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Seed Productivity of Genebank Sorghum Accessions in India (Tamil Nadu) and Japan (Tsukuba)

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Abstract

To compare the seed productivity of germplasm in India (Tamil Nadu) and Japan (Tsukuba), a total of 105 accessions from the Japanese National Agriculture and Food Research Organization (NARO) sorghum core collection were cultivated. The comparative cultivation studies were conducted at two locations in India and one in Japan. Differences in cultivation environments, including day length, temperature, and rainfall were evident in all the studies, and accordingly, seed production varied. The accessions grown in Japan yielded the highest number of grains per panicle. However, 11 accessions cultivated in Japan produced no harvest. Conversely, all accessions grown in parts of India, such as in Coimbatore, produced seeds. Therefore, although seed production in Japan was superior, there were benefits to cultivating the crops in India, including longer cultivation periods and the ability to overcome difficulties with seed multiplication found in Japan. Comparative cultivation projects involving international collaborative research are essential to reveal seed productivity in genetically diverse resources of sorghum. This study provides data about international sorghum production and information about differences in available accessions.

Discipline: Biotechnology
Additional key words: core collection, international collaboration, seed multiplication, sorghum genetic resources

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a member of the Poaceae family and originates in Africa. This important crop has spread its growth habitats to Central Asia and India where it is cultivated agriculturally. Over 160 national/public global genebanks maintain the genetic diversity of sorghum in a large germplasm collection of more than 235,000 accessions (CGRFA 2010). During the spread of this crop from Africa, more regionally suited sorghum varieties were developed in their new environments (Alencar et al. 2008). Sorghum is used as food, livestock fodder, and in the industrial production of alcoholic beverages in Africa, Asia, and America. In Japan, the crop is cultivated for cattle feed and research is currently being conducted to evaluate its potential as a source of biomass.

At the Genetic Resources Center of the National Agriculture and Food Research Organization (NGRC), Japan has been conducting field survey collections, characterizations, preservation, and distribution of genetic resources related to agriculture (Okuno et al. 2005, Takeya et al. 2011). This institute conserves more than 4,000 accessions of sorghum that have been obtained from all over the world. Data including images and phenotypic descriptions that have been collected on the different varieties of sorghum are stored in a publicly available database (Takeya et al. 2013).

A core collection is a set of various accessions that cover a wide range of genetic diversity using a small number of varieties selected from available resources (Frankel 1984). The NARO sorghum core collection was selected from the genetic resources conserved at the NGRC (Shehzad et al. 2009) and has been used widely

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as a research tool to assist in breeding programs, genetic research (Strelchenko et al. 2010, Kawahigashi et al. 2013), quantitative trait loci analyses (EI Mannai et al. 2011, Witt Hmon et al. 2014), and crop evolution studies (Kawahigashi et al. 2016).

The objective at NARO, which functions as a genebank for promoting access to genetic resources, is to preserve and distribute its own collections, and the core collection. Therefore, seed multiplication is essential for the success of NARO as is the production of a large number of grains. However, there are a number of sorghum varieties that originate in tropical regions and hence are difficult to multiply in Japan. As a countermeasure to this problem, it may be feasible to multiply seeds of these accessions at suitable locations in a tropical climate. The International Crop Research Institute for the Semi-Arid Tropics in India offers such an environment, and is where their own mini-core collection of sorghum was originally selected (Upadhyaya et al. 2009).

In the present study, we investigated the cultivation of sorghum in both India (Tamil Nadu) and Japan (Tsukuba) using the NARO sorghum core collection, in order to compare seed production in different environments.

Materials and methods

The 105 accessions available in the NARO sorghum core collection (Shehzad et al. 2009) were used in the present study (Table 1). The seed lots were cultivated at three locations including Kovilpatti (KD: Kovilpatti, Tamil Nadu, India, N09°12′), Coimbatore (CD and CR: Coimbatore, Tamil Nadu, India, N11°01′), and Tsukuba (TR: Tsukuba, Ibaraki, Japan, N36°02′). In Coimbatore, the accessions were cultivated in both the post-rainy (CD: October-May) and rainy (CR: June-September) seasons. Local methods were used to cultivate sorghum at each growing location. Table 2 shows field and environmental data from each site. Sorghum seeds were sown on the following dates: November 7, 2012, in KD; February 19, 2014, in CD; July 3, 2013, in CR; and May 28, 2014, in TR. There was 60 cm of space between the rows of growing plants in KD, CD, and CR, and 80 cm in TR. There was 10 cm of spacing between the plants at all locations. The seeds were sown in a single replication (one row per accession) in KD and TR, and in two replications (two rows per accession) in CD and CR. Irrigation was conducted according to local practice at the time of sowing and when growth was necessary. In KD, five plants from each accession were studied, whereas at the other locations, 10 plants from each accession were used for data collection. To simplify harvesting, the characterization target was limited to the main panicle (first panicle), not for tillers, and the seeds were selfed using self-crossing paper bags. The number of grains per panicle for each accession was calculated using grain weight per panicle and 100-grain weight. Phenotypic data including the date of flowering were collected. However, in TR, some accessions produced no harvest due to late maturing seeds, and the date of heading, obvious for observation and investigation as a seed production factor, was recorded. The characterization on the heading date was conducted until September 30, 2014 in TR because the plants that were subjected to a later heading may be frosted before seed maturation, and seeds may not be harvested. As mentioned above, differences exist in annual variations of weather conditions (e.g., air temperature, precipitation, wind, humidity), soil, day length, irrigation, sowing time, bagging, fertility, pest control, etc. Therefore, all differences in conditions among the research sites were treated as environmental factors and no uniform control was performed.

