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Genotype-by-Environment Interaction and Yield Stability Analysis in Finger Millet (*Elucine coracana* L. Gaertn) in Ethiopia

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ABSTRACT

Finger millet is one of the most neglected and underutilized crops worldwide, yet an important food cereal for millions of poor farmers in Africa. An experiment was carried out to determine adaptation range of diverse set of finger millet accessions and identify superior types with excellent yield potential for use as cultivar or as germplasm source for future breeding endeavors. A total of 44 *indigenous accessions selected in previous evaluations and two check varieties were tested in two sets* (*mixed and colored*) *each containing* 22 *entries in a total of* 11 *environments between* 2004 *and* 2008 *seasons. Data were collected on grain yield, days to flowering, and plant height. The result showed that* 2.5%, 79.1% *and* 18.3% *of the total sum of squares in the mixed set and* 2.1%, 86.9% *and* 11.0% *in the colored set was attributed to genotype, environment, and genotype × environment interaction* (*GEI*) *effects, respectively. Furthermore,* 54.6% *and* 46.19% *of the GEI sum of squares in the mixed and in the colored set, respectively, were contributed by the first two interaction principal component axes* (*IPCA*1 *and IPCA*2). *A white seed accession* (*Acc.* 203572) *from the mixed set and three other accessions* (*Acc.* 229469, *Acc.* 203410 *and Acc.* 203539) *from the colored set were most stable and also had above average mean grain yield across environment and thus are recommended for release as cultivars to improve finger millet production in these environments.*

Keywords: *AMMI, Finger Millet, Genotype, Environment, Stability*

1. Introduction

Finger millet (*Elucine coracana* L. Gaertn), a member of the *Poaceae* (*Gramineae*) family, is one of the most important food cereals in the sub-Saharan Africa and south Asia. It is the third most widely cultivated millets after pearl millet (*Pennisetum glaucum*) and foxtail millet (*Setaria italica*) in the semi-arid tropical and subtropical regions of the world [1]. Indigenous to eastern Africa, finger millet is widely produced in the cool high altitude areas in the region primarily as source of food and also for making traditional alcoholic beverages [2]. In Ethiopia, the crop is mainly grown in the northern, north western and western parts of the country, especially during the main rainy season. Finger millet is often mixed with other grain crops such as tef or sorghum to make composite flour for local food preparation such as *injera* and porridge. It is often valued as nutritious cereal by local people. This observation has scientific merit in that finger millet contains relatively higher concentration of calcium and dietary fiber than other cereals [3].

Notwithstanding its importance, published information is scarce on the agronomy and genetics of the crop. In Ethiopia, finger millet occupies 4% of the total area allocated to cereals (nearly half a million hectares) each year and also contributes about 4% to the total annual cereal grain production in the country [4]. Similar to tef, finger millet grain can be stored for several years under local storage conditions without sustaining significant damage by storage pests [5,6]. This property together with its adaptation to low input conditions and relatively better nutritional value [7] makes it one of the salient crops among resource poor communities living in food insecure areas [8]. In Ethiopia, it is often grown in poor soils without fertilizer, and thus the national average yield rarely exceeds 1 ton per hectare.

Although formal research to improve the crop has started some three decades ago, not much progress has been made because of funding limitation as the crop is not among the priority commodities. As a result, only two varieties have been identified for cultivation to date but appropriate management practices are still lacking. Though the varieties were initially released for cultivation in the sub-humid and mid altitude areas, their inadvertent introduction in to low rainfall areas found new adaptation zones. At present the production of these varieties has expanded to dry low altitude areas including regions where the crop was previously unknown [5]. Frustrated by repeated failure of the maize crop as a result of frequent drought, farmers in the dry Rift Valley region of Ethiopia widely adopted the variety that it is currently grown as one of the most important crops in this region [9].

Encouraged by the expanded adoption, the Ethiopian national sorghum research program increased its effort to identify additional high yielding varieties that can fit in to a wide range of environments. This effort drew an important lesson from past activities where extensive evaluation of hundreds of entries involving exotic sources acquired through the Eastern African Regional Sorghum and Millet (EARSAM) research network produced only limited progress. Hence, as of 2003 much of the focus was placed on evaluation of local sources for adaptation and yield potential. Superior genotypes selected from different stages of screening were pulled together and evaluated at multiple locations representing different agro-ecologies. Therefore, this paper discusses the performance of these genotypes under a range of environments and generates information on the extent of genotype-by-environment interaction which is useful in designing suitable approaches for variety selection.

