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Genotype x Environment Interactions on Seed Yield of Inter-racial Common Bean Lines in Kenya

Jean M. Mondo[1,2,*], Paul M. Kimani[1], Rama D. Narla[1]

[1]Department of Plant Science and Crop Protection, University of Nairobi, P.O. Box 29053-00625, Nairobi, Kenya
[2]Faculty of Agriculture and Environmental Sciences, Université Evangélique en Afrique (UEA), P.O. Box 3323, Bukavu, Democratic Republic of Congo
*Corresponding author: mondo.mubalama@yahoo.fr, mondo.mubalama@uea.ac.cd

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Abstract Determination of yield stability is critical in identifying new common bean cultivars with either specific or broad adaptation in target environments. This study aimed to assess genotype by environment (G x E) effects on agronomic performance of 78 $F_{1.7}$ lines selected with molecular markers for multiple disease resistance from 16 inter-racial bean populations. Field trials were conducted in low-, medium- and high altitude conditions in Kenya. Data collected on seed yield were subjected to additive main-effects and multiplicative interaction (AMMI) model to separate additive variance from the G x E interaction and to determine the stability of genotypes across locations. Results showed that G x E effects were highly significant ($P<0.001$), implying that tested lines behaved differently across the three locations. Better yields were recorded from high altitude Tigoni site while the lowest were from low altitude Mwea site. Yield across sites ranged from 1,518 to 2,748; 1,324 to 3,860; 1,537 to 3,722 and 1,010 to 3,718 kg ha^{-1} for pinto, red mottled, red kidney and mixed color bean lines, respectively. Number of pods plant^{-1} was the most strongly correlated to seed yield and could be, therefore, used as an indirect selection criterion for seed yield. The environment was responsible for the largest part of yield variability (86.4%, 84.8%, 82.3% and 49.5% for pinto, red kidney, red mottled and mixed color bean lines, respectively). KMA13-22-21 and KMA13-29-21 were the most stable high yielding lines across locations. Higher yielding lines were the most unstable across sites. Two pinto, four red kidney, 15 red mottled, and two mixed color lines did better than their corresponding checks with yield advantages of 7.6, 14.3, 71.5, and 34.9%, respectively. These lines should, therefore, be selected for further testing and release.

Keywords: *Phaseolus vulgaris, inter-racial crosses, gamete selection, market class, AMMI model*

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1. Introduction

Common bean (*Phaseolus vulgaris* L.) is the most important grain legume consumed worldwide. Six races of common bean have been distinguished based on morphological, agronomic, adaptive, and molecular characteristics [1]. Three of these races (Durango, Jalisco, and Mesoamerica) belong to the Middle American also referred to as Mesoamerican gene pool. The other three races (Chile, Nueva Granada, and Peru) belong to the Andean South American gene pool [1,2,3]. Small-seeded beans (<25 g 100-seed mass) belong to Mesoamerica race and are well adapted to relatively warmer tropical lowlands. Medium-seeded beans have a 100-seed mass of 25 to 40 g and belong to Durango race for the semi-climbers and Jalisco race for the climbers. They are as well adapted to tropical and subtropical environments [4]. Small- and medium-seeded beans often have indeterminate growth habit and out-yield their large-seeded counterparts (>40 g 100-seed mass) from Chile and Nueva Granada races by as much as 500 to 2000 kg ha^{-1} [1,5]. In addition to their high yield potential, small- and medium-seeded beans are resistant to several diseases devastating the large-seeded beans such as angular leaf spot, anthracnose, rust, bean golden yellow mosaic virus and bean common mosaic virus and possess genes and high level of resistance to drought stress [6]. However, large-seeded Andean beans are the most widely grown in Eastern Africa because they are preferred by farmers and consumers for their seed quality and often fetch higher prices [5,7]. Andean genotypes possess a narrow to moderate genetic base especially for disease resistance and yield potential and thus, threatening progress toward improvements for those traits [8]. The genetic base of common bean varieties grown in Eastern Africa needs to be broadened to enhance yield potential and resistance to diseases. Inter-racial and inter-gene pool crosses provide an important opportunity to create useful genetic variation for maximizing gains from selection, broadening the genetic base of commercial cultivars and making efficient use of available resources [4,9]. Despite of the limitations faced in developing inter-racial and inter-gene pool cultivars (notably the F_1 hybrid dwarfism, weakness, or incompatibility, problems in recovering desirable seed quality and adaption characteristics, and cripples or virus-like foliage symptoms), breeding programs across the world have succeeded through inter-racial and inter-gene crosses to develop genotypes combining desirable traits such as tolerance to production limiting factors (especially diseases, drought), seed quality and high yield potential [10].