Weather data such as the maximum/minimum daily temperatures and rainfall in KD, CD, and CR were observed and recorded at Tamil Nadu Agricultural University, Tamil Nadu, India. The data on temperature and rainfall in TR were obtained from the Japan Meteorological Agency (http://www.data.jma.go.jp/obd/stats/etrn/index.php). The sorghum accumulated temperature threshold was set to 9°C (Parthasarathi et al. 2013). The accumulated temperature was calculated as follows:

$$\text{Accumulated temperature} = \sum \left\{ \frac{(\text{Tmax} - \text{Tmin})}{2} - 9 \right\}$$

where T_{max} is the maximum daily temperature and T_{min} is the minimum daily temperature.

Day lengths in KD, CD, CR, and TR were calculated using latitude-longitude data from the Japan Coast Guard (http://www1.kaiho.mlit.go.jp/KOHO/automail/sun_form3.html).

Results and discussion

In the present study, a comparative cultivation using the NARO sorghum core collection developed in Japan was performed for the first time both in India and Japan. Tables 3A and 3B show the number of grains per panicle, flowering/heading date, and accumulated temperature until flowering/heading of sorghum accessions in the NARO sorghum core collection as cultivated in KD, CD, CR, and TR.

Table 1. Sorghum accessions

WSC ID	JP No.	Accession name	Origin
WSC 01	237348	OOTOYO-MURA ZAIRAI	Kouchi, Japan
WSC 02	237349	TAKAKIMI	Iwate, Japan
WSC 03	237350	IKEDACHO MATSUO ZAIRAI	Tokushima, Japan
WSC 04	237351	KOUCHI OUKAWA ZAIRAI	Kouchi, Japan
WSC 05	237352	DANGOMOROKOSHI	Ibaraki, Japan
WSC 06	237353	TOKIBI	Mie, Japan
WSC 07	237354	HIMEKI ZAIRAI	Hyougo, Japan
WSC 08	237355	KIKUCHI ZAIRAI	Kumamoto, Japan
WSC 09	237356	AKAHO	Gunma, Japan
WSC 10	237357	KANAGAWA ZAIRAI	Kanagawa, Japan
WSC 11	237358	72-10-10-5	Kouchi, Japan
WSC 12	237359	HANGETSUTOSUI	Korean Peninsula
WSC 13	237360	KOUSHUU ZAIRAISHU	Korean Peninsula
WSC 14	237361	CHAL WAXY SORGHUM	Korean Peninsula
WSC 15	237362	KOUBOUSHI	Korean Peninsula
WSC 16	237363	MOCTAC LOCAL	Korea
WSC 17	237364	SENKINHAKU	Korean Peninsula
WSC 18	237365	CHOONCHAN LOCAL	Korea
WSC 19	237366	72-8-13	Taiwan
WSC 20	237367	AI HUI	China
WSC 23	237370	LIAOZA 1	China
WSC 24	237371	BIG WHITE HULL	China
WSC 25	237372	XIONG YUE 334	China
WSC 26	237373	BATTANBAN	Cambodia
WSC 27	237374	AS 5781 HUAN SA PHAUNG AH LPYSU 2	Myanmar
WSC 28	237375	Y. E. (I. P.) INT. TYPE	India
WSC 29	237376	KALJANPUR	India
WSC 30	237377	SC NO.0217 CI1197	India
WSC 31	237378	GOOSENECK	India
WSC 32	237379	MARIANGARI JORA MUDDAHIHAL	India
WSC 33	237380	DHOOTI ANEHULA	India
WSC 34	237381	RABI YANGAR JORA MITHUGADUR	India
WSC 35	237382	AS 4136 MASAKA LUWEMEA	India
WSC 36	237383	COL/PAK/1989/IBPGR/2386(2)	Pakistan
WSC 37	237384	COL/PAK/1991/IBPGR/2724(2)	Pakistan
WSC 38	237385	COL/PAK/1989/IBPGR/2420(1)	Pakistan
WSC 39	237386	COL/PAK/1989/IBPGR/2427(5)	Pakistan
WSC 40	237387	COL/PAK/1989/IBPGR/2439(1)	Pakistan
WSC 41	237388	COL/PAK/1989/IBPGR/2444(1)	Pakistan
WSC 42	237389	COL/PAK/1989/IBPGR/2550(1)	Pakistan
WSC 43	237390	COL/PAK/1989/IBPGR/2553(4)	Pakistan
WSC 44	237391	COL/PAK/1989/IBPGR/2411(1)	Pakistan
WSC 45	237392	COL/PAK/1989/IBPGR/2416(2)	Pakistan
WSC 46	237393	COL/PAK/1989/IBPGR/2592(7)	Pakistan
WSC 47	237394	87-9-21-3-1	Pakistan
WSC 48	237395	87-9-21-3-2	Pakistan
WSC 49	237396	PI 220636 Q 2/3/56	Afghanistan
WSC 50	237397	PI 220636 Q 2/3/56	Afghanistan
WSC 51	237398	ALLAKH	Bangladesh

Table 1. Sorghum accessions (Continued)