2. Materials and Methods

The experiment was conducted from 2004 through 2008 in the main rainy seasons at four locations (Adet, Arsi Negelle, Bako and Pawe) in eleven environments. Major characteristics of the test environments are presented in **Table 1**.

2.1. Genetic Materials

A total of 44 finger millet landraces, selected from tests conducted in previous years, were evaluated in this study. The materials were grouped in to two sets each containing 22 entries. Majority of the test entries were from selections made among the 2003 observation nursery that contained a pool of landrace collections received from the Ethiopian Institute of Biodiversity Conservation (IBC). The grouping was made to reduce the number of genotypes in each set and thus maximize uniformity among experimental units. Hence, the materials were arbitrarily assigned to the two groups with the ten white seeded genotypes purposely placed in the first set to allow within group comparison among white seeded entries. This set is designated as "mixed set". All genotypes assigned to the second set have colored grains (copper, light red, dark red, brown, black) and hence were referred to as "colored set". Moreover, two released varieties (Tadesse and Padet) were included in both sets to serve as standard check.

Table 1. Major geo-climatic characteristics of the test environments.

Location	Year	Environment code‡	Position	Altitude (m)	Soil type	Mean annual rain fall (mm)	Temperature (˚C)	
							Min.	Max.
Adet	2004	A	N11˚16', E37˚29'	2060		1250	7.8	25.4
Arsi-Negele	2004	B	N7˚19', E38˚39'	1960	Vertisol	870	11	21
	2005	D						
	2006	F						
	2007	H						
	2008	K						
Bako	2007	I	N9˚8', E37˚03'	1550	Nitosol	1178	13.2	28
Pawe	2004	C	N11˚18', E36˚24'	1050	Vertisols/Fluvisols	1580	15	32.4
	2005	E						
	2006	G						
	2007	J						

‡ As the environments were common to both sets of trials in a single season, the codes are the same (e.g., A = Adet in 2004 in both trials).

2.2. Experimental Setup

The experiment for both sets was laid in a randomized complete block design with four replications in all locations and seasons. Because there were no recommended spacing and fertilizer rate developed for finger millet, a blanket recommendation adopted from sorghum was used. Each plot consisted of three 5 m long rows spaced 0.75 m apart. The seeds were manually drilled into each row and latter thinned to a spacing of 15 cm between plants. Trials in all environments received Diammonium phosphate fertilizer applied at a rate of 100 kg·ha^{-1} at planting. In order to avoid lodging, nitrogen fertilizer was not applied in all environments. The field was kept free of weeds throughout the testing seasons. Harvesting and threshing were done manually.

2.3. Data Collection and Analysis

Data were recorded on grain yield (kg·ha^{-1}), days to 50% flowering, (from emergence to the time when half of the plants in the plot bloomed) and plant height (cm) (from the ground level to the tip of the longest finger) in all environments. Data on grain was recorded when the moisture content was reduced to 12.5%. Moreover, the accessions were visually evaluated for their reaction to lodging and blast. The data were subjected to analysis of variance (ANOVA) for each of the environments and for the combined data using SAS 9.1 (SAS Institute). Moreover, Additive Main Effects and Multiplicative Interaction (AMMI) ANOVA and AMMI biplot were performed using CropStat 7.2 Software [10]. The additive main effects and multiplicative interaction (AMMI) model is a multivariate approach proposed to dissect the GEI in to two main components. The first component is the ANOVA, which is the additive component and the second is the interaction principal components [11]. The AMMI 1 biplot contains main effect (genotype/environment) means in the x-axis and the first interaction principal component axis (IPCA 1) in the y-axis such that genotypes and/or environments that appear in a perpendicular line have similar means and those that appear on a horizontal line have similar interaction patterns [12]. Further, stable genotypes (with less GEI) are those, which have IPCA 1 values closer to zero regardless of their sign. Therefore, the best genotypes are those, which are placed on the right side of the AMMI 1 biplot origin (the junction of IPCA 1 at zero and the average mean yield) marked at or closer to the IPCA 1 origin (zero).

