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Stability analysis for seed longevity in landraces of sorghum [*Sorghum bicolor* (L.) Moench]

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Abstract

Seed longevity in sorghum is a major determinant in seed production and germplasm preservation. Forty-six local landraces representing nine genetic races of sorghum were evaluated under accelerated aging and natural storage conditions to study the genotype-environment interactions and the stability of landraces for seed longevity. Genotype-environment interactions were highly significant indicating the influence of storage conditions on seed longevity. The stability of landraces was estimated using mean (x_i), regression coefficient (bi) and regression deviation (S^2d_i). Environmental indices for the seed longevity traits were high in E1 (fresh seed) followed by E2 (accelerated aged seeds), E3 (stored seeds for 12 months) and E4 (stored seeds for 24 months). Seven sorghum landraces *viz.,* IC-345729 (*Bicolor*), IC-347571 (*Caudatum*), IC-347577 (*Durra*), IC-345244 (*Durra*), IC-415803 (*Durra*), IC-415822 (*Durra bicolor*) and IC-415829 (*Guinea bicolor*) were stable for seed longevity. These genotypes are therefore, recommended for use in further breeding to improve seed longevity in sorghum, which otherwise is generally poor.

Keywords: Sorghum landraces, seed longevity, G x E interactions, stability analysis

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is extensively cultivated world over in the semi-arid tropics of Africa, Asia and America predominantly as a source of food, feed, fodder and recently as biofuel. It is the fifth most important cereal crop after wheat, rice, maize and barley and is preferred for its adaptation ability to different abiotic stresses, including drought, heat, salinity and flooding (Harris et al. 2006; Ejeta and Knoll 2007). India ranks second in the area after Sudan and fourth in production after the USA, Nigeria and Mexico in the last five years (2013-2017) average (FAO, accessed on 27-Dec-2019). The conservation of genetic resources in germplasm banks and breeder collections assumes genetic stability during storage and renovation. However, genetic changes occur during conservation (Murata 1991, Sano et al. 2016; Rao et al. 2017), and the renovation of germplasm involves risks of genetic drift due to selection, errors, and outcrosses (Kameswara Rao and Jackson 1996; Parzies et al. 2000). In tropical countries like India, ambient environments are generally unfavourable for seed storage, and so the maintenance of viability during storage is generally a greater problem. Quality seed leads to the establishment of good crop stand by influencing good germination and supply of nutrients to the growing seedlings through a better root system (Dhillon and Kler 1976). Vigour of the seedlings influences nutrient uptake from the soil, thereby enhances vegetative growth. Ruiz et al. (1999) found significant differences among and within different cereals for seed viability in active and base collections. Most studies on seed aging have been made using accelerated aging, few genotypes or few years of aging (Ghidoni and Lanzani 1975; Nikonorenkova 1989; Gutie´rrez et al. 1993). As seeds age, they maintain viability for some time and subsequently enter a period of decline during which some seeds completely fail to germinate; while others germinate and grow normally. Agrawal et al. (1981) reported poor storability of several improved varieties in sorghum. Genetic variability for seed aging and longevity traits were reported among the maize inbred lines (Revilla et al. 2006), forage sorghum cultivars (Kannababu et al. 2015) and sweet sorghum cultivars (Kannababu et al. 2016). These studies suggest that the genotypes vary for seed quality and storage potential and there is large

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variability for seed longevity among different species. Seed longevity is a measure of seed viability over dry storage period, which can be for short (6-12 months), medium (12-36 months) and long term (5-20 years) duration. The longevity of seed varies among and within the species and is governed by various factors such as genetic make-up, difference in physiological maturity, handling and processing practices and storage conditions. The ability of seeds to withstand stresses that occur while stored is one aspect of seed longevity. To some extent, these stresses may resemble those occur when imbibed seeds are exposed to unfavorable conditions during germination. A key factor that contributes to seed vigour during germination is the capacity of seeds to remain alive for extended periods of time in the dry state (i.e. longevity). Seeds with elevated longevity will deteriorate only slowly during conservation and will retain high germination and vigour. Both seed industry and gene bank curators express the need for tools to better understand, improve and predict seed longevity.

Assessment of stability of genotypes for their seed longevity is useful for identifying genotypes with good longevity and their employment in breeding programs. The stability of trait expression can be understood by partitioning the genotype × environment (G × E) interaction into linear trends and a departure from linear called residual (Eberhart and Russell 1966). Considering seed storage periods as an environmental factor, the present study was carried out to evaluate a set of sorghum landraces for their seed longevity traits to identify stable genotypes for use in sorghum breeding.

Materials and methods

Forty-six landraces representing nine genetic races of sorghum were used as the study material. Of them, 43 landraces were collected from five sorghum growing states of the country, *viz.,* Andhra Pradesh, Karnataka, Maharashtra, Tamil Nadu and Uttar Pradesh and one each from Canada, Brazil and from the USA (Table 1). The fresh seeds of the genetic accessions with an initial moisture content of 10% were used for the experiment.

