Indian Journal of Agricultural Sciences **87** (7): 899–910, July 2017/Article
https://doi.org/10.56093/ijas.v87i7.71833

Identification, characterization and validation of core collection of foxtail millet (*Setaria italica*)

SUBHASH CHANDER[1], K V BHAT[2], M V C GOWDA[3] and N DIKSHIT[4]

ICAR-National Bureau of Plant Genetic Resources, Regional Station, Akola, Maharashtra 444 104

Received: 21 December 2016; Accepted: 3 January 2017

ABSTRACT

Foxtail millet [*Setaria italica* (L.) P. Beauv.] is an important minor millet, which is drought tolerant, rich in micronutrients and grown in the marginal and rainfed regions of India. Power core software was used to develop the core collection of foxtail millet using total of 1515 germplasm accessions, emanating from 21 different countries. Eleven quantitative and 13 qualitative traits were utilized to characterize the core collection. Each qualitative and quantitative trait was divided into discrete classes and 223 core entries were selected from them. Selected core entries comprises accessions predominantly from India (75.78%). Average Shannon-Weaver diversity (0.73) and Nei's diversity index (0.43) of core collection were higher for the entire collection indicating true representation of diversity available in the entire collection. Average polymorphism information content (PIC) value was 0.99. Core accessions were evaluated and validated using analysis of variance (ANOVA), descriptive statistics, clustering based on neighbour joining tree and principal component analysis. Accessions from Andhra Pradesh, Karnataka, Madhya Pradesh, Tamil Nadu, Uttar Pradesh and North-East Region were distributed in almost all the clusters and sub-clusters suggesting lack of discrete relationship between geographic locations and clustering pattern. Thus, a highly diverse core collection representing the diversity of entire germplasm holding from different parts of the world was identified and this can be used for foxtail millet improvement programs as well as to identify trait-specific reference collections.

Key words: Core collection, Foxtail millet, Nei's diversity index, Shannon-Weaver diversity index

Foxtail millet [*Setaria italica* (L.) P. Beauv.] is a member of Poaceae family and is one of the 10 small millets grown in various parts of the world. Vavilov (1926) identified China as the centre of origin of this crop, where it was domesticated and selected as food grain as early as 8700 years ago (Lu *et al.* 2009). Li *et al.* (1945) has identified *S. viridis* as a wild ancestor of foxtail millet through cytological studies. It is the second largest cultivated millet species in the world and possesses several salient features such as self-pollinating, C_4 panicoid crop and a small genome size (515 Mb; 2n=2x =18; Mishra *et al.* 2014). In India, it is cultivated in areas ranging from high altitudes of Jammu and Kashmir, Himachal Pradesh and Uttarakhand to coastal belts of Kerala, Andhra Pradesh, Tamil Nadu and Karnataka under wide range of soil and environmental conditions. Millets are known as nutri-cereals and can be used for making multi-grain flour for chapati making and porridge preparation. Foxtail millet is highly nutritious due to its protein (12.3 g/100g) with high dietary value and fibre (14 g/100g) and, low carbohydrate content (60.9 g/100g), besides being rich in minerals (3.0 g/100g) and phytochemicals (Vetriventhan 2011). Foxtail millet is a good source of ß-carotene (126 to 191 µg/100g) and proved to be suitable for people suffering from metabolic disorders (Goudar *et al.* 2011).

The large size of the germplasm collection is an obstacle for their characterization and evaluation thereby hampering their utilization in breeding programmes. Frankel (1984) and Brown (1995) developed the concept of core collection that involved identification of a limited set of accessions derived from the entire collection which represent the genetic spectrum of the whole collection. To date core collection has been developed for many millets such as pearl millet (Bhattacharjee *et al.* 2007, Upadhyaya *et al.* 2009b), finger millet (Upadhyaya *et al.* 2006), prosomillet (Upadhyaya *et al.* 2011) and foxtail millet (Upadhyaya *et al.* 2008) using various sampling strategies and clustering methods. Recently, a new strategy, i.e. Advanced M strategy with heuristic search for establishing core sets known as Power Core (http://genebank.rda.go.kr/powercore) was successfully used by Gowda *et al.* (2007, 2013) for developing core set of 78 and 59 accessions of foxtail millet using qualitative and quantitative descriptors. Current study also used the

[1](e mail: singhariya43@gmail.com), Division of Plant Genetic Resources, IARI, New Delhi 110 012. Present address: ICAR-Directorate of Weed Research, Jabalpur 482 004. [2](e mail: kvbhat2001@yahoo.com), ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi 110 012. [3](e mail: mvcgowdapb@gmail.com), All India Coordinated Small Millet Improvement Programme, GKVK , Bengaluru 560 065. [4](e mail: dikshit@gmail.com), ICAR-NBPGR, Regional Station, Akola, Maharashtra