3. Results

3.1. Grain Yield and Phenology

The AMMI ANOVA for the combined data is presented in **Table 2**. Genotype, environment, genotype × environment interaction effects were significant for grain yield and days to flowering in both sets. In the mixed set experiment, 2.5%, 79.1%, and 18.3% of the total sum of squares was attributed to genotypes, environments, and genotype × environment interaction effects. The result for the colored set was also similar to the mixed set and showed that much of the observed variability (86.9%) was attributed to the environmental variance and only 2.08% and 11.02% of the total sum of square for yield could be explained in terms of genotype and genotype × environment interaction, respectively.

Table 2. Analysis of variance for the AMMI model for grain yield.

Source of variation	D.F.	Mixed set		Colored set	
		S.S.	% contribution	S.S.	% contribution
Genotypes (G)	23	8599920	2.53	7631910	2.08
Environments (E)	10	269182000	79.13	318627000	86.90
G × E Interaction	230	62402300	18.34	40403500	11.02
IPCA 1	32	24182100	38.75	11504100	28.47
IPCA 2	30	9858900	15.80	7156500	17.71
IPCA 3	28	8486000	13.60	6506620	16.10
IPCA 4	26	6609360	10.59	5684490	14.07
G × E residual	114	13266000		9551830	
Total	263	340184000		366662000	

The mean grain yield of genotypes included in the mixed set ranged from 2074 kg·ha^{-1} to 2804 kg·ha^{-1} in Acc. 203523 and Acc. 203564, respectively. Fourteen of the 24 genotypes had above average yield, but only Acc. 203564 had significantly higher yield than the entry mean (2541 kg·ha^{-1}) (**Table 3**). Moreover, in the same set, mean grain yield among environments ranged from 1230 kg·ha^{-1} to 4416 kg·ha^{-1} in E and B in that order. Yield at six of the eleven environments was higher than average.

In the colored set, genotype yield ranged from 2369 kg·ha^{-1} in Acc. 203319 to 3217 kg·ha^{-1} in Acc. 203539. Eleven of the 24 genotypes included in this set showed above average performance (**Table 4**). However, only three of them: Acc. 229469, Acc. 203410, and Acc. 203539, had significantly higher yield than the entry mean. Seven and three of the genotypes in this set out yielded the check varieties *Tadesse* and *Padet*, respectively. Similarly, the mean yield among the environments ranged from 1479 kg·ha^{-1} in G to 4698 kg·ha^{-1} in B. Only four of the eleven environments, B, D, F and K, supported yields significantly higher than the overall mean. In both sets of experiments, the standard variety *Padet* out yielded the other standard *Tadesse*. In several locations, accessions in both sets had yields that were significantly higher than both standard varieties but none of the across location mean yield of the mixed set genotypes was significantly higher than the standard varieties.

Table 3. Mean grain yield (Kg·ha^{-1}), days to 50% flowering (DTF), plant height (PH), and the joint regression (bi) of the mixed set finger millet landrace accessions tested in 11 environments.