Seed trait evaluations

The experiments on seed longevity traits were conducted in Randomized Block Design with four replications from 2014 to 2016 at ICAR-Indian Institute of Millets Research, Rajendranagar, Hyderabad under the ambient storage conditions. The fresh seeds of all the entries were treated with Thiram @ 2 g/ kg and sealed in moisture-proof rigid plastic bottles and stored at ambient conditions for 2 years to study the seed longevity. Seed longevity was studied under four environmental treatments, *viz.*, fresh seeds (E1), artificially accelerated aged seeds (E2), seeds stored under ambient conditions for 12 months (E3) and for 24 months (E4). For accelerated aging of seeds, a sub-set from each landrace seed sample was used in an aging chamber as described (Delouche and Baskin 1973). Briefly, seed samples were placed on a wire-mesh tray above the water level in desiccators and then sealed to maintain high humidity (around 100%). These sealed desiccators were transferred to the incubator at 40-45 °C temperature for three days. Accelerated aging causes fast deterioration of seeds due to stress created under high temperatures and humid conditions. The fresh seeds (E1), accelerated aged seeds (E2) and the stored seeds for 12 (E3) and 24 (E4) months interval were tested for seed longevity component traits like seed germination (GR), root length (RL), shoot length (SL), seedling dry weight (SDW), seedling vigor index (SVI) and field emergence (FE). The seed germination test was conducted in paper towels as per the rules of the International Seed Testing Association (2004). Seeds were germinated in a seed germinator maintained at 25±5°C and 90±3% relative humidity. Germination counts were made on 10^{th}day and the seedlings were evaluated for growth. The germination percentage (GR) was calculated based on the number of normal seedlings produced per 100 seeds. Ten normal seedlings were selected at random for recording seedling characters. Root length (RL) was measured from the collar region to the tip of the primary root and shoot length (SL) from the collar region to the tip of the first leaf. Seedlings with abnormal growth were separated. Measurement of the length of root and shoot was carried out on each of the 10 randomly selected normal seedlings. Seedling dry weight (SDW) was measured after drying the 10 normal seedlings in a hot air oven maintained at 80°C for 24 h. Immediately after completion of drying, seedlings were transferred to desiccators for half an hour for cooling and then the weight was taken. The mean dry weight of normal seedling was reported. The seedling vigor index (SVI) was calculated by multiplying the mean germination percentage by mean dry weight of single seedling and expressed in the nearest whole number. The field emergence (FE) of fresh and accelerated aged seeds was tested by sowing the seeds in four replications each of 50 seeds in cement pots (45 cm diameter)

Table 1. Details of genotypes used for seed longevity traits in sorghum

Sorghum race	No. of entries	S.no.	Entry	District	State/Country
Bicolor	10	1	IC - 345726	Cuddapah	Andhra Pradesh
		2	IC - 345729	Kurnool	Andhra Pradesh
		3	IC - 347588	West Godavari	Andhra Pradesh
		4	IC - 345194	Raichur	Karnataka
		5	IC - 345197	Raichur	Karnataka
		6	IC - 345243	Dindigul	Tamil Nadu
		7	IC - 541315	Coimbatore	Tamil Nadu
		8	IC - 541319	Coimbatore	Tamil Nadu
		9	IC - 541321	Coimbatore	Tamil Nadu
		10	IC - 541332	Karur	Tamil Nadu
Bicolor caudatum	1	11	EC 507688	-	Brazil
Caudatum	3	12	IC - 345724	Cuddapah	Andhra Pradesh
		13	IC - 347571	Khammam	Andhra Pradesh
		14	IC - 541322	Coimbatore	Tamil Nadu
Durra	16	15	IC - 345189	Raichur	Karnataka
		16	IC - 369131	Mahaboobnagar	Andhra Pradesh
		17	IC - 347577	Khammam	Andhra Pradesh
		18	IC - 343556	Beed	Maharashtra
		19	IC - 343577	Ahmednagar	Maharashtra
		20	IC - 345244	Dindigul	Tamil Nadu
		21	IC - 345253	Madurai	Tamil Nadu
		22	IC - 415803	Rae Bareli	Uttar Pradesh
		23	IC - 415819	Jaunpur	Uttar Pradesh
		24	IC - 415823	Sulthanpur	Uttar Pradesh
		25	IC - 392127	Lathur	Maharashtra
		26	IC - 392130	Lathur	Maharashtra
		27	IC - 392131	Lathur	Maharashtra
		28	IC - 541309	Coimbatore	Tamil Nadu
		29	IC - 541311	Erode	Tamil Nadu
		30	IC - 541318	Coimbatore	Tamil Nadu
Durra bicolor	5	31	IC - 345718	Kurnool	Andhra Pradesh
		32	IC - 415822	Azamgarh	Uttar Pradesh
		33	IC - 415824	Sulthanpur	Uttar Pradesh
		34	IC - 415828	Faizabad	Uttar Pradesh
		35	IC - 392151	Rangareddy	Andhra Pradesh
Durra caudatum	5	36	IC - 345703	Mahaboobnagar	Andhra Pradesh
		37	IC - 345193	Raichur	Karnataka
		38	IC - 345249	Dindigul	Tamil Nadu
		39	IC - 415792	Kanpur Dehat	Uttar Pradesh
		40	IC - 415793	Kanpur Dehat	Uttar Pradesh
Guinea	1	41	IC - 415805	Sulthanpur	Uttar Pradesh
Guinea bicolor	1	42	IC - 415829	Faizabad	Uttar Pradesh
Guinea caudatum	2	43	IC - 345248	Dindigul	Tamil Nadu
		44	IC - 541330	Karur	Tamil Nadu
Kafir	2	45	EC 507868	-	Canada
		46	EC 538170	-	USA

filled with soil. After 10 days, the seedlings with leaves above the soil surface were considered as emerged and noted in percentage.