Table 1 List of 223 foxtail millet core accessions with their source

Acc. No.	Location	Acc. No.	Location
SiA 326	Andhra Pradesh (Check)	ISE 194	Tamil Nadu
PS 4	Uttar Pradesh (Check)	Pratap Kangini	Rajasthan
SiA 3085	Andhra Pradesh (Check)	GS 2259	Uttar Pradesh*
GS 130	Himachal Pradesh	ISE 1162	Syria (West Asia)
Arjuna	Andhra Pradesh	GS 2040	China
ISE 1597	Odisha	ISE 1227	Russia (Northern Eurasia)
GS 2235	Uttar Pradesh*	ISE 1685	NE Region (Tripura)
ISE 1454	Uttar Pradesh	CO 1	Tamil Nadu
GS 134	Himachal Pradesh	GS 125	Gujarat
ISE 2	Andhra Pradesh	ISE 237	Karnataka
GS 2183	Uttar Pradesh*	GS 2164	Uttar Pradesh*
ISE 907	Tamil Nadu	ISE 931	Tamil Nadu
GS 2239	Uttar Pradesh*	GS 1897	Odisha
Chitra	Andhra Pradesh	ISE 1408	Andhra Pradesh
ISE 1610	South Africa (Africa)	GS 26	Andhra Pradesh
GS 140	Jammu and Kashmir	ISE 1137	Syria (West Asia)
ISE 18	Andhra Pradesh	ISE 1674	Odisha
GS 2041	China (East Asia)	SR 11	Rajasthan
ISE 1468	Andhra Pradesh	GS 343	Odisha
ISE 156	Madhya Pradesh	ISE 1846	Karnataka
GS 1929	Bangladesh (South Asia)	ISE 364	Uttar Pradesh
ISE 1780	Himachal Pradesh	GS 2092	Karnataka
ISE 1474	U.K. (European Union)	GS 40	West Bengal
ISE 144	Madhya Pradesh	ISE 995	Tamil Nadu
ISE 1655	Taiwan (East Asia)	GS 1489	Andhra Pradesh
ISE 869	Tamil Nadu	ISE 1808	Maharashtra
Narsimharaya	Andhra Pradesh	GS 2261	Uttar Pradesh*
ISE 132	Jammu and Kashmir	GS 158	Madhya Pradesh
GS 2155	Uttar Pradesh*	ISE 1647	Taiwan (East Asia)
ISE 1629	Kerala	ISE 1745	Myanmar (S.E. Asia)
GS 515	Karnataka	ISE 238	Karnataka
GS 127	Gujarat	GS 2107	Uttar Pradesh*
ISE 96	Gujarat	ISE 1161	Syria (West Asia)
ISE 1511	Maharashtra	ISE 254	Karnataka
GS 541	Karnataka	ISE 1687	NE Region (Tripura)
ISE 1418	Andhra Pradesh	CO 2	Tamil Nadu
GS 2026	Tamil Nadu	ISE 1547	Korea (East Asia)
MEERA	Rajasthan	GS 34	West Bengal
ISE 140	Kerala	ISE 1666	Maharashtra
GS 56	Bihar	ISE 301	Punjab
ISE 1789	Madhya Pradesh	ISE 1725	Nepal (South Asia)
GS 1618	Karnataka	GS 583	Uttar Pradesh*
ISE 1773	Bihar	ISE 1820	Maharashtra
GS 8	Andhra Pradesh	ISE 362	Uttar Pradesh
ISE 217A	Maharashtra	H 1	Karnataka

Cond.

Table 1 (*Continued*)

Acc. No.	Location	Acc. No.	Location
GS 511	USA	ISE 999	Tamil Nadu
ISE 195	Tamil Nadu	ISE 289	Karnataka
ISE 1767	West Bengal	ISE 710	Andhra Pradesh
GS 164	Madhya Pradesh	GS 345	Odisha
Srilakshmi	Andhra Pradesh	CO 4	Tamil Nadu
ISE 179	Tamil Nadu	ISE 1151	Syria (West Asia)
GS 656	Uttar Pradesh*	GS 455	USA
ISE 914	Tamil Nadu	ISE 1258	Russia (Nothern Eurasia)
ISE 388	Bihar	ISE 375	NE Region (Assam)
GS 102	Bihar	ISE 936	Tamil Nadu
ISE 900	Tamil Nadu	GS 359	Rajasthan
ISE 1406	Andhra Pradesh	GS 949	Uttar Pradesh*
ISE 1254	Russia (Northern Eurasia)	ISE 748	Andhra Pradesh
ISE 458	USA	GS 432	Madhya Pradesh
GS 639	Uttar Pradesh*	ISE 1320	USA (Iowa)
H 2	Karnataka	ISE 758	Andhra Pradesh
ISE 302	Punjab	GS 2154	Uttar Pradesh*
ISE 1169	Syria (West Asia)	ISE 1187	China (East Asia)
GS 592	Uttar Pradesh*	ISE 771	Andhra Pradesh
ISE 1851	Karnataka	ISE 1575	Korea (East Asia)
GS 2029	China (East Asia)	GS 766	Uttar Pradesh*
ISE 946	Tamil Nadu	ISE 785	Maharashtra
GS 792	Uttar Pradesh*	ISE 1209	Russia (Northern Eurasia)
K-221-1	Karnataka	Krishnadevaraya	Andhra Pradesh
ISE 398	Madhya Pradesh	GS 2147	Uttar Pradesh*
ISE 1593	Korea (East Asia)	ISE 1581	Korea (East Asia)
ISE 963	Tamil Nadu	GS 450	NE Region (N.E. Himalaya)
GS 700	Uttar Pradesh*	TNAU 59	Tamil Nadu
ISE 717	Pakistan (South Asia)	GS 956	Uttar Pradesh*
ISE 1181	China (East Asia)	ISE 1059	NE Region (Meghalya)
ISE 969	Tamil Nadu	GS 493	Turkey (Eurasia)
ISE 719	Pakistan (South Asia)	ISE 1136	Syria (West Asia)
K 2	Tamil Nadu	GS 2035	China (East Asia)
ISE 1892	USA (Iowa)	ISE 1664	Maharashtra
ISE 1269	South Africa (Africa)	GS 443	Madhya Pradesh
GS 396	Uttar Pradesh	ISE 1037	Lebanon (West Asia)
ISE 507	Kenya (Africa)	ISE 1704	Karnataka
ISE 1204	Russia (Nothern Eurasia)	GS 779	Uttar Pradesh*
ISE 663	Switzerland (Europian Union)	ISE 1387	Srilanka (South Asia)
GS 1893	Andhra Pradesh	RFM 14	Karnataka
GS 1032	Uttar Pradesh*	ISE 1026	Lebanon (West Asia)
GS 498	Kenya (Africa)	GS 2036	China (East Asia)
ISE 1400	Andhra Pradesh	ISE 1736	Nepal (South Asia)
GS 754	Uttar Pradesh*	GS 433	Madhya Pradesh
ISE 1563	Korea (East Asia)	GS 1605	Karnataka

Cond.

Table 1 (*Concluded*)

Acc. No.	Location	Acc. No.	Location
GS 419	NE Region (Manipur)	GS 961	Uttar Pradesh*
RS 118	Karnataka	ISE 1234	Russia (Northern Eurasia)
ISE 1299	Iran (West Asia)	GS 147	Jammu and Kashmir
ISE 525	USA	ISE 31	West Bengal
ISE 703	Karnataka	GS 957	Uttar Pradesh*
GS 372	Uttar Pradesh	ISE 1805	Maharashtra
RFM 10	Karnataka	GS 160	Madhya Pradesh
ISE 569	Karnataka	ISE 846	Tamil Nadu
GS 760	Uttar Pradesh*	GS 563	Tamil Nadu
ISE 735	Pakistan (South Asia)	ISE 1888	Ethiopia (Africa)
ISE 1305	Spain (European Union)	ISE 1858	Karnataka
CO 7	Tamil Nadu	ISE 1881	Madhya Pradesh
GS 415	Uttar Pradesh	ISE 480	China (East Asia)
ISE 683	Karnataka	ISE 1000	Tamil Nadu
GS 1017	Uttar Pradesh	GS 966	Uttar Pradesh*
GS 1468	Andhra Pradesh	ISE 376	NE Region (Asom)
ISE 746	Andhra Pradesh	GS 403	Uttar Pradesh
GS 430	Madhya Pradesh	ISE 792	Maharashtra
RAU 2	Bihar	ISE 795	Maharashtra
ISE 1129	Syria (West Asia)	GS 695	Uttar Pradesh*
GS 763	Uttar Pradesh*	ISE 769	Madhya Pradesh
ISE 985	Tamil Nadu		

Uttar Pradesh*= Pantnagar (Uttarakhand)

Power Core for developing core set of foxtail millet using qualitative and quantitative descriptors from 1515 accessions available in national germplasm system including ICAR-National Bureau of Plant Genetic Resources (NBPGR), New Delhi and All India Coordinated Small Millet Improvement Programme (AICSMIP), Bengaluru which represent the diversity from within and outside the country.