Genotypes**	Grain yield-by-environment												DTF	PH	bi
	A	B	C	D	E	F	G	H	I	J	K	Mean			
1. Acc. 229345	1988	3311	2677	2645	1636	4180	1404	3422	1954	1684	2444	2486	96	103.1	0.75
2. Acc. 229349(W)	2441	4347	1948	2289	828	3976	349	4433	1060	737	2311	2247	97	106.7	1.35*
3. Acc. 229367	1817	4222	2587	3467	1694	4678	950	3400	1666	1835	2911	2657	96	106.1	1.02
4. Acc. 229380(W)	2986	5156	2242	3733	592	3367	1329	4556	1433	1759	3444	2782	97	104.6	1.25
5. Acc. 229401	1947	4378	2504	2911	1498	3456	1661	3867	2791	2140	2822	2725	98	100.1	0.79
6. Acc. 229463(W)	2638	4511	2069	2578	405	3484	1788	4711	1821	826	2667	2500	101	112.2	1.19
7. Acc. 229465(W)	2711	4711	2138	1533	922	4011	1275	2622	585	1607	3389	2319	99	110.5	1.10
8. Acc. 229470	2648	5156	2279	2889	373	3444	2874	4133	1242	1084	2800	2629	97	107.3	1.16
9. Acc. 203358(W)	2406	4667	2068	2245	470	3356	1296	3933	675	2333	3000	2404	100	111.1	1.13
10. Acc. 203402	2250	4400	2574	2889	1626	4322	1467	3296	2022	1820	2444	2646	98	99.6	0.91
11. Acc. 203509	2172	4644	2562	2578	1733	3416	1389	3933	2192	1867	2889	2670	97	98.9	0.90
12. Acc. 203523	1778	4067	716	1667	988	4133	1059	2933	1637	1702	2133	2074	100	108.0	0.99
13. Acc. 203530(W)	2251	4578	1775	2378	451	3544	2535	4644	1976	1000	2978	2555	102	117.3	1.12
14. Acc. 203542	2448	4867	2584	3000	1946	3817	1285	3533	1933	2025	2644	2735	97	102.4	0.93
15. Acc. 203562	2298	4356	2371	3133	1685	2944	937	3222	2380	1732	2911	2543	96	98.4	0.78
16. Acc. 203564	2427	4667	2527	3200	1906	4311	1557	3489	2531	1753	2478	2804	97	105.8	0.91
17. Acc. 203572(W)	2866	5280	2102	3355	996	4491	1409	2667	1474	1756	3089	2680	96	98.7	1.16
18. Acc. 203587(W)	2719	4778	2073	1778	411	5344	1446	3900	1807	979	2622	2532	99	112.5	1.39*
19. Acc. 203558	2227	4778	2590	2778	1649	4156	921	3751	1851	1286	2378	2578	97	105.9	1.11
20. Acc. 215986	1714	3111	3053	1578	2451	3700	1452	2711	2468	2131	2456	2439	102	94.8	0.40*
21. Acc. 215869(W)	2780	4244	2228	1889	650	3867	1266	4033	1755	781	2867	2396	101	109.5	1.15
22. Acc. 215962(W)	2531	4311	1702	1711	790	4033	1617	4089	675	772	2689	2265	101	112.2	1.23
23. Tadesse	2541	3622	1749	3556	1983	3804	1599	3356	1819	2092	2822	2631	97	108.0	0.69*
24. Padet	2358	3822	3008	2734	1832	3422	2024	3200	1917	2155	3044	2683	97	105.9	0.60*
Mean	2372	4416	2255	2605	1230	3886	1454	3660	1736	1577	2760	2541	98	105.8	
LSD (0.05)	477.3	1288	497	927	321	1578	617	966	668	393	802.6	258	8	9.0	
CV (%)	14.25	20.68	15.6	25.2	18.5	28.8	30.1	18.7	27.2	17.6	20.6	24	5	12.7	

*slopes significantly different from 1.00 (the slope for the overall regression), **W = accessions with white kernel color, the rest are brown.

Table 4. Mean grain yield (Kg·ha^{-1}), days to 50% flowering (DTF), plant height (PH), and the joint regression (bi) of the colored set finger millet landrace accessions tested in 11 environments.