WSC ID	JP No.	Accession name	Origin
WSC 52	237399	EC 18868	Nepal
WSC 53	237400	JUNELO	Nepal
WSC 54	237401	PI 229486 VULGARE	Iran
WSC 55	237402	HAZERA 6014	Israel
WSC 56	237403	E 9	Chad
WSC 57	237404	PI 282834	Chad
WSC 58	237405	E 17	Chad
WSC 59	237406	MAKHOTLONG I	Lesotho
WSC 60	237407	TENANT WHITE	Lesotho
WSC 61	237408	NYAKASOBA BEST	Lesotho
WSC 62	237409	AIT BRAHIM	Morocco
WSC 63	237410	CODY	Morocco
WSC 64	237411	KOURNIANIA	Morocco
WSC 65	237412	PHATSAI	Morocco
WSC 66	237413	SCHROCK	Morocco
WSC 67	237414	ESHOME	Morocco
WSC 68	237415	E 232 INGWARUMA PEARLY	South Africa
WSC 69	237416	AW 70/12 DL/59/1532	South Africa
WSC 70	237417	E 233 BARNARD RED	South Africa
WSC 71	237418	RED KAFIR	South Africa
WSC 72	237419	S.BASUTORUM DL/60/97	South Africa
WSC 73	237420	EAR FROM PIETESBURG DL/60/107	South Africa
WSC 74	237421	MILO PET. 139/51 EX TANGANYIKA	Central Africa
WSC 75	237422	HEGARI MALOWAR	Sudan
WSC 76	237423	143 DINDERAWI 1	Sudan
WSC 77	237424	REDBINE 655	Sudan
WSC 78	237425	E 1089	Sudan
WSC 79	237426	LAMBAS	Sudan
WSC 80	237427	DINDERAWI 1	Sudan
WSC 81	237428	240 WAD UMM BENEIN	Sudan
WSC 82	237429	MUGBASH WHITE	Sudan
WSC 83	237430	B-112	Sudan
WSC 84	237431	E 1091	Sudan
WSC 85	237432	109 TONJI	Sudan
WSC 86	237433	ZA113 DAWA PAS PARA	Nigeria
WSC 87	237434	AS 4547 JARDIRA	Nigeria
WSC 88	237435	MN 1277 MUHEYAR	Nigeria
WSC 89	237436	KA 24	Nigeria
WSC 90	237437	MN 401	Algeria
WSC 91	237438	S. VULGARE 72-726-7	Uganda
WSC 92	237439	S. VULGARE 72-728-1	Uganda
WSC 93	237440	E 276 FRAMIDA	Uganda
WSC 94	237441	UGANDA L 1	Uganda
WSC 95	237442	MORABA 74	Ethiopia
WSC 96	237443	THIBA RED	Ethiopia
WSC 97	237444	SC 112	Ethiopia
WSC 98	237445	GIZA 3/59	Ethiopia
WSC 99	237446	PI 329762	Ethiopia
WSC 100	237447	AKLMOI WHITE	Kenya

Table 1. Sorghum accessions (Continued)

WSC ID	JP No.	Accession name	Origin
WSC 101	237448	E 959	Kenya
WSC 102	237449	PI 152748 C	Kenya
WSC 103	237450	WAD YABOO 132/53	Zimbabwe
WSC 104	237451	CAPE COLO 28/53	Zimbabwe
WSC 105	237452	TSETA LOCAL NATURE TYPE 27/51	Zimbabwe
WSC 106	237453	AS 4637 NHORONGO NENPI	Tanzania
WSC 107	237454	E 37	Tanzania

Table 2. Details and environmental conditions of research sites, and cultural practices

Site (ID)	Latitude	Longitude	Altitude (m)	Sowing date (day-month-year)	Row spacing (cm)	Soil texture	Previous crop	Fertilizer	Irrigation (times)
Kovilpathi (KD)	N09°12′	E77°53′	166	7-Nov-2012	60	Black-clay	Cotton	N: 40kg/ha P : 20kg/ha K: 20kg/ha	2
Coinbatore (CD)	N11°01′	E76°56′	412	19-Feb-2014	60	Clay-loam	Bean	N: 90kg/ha P : 40kg/ha K: 40kg/ha	4
Coinbatore (CR)	N11°01′	E76°56′	412	3-Jul-2013	60	Clay-loam	Bean	N: 90kg/ha P : 40kg/ha K: 40kg/ha	4
Tsukuba (TR)	N36°02′	E140°06′	23	28-May-2014	80	Loam	Bean	N: 52kg/ha P : 72kg/ha K: 56kg/ha	0

1. Individual plant spacing was 10 cm in KD, CD, CR, and TR.
2. Replications were one each in KD and TR and two each in CD and CR.
3. Evaluated individuals per accession included five plants in KD and 10 plants each in CD, CR, and TR.
4. Irrigation was conducted according to local practice at the time of sowing and when growth was necessary.

1. Accessions that produced no harvest

Overall, 25 accessions formed no harvestable grain in KD (due to shoot fly attack or unclear reasons) and TR (due to late heading) (Table 3A), although all the accessions produced grain in both CD and CR. The average number of grains per panicle of the 105 successfully grown accessions was 190 ± 140 in CD and 290 ± 150 in CR (Tables 3A and 3B). The number of harvested grains was higher in CR than that in CD. Based on these results, it was deduced that CR had the greatest potential for larger harvests in Tamil Nadu, India. WSC7 "HIMEKI ZAIRAI" and WSC8 "KIKUCHI ZAIRAI" are both Japanese landraces; however, in TR, they could not be harvested because of late heading (Table 3A). Furthermore, the NARO-GB characteristic database contains the past records of heading before the end of September. In 2014, the heading of these accessions was delayed for unclear reasons. Following detailed research into the origins of these accessions, we observed that WSC7 and WSC8 were both native to Japan, and originated in Hyougo and Kumamoto prefectures, respectively. These accessions may have been harvested in Japan under climatic conditions similar to their places of origin in areas warmer than TR. Few accessions of Japanese origin were suited to the climatic conditions observed at the growing locations in India. Thus, the limiting factors for seed production were thought to be due to insect damage in India and photosensitivity and/or an insufficient period (for seed maturity) in Japan.