MATERIALS AND METHODS

The designated core collection of 223 accessions including three released checks (SiA 326, SiA 3085 and PS-4) were grown at NBPGR Regional Station, Akola, Maharashtra and UAS, Bengaluru, Karnataka in July, 2012. The average temperature and total rainfall were 27.04^{o}C and 701.1 mm at Akola, and 24.2^{o} C and 716.8 mm at Bengaluru. The experiment was in Augmented Block Design (Federer 1956) and each accession was sown in three rows of 300cm length and 30 cm between rows. Standard package and practices were followed for the management of the crop throughout the cropping season.

The data were recorded on 13 qualitative and 11 quantitative traits following the descriptor of *Setaria italica* and *Setaria pumila* (IBPGR 1985). The data on 13 qualitative traits, namely, plant pigmentation, leaf colour, blade pubescence, sheath pubescence, degree of lodging at maturity, senescence, inflorescence lobes, inflorescence bristles, inflorescence compactness, lobe compactness, inflorescence shape, colour of fruit and grain shape and, two quantitative traits, i.e. days flowering and days to maturity were recorded on the plot basis. Remaining nine quantitative traits, namely, yield/plant, panicle exsertion, peduncle exsertion, ear length, flag leaf length, flag leaf width, basal tiller number, test weight and plant height were recorded by averaging five plants for each accession (Table 2).

Entire collection of 1515 accessions from different countries supported by their passport information (Gowda *et al.* 2002) was used for the study. These germplasm accessions represented 20 different countries from different regions of the world, i.e. South Asia, 1370 (93.20%), West Asia, 10 (0.66%), East Asia, 34 (2.4%), South-east Asia, 1 (0.07%), USA, 42 (2.77%), European Union, 3 (0.20%), Africa, 8 (0.53%), Eurasia, 8 (0.53%) (Fig 1). Indian germplasm represented accessions from 20 different states.

Power Core software (http://genebank.rda.go.kr/powercore) was used to identify core collection of foxtail millet based on 11 quantitative and 13 qualitative traits. For each qualitative and quantitative trait, the data for each trait was divided into different classes and core entry was picked randomly for each class by the software and the various classes are presented in Table 3 and 4. Common accessions across traits were removed from each class and a core of

Table 2 Details of qualitative and quantitative traits used in scoring of the foxtail millet accessions

Quantitative trait	
Plant height (cm)	From ground level to the tip of the inflorescence at dough stage
Days to maturity	From sowing to stage when 50% of tillers have attained physiological maturity
Flag leaf length (mm)	Measured from ligule to tip
Flag leaf width (mm)	Measured at widest point
Peduncle exertion (mm)	Measured from the topmost node to base of the inflorescence
Basal tillers	Number of tillers at ground level or from the basal nodes
Days to flowering	From sowing to stage when the ears have emerged on 50% of the main tillers
Yield/plant (g)	Mean of five randomly selected plant
Test weight (g)	Weight of random sample of 1000 seeds from the total harvest of an accession
Panicle exsertion (cm)	Measured from the exposed point of the peduncle from the leaf sheath up to base of the inflorescence
Ear length (cm)	From base to the tip of ear on the main tiller at dough stage
Leaf colour	1=green; 2=yellow; 3=pigmented; 4=purple
Blade pubescence	1=essentially glabrous; 5=medium pubescent; 9=strongly pubescent
Sheath pubescence	1=essentially glabrous; 5=medium pubescent; 9=strongly pubescent
Degree of lodging at maturity	1=very slight; 5=medium; 9=extensive
Senescence	Degree to which the plant is still green at time the primary inflorescence on each culm (tiller) reaches maturity: 1=actively growing; 9=dead
Inflorescence lobes	0=absent; 3=short; 7=long; 9=large and thick
Inflorescence bristles	1=very short; 3=short but obvious; 5=medium; 7=long; 9=carrying a spikelet
Inflorescence compactness	lobes are arranged on the primary 3=loose; 5=medium; 7=compact; 9=spong
Lobe compactness	3=loose; 5=medium; 7=compact; 9=spong
Inflorescence shape	1=oblong; 3=ovate; 5=elliptic; 7=obovate
Fruit color	1=red; 2=black; 3=white; 4=yellow
Grain shape	1=oval; 2=elliptical
Plant pigmentation	0=no pigmented (green); 3=pigmented; 7=deep purple

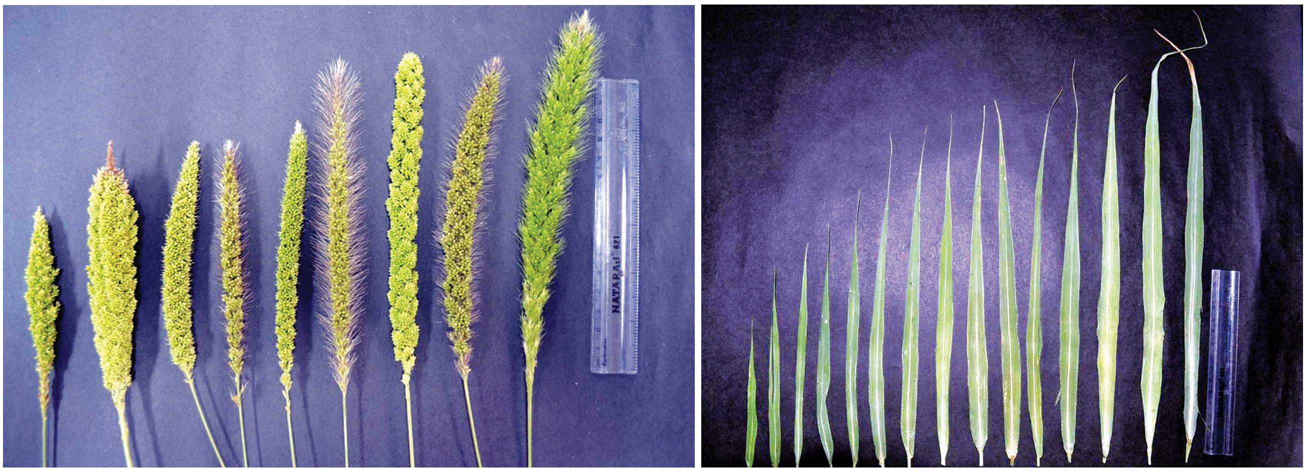

Fig 1 The spectrum of phenotypic variation for inflorescence and leaf characteristics in the core collection of foxtail millet