Genotypes	Grain yield-by-environment												DTF	PH	bi
	A	B	C	D	E	F	G	H	I	J	K	Mean			
1. Acc. 229376	2497	4311	3063	5211	1789	4220	1397	2228	1954	2056	3400	2921	93	101.5	1.02
2. Acc. 229381	2147	4578	2661	4833	1846	3505	1364	2484	1194	2082	2867	2687	93	103.0	0.987
3. Acc. 229383	2604	4045	2292	4022	2027	4322	1527	1984	1666	2258	3578	2757	91	100.5	0.857
4. Acc. 229398	2902	4156	2482	5411	1389	4267	1113	1774	1433	1760	2911	2691	93	108.0	1.175
5. Acc. 229399	2652	4867	2027	4722	1568	4071	1561	2058	2791	2289	3245	2895	91	101.4	0.982
6. Acc. 229400	2630	3978	2727	4045	2414	3665	2439	2405	1821	2262	2289	2788	91	99.8	0.594*
7. Acc. 229407	2792	4489	2643	4244	2417	4253	1304	2042	585	2754	2867	2763	94	101.4	0.971
8. Acc. 229415	2944	4845	2207	4445	2485	3933	1770	2093	1242	2686	3156	2891	94	104.4	0.941
9. Acc. 229417	2876	5289	2256	4889	1990	4400	1106	1670	595	2162	3622	2805	92	99.5	1.318*
10. Acc. 229440	2884	5178	2054	4873	1455	3613	1759	1459	2022	1824	1956	2643	88	105.4	1.088
11. Acc. 229442	2797	4933	2264	4800	1723	3467	1276	1444	2192	1982	3334	2746	94	110.1	1.068
12. Acc. 229458	3172	4511	2416	4667	2080	3896	1399	1340	1629	2311	3556	2816	93	104.7	1.026
13. Acc. 229461	3199	4978	2437	4211	2098	4200	1340	2120	1975	2630	3000	2926	94	106.6	0.95
14. Acc. 229462	2842	4022	2206	4613	2164	3136	1603	2025	1933	2451	3000	2727	90	104.6	0.774*
15. Acc. 229468	2909	5222	2093	4545	1940	3422	1422	1616	2379	2172	3289	2819	92	109.0	1.011
16. Acc. 229469	2810	5022	2303	5656	1840	4244	1537	1719	2827	1911	3533	3036	91	111.6	1.169
17. Acc. 203410	3330	4756	2534	5444	2086	4045	1403	2246	1474	2239	4089	3059	92	104.6	1.142
18. Acc. 203539	3100	5511	2541	4578	3627	3847	1247	2334	1807	3572	3222	3217	90	85.5	0.914
19. Acc. 203289	2767	4267	2005	4656	1742	3247	1356	1887	1851	2489	2978	2658	94	99.0	0.895
20. Acc. 203300	2347	4511	2067	4456	1835	4531	1632	1708	2468	750	2800	2646	95	103.4	1.02
21. Acc. 215961	2341	4134	2301	4889	1746	4045	1538	1709	1460	1853	3156	2652	94	99.2	1.026
22. Acc. 203319	2759	5200	2138	3111	898	3756	1740	1434	830	1180	3011	2369	93	106.9	1.048
23. Tadesse	2623	5022	2403	4434	1621	3356	1471	1429	1819	1636	2822	2603	92	106.8	1.038
24. Padet	2661	4934	2763	3933	1608	4225	1201	1820	1917	2196	3045	2755	95	102.1	0.99
Mean	2774	4698	2370	4612	1933	3903	1479	1876	1744	2146	3113	2786	93	103.3	
LSD (0.05)	495	865	618	1110	457	1235	591	613	653	494	915	232	3	6.6	
CV (%)	12.62	13.04	18.5	17	16.8	22.4	28.3	23.1	26.5	16.3	20.8	19.65	3	9.8	

*Slopes significantly different from 1.00 (the slope for the overall regression).

Days to flowering ranged from 96 to 102 in the mixed set, and from 88 to 95 in the colored set. Similarly, the range for plant height was 94.5 cm to 117.3 cm in the mixed set and 85.5 cm to 111.6 cm in the colored set. Plant height (r1 = –0.36, r2 = –0.34) and days to flowering (r1 = –0.53, r2 = –0.23) were found to have negative correlation with grain yield.

3.2. Response and Stability of the Landraces

Genotypes, Acc. 229349 and Acc. 203587 from the mixed set had linear regression coefficient significantly higher than 1.0 (the overall regression) and hence were highly responsive to the suitable environments (**Table 3**). However, since they are tall accessions (**Table 2**), adding more inputs may enhance lodging. On the other hand, Acc. 215986, *Tadesse* and *Padet* had slopes significantly lower than 1.0 and hence were better adapted to marginal environments.

The AMMI analysis showed that all of the 4 principal component axes were significant in both sets. However, 54.6% and 46.19% of the GEI sum of squares in the mixed set and in the colored set, respectively, were contributed by the first two interaction principal components (IPCA1 and IPCA2). Five accessions in the mixed set, Acc.

