C)									
Lowest	21.5	20.3	21.9	20.1	17.6	13.4	8.6	–4.2	–1.7
Highest	24.1	24.6	28.8	29.1	30.9	28.6	25.4	24.3	22.3
Rainfall (mm)	1094	1083	718	743	877	829	743	490	694
Total landraces	2470 (11.9)†	3785 (18.3)	6486 (31.3)	4135 (20.0)	2180 (10.5)	1204 (5.8)	267 (1.3)	164 (0.8)	19 (0.1)
No. of photoperiod- and temperature-insensitive landraces†	97 (5.7)	228 (13.4)	434 (25.6)	433 (25.5)	128 (7.5)	207 (12.2)	89 (5.2)	79 (4.7)	2 (0.1)
No. of photoperiod-sensitive and temperature-insensitive landraces	2360 (12.5)	3543 (18.9)	6009 (32.0)	3655 (19.5)	1987 (10.6)	934 (5.0)	178 (0.9)	85 (0.6)	15 (0.01)
No. of photoperiod- and temperature-sensitive landraces	13 (5.3)	14 (5.7)	43 (17.4)	47 (19.0)	65 (26.3)	63 (25.5)	0 (0)	0 (0)	2 (0.8)

† Values in parenthesis are the frequency of landraces (%).

lowest DFL (36 d) and CGDD (489.8°C d) requirements in the post-rainy season, were identified as promising sources of early maturity. IS 17894, a *guinea-durra* landrace collected in India, flowered very late (180 d) and had highest CGDD (2679.2°C d) requirement in the rainy season, and IS 39879, a *caudatum* from Uganda with the highest DFL (154 d) and CGDD (1952.6°C d) requirements during the post-rainy season, should be useful in breeding fodder sorghum cultivars. IS 5676, a *kafir-durra* from India, and IS 38212, a *caudatum* from Ethiopia, were short statured (<100 cm) in both seasons. IS 4643, IS 4984, and IS 5631, all belonging to race *durra* from India, were resistant to shoot fly (*Atherigona saccata* Rond.) in both the rainy and post-rainy seasons. IS 20038, a *guinea* landrace, and IS 19977, a *guinea-caudatum* from Senegal, were found to be promising for anthracnose [*Colletotrichum graminicola* (Ces.) Wilson] and rust (*Puccinia purpurea* Cooke) resistance and high seed protein content (>15%). IS 28451, a *guinea-caudatum* from Yemen, was a good source of high seed Fe and Zn content (>30 mg kg^{-1} seed). Upadhyaya et al. (2016) found IS 28451, a *guinea-caudatum*, and IS 28747, a *durra-caudatum*, both from Yemen, to be promising sources of high seed Fe and Zn content (>30 mg kg^{-1} seed). Among the PTS landraces, IS 13868, a *kafir*, IS 13870, a *kafir-durra* from South Africa, and IS 21446, a *guinea* landrace from Malawi, were found to be promising for rust resistance.

Among the PTINS landraces, 15 landraces in the rainy season and 18 in the post-rainy season flowered early (<50 d), and 10 of them flowered early in both seasons (Table 6). Three landraces—IS 24422 from India and IS 31769 from Yemen, both *durra-caudatums*, and IS 35223, a *bicolor* from Pakistan—flowered early (<50 d) and required low CGDD (<800°C d) in the rainy season. Eighteen landraces showed low CGDD requirement (<650°C d) for flowering in the post-rainy season. Three landraces—IS 32833, IS 39849 and IS 39897—flowered very late (>130 d) and required high CGDD in both seasons (>2100°C d in the rainy season and >1650°C d in the post-rainy season). Three landraces for short height (<100 cm) in the rainy and post-rainy seasons, four for tallness (>525 cm) in the rainy season, and five for tallness (>350 cm) in the post-rainy season, high panicle exertion (>45 cm), and large seeds (100-seed weight >5.5 g) were found to be superior PTINS landraces. IS 4698, a *durra* landrace from India, could be useful in developing dual purpose sorghum cultivars suitable for diverse climates and seasons. An evaluation conducted at ICRISAT (http://genebank.icrisat.org), showed the PTINS sources IS 22364 and IS 22408 to have high seed lysine content (>3%), and IS 2305, IS 3881, and IS 5333 to have high seed protein content (>15%) (Table 6). IS 12639, with high stalk sugar (>16% brix), should be highly useful in developing sweet sorghum cultivars with improved sugar content, and IS 5566, IS 5638, and IS 5653, all *durra-bicolor* landraces from India, were found to be promising as pop sorghums. Several of the PTINS landraces showed resistance to leaf blight [*Exserohilum turcicum* (Pass.) Leo & Suggs], anthracnose, downy mildew [*Peronosclerospora sorghi* (West. & Upp.) C.G. Shaw], grain mold [*Curvularia lunata* (Wakk.) Boed.], rust, aphids [*Melanaphis sacchari* (Zehnt.)], shoot fly, sorghum midge [*Contarinia sorghicola* (Coq.)], and stem borer (*Chilo partellus* Swin.) (Table 6,