Common bean yields in Eastern and Central Africa are among the lowest in the world (0.5 t ha^{-1}) while the potential is between 1.5 to 3 t ha^{-1} for bush beans, and up to 5 t ha^{-1} for climbing beans [11,12,13]. Diseases are among the major factors constraining bean production in the region, and therefore, the improvement of bean productivity requires effective and efficient selection for yield traits along with controlling major diseases [8,14,15]. Plant breeding is the most cost-effective and sustainable approach to cope with bean diseases since no additional investment is required from farmers. However, as several pathogens co-infect beans at the farmer level, breeding for one trait would not result in a significant change, and thus, a multiple disease resistance approach should be promoted for a more and durable impact on yield and farmers' livelihood.

In bean breeding programs, a large number of genotypes are tested for many generations within contrasting environments before release for seed multiplication and distribution to growers. Because environmental conditions for testing are distinct, the genotype by environment interaction (G x E) affects the agronomic performance, and thus, it is necessary to analyze the stability of genotypes across environments [16,17]. This allows the assessment of the real impact of selection and ensures high reliability in the genotype recommendation for a specific place or environment groups [18,19]. Another key reason for the G x E analyses in bean breeding in Africa is that lines adapted to an African bean environment (AFBE) can be grown in similar areas in other parts of Africa [20]. Due to differences among growing regions, breeding might be more effective if it was AFBE based. Therefore, we hope that lines developed through the current breeding program in the AFBE of Kenya could be adapted and disseminated in African areas with similar agro-ecological conditions.

The specific objective of this study was to assess the G x E effects on the agronomic performance of 78 advanced $F_{1.7}$ lines previously selected for multiple disease resistance using molecular markers. These lines originated from 16 small- and medium-seeded inter-racial bean populations, which were subsequently grouped in four market classes.

2. Material and Methods

2.1. Experimental Sites

This study was conducted in three different agro-ecological zones, representing major bean growing environments in Kenya. Experiments were conducted during 2017 short rain season at KALRO (Kenya Agricultural and Livestock Research Organization)-Mwea representing low altitude conditions, Kabete Field Station of the University of Nairobi, the medium altitude, and KALRO-Tigoni for the high altitude environments. KALRO-Mwea is located on coordinates 0°38'S (latitude); 37°22'E (longitude) and at approximately 1150 masl. This research station receives mean precipitation of 850 mm per year with a bimodal distribution. The long rain season starts in March and ends in May. The short rain season usually starts in October to end in late December. Mean annual temperatures range from 15.6°C to 28.6°C. Soils at this station are vertisols with an acidic pH of about 5.1 [21]. KALRO-Tigoni is located at coordinates 01°08'S; 036°40'E and at approximately 2130 masl. It receives bimodal rainfall of 1100 mm per year. Temperatures range from 12°C to 24°C. Soils at Tigoni are humic nitisols with soil pH of approximately 4.6 [22]. Kabete Field Station is located at 01°15'S; 036°44'E and 1820 masl. The station experiences mean bimodal precipitation of 1059 mm per year. Mean monthly temperatures range between 12.3°C and 22.5°C [23]. Soils are humic nitisols, very deep, well-drained, friable clay with acid humic topsoil, and dark reddish brown in color. The pH is about 5.0 to 5.4 and a mean sunshine of 6.6 hours per day. Following Wortmann and Allen (1994) classification, Kabete and Tigoni are located in the African Bean Environment I (AFBE 1) while Mwea is in the AFBE 8.