Table 3A. Flowering/heading date, accumulated temperature, and number of grains per panicle that did not produce seeds in one or two studies

WSC ID	Flowering/heading date				Accumulated temperature from sowing until flowering/heading (°C)				Number of grains per panicle (seeds)			
	KD	CD	CR	TR▪	KD	CD	CR	TR▪	KD	CD	CR	TR
WSC 02	9-Jan	15-Apr	26-Aug	18-Aug	1,122	1,084	953	1,268	$	200	300	750
WSC 07	11-Jan	17-Apr	28-Aug	#	1,151	1,125	990	#	300	300	420	#
WSC 08	*	11-Apr	21-Aug	#	*	999	863	#	*	400	450	#
WSC 11	*	18-Apr	29-Aug	25-Aug	*	1,145	1,009	1,402	*	600	560	2,700
WSC 19	17-Jan	15-Apr	26-Aug	18-Aug	1,246	1,084	953	1,268	$	200	200	890
WSC 30	*	11-Apr	20-Aug	8-Sep	*	999	844	1,592	*	200	950	1,700
WSC 37	15-Jan	7-Apr	24-Aug	5-Aug	1,215	913	917	1,036	*	300	480	500
WSC 39	$	14-Apr	24-Aug	8-Aug	$	1,062	917	1,098	$	200	400	740
WSC 42	12-Jan	6-Apr	20-Aug	8-Aug	1,168	891	844	1,098	$	200	400	2,800
WSC 64	*	15-Apr	27-Aug	5-Aug	*	1,084	972	1,036	*	300	400	2,900
WSC 66	13-Jan	13-Apr	24-Aug	19-Aug	1,185	1,042	917	1,287	$	400	400	1,500
WSC 79	7-Jan	13-Apr	24-Aug	#	1,086	1,042	917	#	90	90	80	#
WSC 80	8-Jan	13-Apr	23-Aug	#	1,105	1,042	899	#	100	50	200	#
WSC 82	7-Jan	6-Apr	18-Aug	#	1,086	891	807	#	30	60	100	#
WSC 89	11-Jan	11-Apr	20-Aug	11-Aug	1,151	999	844	1,148	*	200	340	790
WSC 91	15-Jan	11-Apr	20-Aug	#	1,215	999	844	#	30	300	370	#
WSC 92	9-Jan	13-Apr	24-Aug	#	1,122	1,042	917	#	100	100	100	#
WSC 93	10-Jan	18-Apr	29-Aug	#	1,136	1,145	1,009	#	100	60	90	#
WSC 94	*	20-Apr	31-Aug	#	*	1,187	1,046	#	*	200	200	#
WSC 99	*	17-Apr	28-Aug	8-Sep	*	1,125	990	1,592	*	200	200	1,100
WSC 100	*	15-Apr	27-Aug	16-Sep	*	1,084	972	1,691	*	200	300	3,000
WSC 101	10-Jan	20-Apr	31-Aug	15-Aug	1,136	1,187	1,046	1,218	*	300	340	1,300
WSC 102	*	21-Apr	1-Sep	25-Aug	*	1,209	1,066	1,402	*	90	200	780
WSC 103	9-Jan	21-Apr	1-Sep	#	1,122	1,209	1,066	#	100	90	200	#
WSC 107	8-Jan	18-Apr	29-Aug	#	1,105	1,145	1,009	#	100	100	200	#
Min(Earliest)	-	(6-Apr)	(18-Aug)	(5-Aug)	1,086	891	807	1,036	30	50	80	500
Max(Latest)	-	(21-Apr)	(1-Sep)	-	1,246	1,209	1,066	1,691	300	600	950	3,000
Average(Mean)	-	(15-Apr)	(26-Aug)	-	(1,136)	(1,084)	(953)	(1,268)	110	210	310	1,500
S.D.**					46	90	75	207	70	130	190	900

No seeds were obtained due to a shoot fly attack (*), late heading (#), unclear reason ($). These data were excluded from calculations.
▪ Heading
** Standard deviation (S.D.)

Table 3B. Flowering/heading date, accumulated temperature, and number of grains per panicle that produced seeds in four studies