Data analysis

Stability analysis was carried out by using the Windowstat programme (Indostat Services, Hyderabad, India) following the stability model (Eberhart and Russell 1966). Phenotypic stability was measured by estimating the linear regression coefficient (bi) and deviation from regression (σ^2di) components of genotype x environment interaction, and this should be considered with the mean performance of a genotype.

Data were subjected to a one-way ANOVA using OPSTAT (http://14.139.232.166/opstat/default.asp). Tukey test (P<0.05) following one-way ANOVA was used to compare the significances among all means of races and states in different treatments, at P<0.05 or 0.01.

Results and discussion

Seed longevity (time span during which seeds remain viable on dry storage) is affected by the storage conditions like moisture content, temperatures and relative humidity, oxygen pressure (Sano et al. 2016), which accelerate seed deterioration and degradation leading to loss of seed viability. The potential storage life of sorghum seed varies among and within species and is governed by various factors such as genetic make-up, differences in physiological maturity, handling and processing practices and storage conditions. Seeds with low viability show low germination activity and delayed development resulting in poor seedling establishment and ultimately reduced grain yield. Farmer is concerned with the phenomenon of seed longevity as he desires good germination and vigorous emergence from the sown seeds. The sorghum seed industry is also concerned with the longevity of seeds because if germination drops below a certain limit, seeds are unsalable and suffer from financial losses. In addition, storing accessions with increased longevity in gene banks could reduce the required frequency of restocking, thus saving time and labor. A study on seed longevity is a potential area for breeders to screen genotypes as well as for laboratory applications to predict seedling vigor. Developing and breeding varieties with highly viable seeds after dry storage is urgent for meeting the demands of sorghum farmers, industry and gene banks. Understanding the genotype x environment interaction is vital for plant breeders and geneticists. The observed trait phenotype is a function of genotype (G), environment (E) and genotype-environment interaction (GEI). With increased GEI, trait heritability is going to be lower. Understanding the structure and nature of GEI is important because a significant GEI can seriously impair efforts in the selection of superior genotypes (Shafii and Price, 1998).

Seed longevity among sorghum races

In cultivated sorghum, five basic (*Bicolor*, *Caudatum*, *Durra*, *Guniea* and *Kafir*) and their 15 intermediate races have been described based on grain shape, glumes, and panicle features. The material under study represented five basic races and five of its intermediate races geographically representing five Indian states and the USA, Brazil and Canada. One-way analysis of seed longevity traits for races did not indicate much differences between the races for seed longevity traits expect for root length (RL) and shoot length (SL) (Table 2). *Durra*, a major basic race cultivated in *rabi* season in India, was found to be good for most of the seed longevity traits with the highest mean for SDW and SVI. Further, One way ANOVA with post-hoc Tukey tests indicated differences between landraces from states for GR, SDW, SVI and FE but not for SL and RL (Table 3). Five landraces from the states of Maharashtra, all of which belonged to *durra* race, were found better for SDW and SVI, and those from Karnataka, representing *durra, dura-caudatum* and *bicolor* found better for SL and RL. GR and FE were better for landraces collected from Uttar Pradesh.

G x E interaction

In the present investigation, 43 sorghum landraces from various parts of India, and one landrace each from Canada, Brazil and the USA were subjected to a pooled analysis of variance for six seed longevity traits. Environmental indices indicate the favorability of an environment for the trait and can provide the basis for identifying a favorable environment for the potential expression of a genotype. Environmental means and indices (Table 4) for the seed longevity traits, as expected, were high in E1 (fresh seed) followed by E2 (accelerated aged seeds), E3 (stored seeds at 12 months) and E4 (stored seeds at 24 months). The range in environmental values indicated that the environments were quite varied, contrasting as reflected in the significant differences in the environments for all the traits studied (Table 5). The GEI was significant for five traits (SL-shoot length,

Table 2. One-way analysis of seed longevity traits in different sorghum races

Race	N	Race means					
		GR	SL	RL	SDW	SVI	FE
Guinea bicolor	1	**64.63^{A}**	18.35^{AB}	7.30^{D}	8.42^{A}	685.2^{A}	**60.99^{A}**
Durra caudatum	5	63.79^{A}	20.46^{AB}	**11.97^{A}**	15.05^{A}	1200.3^{A}	59.35^{A}
Durra bicolor	5	62.86^{A}	19.69^{AB}	11.24^{AB}	15.61^{A}	1232.6^{A}	59.02^{A}
Bicolor	10	62.04^{A}	**21.20^{A}**	11.43^{A}	14.39^{A}	1104.2^{A}	58.08^{A}
Caudatum	3	61.84^{A}	19.91^{AB}	11.80^{A}	15.95^{A}	1233.0^{A}	58.51^{A}
Bicolor caudatum	1	60.91^{A}	20.88^{AB}	10.23^{ABCD}	14.03^{A}	1072.0^{A}	57.71^{A}
Guinea	1	60.52^{A}	17.60^{AB}	8.78^{BCD}	8.82^{A}	663.1^{A}	54.10^{A}
Guinea caudatum	2	60.42^{A}	16.72^{B}	11.02^{ABC}	15.75^{A}	1194.0^{A}	56.36^{A}
Durra	16	59.95^{A}	21.06^{A}	11.42^{A}	**17.49^{A}**	**1270.2^{A}**	55.73^{A}
Kafir	2	57.58^{A}	19.18^{AB}	9.20^{CD}	13.15^{A}	943.0^{A}	54.53^{A}