229465, Acc. 203509, Acc. 203523, Acc. 203572, and Acc. 203558 were shown to have the highest stability as revealed by their relative position with respect to the biplot origin (**Figure 1**). However, none of these accessions had significantly higher yield than the overall entry mean and the check varieties. Among the colored set, five accessions, Acc. 229458, Acc. 203410, Acc. 203289, Acc. 215961, Acc. 203319, and the check variety Padet showed better stability than the rest of the entries (**Figure 2**). Again none of these accessions did exceed the standard checks except Acc. 203410 that produced significantly higher yield than both check varieties. This accession is also within the same range of maturity (days to flowering) and height group with that of the standard varieties.

4. Discussion

In general, the genotypic variation in the studied traits was considerably narrow probably because of the rigorous selection process conducted in the previous year which might have not intentionally targeted these traits. The influence of GEI resulted in variable performance of the genotypes in the different test environments. Varieties with high levels of heterozygosity and/or heterogeneity are less sensitive to environmental variation and are, therefore, more stable-yielding. On the other hand, the Elucines generally are reported to be strictly autogamous with low levels of heterozygosity. This is perhaps the major factor that contributed to the high GEI in finger millet in the present study.

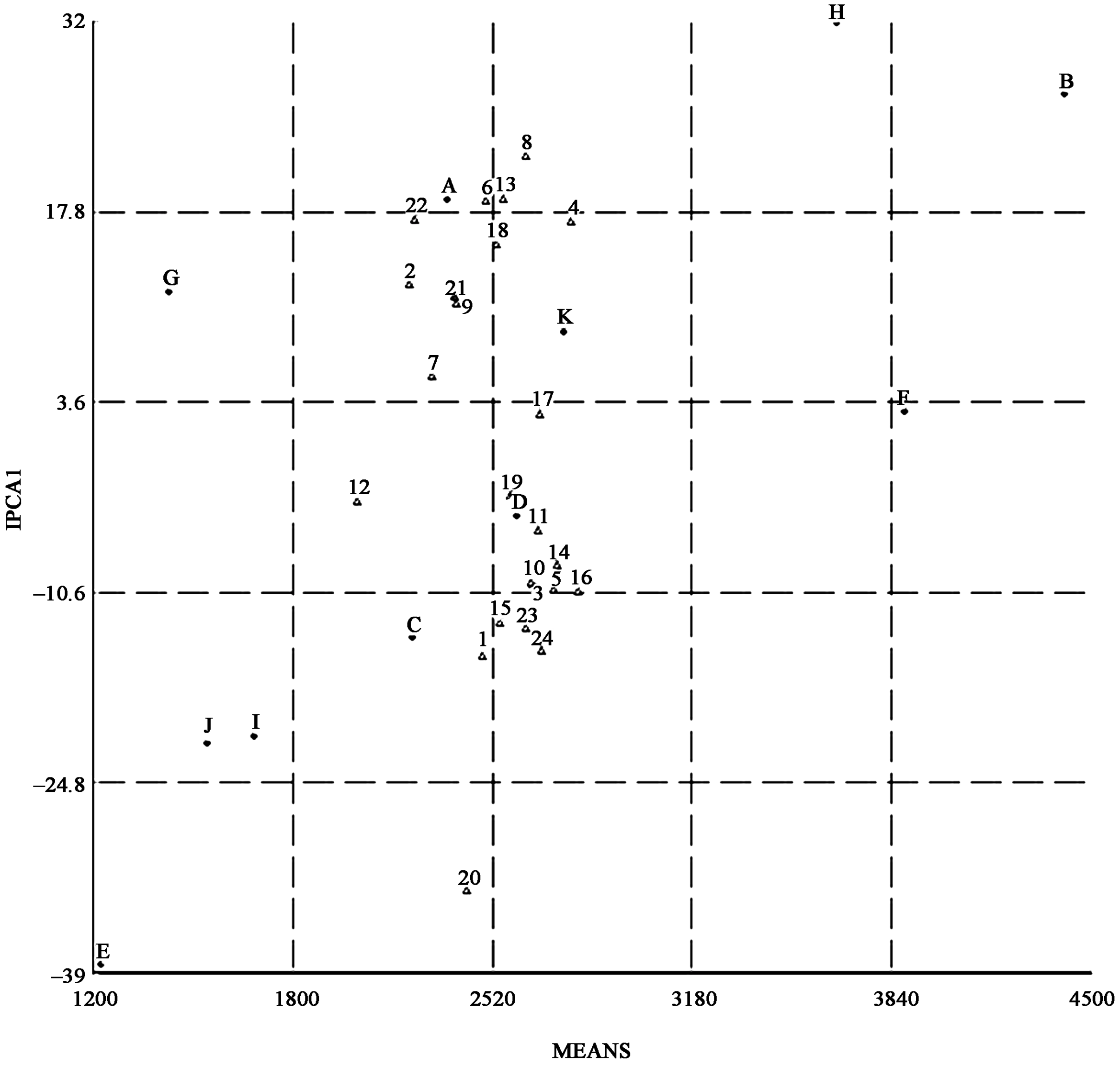

Figure 1. AMMI 1 Biplot of the 24 finger millet varieties and the 11 test environments in the mixed set.