WSC ID	Flowering/heading date				Accumulated temperature from sowing until flowering/heading (°C)				Number of grains per panicle (seeds)			
	KD	CD	CR	TR▪	KD	CD	CR	TR▪	KD	CD	CR	TR
WSC 01	11-Jan	15-Apr	26-Aug	8-Aug	1,151	1,084	953	1,098	750	710	600	1,500
WSC 03	8-Jan	13-Apr	24-Aug	8-Sep	1,105	1,042	917	1,592	570	460	400	740
WSC 04	10-Jan	13-Apr	24-Aug	18-Aug	1,136	1,042	917	1,268	310	300	410	1,200
WSC 05	7-Jan	13-Apr	23-Aug	4-Aug	1,086	1,042	899	1,016	910	570	440	2,500
WSC 06	8-Jan	13-Apr	23-Aug	7-Aug	1,105	1,042	899	1,078	100	200	380	1,600
WSC 09	8-Jan	7-Apr	21-Aug	28-Jul	1,105	913	863	887	200	200	440	670
WSC 10	7-Jan	13-Apr	24-Aug	7-Aug	1,086	1,042	917	1,078	890	770	540	5,100
WSC 12	10-Jan	11-Apr	21-Aug	25-Jul	1,136	999	863	827	200	200	520	2,400
WSC 13	9-Jan	11-Apr	21-Aug	28-Jul	1,122	999	863	887	670	640	430	1,100
WSC 14	12-Jan	13-Apr	23-Aug	4-Aug	1,170	1,042	899	1,016	250	390	330	1,500
WSC 15	10-Jan	13-Apr	23-Aug	4-Aug	1,136	1,042	899	1,016	300	300	560	1,700
WSC 16	20-Jan	13-Apr	24-Aug	6-Aug	1,295	1,042	917	1,057	200	100	570	2,800
WSC 17	10-Jan	15-Apr	26-Aug	1-Aug	1,136	1,084	953	956	300	200	200	1,400
WSC 18	11-Jan	14-Apr	25-Aug	4-Aug	1,151	1,062	935	1,016	170	100	300	2,100
WSC 20	10-Jan	13-Apr	23-Aug	28-Jul	1,136	1,042	899	887	310	90	200	830
WSC 23	11-Jan	8-Apr	21-Aug	15-Aug	1,151	935	863	1,218	60	300	300	1,200
WSC 24	7-Jan	13-Apr	23-Aug	31-Jul	1,086	1,042	899	937	70	60	200	520
WSC 25	8-Jan	13-Apr	23-Aug	30-Jul	1,105	1,042	899	920	20	100	300	2,500
WSC 26	7-Jan	8-Apr	21-Aug	30-Jul	1,086	935	863	920	30	200	300	1,100
WSC 27	9-Jan	13-Apr	24-Aug	25-Aug	1,122	1,042	917	1,402	100	200	400	520
WSC 28	12-Jan	11-Apr	21-Aug	18-Aug	1,168	999	863	1,268	40	200	560	830
WSC 29	8-Jan	13-Apr	24-Aug	18-Aug	1,105	1,042	917	1,268	100	200	340	2,700
WSC 31	10-Jan	18-Apr	29-Aug	19-Aug	1,136	1,145	1,009	1,287	100	100	670	2,000
WSC 32	13-Jan	7-Apr	18-Aug	8-Aug	1,185	913	807	1,098	50	100	400	1,800
WSC 33	8-Jan	9-Apr	19-Aug	12-Aug	1,105	957	826	1,168	100	100	200	2,100
WSC 34	10-Jan	14-Apr	25-Aug	22-Sep	1,136	1,062	935	1,751	100	100	200	670
WSC 35	13-Jan	15-Apr	27-Aug	12-Aug	1,185	1,084	972	1,168	100	100	200	2,100
WSC 36	13-Jan	5-Apr	16-Aug	28-Jul	1,185	869	771	887	40	200	300	200
WSC 38	7-Jan	5-Apr	16-Aug	18-Aug	1,086	869	771	1,268	60	60	200	1,100
WSC 40	8-Jan	5-Apr	25-Aug	26-Aug	1,105	869	935	1,418	30	100	300	1,100
WSC 41	10-Jan	11-Apr	14-Aug	4-Aug	1,136	999	736	1,016	100	90	100	1,500
WSC 43	11-Jan	11-Apr	21-Aug	1-Aug	1,151	999	863	956	40	300	460	1,500

Table 3B. Flowering/heading date, accumulated temperature, and number of grains per panicle that produced seeds in four studies (Continued)

WSC ID	Flowering/heading date				Accumulated temperature from sowing until flowering/ heading (°C)				Number of grains per panicle (seeds)			
	KD	CD	CR	TR▪	KD	CD	CR	TR▪	KD	CD	CR	TR
WSC 44	12-Jan	7-Apr	16-Aug	30-Jul	1,168	913	771	920	70	100	480	1,600
WSC 45	10-Jan	8-Apr	26-Aug	6-Aug	1,136	935	953	1,057	50	200	320	770
WSC 46	8-Jan	9-Apr	19-Aug	21-Aug	1,105	957	826	1,328	60	100	200	2,300
WSC 47	15-Jan	7-Apr	24-Aug	21-Aug	1,215	913	917	1,328	80	100	200	2,500
WSC 48	17-Jan	13-Apr	24-Aug	21-Aug	1,246	1,042	917	1,328	430	440	430	3,800
WSC 49	13-Jan	13-Apr	23-Aug	19-Aug	1,185	1,042	899	1,287	40	90	200	880
WSC 50	7-Jan	13-Apr	23-Aug	13-Aug	1,086	1,042	899	1,184	80	90	200	1,600
WSC 51	10-Jan	13-Apr	24-Aug	27-Aug	1,136	1,042	917	1,432	100	200	300	300
WSC 52	11-Jan	8-Apr	17-Aug	6-Aug	1,151	935	788	1,057	100	100	200	1,100
WSC 53	7-Jan	7-Apr	16-Aug	4-Aug	1,086	913	771	1,016	100	70	200	450
WSC 54	10-Jan	8-Apr	16-Aug	5-Aug	1,136	935	788	1,036	70	200	300	1,600
WSC 55	11-Jan	13-Apr	24-Aug	11-Aug	1,151	1,042	917	1,148	40	60	100	540
WSC 56	8-Jan	7-Apr	18-Aug	25-Aug	1,105	913	807	1,402	60	60	100	1,500
WSC 57	7-Jan	11-Apr	21-Aug	7-Aug	1,086	999	863	1,078	50	80	200	1,500
WSC 58	7-Jan	13-Apr	24-Aug	5-Aug	1,086	1,042	917	1,036	100	100	300	1,600
WSC 59	10-Jan	11-Apr	20-Aug	1-Aug	1,136	999	844	956	30	60	100	400
WSC 60	10-Jan	12-Apr	22-Aug	12-Aug	1,136	1,020	881	1,168	70	200	300	1,000
WSC 61	11-Jan	13-Apr	24-Aug	6-Aug	1,151	1,042	917	1,057	200	300	400	440
WSC 62	12-Jan	13-Apr	24-Aug	29-Jul	1,168	1,042	917	904	50	200	290	1,000
WSC 63	10-Jan	17-Apr	28-Aug	6-Aug	1,136	1,125	990	1,057	40	100	200	1,300
WSC 65	10-Jan	8-Apr	19-Aug	5-Aug	1,136	935	826	1,036	70	70	100	840
WSC 67	8-Jan	13-Apr	24-Aug	5-Aug	1,105	1,042	917	1,036	70	90	300	2,100
WSC 68	10-Jan	18-Apr	29-Aug	4-Aug	1,136	1,145	1,009	1,016	80	100	200	1,400
WSC 69	8-Jan	11-Apr	20-Aug	5-Aug	1,105	999	844	1,036	80	90	100	1,100
WSC 70	9-Jan	13-Apr	23-Aug	11-Aug	1,122	1,042	899	1,148	300	300	400	1,400
WSC 71	11-Jan	13-Apr	24-Aug	17-Sep	1,151	1,042	917	1,705	100	100	310	5,500
WSC 72	10-Jan	5-Apr	14-Aug	5-Aug	1,136	869	736	1,036	60	80	100	2,400
WSC 73	10-Jan	17-Apr	28-Aug	7-Aug	1,136	1,125	990	1,078	30	100	200	670
WSC 74	8-Jan	7-Apr	19-Aug	26-Aug	1,105	913	826	1,418	80	200	200	200
WSC 75	9-Jan	8-Apr	17-Aug	5-Aug	1,122	935	788	1,036	60	90	100	1,600
WSC 76	8-Jan	15-Apr	27-Aug	17-Sep	1,105	1,084	972	1,705	50	100	200	2,700
WSC 77	7-Jan	6-Apr	15-Aug	19-Aug	1,086	891	754	1,287	90	200	330	300