Group means sharing a subscript are not significantly different using Tukey post hoc tests; In Bold indicate highest mean

Table 3. One-way analysis of seed longevity traits with respect to state/country

State/Country	N	Race means					
		GR	SL	RL	SDW	SVI	FE
Tamil Nadu	14	62.42^{A}	20.28^{A}	11.59^{A}	13.71^{CD}	1060.4^{C}	57.98^{AB}
Uttar Pradesh	10	**64.38^{A}**	19.25^{A}	10.89^{A}	13.03^{D}	1053.6^{BC}	**60.20^{A}**
Andhra Pradesh	10	62.01^{A}	20.98^{A}	11.42^{A}	17.02^{B}	1320.6^{AB}	57.80^{AB}
Maharashtra	5	53.50^{B}	21.36^{A}	10.85^{A}	**22.17^{A}**	**1438.5^{A}**	50.29^{B}
Karnataka	4	59.74^{AB}	**21.44^{A}**	**11.76^{A}**	17.57^{ABC}	1296.4^{ABC}	56.13^{AB}
Canada	1	61.60^{AB}	18.93^{A}	9.16^{A}	14.52^{ABCD}	1124.0^{ABC}	57.85^{AB}
Brazil	1	60.91^{AB}	20.88^{A}	10.23^{A}	14.03^{BCD}	1072.0^{ABC}	57.71^{AB}
USA	1	53.56^{AB}	19.44^{A}	9.24^{A}	11.77^{BCD}	761.4B^{C}	51.21^{AB}

Group means sharing a subscript are not significantly different using Tukey post hoc tests; In Bold indicate highest mean

Table 4. Trait environment mean for seed longevity traits in sorghum

Trait	Mean				Pop. mean	SE
	E1	E2	E3	E4		
GR	68.41 (7.10)	61.17 (-0.14)	61.27 (-0.04)	54.39 (-6.92)	61.31	1.71
SL	24.09 (3.70)	21.34 (0.95)	20.05 (-0.34)	16.08 (-4.31)	20.39	0.81
RL	13.10 (1.90)	10.85 (-0.35)	11.16 (-0.04)	9.68 (-1.52)	11.20	0.40
SDW	17.22 (1.71)	15.55 (0.03)	15.51 (-0.01)	13.79 (-1.73)	15.52	0.46
SVI	1458.76 (286.52)	1175.85 (3.62)	1163.45 (-8.78)	890.87 (-281.37)	890.87	46.9
FE	63.23 (5.97)	56.90 (-0.37)	57.55 (-0.29)	51.38 (-5.89)	57.23	1.30

Values in Parenthesis are environment index values

RL-root length,SDW-seedling dry weight, SVI-seedling vigour index and FE-field emergence) implying differential responses of genotypes under four storage environments for seed longevity traits. The GEI for GR-germination was not significant, which indicated that the germination was not much affected by the

Table 5. Pooled mean sum of squares for seed longevity traits in sorghum

Source of Variation	df	GR	SL	RL	SDW	SVI	**FE**
Rep within Environment	12	16.499*	6.726***	6.795***	2.926***	41886.85***	7.865
Genotypes	45	121.7***	13.30979***	4.72***	51.12***	219191.66***	108.42***
Environments	3	1506.25***	510.62***	92.70***	90.44***	2474070.16***	1080.32***
Environment + (Genotype x Environment)	138	44.17***	13.86302***	2.70***	2.86***	66767.38***	31.97***
Genotype x Environment	135	11.67	2.82*	0.70*	0.91*	13271.75***	8.68**
Environments (Linear)	1	4518.75***	1531.86***	278.10***	271.32***	7422210.50***	3240.96***
Genotype x Environment (Linear)	45	16.9**	4.42***	1.11***	1.45***	26315.72***	15.57***
Pooled Deviation	92	8.86***	1.97***	0.49	0.63*	6603.03**	5.12***
Pooled error	540	3.69	0.92	0.66	0.48	4593.58	2.25
Total	183	63.236	13.727	3.206	14.733	104248.8	50.776

seed aging. The mean sum of squares due to genotypes was highly significant for all the traits studied which indicated the presence of a substantial amount of variation in the genetic material studied. These results agree with the findings of Revilla et al. (2006) in maize, Kannababu et al. (2015) in forage sorghum and Kannababu et al. (2016) in sweet sorghum and Kannababu et al. (2017) in grain sorghum.