Table 6. Photoperiod- and temperature-insensitive sorghum landraces (IS no.) identified as promising sources for different traits.

Trait	Season†	IS no.
Agronomic traits		
Days to 50% flowering (<50 d)	R	2339, 3075, 6277, 6316, 6317, 6320, 9761, 24422, 28548, 31769, 35214, 35223, 35250, 35254, 35255
Days to 50% flowering (<50 d)	PR	1361, 3075, 4003, 6277, 6314, 6315, 6316, 6317, 6320, 6342, 24422, 24423, 28548, 28566, 30445, 31769, 35223, 35250
Days to 50% flowering (>130 d)	R	32833, 39849, 39897
Days to 50% flowering (>130 d)	PR	32833, 39849, 39897
Cumulative growing degree days (<800°C d)	R	24422, 31769, 35223
Cumulative growing degree days (<650°C d)	PR	1361, 3075, 4003, 6277, 6314, 6315, 6316, 6317, 6320, 6342, 24422, 24423, 28548, 28566, 30445, 31769, 35223, 35250
Cumulative growing degree days (>2100°C d)	R	32833, 39849, 39897
Cumulative growing degree days (>1650°C d)	PR	32833, 39849, 39897
Plant height <100 cm	R	4419, 8398, 38238
Plant height <100 cm	PR	8398, 13067, 38238
Plant height >525 cm	R	27530, 37860, 38271, 39454
Plant height >350 cm	PR	27485, 28166, 28179, 39411, 39484
Panicle exertion >45 cm		11785, 12654, 27565, 30913, 31807
100-seed weight >5.5 g		27646, 27651, 27652, 30847, 33260
Dual purpose		4698
Nutritional traits		
High seed lysine content (3%)		22364, 22408
High seed protein content (>15%)		2305, 3881, 5333
High stalk sugar (>16% brix)		12639
Pop sorghum		5566, 5638, 5653
Abiotic and biotic stress resistance		
Drought		5094
Anthracnose		17141, 19108, 19169, 19682
Charcoal rot		5094, 30092
Aphids		4581, 4698, 29314
Downy mildew		1032, 5094, 11223, 11597, 12197, 29239, 29314, 30092, 30443, 30466
Grain mold		1129, 4720, 4907, 6060, 8982, 12862, 14756, 17141, 21509, 21599, 25085, 29241, 29304, 29314, 29326, 29335, 30092
Leaf blight		1436, 2378, 2380, 2399, 3075, 3402, 3566, 3881, 4226, 5259, 5772, 9070, 9618, 9620, 9649, 9677, 19468, 29233
Rust		1104, 7775, 9677, 11645, 11729, 12197, 13977, 19474, 21599, 26151, 30443, 30466, 34166, 34167, 36490
Shootfly		1034, 1052, 1056, 1062, 1067, 1071, 1104, 1125, 1148, 1458, 1461, 1479, 1484, 1497, 1501, 1503, 1510, 1516, 1524, 2162, 2163, 2168, 2195, 2291, 2305, 2312, 3604, 4065, 4066, 4419, 4478, 4537, 4540, 4546, 4553, 4573, 4581, 4612, 4661, 4663, 4664, 4665, 4668, 4687, 4675, 4698, 4710, 4711, 4739, 4773, 4789, 4886, 4895, 4967, 5039, 5094, 5205, 5211, 5268, 5313, 5480, 5494, 5510, 5566, 5621, 5642, 5653, 9840, 17933, 18296, 18317, 18414, 19012, 19014, 19015, 19017, 19032, 19046, 19048, 19059, 19108, 19115, 19141, 19157, 19195, 19203, 19232, 19233, 19245, 19474, 19682, 22113, 22144, 22145, 28333
Sorghum midge		19474, 19512
Stem borer		2163, 2168, 4546, 4698, 5094, 5268, 17747, 22039, 22091