223 accessions was selected from entire collection (1515 accessions). The ANOVA was calculated using the IASRI website portal (online analysis of data; http://iasri.res.in/analysis/online_analysis.htm) for all the quantitative and qualitative traits. Shannon and Weaver (1949) diversity and Nei's diversity index were used to measure and compare the phenotypic diversity for 13 qualitative traits in the core and entire collection. Based on common qualitative and quantitative traits recorded at both the locations, clustering and principal component analysis was done by using NTSYSpc version 2.02e software (Rohlf 1998). Manhattan distance between pairs of accessions was calculated and

Table 3 Different classes of quantitative traits as generated with Power Core software for the foxtail millet core collection

Days to 50% flowering			Basal tillers			Panicle exsertion		
Class	CC	EC	Class	CC	EC	Class	CC	EC
33.00 ~ 36.00	1	3	1.00 ~ 1.93	9	85	1.50 ~ 3.79	1	2
36.00 ~ 39.00	1	14	1.93 ~ 2.87	13	262	3.79 ~ 6.08	1	7
39.00 ~ 42.00	3	57	2.87 ~ 3.80	19	462	6.08 ~ 8.38	4	58
42.00 ~ 45.00	9	94	3.80 ~ 4.73	13	322	8.38 ~ 10.67	13	241
45.00 ~ 48.00	9	204	4.73 ~ 5.67	6	233	10.67 ~ 12.96	20	439
48.00 ~ 51.00	19	576	5.67 ~ 6.60	2	105	12.96 ~ 15.25	14	389
51.00 ~ 54.00	18	456	6.60 ~ 7.53	4	26	15.25 ~ 17.54	5	225
54.00 ~ 57.00	6	78	7.53 ~ 8.47	1	9	17.54 ~ 19.83	7	103
57.00 ~ 60.00	4	32	8.47 ~ 9.40	1	5	19.83 ~ 22.12	2	35
60.00 ~ 63.00	0	0	9.40 ~ 10.33	1	2	22.12 ~ 24.42	2	10
63.00 ~ 66.00	0	0	10.33 ~ 11.27	1	2	24.42 ~ 26.71	1	4
66.00 ~ 69.00	1	1	11.27 ~ 12.20	1	2	26.71 ~ 29.00	1	2
Peduncle exsertion			*Ear length*			*Plant height*		
13.40 ~ 16.99	2	3	3.60 ~ 5.34	1	2	52.20 ~ 63.18	1	6
16.99 ~ 20.58	3	29	5.34 ~ 7.08	0	0	63.18 ~ 74.17	1	1
20.58 ~ 24.18	12	210	7.08 ~ 8.82	1	2	74.17 ~ 85.15	1	2
24.18 ~ 27.77	17	548	8.82 ~ 10.57	1	32	85.15 ~ 96.13	3	7
27.77 ~ 31.36	19	446	10.57 ~ 12.31	11	193	96.13 ~ 107.12	2	11
31.36 ~ 34.95	8	197	12.31 ~ 14.05	18	377	107.12 ~ 118.10	6	46
34.95 ~ 38.54	4	46	14.05 ~ 15.79	15	425	118.10 ~ 129.08	7	160
38.54 ~ 42.13	2	21	15.79 ~ 17.53	12	287	129.08 ~ 140.07	8	323
42.13 ~ 45.72	1	8	17.53 ~ 19.27	8	142	140.07 ~ 151.05	24	570
45.72 ~ 49.32	1	3	19.27 ~ 21.02	2	38	151.05 ~ 162.03	13	311
49.32 ~ 52.91	1	2	21.02 ~ 22.76	1	15	162.03 ~ 173.02	3	68
52.91 ~ 56.50	1	2	22.76 ~ 24.50	1	2	173.02 ~ 184.00	2	10
Days to maturity			*Yield per plant*			*Flag leaf length*		
72.00 ~ 75.17	1	1	2.10 ~ 3.91	3	58	16.00 ~ 18.62	4	28
75.17 ~ 78.33	6	67	3.91 ~ 5.72	8	175	18.62 ~ 21.25	5	122
78.33 ~ 81.50	1	20	5.72 ~ 7.52	15	234	21.25 ~ 23.88	8	293
81.50 ~ 84.67	8	178	7.52 ~ 9.33	7	297	23.88 ~ 26.50	13	297
84.67 ~ 87.83	12	317	9.33 ~ 11.14	9	269	26.50 ~ 29.12	11	221
87.83 ~ 91.00	11	116	11.14 ~ 12.95	13	180	29.12 ~ 31.75	9	189
91.00 ~ 94.17	12	372	12.95 ~ 14.76	3	132	31.75 ~ 34.38	7	160
94.17 ~ 97.33	0	0	14.76 ~ 16.57	7	79	34.38 ~ 37.00	4	104
97.33 ~ 100.50	11	317	16.57 ~ 18.38	2	40	37.00 ~ 39.62	6	68
100.50 ~ 103.67	7	123	18.38 ~ 20.18	2	49	39.62 ~ 42.25	1	24
103.67 ~ 106.83	1	2	20.18 ~ 21.99	1	1	42.25 ~ 44.88	2	7
106.83 ~ 110.00	1	2	21.99 ~ 23.80	1	1	44.88 ~ 47.50	1	2
Flag leaf width			*Test weight*					
0.78 ~ 1.08	4	30	1.90 ~ 2.07	1	7			
1.08 ~ 1.38	21	476	2.07 ~ 2.25	1	20			
1.38 ~ 1.68	23	686	2.25 ~ 2.42	2	57			
1.68 ~ 1.99	12	260	2.42 ~ 2.60	3	54			
1.99 ~ 2.29	4	43	2.60 ~ 2.78	6	141			
2.29 ~ 2.59	3	12	2.78 ~ 2.95	11	181			
2.59 ~ 2.89	1	3	2.95 ~ 3.12	15	436			
2.89 ~ 3.19	1	1	3.12 ~ 3.30	10	222			
3.19 ~ 3.50	0	0	3.30 ~ 3.48	5	143			
3.50 ~ 3.80	1	2	3.48 ~ 3.65	13	214			
3.80 ~ 4.10	0	0	3.65 ~ 3.82	3	27			
4.10 ~ 4.40	1	2	3.82 ~ 4.00	1	13			