Table 3B. Flowering/heading date, accumulated temperature, and number of grains per panicle that produced seeds in four studies (Continued)

WSC ID	Flowering/heading date				Accumulated temperature from sowing until flowering/heading (°C)				Number of grains per panicle (seeds)			
	KD	CD	CR	TR▪	KD	CD	CR	TR▪	KD	CD	CR	TR
WSC 78	11-Jan	8-Apr	17-Aug	12-Aug	1,151	935	788	1,168	100	200	200	1,400
WSC 81	8-Jan	13-Apr	23-Aug	16-Sep	1,105	1,042	899	1,691	90	200	200	1,300
WSC 83	10-Jan	11-Apr	21-Aug	26-Aug	1,136	999	863	1,418	50	100	200	1,400
WSC 84	9-Jan	13-Apr	24-Aug	12-Sep	1,122	1,042	917	1,641	70	300	400	2,200
WSC 85	9-Jan	7-Apr	19-Aug	30-Jul	1,122	913	826	920	100	100	100	790
WSC 86	8-Jan	8-Apr	19-Aug	12-Aug	1,105	935	826	1,168	60	100	300	550
WSC 87	7-Jan	17-Apr	28-Aug	22-Aug	1,086	1,125	990	1,347	80	80	100	400
WSC 88	12-Jan	18-Apr	29-Aug	5-Aug	1,168	1,145	1,009	1,036	100	200	320	1,100
WSC 90	12-Jan	19-Apr	30-Aug	29-Aug	1,168	1,166	1,028	1,454	80	100	200	2,900
WSC 95	10-Jan	20-Apr	31-Aug	5-Aug	1,136	1,187	1,046	1,036	40	200	200	760
WSC 96	11-Jan	21-Apr	1-Sep	25-Aug	1,151	1,209	1,066	1,402	50	200	200	880
WSC 97	9-Jan	21-Apr	1-Sep	7-Aug	1,122	1,209	1,066	1,078	50	200	290	520
WSC 98	10-Jan	20-Apr	31-Aug	2-Sep	1,136	1,187	1,046	1,506	90	100	200	370
WSC 104	10-Jan	13-Apr	24-Aug	6-Aug	1,136	1,042	917	1,057	90	100	200	830
WSC 105	12-Jan	13-Apr	24-Aug	19-Aug	1,168	1,042	917	1,287	40	400	310	490
WSC 106	10-Jan	13-Apr	24-Aug	19-Aug	1,136	1,042	917	1,287	30	200	200	1,300
Min(Earliest)	(7-Jan)	(5-Apr)	(14-Aug)	(25-Jul)	1,086	869	736	827	20	60	110	200
Max(Latest)	(20-Jan)	(21-Apr)	(1-Sep)	(22-Sep)	1,295	1,209	1,066	1,751	910	770	670	5,500
Average(Mean)	(10-Jan)	(13-Apr)	(23-Aug)	(7-Aug)	(1,136)	(1,042)	(899)	(1,078)	140	190	280	1,400
S.D.**					36	82	76	218	180	140	130	970

▪ Heading
** Standard deviation (S.D.)

2. Seed productivity comparison

The average number of grains per panicle of the harvested accessions differed significantly ($P < 0.05$) with 140 ± 180 grains per panicle in KD, 190 ± 140 in CD, 280 ± 130 in CR, and 1,400 ± 970 in TR. Overall, the largest number of grains per panicle was observed in the accessions grown in Japan, and the heads producing the highest number of grains in India were those grown in CR. A comparison of the average number of grains per panicle from each accession in TR and CR revealed that from the 80 successfully grown accessions (Table 3B), 76 (95%) produced a larger harvest in TR (Fig. 1). For example, the accession with the largest harvest produced 670 grains per panicle (WSC31, Indian origin) in CR and 2,000 grains per panicle in TR, or about a threefold increase. Moreover, 19 out of the 80 accessions (24%) produced 2,000 or more grains per panicle in TR, marking a threefold increase from the most productive accession in CR (Table 3B). The origins of these 19 productive seed lots were diverse: four were from India; three were from Pakistan; two each were from Japan, Korea, South Africa, and Sudan; one each was from China, North Korea, Morocco, and Algeria. Of those 19 accessions, seven (9%) produced no more than 200 grains per panicle in CR. These included WSC33 "DHOOTI ANEHULA" from India; WSC35 "AS 4136 MASAKA LUWEMEA" from India; WSC46 "COL/PAK/1989/IBPGR/2592(7)" from Pakistan; WSC47 "87-9-21-3-1" from Pakistan; WSC72 "S. BASUTORUM DL/60/97" from South Africa; WSC76 "143 DINDERAWI 1" from Sudan, and WSC90 "MN 401" from Algeria. A similar tendency was observed when TR was compared with CD or KD. From these results, we observed that some accessions originating in such places as India, which were presumed to yield a low harvest, could yield a higher harvest under Japanese climatic conditions.