2.2. Plant Materials

Study materials were 78 lines including 73 $F_{1.7}$ bean lines selected from 16 inter-racial populations, and five check varieties (Mex54, AND1062, BRB191, GLP92, and KATB1). The 73 $F_{1.7}$ lines were grouped in four market classes on the basis of their seed color, shape and size. The 73 $F_{1.7}$ bean lines comprised of, 14 red kidney, 16 red mottled, 12 pinto and 31 mixed color bean lines. The four market classes were evaluated in separate trials and compared with appropriate checks selected among parental genotypes. In these trials, AND1062 and Mex54 were used as checks for red kidney, BRB191 for red mottled, GLP92 for pinto, and KATB1 for mixed color lines. These plant materials were developed following the gamete selection procedure as summarized in Table 1.

2.3. Experimental Design and Crop Management

A simple lattice experimental design with four replicates was used for each market class depending on the number of tested lines; a 4 x 4 lattice design for red kidney, red mottled and pinto and a 6 x 6 lattice for mixed color market class. A plot consisted of three 4m rows. Seed rate was 10 seeds m^{-1} spaced by 0.2 m within rows and 0.5 m between rows. Two guard rows were erected to avoid competition and interference between genotypes. All the field experiments were planted in October 2017 during the short rain season. Diammonium phosphate (DAP) at a rate of 80 kg ha^{-1} was applied at planting. Weeding at all sites were carried out three times: two weeks after seedling emergence, before flowering and after podding. The pesticide Confidor (200 g l^{-1} Imidacloprid) was used to control whiteflies and leafminers.

Table 1. Breeding scheme for the development of bean lines evaluated in three agro-ecological conditions in Kenya

Year	Generations	Achievements
Before 2009	Parents	Donor parents were selected for their resistance genes; Mex54 and G10909 for angular leaf spot; G2333 for anthracnose; AND1062 and RWR719 for *Pythium* root rot and BRB191 for bean common mosaic virus.
2009 – 2010	Single crosses	Single crosses were developed between genotypes carrying resistance genes to angular leaf spot and anthracnose (Mex54/G2333, G10909/G2333), and between *Pythium* root rot and bean common mosaic virus (AND1062/BRB191, RWR719/BRB191).
2010 – 2011	Double crosses	Four double cross males were produced by combining two single crosses: (Mex54/G2333) and (AND1062/BRB191); (Mex54/G2333) and (RWR719/BRB191); (G10909/G2333) and (AND1062/BRB191) and (G10909/G2333) and (RWR719/BRB191).
2010 – 2011	Identification of male gametes for the final cross	Male gametes were screened for desirable resistance genes with molecular markers i.e. SH-13 for angular leaf spot, SAB-3 for anthracnose, PYAA-19 for *Pythium* root rot and SW-13 for bean common mosaic virus. Selected single plants were utilized for the production of final multiple-parent crosses with commercial varieties (GLP585, GLP92, KATB1 and KATB9) using plant-to-plant paired hybridization.
2011 – 2012	$F_{1.1}$	Evaluation of the final $F_{1.1}$ for successful introgression of resistance genes in the field at Kabete against target pathogens and for agronomic traits. As the $F_{1.1}$ was segregating, markers were used for the second time to select specific desirable combinations.
2012 – 2013	$F_{1.2}$	Early generation testing in replicated yield trials at Kabete and Tigoni. Identifying high yielding populations and discarding undesirable populations.
2013 – 2016	$F_{1.3} – F_{1.6}$	Line development from segregating populations and switching from heterozygous and heterogeneous populations to pure lines in trials conducted at Kabete and Mwea. Selection for yield potential and separation into distinct market classes. Single plant selection was performed at $F_{1.6}$ and the seed was increased at Mwea Research Station in 2016.
2017 – 2018	$F_{1.7}$	Yield stability analysis of elite lines across three agro-ecological environments. These were Mwea (low altitude), Tigoni (high altitude) and Kabete (medium altitude). Four market classes were evaluated.