CC: Core count, EC: Entire count

Table 4 Different classes of qualitative traits as generated with Power Core software for the foxtail millet core collection

Senescence			Grain shape			Plant pigmentation			Inflorescence compatness		
Class	CC	EC	Class	CC	EC	Class	CC	EC	Class	CC	EC
1	15	172	1	59	1357	0	50	1312	1	59	1402
9	56	1343	2	12	158	1	21	203	2	11	112
Blade pubscence			*Lodging at maturity*			*Fruit color*			*Sheath pubescencce*		
1	13	170	1	52	1201	1	3	46	1	66	1506
2	51	1152	3	1	2	2	1	15	2	1	2
5	6	191	5	17	260	3	45	1045	3	1	1
7	1	2	7	1	18	4	22	409	5	1	4
									9	2	2
Inflorescence lobes			*Inflorescence shape*			*Inflorescence bristle*			*Lobe compactness*		
0	16	249	1	1	1	0	1	27	1	1	1
1	1	1	2	1	1	1	7	146	3	3	28
3	38	972	3	14	209	3	17	296	5	14	173
5	1	11	5	21	525	5	21	499	6	1	1
7	14	244	7	12	358	7	24	535	7	34	1020
9	1	5	9	22	421	9	1	12	9	17	291
Leaf color											
0	1	1									
1	41	1172									
2	13	203									
3	7	84									
4	7	49									
5	1	5									
7	1	1									

CC: Core count, EC: Entire count

clustering was done using Neighbor Joining procedure. Pearson correlation coefficient and descriptive statistics were calculated for all the quantitative traits using SAS version 9.3 software.

RESULTS AND DISCUSSION

Diversity in the core collection

A core of 223 accessions (14.7%) of foxtail millet was selected from a full collection of 1515 accessions (Table 1). This core collection included accessions from different countries of the world, mostly from India (169 ; 75.78%) with representations from all 20 foxtail cultivating states and countries. In comparison, the core developed by Upadhyaya *et al.* (2008) included only 93 (60%) accessions from India. However, the representation of diversity in the present core collection was higher from India, indicating sufficient genetic variability in the Indian germplasm. The exotic accessions of different countries in the identified core was comparable to the core developed by Upadhyaya *et al.* (2008).

Geographic distributions

The perusal of patterns indicated that in general, early maturing accessions (<85 days) were representing the states Andhra Pradesh, Bihar, Madhya Pradesh and Maharashtra, and late maturing (>90 days) were from Karnataka, Tamil Nadu, Rajasthan, Uttar Pradesh, USA and China. Tall type accessions (>140 cm height) were from Uttar Pradesh, Maharashtra and Tamil Nadu, whereas dwarf type (<100 cm) were from East Asia and NE region of India. Reddy *et al.* (2006) also reported tallest accessions from India. The longer ear length (>14 cm) accessions were predominantly from eastern, central and southern parts of the country and in general longer ear length were high yielders (Reddy *et al.* 2006). Most of the accessions were dominated by oblong and elliptic type of inflorescence, but very few accessions belong to ovate type and they were representing the states of NE Region, Odisha, Tamil Nadu, Korea, Russia, Taiwan and USA. The association of trait-specific variations with regional climatic gradient may be related to the farmers' preferences and seasonal requirements of cultivars. Foxtail millet is cultivated in India across diverse climatic gradients from elevations close to sea level to lower hills of Himalayas. The process of acclimatization of cultivars involving selection of better performing plants in landraces of crops tends to result in preferential changes in allelic frequencies thereby bringing about associations between specific trait variations and eco-geographies. This is much apparent in the foxtail millet germplasm which is mainly composed of farmers' varieties and landraces. This has clearly indicated that core collection is genetically diverse and geographical conditions have played an important role in their distribution and local adaptation.

Validation of the core collection

Descriptive statistics for eleven quantitative traits has been given in Table 5. Range was wide for all the quantitative traits and highest for plant height, i.e. 41.32 to 191.7 cm and lowest for number of basal tiller, i.e. 1.0 to 4.2. Coefficient of variation was highest for yield/plant, i.e. 42.65 and lowest for days to maturity, i.e. 5.00. Range and coefficient of variation showed that enough variation is present among the core accessions. The flag leaves and inflorescence shape showed sufficient variation in core accessions (Fig 1). Skinner *et al.* (1999) advised that correlation coefficient with >0.71 is good for prediction of more than 50% variation in one trait by other. In this study we found statistically high positive correlation between days to maturity and days to 50% flowering (0.82). Similarly, ear length and flag leaf blade length also showed high positive correlation (0.68; P=0.01) (Table 6). These results corroborate the earlier findings (Upadhyaya *et al.* 2008) where similar results had led to the suggestion that highly correlated characters should be used to identify the redundancy in the traits and can reduce the number of traits to be used for characterization.

The analysis of variance (ANOVA) revealed significant effects of genotypes ($P \leq 0.01$ and 0.05) for quantitative traits, viz. 50% flowering, yield/plant, flag leaf length, panicle exsertion, and plant height (Table 7 and 8). Similarly, the significant genotypes effect was found for qualitative traits such as inflorescence compactness, lobe compactness, inflorescence shape, senescence, degree of lodging at maturity and sheath pubescence (Table 8 and 9). More than half the traits showed significant variation among the accessions which indicate the presence of substantial variation in the core accessions. Thus these traits can be used for further breeding purposes.