As there was a significant interaction between genotypes with environments, we need to find out the most stable genotype among the landraces studied. The mean square values due to Environments + (Genotypes x Environments) were found to be significant for all the characters which suggested the distinct nature of environments and genotype x environment interactions in phenotypic expression. The variances due to Environment + (Genotype x Environment) were further partitioned into components *viz*., (i) E (linear) and (ii) G x E (linear) and (iii) pooled deviation. Significant variances due to Environment (linear) showed the presence of larger environmental differences among the four storage environments for all the traits and that these traits were influenced significantly by storage environments. It also suggested that the genetic differences between the genotypes for their regression on the environmental index were highly significant. The higher magnitude of mean squares for E (linear) compared to G x E (Linear) indicated that linear response of environment accounts for the major part of the total variation for all the traits studied and may be responsible for high adaptation in relation to seed longevity traits. Variance due to G × E (Linear) was significant for shoot length (SL), root length (RL), seedling dry weight (SDW), seedling vigour index (SVI), field emergence (FE) and germination (GR) implying differential linear response of genotypes under varied seed aging processes (Table 5). In concurrence to the present results, Revilla et al. (2006) reported that coefficients of linear regression over longevity in cold storage were significantly different among maize inbred lines for percent emergence and emergence score. Fleming et al. (1964) reported the divergence in the conservation of maize inbred lines in different locations. Russell and Vega (1973) evaluated several maize inbred lines maintained at different stations for 10 years and found significant differences for several quantitative traits among some inbreds. Bogenschutz and Russell (1986) concluded that the method used to maintain the inbreds induces genetic variation. The linear component was significant as against the nonlinear component (pooled deviation), which revealed that a large portion of GEI was accounted for by the linear regression although pooled deviation was significant. The predominance of a linear component which was noticed would help in predicting the performance of genotypes across environments.

Stability for seed longevity

Eberhart and Russell (1966) defined a stable genotype as the one which showed high mean yield, regression co-efficient (bi) around unity and deviation from regression near to zero. Linear regression (bi) is a measure for genotypic sensitivity to change in environment while the deviation from regression measures the stability of the genotype. Accordingly, the mean and deviation from the regression of each genotype were considered for stability, and linear regression was used for testing the genotypic response. Genotypes with high mean, bi = 1 with non-significant δ^2di are suitable for general adaptation, i.e., suitable to overall environmental conditions and they are considered as stable genotypes. Genotypes with high mean, bi > 1 with non-significant δ^2di are considered to be below average in stability. Such genotypes tend to respond favorably to better environments but give poor yield in unfavorable environments. Hence, they are suitable for favorable environments. Genotypes with low mean, bi < 1 with non-significant δ^2di do not respond favorably to improved environmental conditions and hence, it could be regarded as specifically adapted to poor environments. Genotypes with any bi value with significant δ^2di are unstable.

Seed longevity is very important as it determines the quality of the seeds, and plant population and crop establishment. Loss in crop stand brings in a significant loss in economic returns. Hence, a genotype possessing reasonable stability for seed longevity traits is desirable for minimizing the risk of germination and crop establishment loss. Taking the stability parameters into consideration, the results in respect of seed longevity traits are discussed. Earlier studies on viability of seed under storage conditions (Stanwood and Sowa, 1995 in *Allium cepa*; Ruiz et al. 1999 in *cereals;* Pita et al. 1998 in *Avena sativa,* Lee et al. 2019 in rice, Niedzielski et al. 2004 in rye, wheat and triticale, Jagadish et al. 2018 in soybean) suggest that there is variability among genotypes for seed stability and viability under storage.

Seed germination is a unique process in which a series of well-programmed steps enable the expression of the inherent genetic information of seed in the form of embryo emergence. All the seeds must germinate to continue the generational march of plant species. Obviously, germination is the first visible symptom of growth and development of an embryo. The mean germination (xi) among the landraces ranged from 57.6 (IC-345189) to 90.7% (IC-541332) with population mean (x) 78.4 % (Table 6). Twelve genotypes were unstable as indicated by the significant δ^2di. Genotypes IC-347577, IC-345248, IC-345243, IC-415824, IC-345249 and IC-345253 were found better adapted to all storage environments with their bi=1 and mean (xi) more than population mean (x). Genotype IC-541311 was better adapted to the favorable environment (bi>1 and xi>x). Nine genotypes *viz*., IC-345718, IC-347571, IC-347588, IC-345193, IC-345244, IC-415803, IC-415819, IC-415822 and IC-415829 have shown better adaptability to unfavorable conditions (bi<1 and Xi>1). These nine-genotypes could be of more value in breeding as they have shown better performance even in unfavorable storage environments of seed aging. These genotypes may not lose much of their germination ability even after years of storage. The present results are in concurrence with the report of Tomer and Maguire (1990) who compared six varieties of wheat stored for four years and found that percent germination of seeds did not decline markedly with aging.

Shoot length (SL), root length (RL) and seedling dry weight (SDW) indicate the rate of growth and development of a seedling after seed germination, which contributes to the expression of seedling vigor index. Shoot length varied from 15.04 (IC-541330) to 23.53 cm (IC-345193) with a population mean of 20.40 cm. Eight of the studied genotypes were highly unstable in their shoot length over environments. Genotypes viz. IC-345726, IC-347588, IC-345244, IC-345253, IC-415803, IC-392131, IC-541309 and IC-541311 were better adapted to all environments. Genotypes IC-345729, IC-343556, IC-345194 and IC-415793 were better adapted to favorable environment while IC-541321was adapted to the poor environment. Root length varied from 7.30 (IC-415829) to 13.21cm (IC-541321) with a population mean of 11.20 cm. None of the genotypes were found unstable. Genotypes IC-345189, IC-369131, IC-347571, IC-345193, IC-415793, IC-415803, IC-415823 and IC-541330 were adapted better to all environments. Genotypes IC-345197, IC-345703, IC-392151, IC-541309, IC-541315, IC-541321, IC-541322 had better adaptability to favorable environments, while two genotypes, IC-345244 and IC-345253 were adapted to unfavorable environments. For seedling dry weight (SDW), the range was high with a minimum of 8.42 (IC-415829) to 23.31 g (IC-392130) and a population mean of 15.52 g. Four genotypes were highly unstable in their SDW. Nine genotypes *viz*., IC-369131, IC-345718, IC-345724, IC-345726, IC-347571, IC-343556, IC-343577, IC-541309 and IC-541311 had better adaptability to all environments, while three genotypes, IC-345248, IC-392130 and IC-392131 were better adapted to favorable environments. Two genotypes, IC-345729 and IC-347577 were better adapted to unfavorable environments.