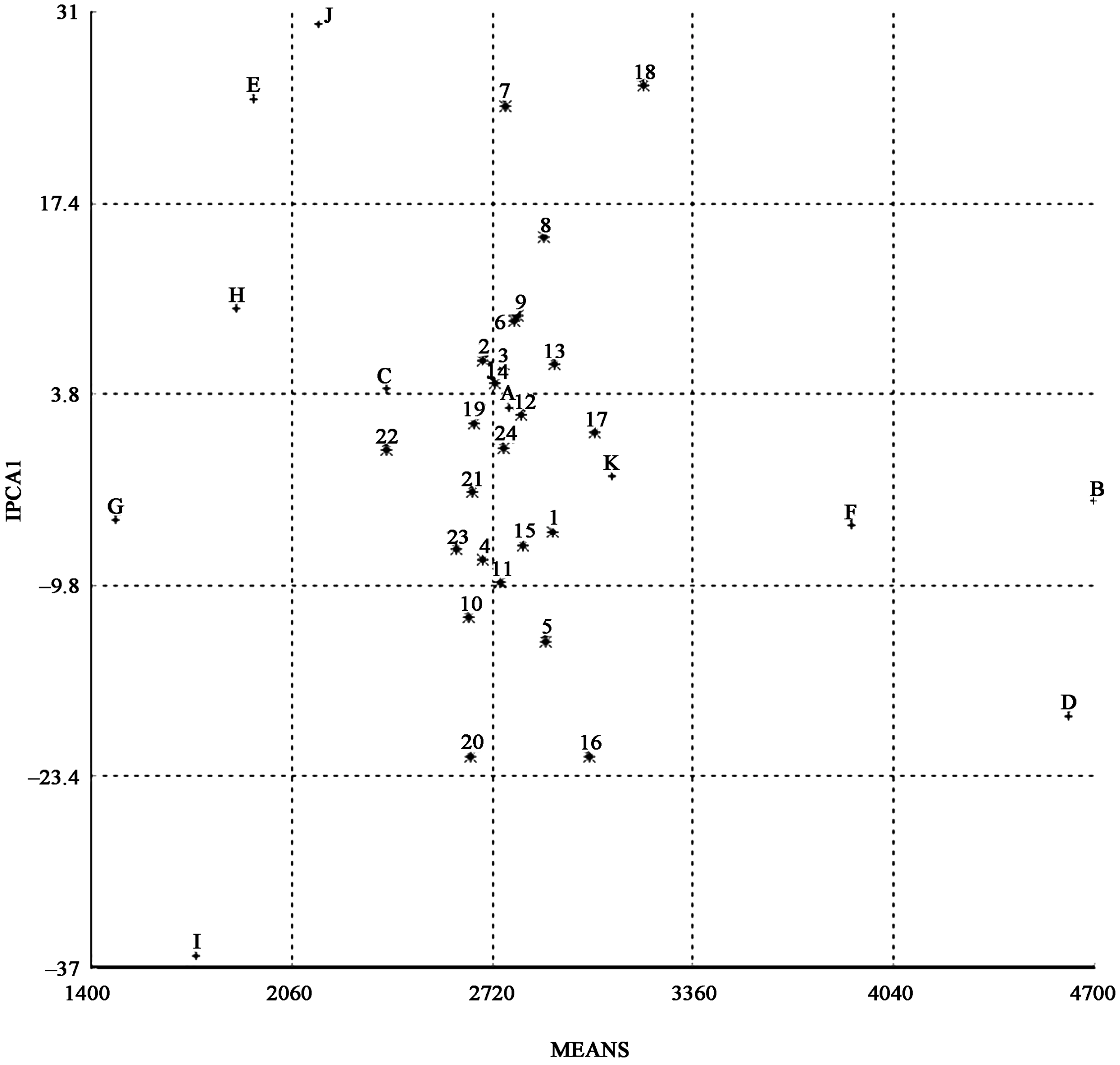

Figure 2. AMMI1 Biplot of the 24 finger millet varieties and the 11 test environments in the colored set.

While positive correlation between days to flowering/maturity and yield seems to be a common phenomenon in crop plants, the negative correlation in the present experiment was perhaps due to the concomitant occurrence of late flowering with the suitable period of fungal (blast) infection that reduces yield. Moreover, the negative correlation between plant height and grain yield might be due to lodging. Taller plants tend to lodge more than shorter ones and lose their yield. Some of the testing sites (especially Pawe and Bako) have high rainfall and high temperature, which is suitable for the development of fungal diseases like blast (*Pyricularia spp.*) that reduce yield more on the lodged plants.

Various models to measure stability of genotype performance across multi-environments are available in literature. At present, the most widely used model is AMMI, which involves both ANOVA and principal component analysis to dissect GEI into the causes of variation. However, stability per se is not necessarily a positive factor and it is desirable only when associated with a high mean yield (Yan and Hunt, 2002). In the present experiment, a white seed accession (Acc. 203572) from the mixed set and three other accessions (Acc. 229469, Acc. 203410 and Acc. 203539) from the colored set were found to be most stable based on the AMMI model and also had above average mean grain yield across environments and thus are recommended for release as cultivars to contribute for enhanced finger millet production in these environments. The response of Tadesse to the poor environments in the first set was in agreement with the previous observation during the scaling up activity in the dry lowland areas of the Ethiopian rift valley (Siraro and Alaba). However, a similar response was not observed in the other set because coefficient of joint regression (b_i) is a relative measure, which varies with the genotypes included in the set [13].