Shannon-Weaver diversity (H') index is a measure of phenotypic diversity, allelic richness and evenness in the populations. The average H' index for the core collection (0.73) was greater than entire collection (0.64). Lodging at maturity has the lowest H′ value, and inflorescence compactness and bristles on inflorescence have the comparable H′ estimates in both core and entire collections (Table 6). However, in the world core collections higher H' were reported in both foxtail and sorghum (Upadhyaya *et al*. 2008, 2009a). The average Nei's diversity index for the core collection (0.43) was comparable with the entire collection (0.39) and highest value was for inflorescence compactness and inflorescence bristles as in the case of the H′ index. The alleles in the core collection were retained for all the qualitative traits when it was compared with the entire collection. The average polymorphism information content (PIC) and its efficiency values were 0.99 and 0.84, respectively. Therefore, accessions selected to constitute the core are highly diverse.

Based on clustering using Neighbor Joining method, the total 223 core accession were grouped into two major clusters (I and II) each at Bengaluru and Akola location. Further, the first major cluster (I) was sub-grouped into four (Ia, Ib, Ic and Id) and three (Ia, Ib, Ic) and second major cluster (II) into two (IIa and IIb) and three (IIa, IIb, IIc) sub-clusters at Akola and Bengaluru, respectively (Fig 1). Early flowering and maturity genotypes were grouped in the same cluster at both locations, which mean they are less affected by the environment and genotype (G) × environment (E) interaction. However, the late flowering, late maturity and high yielding accessions were distributed in different clusters in Bengaluru (Ia and IIa) and Akola (Ia, Ib, Ic and Id) location. This shows the significant effects of (G) × environment (E) interaction over the expression of these traits. At Bengaluru location, ISE-1181, ISE-1234, ISE-748 and ISE-769 were showing distinct position in the cluster. Compared to other accessions, these four were showing extreme variability for flowering and maturity. Similarly in the Akola tree, genotype ISE-2, ISE-217-A, ISE-769, GS-415 and ISE-1181 were showing the diversity for different traits, such as ear length, plant height, flowering and maturity. Hence, these genotypes could be utilized in broadening of foxtail millets genetic base.

In the trees, accessions from Andhra Pradesh, Madhya Pradesh, Tamil Nadu and Uttar Pradesh were equally distributed among both major clusters as well as sub-clusters which indicate higher diversity present in

Table 5 Descriptive statistics of 11 quantitative traits in core collection of foxtail millet indicating presence of high diversity among the accessions

Trait	Range		Mean		SD	CV
	Min	Max	M	SE		
DMAT	78	120	87.8	0.29	4.39	5.00
DWF	42	92.0	58.0	0.37	5.56	9.58
YPP	1.2	64.7	24.2	1.0	10.3	42.65
TEST_WT	1.1	7.80	2.60	0.03	0.48	18.65
PAN_EX	4.0	24.1	14.0	0.23	3.49	24.89
EAR_LTH	4.7	19.3	12.7	0.17	2.5	19.76
PED_EX	21.4	39.8	28.5	0.21	3.18	11.13
FLG_LL	10.8	32.4	22.1	0.25	3.74	16.94
FLG_LW	1.04	2.70	1.21	0.02	0.27	22.29
BAS_TIL	1.0	4.2	1.65	0.04	0.61	36.84
PLT_HT	41.3	191.7	124.3	1.13	17.93	14.41

DMAT: Days to maturity; DWF: Days to 50% flowering; YPP: Yield per plant; TEST_WT: Test weight; PAN_EX: Panicle exsertion; EAR_LTH: Ear length; PED_EX: Peduncle exsertion; FLG_LL: Flag leaf length; FLG_LW: Flag leaf length; BAS_TIL: Basal tiller; PLT_HT: Plant height; M: Mean; SE: Standard Error; SD: Standard Deviation; CV: Coefficient of variation

Table 6 Pearson correlation among 11 quantitative and 5 qualitative traits in core collection of foxtail millet indicating presence of high diversity among the accessions

Trait	DTM	DWF	TEST_WT	YPP	PAN_EX	EAR_LTH	PED_EX	FLG_LW	FLG_LL	BAS_TIL	PLT_HT	INF_CPT	LB_CPT	INF_LB	LOD_MAT	LF_SEN
DTM	1	.820**	-.199**	-.049	-.104	.043	-.007	-.038	-.015	-.052	.129*	.004	-.057	-.123	-.138*	-.303**
DWF		1	-.194**	-.044	-.137*	-.076	-.086	-.057	-.061	-.099	.029	.046	-.096	-.159*	-.112	-.215**
TEST_WT			1	.046	.053	.157*	-.018	-.020	.128*	-.020	.014	-.190**	-.090	.145*	-.043	.079
YPP				1	.094	.020	.140*	-.029	-.012	-.050	.009	.077	.077	-.021	-.025	.009
PAN_EX					1	.138*	.392**	.016	.134*	.039	.215**	.027	.038	.096	.002	-.038
EAR_LTH						1	.315**	.267**	.680**	.281**	.512**	-.282**	-.061	.194**	-.081	-.072
PED_EX							1	.051	.311**	.086	.388**	.036	.049	-.024	-.078	-.060
FLG_LW								1	.428**	.515**	.028	-.066	.076	.238**	.001	.001
FLG_LL									1	.394**	.411**	-.086	.028	.094	-.075	-.005
BAS_TIL										1	.168**	.113	.146(*)	-.060	-.002	-.139*
PLT_HT											1	-.059	.099	.006	-.047	-.061
INF_CPT												1	.423**	-.424**	.088	-.016
LB_CPT													1	-.122	-.053	.064
INF_LB														1	.103	.127*
LOD_MAT															1	.036
SEN																1

DMAT: Days to maturity; DWF: Days to 50% flowering; TEST_WT: Test weight; YPP: Yield per plant; PAN_EX: Panicle exsertion; EAR_LTH: Ear length; PED_EX: Peduncle exertion; FLG_LW: Flag leaf width; FLG_LL: Flag leaf length; BAS_TIL: Basal tiller; PLT_HT: Plant height; INF_CPT: Inflorescence compactness; LB_CPT: Lobe compactness; INF_LB: Inflorescence lobes; LOD_MAT: Lodging at maturity; SEN: Senescence **Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

Table 7 ANOVA of 11 quantitative traits for Akola location in core collection of foxtail millet

Sources of variation/Traits	df	BAS_TIL	DWF	DMAT	EAR_LTH	FLG_LL	FLG_LW
Treatment	222	36.94	6541.8**	3880.5	1179.2	1987.9**	8.775
Error	20	4.55	228.4	280.3	70.944	76.99	0.781
	df	*PAN_EX*	*PED_EX*	*PLT_HT*	*YPP*	*TEST_WT*	
Treatment	222	6842.1**	2235.5	61046.3**	319990.9**	49.58**	
Error	20	91.74	117.3	1128.2	9.22	0.57	

BAS_TIL: Basal tiller; DWF: Days to 50% flowering; DMAT: Days to maturity; EAR_LTH: Ear length; FLG_LL: Flag leaf length; FLG_LW: Flag leaf length; PAN_EX: Panicle exsertion; PED_EX: Peduncle exsertion; PLT_HT: Plant height; YPP: Yield per plant; TEST_WT: Test weight. Significant at P=0.05; ** Significant at P=0.01.