The expression of the inherent genotypic potential of the seed is dependent upon the

Table 6. Mean and stability parameters for seed longevity traits in sorghum landraces

S.No.	Landraces	(GR)			(SL)			(RL)			(SDW)			(SVI)			(FE)		
		Mean	bi	S^2di	Mean	bi	S^2di	Mean	bi	S^2di	Mean	bi	S^2di	Mean	bi	S^2di	Mean	bi	S^2di
1	IC-345726	80.0 (63.46)	1.62	18.17**	21.47	1.23	-0.45	11.34	0.97	1.22	18.47	0.85	-0.26	1469.8	1.43	22942.6**	64.9 (53.68)	1.17	6.48*
2	IC-345729	73.1 (58.74)	0.66	-0.57	21.24	1.52	0.14	10.76	0.58	-0.21	18.3	0.20*	-0.47	1322.3	0.50*	-3904.3	68.8 (56.08)	0.69	2.82
3	IC-347588	79.9 (63.39)	0.17	2.57	23.35	1.13	0.19	10.65	0.46	-0.6	14.38	0.95	-0.46	1140.6	0.52	-899.2	75.6 (60.41)	0.35	11.83**
4	IC-345194	82.0 (64.93)	0.63	-2.79	22.09	1.39	0.37	11.31	1.08	0.17	14.66	0.73	-0.41	1200.9	0.63*	-5077.4	77.6 (61.78)	0.57	-0.71
5	IC-345197	75.7 (60.52)	0.62	-0.73	19.59	0.71	0.47	12.29	1.31	0.45	16.58	0.68	-0.25	1256	0.7	-4314.7	72.2 (58.18)	0.96	-1.36
6	IC-345243	83.3 (65.90)	0.93	1.71	19.98	0.60*	-1.02	10.57	0.66	-0.7	10.95	0.64*	-0.53	909.5	0.64	-4092.7	75.6 (60.42)	0.83*	-2.34
7	IC-541315	62.0 (51.96)	1.49	10.30*	20.91	1.34	-0.31	12.3	2.16	-0.08	14.72	0.20*	-0.43	908.1	0.98	5023.7	58.8 (50.12)	1.79	5.77*
8	IC-541319	64.0 (53.16)	1.29	0.63	21.01	0.68*	0.67	11.34	1.39	-0.21	11.33	1.34	0.09	738.7	1.08	-3004.3	55.5 (48.21)	1.13	-0.1
9	IC-541321	83.6 (66.11)	1.67	20.83**	21.74	0.63	-1.04	13.21	1.81	-0.51	13.02	0.82	0.23	1065.7	0.98	-376.4	78.7 (62.51)	1.61	22.65***
10	IC-541332	90.7 (72.26)	1.36	30.37***	20.7	0.53	-0.08	10.62	1.88	1.59	11.53	0.76	-0.48	1030.3	0.71	-261.8	87.6 (69.38)	0.98	7.2665*
11	EC 507688	76.3 (60.91)	1.04	21.69**	20.88	0.74	-0.83	10.23	0.65	-0.73	14.03	1.22	0.27	1072	1.11	15766.3*	71.4 (57.71)	0.83	2.05
12	IC-345724	76.0 (60.63)	0.35*	-3.3	19.49	1.1	-0.26	11.21	0.81	-0.65	19.26	1.07	0.81	1450.6	0.69	-213.8	69.7 (56.65)	0.7	-1.75
13	IC-347571	83.4 (65.96)	0.53*	-3.7	23.3	1.45	0.09	12.11	1.19	-0.73	16.75	0.88	-0.29	1392	0.74	-2215	78.2 (62.22)	0.60*	-2.1
14	IC-541322	73.3 (58.92)	1.83	16.39**	16.95	0.59*	-0.54	12.09	1.75	-0.24	11.83	0.76*	-0.54	857.4	1.11	447	69.7 (56.65)	2.19	19.38***