In the past decade, 2001-2010, finger millet production area in Ethiopia increased from 342,120 ha to 368,999 ha with an increase of 7.3%, and the production increased from 3,769,290 to 5,241,911 quintals with a proportion of 28% [4,14]. This was partly due to the adoption of improved varieties and production practices or possibly an indication of the fact that agriculture is being pushed to the more marginal areas due to the associated change in climate demanding adaptable crops. Thus, a continuous supply of high yielding varieties that have stable performance in a wide range of environments is needed for sustainable production. To this end, we believe that the 4 genotypes selected in this experiment will have significant contribution to enhance production in areas where there is similar agro-climatic conditions with the test environments.

In conclusion, east Africa is reported to be a region of contrasts, where Africa's lowest and highest elevations are found; the differences of which coupled with the differences in rainfall and temperature over short geographic distances provided varying environments suitable for crop diversification, early domestication and subsequent cultivation of landraces. In Ethiopia, diverse forms of finger millet landraces are found in altitude ranges of around 500 m (e.g. Chikumbo) to 2500 m (e.g. South Gondar). However, selection of high yielding and stable genotypes in nation wide multi-environments has not been successful. While finger millet can be a potential cereal for food security under the rapidly changing climate, alleviating its constraints will remain a challenging task for the researchers. In addition to the prevailing production constraints of finger millet, which are mainly related to poor management practices, some more are still emerging. For instance, in northern Ethiopia, the parasitic weed, Striga spp. is expanding its host range from maize and sorghum, its principal hosts to small cereals, tef and finger millet. Hence, exhaustive work should be done on identifying the landraces and side by side introduction and evaluation of exotic germplasm. Moreover, no agronomic recommendations such as spacing and fertilizer rate are available to date for finger millet in the country. Therefore, multidisciplinary work is binding in order to break the yield barriers and to reap the potential from these untapped genetic resources.

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