Table 8 ANOVA of 13 qualitative traits for Akola location in core collection of foxtail millet

Sources of variation/Traits	df	BL_PUB	FRT_CLR	GRN_SHP	INF_BRL	INF_CPT	INF_LB	INF_SHP
Treatment	222	601.3	82.04	29.32	520.1	567.7**	796.1*	625.5**
Error	20	35.88	4.30	3.0	29.09	9.70	35.88	8.97
	df	*LB_CPT*	*LF_CLR*	*SEN*	*LOD_MAT*	*PLT_PIG*	*SH_PUB*	
Treatment	222	371.13**	70.292	2354.1**	15.30**	1056.7	669.2**	
Error	20	-0.00	7.27	0.00	-0.00	89.09	0.00	

BL_PUB: Blade pubescence; FRT_CLR: Fruit color; GRN_SHP: Grain shape;INF_BRL: Inflorescence bristles;INF_CPT: Inflorescence compactness;INF_LB: Inflorescence lobes;INF_SHP: Inflorescence shape;LB_CPT: Lobe compactness; LF_CLR: Leaf colour; SEN: Leaf senescence; LOD_MAT: Lodging at maturity;PLT_PIG: Plant pigmentation;SH_PUB: Sheath pubescence

*significant at P=0.05; ** significant at P=0.01

Table 9 ANOVA of 11 qualitative and quantitative traits for Bangalore location in core collection of foxtail millet

Sources of variation/Traits	df	YPP	TEST_WT	DWF	DMAT	FRT_CLR	INF_CPT
Treatment	222	5187.4	51.87	4007.4**	865.4	48.77**	568.3**
Error	20	375.8	3.76	31.76	57.52	0.61	9.70
	df	*INF_LB*	*LB_CPT*	*LF_CLR*	*LOD_MAT*	*PLT_PIG*	
Treatment	222	927.9	391.6*	11.88	717.7	562.3*	
Error	20	46.30	17.21	1.82	49.45	9.82	

YPP: Yield per plant; TEST_WT: Test weight; DWF: Days to 50% flowering; DMAT: Days to maturity; FRT_CLR: Fruit color; INF_CPT: Inflorescence compactness; INF_LB: Inflorescence lobes; LB_CPT: Lobe compactness; LF_CLR: Leaf color; LOD_MAT: Lodging at maturity; PLT_PIG: Plant pigmentation. *Significant at P=0.05; ** Significant at P=0.01.

the selected core accessions. All other Indian accessions such as from Bihar, Gujarat, Himachal Pradesh, Jammu and Kashmir, Kerala, Maharashtra, NE Region, Odisha, Punjab and Rajasthan were distributed in the sub-clusters of either major cluster I or II. Based on the RAPD and ISSR analysis clustering, Kumari *et al.* (2011) had also showed that accessions from different Indian locations distributed among the major clusters and sub-clusters. Exotic accessions from China, Korea, Kenya, Lebanon, Nepal, Pakistan, South Africa, Russia, Syria, and USA were present in both major clusters and sub-clusters in Bengaluru and Akola clustering also indicating that highly diverse exotic accessions were included in core collection. Different studies (Li *et al.* 1995, Jusuf and Pernes 1985) showed that accessions from Kenya and China were grouped with Indian accessions (Kumari *et al.* 2011, Li *et al.* 1998), which is in agreement with pattern of grouping found in our study. The clustering pattern from both locations indicates that there is no discrete relationship between the geographic location and the clustering of accessions (Kumari *et al.* 2011). Accessions from different locations grouped together in different clusters might suggest frequent exchange of accessions for the crop improvement.

First four principal components of whole collection explained 33% variation, whereas core accessions grown at Akola and Bengaluru showed 40% and 53% variation respectively, which is higher in comparison to the entire collection hence identified core represent substantial variation.

The foxtail millet core identified here includes accessions from 20 states of the India and 20 different countries, which encompasses significantly high genetic variation. These manageable group of accessions will facilitate efficient and

Table 10 Comparison of Shannon-Weaver and Nei's diversity index for 13 qualitative traits in foxtail millet core and entire collection

Traits	Entire collection			Core collection		
	Sh.W. (H')	Nei	Allele	Sh.W. (H')	Nei	Allele
FRT_CLR	0.75	0.453	4	0.826	0.453	4
INF_CPT	1.155	0.669	4	1.188	0.672	4
LB_CPT	0.905	0.547	3	0.813	0.483	3
INF_BRL	1.012	0.597	4	1.192	0.675	4
INF_LOBES	0.643	0.372	3	0.78	0.491	3
LOD_MAT	0.029	0.009	2	0.158	0.071	2
LF_CLR	0.21	0.102	2	0.264	0.137	2
PLT__PIG	0.705	0.4	3	0.804	0.458	3
GRN_SHP	0.269	0.141	2	0.419	0.252	2
INF_SHP	0.775	0.458	3	0.916	0.535	3
SEN	0.587	0.397	2	0.479	0.302	2
SH_PUB	0.718	0.504	3	0.814	0.524	3
BL_PUB	0.581	0.374	3	0.78	0.491	3
Average	0.64	0.39		0.73	0.43	

FRT_CLR: Fruit color; INF_CPT: Inflorescence compactness; LB_CPT: Lobe compactness; INF_BRL: Inflorescence bristles; INF_LB: Inflorescence lobes; LOD_MAT: Lodging at maturity; LF_CLR: Leaf colour; PLT_PIG: Plant pigmentation; GRN_SHP: Grain shape; INF_SHP: Inflorescence shape; SEN: Senescence; SH_PUB: Sheath pubescence; BL_PUB: Blade pubescence; Sh.W (H'): Shannon and Weaver diversity index; Nei: Nei's diversity index.

effective characterization of germplasm for various useful breeding traits with use of limited resources. Further, the core accessions will provide better access to diverse germplasm for use by the scientific community. The designated core collection may be revised progressively as and when new genetic variations get introduced. The diverse accessions with specific trait variations identified here could be of much use in foxtail improvement programmes.