15	IC-345189	57.6 (49.94)*	1.14	3.43	20.58	1.66	4.31**	11.74	1.27	0.16	19.82	2.81	4.95***	1189.2	1.85	10976.5*	53.9 (47.24)	1.26	4.92*
16	IC-369131	76.3 (60.86)	0.69*	-3.73	21	1.97	11.94***	12	0.97	-0.03	18.1	1.14	0.39	1379.2	0.97	-1418.7	71.9 (58.02)	0.56	-1.24
17	IC-347577	81.5 (64.53)	0.76	3.52	21.08	0.87	-0.78	10.51	0.84	-0.71	16.23	0.466*	-0.53	1316.6	0.62	-2349.9	77.2 (61.52)	0.92	1.68
18	IC-343556	62.6 (52.33)	0.86	0.3	21.86	1.38*	-0.94	11.04	1.01	-0.41	20.74	1	0.34	1305.7	1.14	10780.3	59.6 (50.57)	1.3	-0.5
19	IC-343577	67.9 (55.00)	1.65	17.32**	20.93	1.49	-0.19	10.5	0.66	-0.55	20.73	0.9	-0.47	1390	1.7	11991*	60.9 (51.34)	1.63	1.52
20	IC-345244	85.4 (67.54)	0.62	1.26	21.94	0.79	-0.68	11.7	0.63	-0.74	11.61	0.7	-0.49	988.7	0.57	-3038.1	79.8 (63.33)	0.45*	-1.47
21	IC-345253	87.4 (69.28)	0.89	2.79	22.58	1.1	-0.18	11.98	0.61	-0.66	12.24	0.45	-0.42	1066.6	0.57*	-4617	78.6 (62.45)	0.94	-1.26
22	IC-415803	85.5 (67.63)	0.43*	-3.32	17.86	0.77	-0.71	12.1	1.18	-0.38	11.94	0.81	-0.48	1018.7	0.57*	-4142.7	80.0 (63.48)	0.47	-0.33
23	IC-415819	86.0 (68.04)	0.69	-0.89	20.7	0.96	-0.87	11.51	0.65	-0.64	15.09	1.17	0.3	1296.3	0.92	3022.3	78.9 (62.71)	0.76	-1.71
24	IC-415823	79.9 (63.37)	1.09	9.23*	19.39	1.22	-0.54	11.86	0.85	-0.4	13.69	0.64	0.61	1087.8	0.86	2480.9	70.6 (57.17)	0.58	-1.39
25	IC-392127	66.2 (54.46)	1.15	6.34	21.79	1.07	-0.78	10.34	0.449*	-0.71	22.84	1.93	1.26*	1513.8	1.81*	-5321.5	59.3 (50.36)	1.55	12.01**
26	IC-392130	64.4 (53.37)	1.4	-2.83	20.96	0.88	-0.28	11.03	0.59	-0.54	23.31	1.6	1.01	1508.7	2.00*	-194.3	57.7 (49.46)	1.32	1.25
27	IC-392131	62.6 (52.35)	1.28	-1.35	21.28	1.15	0.95	11.34	1.14	-0.75	23.24	2.06	0.65	1474.1	1.92	5725.4	58.2 (49.73)	1.94	9.76**
28	IC-541309	77.9 (62.02)	1.27	-1.86	22.24	0.87	1.37	12.33	1.418*	-0.8	17.77	1.07	-0.51	1378.3	1.26*	-5041	63.6 (52.93)	0.79	1.32
29	IC-541311	80.9 (64.14)	1.38	2.59	23.02	0.78	-0.13	11.51	1.3	-0.01	18.19	0.75	-0.42	1458.7	1.15	909.6	76.4 (60.97)	1.55	4.80*
30	IC-541318	66.1 (54.40)	1.33	7.15	19.75	0.43	-0.66	11.24	1.18	0.07	14.34	0.74	-0.07	950.8	1.08	1379.2	59.3 (50.37)	1.73	10.81**