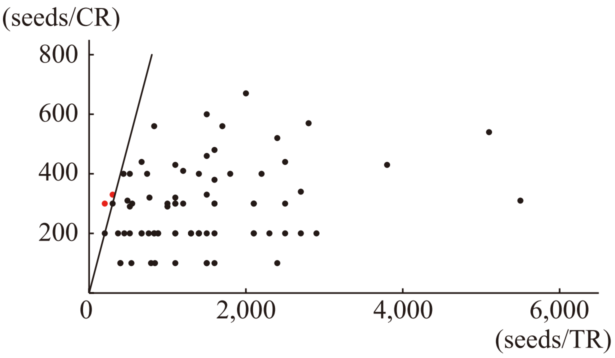

Fig. 1. Comparison of the number of grains per panicle for each accession grown in TR and CR

The straight line shows that the number of grains per panicle is equivalent in Tsukuba, Japan (TR), and Coimbatore, India, when cultivated during the rainy season (CR). The two accessions (two red dots) on the left side of the straight line show a greater number of grains per panicle in CR than in TR.

3. Flowering and heading

Flowering in sorghum begins when yellow anthers appear at the tip of the head at 5-7 days after head extension (Gerik et al. 2003, Jason et al. 2004, Venderlip 1993). Therefore, it could be estimated that the flowering date ≒ heading date + 6 days. The flowering data from KD, CD, and CR, and heading data from TR were used for the comparisons presented in this study. In KD, 96 accessions flowered; however, the remaining nine did not reach the flowering stage due to an attack by shoot flies or for unclear reasons. The number of days between sowing and flowering among the 80 accessions that produced grain (Table 3B) was 65 ± 2.3 days (range: 62-75). All the accessions grown in CD flowered. The number of days from sowing to flowering was 54 ± 3.9 (range: 46-62), and notably flowering was concentrated within a 17-day period. All the accessions grown in CR also flowered. The number of days from sowing to flowering was 53 ± 4.2 (range: 43-61). CD and CR displayed similar numbers of days until flowering, although their sowing time was shifted by half a year. Therefore, day length at the time of sowing was considered less than the threshold for flowering/heading and sorghum were presumed to shift to the reproductive stage immediately following germination in the low latitude regions of India. In TR, 94 accessions produced heads. The number of days from sowing to heading was 77 ± 13.1 (range: 58-117)—a significantly longer period than that observed in CD. The flowering/heading period range varied at different locations, with the range in TR being three times longer than that of plants cultivated in India (Fig. 2 (a) and Table 3B). The 11 remaining accessions in TR (Table 3A) did not head before the end of the cultivation period (the end of September for heading), and thus were considered to be affected by differences in day length (Fig. 2 (b)).

Mannai et al. (2011) used association analysis to evaluate that a 12 h photoperiod could be considered the threshold above which day length delays flowering in sorghum. Tarumoto (2011) demonstrated that flower bud initiation in cultivars such as cv. Tentaka occurred below the critical day length of 12.25 h. In our studies, 54 days elapsed before 50% of the accessions (40 out of 80 accessions in Table 3B) reached flowering in CD; however, the day length was between 12.6 and 12.7 h at the third to fifth leaf stage (Fig. 2 (b); Vanderlip RL 1993). According to Tarumoto (2011), the effective timing of the 12.25 h day length is 10-30 days after