ACKNOWLEDGEMENT

The authors are thankful to the Director, National Bureau of Plant Genetic Resources (NBPGR), New Delhi, India, for providing the facilities for the study and Indian Council of Agricultural Research for the funding. The scholarship provided to the first author by the RGNF-UGC for Ph D degree is gratefully acknowledged.

REFERENCES

Bhattacharjee R, Bramel P J, Khairwal I S and Reddy K N. 2007. Establishment of a pearl millet [*Pennisetum glaucum* (L) R. Br.] core collection based on geographical distribution and quantitative traits. *Euphytica* **155**: 35–45.

Brown A H D. 1995. The core collection at the crossroads. (*In*) *Core Collections of Plant Genetic Resources*, pp 3-19. Hodgkin T, Brown A H D, Th. J.L. van Hintum and Morales E A V (Ed.). John Wiley and Sons, UK.

Federer W T. 1956. Augmented (or hoonuiaku) designs. *Hawaii Plant Records* **2**: 191–208.

Frankel O H. 1984. Genetic perspectives of germplasm conservation. (*In*) *Genetic Manipulation: Impact on Man and Society,* pp 161–70. Arber W, Llimensee K, Peacock W J and Starlinger P (Eds). Cambridge University Press, Cambridge.

Goudar G, Hemalatha S, Naik R K and Kamatar M Y. 2011. Evaluation of nutritional composition of foxtail millet (*Setaria italica)* grains cultivated in agro climatic zones of Karnataka by NIR. Paper presented in National Symposium Recapturing Nutritious Millets for Health and Management of Diseases, UAS, Dharwad, 16-17 December, p 37.

Gowda J, Halaswamy K B H, Magar V K, Ramakrishna B M, Krishnappa M, Vasanth K R, Seenappa, Somu G and Seetharam A. 2002. *Catalogue on Evaluation of Foxtail Millet* [*Setaria italica* (*L.*) Beauv] *Germplasm*, pp 1–80.

Gowda J, Krishanappa M, Pathak N, Mathur P N and Seetharam A. 2013. Use of Heuristic approach for the development of a core set from large germplasm collection of foxtail millet (*Setaria italica* L.). *Indian Journal of Plant Genetic Resources* **26**: 13–8.

Gowda J, Rekha D, Bharathi S and Krishnappa M. 2007. Methods of constructing core set using agro-morphological traits in foxtail millet [*Setaria italica* (L.) Beauv]. *Journal of Plant Genetic Resources* **20**: 193–8.

IBPGR. 1985. Descriptors for *Setaria italica* and *S. pumila*. IBPGR Secretariat, Rome, Italy.

Jusuf M and Pernes J. 1985. Genetic variability of foxtail millet [*Setaria italica* (L.) P. Beauv.]. *Theoretical and Applied Genetics* **71**: 385–91.

Kumari R, Dikshit N, Sharma D and Bhat K V. 2011. Analysis of molecular genetic diversity in a representative collection of foxtail millet [*Setaria italica* (L.) P. Beauv.] from different agro-ecological regions of India. *Physiology and Molecular Biology of Plants* **17**: 363–74.

Li H W, Li C H and Pao W K. 1945. Cytological and genetical studies of the interspecific cross of the cultivated foxtail millet, *Setaria italica* (L.) P. Beauv. and the green foxtail millet, *S. viridis* L. *Journal of American Society of Agronomy* **37**: 32–54.

Li Y, Jia J, Wang Y and Wu S. 1998. Intraspecific and interspecific variation in *Setaria* revealed by RAPD analysis. *Genetic Resources and Crop Evolution* **45**: 279–85.

Li Y, Wu S and Cao Y. 1995. Cluster analysis of international collection of foxtail millet (*Setaria italica* (L.) P. Beauv.). *Euphytica* **83**: 79–85.

Lu H, Zhang J, Liu K B, Wu N and Li Y. 2009. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. *Proceedings of National Academy of Science USA* **106**: 7 367–72.

Mishra A K, Muthamilarasan M, Khan Y, Parida S K and Prasad M. 2014. Genome-wide investigation and expression analyses of WD40 protein family in the model plant foxtail millet (*Setaria italica* L.). *PLOS ONE* **9**: 1–13.

Reddy V G, Upadhyaya H D and Gowda C L L. 2006. Characterization of world's foxtail millet germplasm collections for morphological traits. *ICRISAT eJournal* **2**(1).

Rohlf F J. 1998. NTSYSpc Numerical Taxonomy and Multivariate Analysis System Version 2.0 User Guide. Applied Biostatistics Inc., Setauket, New York, 37 p.

Shannon C E and Weaver W. 1949. The mathematical theory of communication. University of Illinois Press, Urbana.

Skinner D Z, Bauchan G R, Auricht G and Hughes S. 1999. A method for efficient management and utilization of large germplasm collection. *Crop Science* **39**: 1 237–42.

Upadhyaya H D, Gowda C L L, Pundir R P S, Reddy V G, and Singh S. 2006. Development of core subset of finger millet germplasm using geographical origin and data on 14 quantitative traits. *Genetic Resources and Crop Evolution* **53**: 679–85.

Upadhyaya H D, Gowda C L L, Reddy K N and Singh S. 2009b. Augmenting the pearl millet core collection for enhancing germplasm utilization in crop improvement. *Crop Science* **49**: 573–80.

Upadhyaya H D, Pundir R P S, Dwivedi S L, Gowda C L L, Reddy V G and Singh S. 2009a. Developing a mini core collection of sorghum for diversified utilization of germplasm. *Crop Science* **49**: 1 769–80.

Upadhyaya H D, Pundir R P S, Gowda C L L, Reddy V G and Singh S. 2008. Establishing a core collection of foxtail millet to enhance the utilization of the germplasm of an underutilized crop. *Journal* of *Plant Genetic Resources* **7**: 177–84.

Upadhyaya H D, Sharma S, Gowda C L L, Reddy V G, and Singh S. 2011. Developing proso millet (*Panicum miliaceum* L.) core collection using geographic and morpho-agronomic data. *Crop and Pasture Science* **62:** 383–9.

Vavilov N I. 1926. Studies on the origin of cultivated plants. *Applied Botany and Plant Breeding* **26**: 1–248.

Vetriventhan M. 2011. 'Phenotypic and genetic diversity in the foxtail millet (*Setaria italica* (L.) P. Beauv) core collection.' Thesis, Tamil Nadu Agricultural University.