† R, rainy season; PR, post-rainy season.

http://genebank.icrisat.org). Upadhyaya et al. (2017) found IS 5094, a medium-flowering *durra* landrace from India, to be stable for drought tolerance in both the rainy and post-rainy seasons; it also possessed photoperiod and temperature insensitivity and resistance to charcoal rot [*Macrophomina phaseolina* (Tassi) Goid], shoot fly, and stem borer. These PTINS landraces with resistance are of great value in breeding programs to develop climate-resilient cultivars with resistance to abiotic and biotic stresses.

Sorghum landraces stratified for photoperiod and temperature sensitivity are highly useful in crop improvement programs. The insensitive landraces with high adaptation, high biomass, and disease resistance are useful in developing fodder sorghum cultivars suitable for diverse climatic conditions. The sorghum adapted to tropical regions has been shown to be resistant to diseases and insects and tolerant to lodging vis-à-vis the sorghums adapted to temperate regions, which lacked these attributes (Perez Cabrera and Miller, 1985). Insensitive parental lines are of particular interest to breeders as synchronized flowering of parental lines is essential for successful commercial hybrid seed production. The present study serves as a model for making use of the data from large germplasm collections, planning collection missions to collect trait-specific germplasm from diverse climates, conducting experiments, regenerating trait-specific germplasm, and introducing elite germplasm in diverse climates. Evaluation of the landraces for traits showing high response to climate in diverse seasons, such as rainy and post-rainy seasons at Patancheru, is essential to determine their insensitivity to climate factors. As all insensitive sources identified in this study are adaptable to diverse climate, their evaluation for resistance to abiotic and biotic stresses and seed quality traits is required to exploit the assembled large collections in genebanks to mitigate the effects of climate change on sorghum production. For research purposes, small quantities of seeds of all photoperiod- and temperature-sensitive and -insensitive sources are available at the ICRISAT genebank, India, on signing the Standard Material Transfer Agreement.

CONCLUSIONS

In conclusion, the northern hemisphere was found to be an important region for sorghum cultivation. Because of the near-optimal conditions, lower latitudes (0.00–25.00°) were found to be important source regions for sorghum (92% of total landraces) when compared with other latitudes. Range as well mean DFL were equal in both the rainy and post-rainy seasons for PTINS landraces from both hemispheres and latitudes within hemispheres, whereas range and mean DFL were relatively high for PSTINS and relatively low for PTS in the rainy season in all latitudes across the hemispheres. The range and mean CGDD requirements for flowering in the entire collection were higher for PSTINS landraces compared with PTINS and PTS landraces. The CGDD requirement was relatively high in lower latitudes and decreased with increase in latitude. When compared with the post-rainy season, CGDD was higher in the rainy season in all latitudes in both hemispheres for PTINS and PSTINS landraces, but for PTS landraces, CGDD requirement was similar in both seasons. Insensitive landraces were found in higher proportions at lower latitudes (10.00–20.00°). The highly photoperiod-sensitive and late-maturing forage sorghum landraces were leafier and had a better seasonal distribution for forage production. A clear association among sensitivity of landraces, latitude, and climate was observed. The PTINS sources identified in this study were highly adaptable to diverse climates and useful in the present climate change scenarios.

Conflict of Interest

The authors declare that there is no conflict of interest.

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