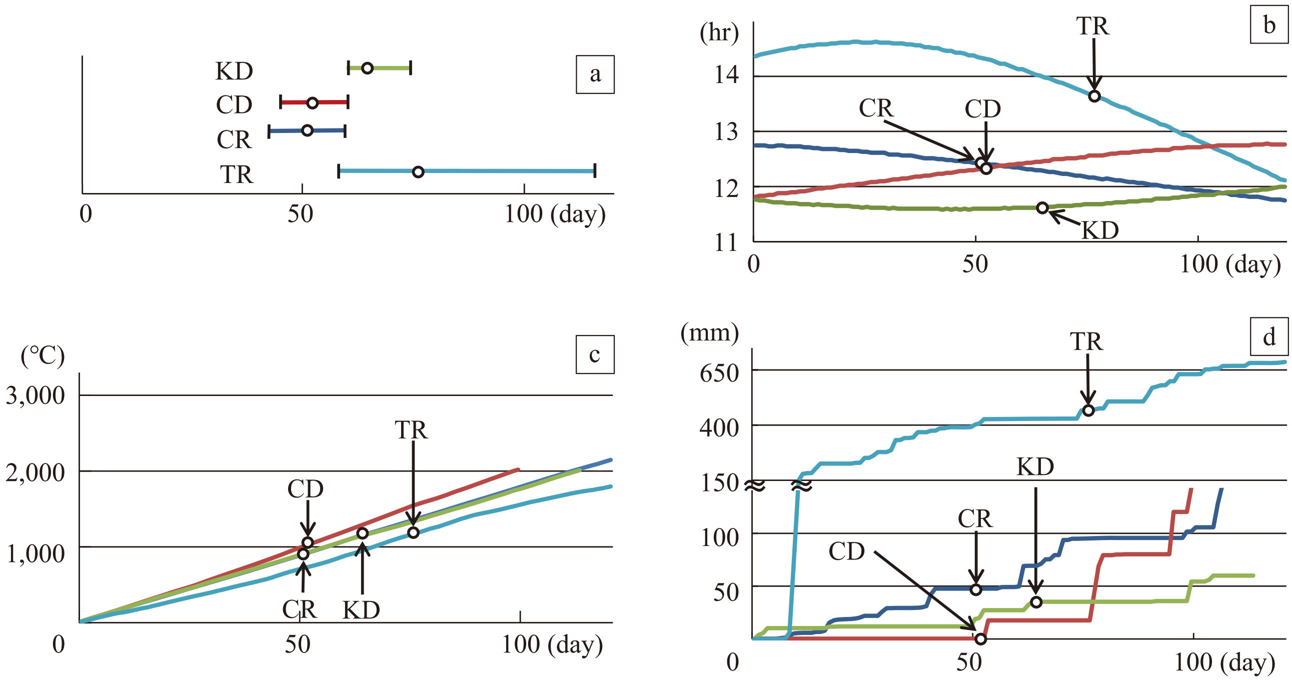

Fig. 2. Flowering/heading timing and climatic conditions during cultivation

Environmental conditions at each site from sowing, Day 1 to Day 120. (a) Range of flowering/heading days (bar) and number of days until 50% of the accessions reached the flowering/heading stage (○). (b) Theoretical day length. (c) Accumulated temperature. (d) Accumulated rainfall. Arrows indicate the number of days until 50% accession reached the flowering/heading stage at each site. Accessions that did not reach the flowering/heading stage due to a shoot fly attack, late heading, etc. were excluded.

emergence of the seedling (third to fifth leaf stage). Therefore, the day length threshold for flowering/heading could possibly be longer than 12 h in India or 12.25 h in Japan. However, this observation has yet to be confirmed and future studies must further investigate it.

The accumulated temperature of each accession, once 50% of the accessions reached the flowing or heading stage, was 1,136°C in KD, 1,042°C in CD, 899°C in CR, and 1,078°C in TR (Fig. 2 (c)). The ranges of accumulated temperatures up to the point of flowering for accessions grown in India were 209°C in KD, 340°C in CD, and 330°C in CR. There was a 924°C range in the accumulated temperature up to the heading stage in TR.

When CR and KD were compared (Fig. 2 (c)), the transition (curve) of accumulated temperatures was almost the same, but the number of days until flowering in KD was delayed by 12 days compared with that in CR. Therefore, we compared the distribution of days to flowering/heading of each accession in India and Japan (Fig. 3). However, there was almost no correlation between the number of days to heading in TR and the number of days to flowering in KD, CD, and CR. The results of CR and KD suggest the presence of other unknown factors apart from the accumulated temperature that are presently not known related to heading. *Ed1* and *Hd3a* genes are related to photoperiod in rice (Yano et al. 2001), whereas *SbCO* and *SbCN15* genes are related to the similar function in sorghum (Yang et al. 2014). It would be useful to examine the contribution of these genes as well as unknown genes and other factors in the future.

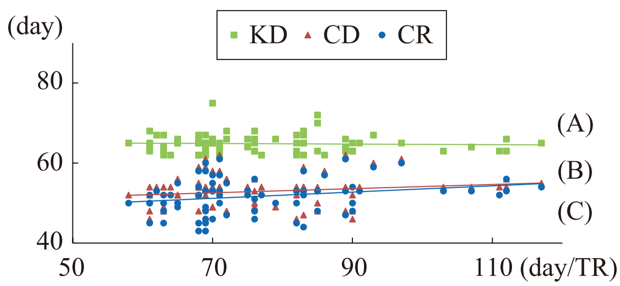

Fig. 3. Distribution of days to the flowering/heading stage for each accession in India and Japan

The straight lines are regression lines between the days to the heading stage in Tsukuba, Japan (TR), and the days to the flowering stage of each accession during the post-rainy season in Kovilpatti, India (KD, ■) and Coimbatore, India (CD, ▲), and the rainy season in Coimbatore, India (CR, ●). r denotes the correlation coefficient. A: (KD) $y = -0.007x + 65$ ($r = 0.043$); B: (CD) $y = 0.052x + 49$ ($r = 0.177$); C: (CR) $y = 0.078x + 46$ ($r = 0.246$).

4. Rainfall

The accumulated rainfall for each accession, when 50% of accessions reached the flowering or heading stage (Fig. 2 (d)), was 35 mm in KD, 0.2 mm in CD, 48 mm in CR, and 429 mm in TR. TR overwhelmingly had the largest accumulated rainfall, with five times the number of grains per panicle when compared with those grown in India. Most rainfall precipitation in India occurred in CR, and the plants grown here produced a larger number of grains per panicle compared with those grown in KD and CD. The reason why more seeds were produced even though CD had less accumulated rainfall than KD may be because there were two more irrigations. Considering that the accumulated rainfall in Japan was higher than that in India, the larger seed harvests in Japan were thought to be due to a lesser drought stress (Rogers et al. 2016). Therefore, the seed harvest of each accession may be expected to increase through the availability of enough water in India.

Conclusions

In the present study, the seed productivity of genebank sorghum accessions was examined using the NARO sorghum core collection cultivated in India and Japan under different climatic conditions. Although sorghum seed productivity was highest in Japan, the cultivation of some varieties in India (such as in Coimbatore) was advantageous, particularly for those varieties unable to produce seeds in Japan. Two or three cycles of crop cultivation per year may prove beneficial in India for faster seed multiplication. Moreover, the concentration of flowering in short day periods in India is beneficial for efficient harvest from various accessions. The utilization of data about cultivar characteristics is important for maximizing the number of accessions that produce enough amount of seeds for preservation in the genebank. And international collaboration is essential for evaluating these characteristics and utilizing diverse genetic resources.

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