Table 6. Contd....

			(1)			(2)			(3)			(4)			(5)			(6)	
31	IC-345718	80.5 (63.81)	0.65	-2.35	20.93	1.49	11.20***	11.37	0.84	-0.46	18.24	1.18	-0.52	1468.6	0.99	-5115.6	75.1 (60.08)	0.85	-1.48
32	IC-415822	79.8 (63.29)	0.51	-0.97	19.46	0.9	-0.06	11.26	1.18	-0.33	15.45	0.93	0.02	1233.9	0.73	1970.6	74.7 (59.83)	0.27	6.78*
33	IC-415824	84.6 (66.94)	0.89	-2.62	19.16	0.86	5.04**	9.86	0.83	-0.65	13.24	1.43	1.17*	1122.9	1.1	10985.6	78.9 (62.68)	0.77	-1.06
34	IC-415828	75.5 (60.33)	1.16	1.57	17.98	0.87	0.07	11.52	0.93	-0.75	15.07	1.17*	-0.54	1136.7	1.16	-2903.8	69.1 (56.26)	0.91	-1.28
35	IC-392151	74.9 (59.93)	1.33	11.41*	20.94	0.85	1.8	12.22	1.46	-0.47	16.07	1.25	-0.01	1200.9	1.31	-3055.4	69.1 (56.24)	1.09	-0.72
36	IC-345703	73.2 (58.86)	0.61	-2.12	17.08	1.54	3.48*	12.04	1.69	-0.07	14.4	2.02	0.41	1065	1.24	3007	63.9 (53.12)	0.67	0.15
37	IC-345193	80.1 (63.57)	0.64*	-3.63	23.53	1.45	3.72*	11.72	0.82	-0.4	19.24	0.84	1.59*	1539.6	0.81	5827.6	70.8 (57.30)	0.69	0.02
38	IC-345249	85.2 (67.38)	0.89	-0.5	19.68	0.69	-0.72	11.4	1.02	-0.12	13.01	0.67	-0.27	1105.1	0.69	-2916.4	77.3 (61.58)	1.01	-1.83
39	IC-415792	86.1 (68.12)	1.56	14.60**	20.23	0.57	0.43	12.39	1.17	0.17	13.36	1.04	-0.44	1131.2	1.06	-873.2	78.3 (62.28)	1.26	0.3
40	IC-415793	76.5 (61.01)	1.68	14.47*	21.78	1.35	-0.8	12.34	0.84	0.91	15.24	0.86	-0.48	1160.4	1.3	8953.4	78.6 (62.48)	0.09	15.64***
41	IC-415805	75.8 (60.52)	1.16	48.94***	17.6	0.67	-0.77	8.78	0.3	-0.1	8.82	0.33*	-0.51	663.1	0.52	4669.7	65.6 (54.10)	1.21	-0.35
42	IC-415829	81.6 (64.63)	0.34*	-2.67	18.35	1.1	2.2*	7.3	0.67	-0.74	8.42	0.68	-0.43	685.2	0.43*	-3934.4	76.4 (60.99)	0.31	-0.16
43	IC-345248	84.5 (66.86)	1.16	1.15	18.4	0.57	-0.03	10.39	0.81	-0.72	17.06	1.4	0.41	1439.6	1.35	-3532.9	77.6 (61.79)	1.43	3.89
44	IC-541330	65.4 (53.98)	1.04	-3.71	15.04	0.52	5.97**	11.65	1.22	-0.51	14.44	1.32	0.7	948.3	1.09	-782.2	60.3 (50.94)	1.52	-1.09
45	EC 507868	77.3 (61.60)	1	3.23	18.93	0.64	-0.24	9.16	0.098*	-0.8	14.52	0.96	0.44	1123.9	0.94	7240.1	71.6 (57.85)	1	-1.71
46	EC 538170	64.7 (53.56)	0.52*	-3.43	19.44	0.93	1.95	9.24	0.7	-0.75	11.77	0.57	-0.45	761.4	0.45*	-5360.3	60.7 (51.21)	0.76	-0.71

*Values in parenthesisare arcsine transformed value

environment, both internal and external. The internal environment refers to seed health, which is crucial for the survival of both the seed and the seedling derived from it. Therefore, whether a farmer produces a good or a bad crop utilizing all the inputs at his disposal largely depends on the quality of seed used by him. Quality seeds, being the cheapest of the inputs for crop production, are critical for maintaining increased productivity. One of the most important methods to assess seed quality is to determine seed vigor which is considered as an index of seed quality. With reference to seeds, viability is the state of being alive, while vigor denotes the degree of their aliveness. In the current study, the seedling vigor index (SVI) varied from 663 (IC-415805) to 1539 (IC-345193) with a population mean of 1172. Five of the genotypes were unstable. Six genotypes viz. IC-369131, IC-345718, IC-343556, IC-345193, IC-415819 and IC-541311 showed better adaptability to all environments, while IC-345248, IC-392127, IC-392130, IC-392131 and IC-541309 were better adaptability to favorable environments. Six genotypes IC-345724, IC-345729, IC-347571, IC-347577, IC-345197 and IC-415822 were adapted better to poor environments. Gutie´rrezet al. (1993) evaluated the effects of seed aging on four maize genotypes, comparing new and four years old seeds, and found that vigorous genotypes suffered less severe damage than low-vigour seed under natural aging.

Field emergence (FE) is the ability of seeds to germinate in the soil and emerge out under the natural field environment which is also a measure of seed vigour and viability. Thirteen of the studied genotypes were unstable. In the present study, field emergence varied from 53.9 (IC-345189) to 87.6% (IC-541332) with a population mean of 70.7%. Seven genotypes *viz*., IC-345718, IC-347577, IC-345243, IC-345249, IC-415792, IC-415819 and IC-415824 have shown better adaptability to all environments. While genotype IC-345248 was adapted to favorable environment, IC-347571, IC-345194,IC-345244, IC-415803 and IC-415829 were better adapted to poor environments.

In summary, forty-six sorghum landraces were evaluated across four seed aging processes to study their seed longevity and stability performance with the aim of selecting superior and stable genotypes. The test genotypes showed considerable variations for seed longevity and were sensitive to factors limiting seed quality. Mean performance and coefficient of regression (bi) were used as response indices while deviation from regression (S^2di) was used as a stability index. Seven sorghum landraces *viz.,* IC-345729 (*Bicolor*), IC-347571 (*Caudatum*), IC-347577 (*Durra*), IC-345244 (*Durra*), IC-415803 (*Durra*), IC-415822 (*Durra bicolor*) and IC-415829 (*Guinea bicolor*) performed well across seed aging conditions indicating good stability. Seeds with age resistance would be needed for stable seedling establishment in the fields. It appears from the study that the *Durra* race may inherently good for seed longevity. These genotypes are therefore recommended for use in further breeding to improve seed longevity in sorghum, which otherwise is generally poor. This is the first report on identifying the stable genotypes for seed longevity traits in sorghum.

Authors' contribution

Conceptualization of research (KB, RM); Designing of theexperiments (KB, RM, VAT); Contribution of experimental materials (ME); Execution of field/lab experiments and data collection (KB); Analysis of data and interpretation (RM,KB); Preparation of the manuscript (RM, KB, SA, IKD).

Declaration

The authors declare no conflict of interest

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