2.4. Data Collection and Analysis

Data were collected on seedling emergence rate, plant vigor, days to flowering, growth habit, days to maturity, number of pods per plant, number of seeds per pod, 100-seed mass, grain yield, and harvest index using the standard system for the evaluation of bean germplasm as described by [24]. Statistical analyses were performed using GenStat 17th edition [25] and Statistix 8.0 version [26]. Combined analysis of variance (ANOVA) was conducted to determine the magnitude of variation associated with each source (environment, genotype and their interaction). Fisher's least significant difference (LSD) test was used for separation of means at 5% probability level. ANOVA is an additive model in which the G x E interaction is a source of variation, but its intrinsic effects are not analyzed. The additive main effect and multiplicative interaction (AMMI) model was, therefore, necessary to separate the additive variance from the G x E interaction [27,28]. In fact, AMMI uses ANOVA to test the main effects of genotypes and environments, and principal component analysis (PCA) to analyze the residual multiplicative interaction between genotypes and environments to determine the sum of squares of the G × E interaction, with a minimum number of degrees of freedom [29]. The AMMI model used was:

$$y_{ger} = \mu + \alpha_g + \beta_e + \Sigma\lambda_n y_{gn}\delta_{en} + \rho_{ge} + \varepsilon_{ger} \quad (1)$$

Where: Y_{ger} is the yield of genotype g in the environment e for replicate r; μ is the grand mean; αg is the genotype mean deviations; β_e is the environment mean deviation; n is the number of PCA axes retained in the model, λ_n is singular value for PCA axis n; y_{gn} is the genotype eigenvector values for PCA axis n; δ_{en} is the environment eigenvector values for PCA axis n; ρ_{ge} represents the residuals and ε_{ger} is for error.

AMMI analysis was also used to determine the stability of the genotypes across locations using the PCA scores (IPCA1 and IPCA2). The IPCA score near zero reveals more stable genotypes, while large values indicate more responsive and less stable genotypes. AMMI stability value for the grain yield was estimated as shown as follows [30]:

$$ASV = \sqrt{\left[\frac{SS\ IPCA1}{SS\ IPCA2}(IPCA1Score)\right]^2 + (IPCA2Score)^2} \quad (2)$$

Where: ASV is the AMMI stability value, SS IPCA 1 and SS IPCA 2 are the sum of squares of IPCA 1 and 2, respectively and IPCA is the interaction principal component analysis. Thus, lowest ASV indicates a wide adaptation of specific genotypes for certain environments and vice-versa.

Genotype main effect plus genotype by environment interaction (GGE) biplots were subsequently constructed to determine adaptation and stability of genotypes across test environments. From this analysis, genotypes located near the biplot origin were considered as widely adapted, while genotypes located far were specifically adapted. All the genotypes with positive IPCA1 scores responded positively to the environment having positive IPCA1 scores, and were, therefore, adapted to that particular environment [31,32].

3. Results

3.1. ANOVA of Main Effects and Multiplicative Interaction (AMMI)

Analysis of the main effects and multiplicative interaction (AMMI) for inter-racial bean lines showed that the effects on seed yield due to genotypes (G), environments (E) and interactions between genotypes and environments (G x E) were significant (*P<0.01*) regardless of the market class. Treatments (G, E, and G x E) contributed up to 83.7% to the total variability for pinto, 90.8% for red kidney, 91.3% for red mottled, and 93.3% for mixed color bean lines. When partitioning the treatment variability, the environment contributed most to the variance (86.4% for pinto, 84.8% for red kidney, 82.3% for the red mottled, and 49.5% for mixed color lines). The variability due to interaction between genotypes and environments was high for mixed color bean lines (26.7%). This high contribution of variability due to the interaction between genotypes and environments suggests that test lines were not stable and thus responded differently across locations and should, therefore, be selected and recommended to specific environments. IPCA1 contributed the most to the G x E effects accounting for more than 80% of the variability regardless of the market class, suggesting a high contribution of the genotypes in the interaction (Table 2, Table 3, Table 4, and Table 5).

Table 2. Summary of ANOVA for Additive Main effects and Multiplicative Interaction (AMMI) for seed yield (kg ha^{-1}) of pinto bean lines grown at three locations in Kenya

Source of variation	df	MS	% CTV	% CGxE
Total	155	3642323		
Treatments (G, E, G x E)	38	12429868***	83.7	
Genotypes (G)	12	1972916**	5.0	
Environments (E)	2	204067922***	86.4	
Interactions (G x E)	24	1688507**	8.6	
IPCA1	13	2998943***	6.9	96.2
IPCA2	11	139810^{ns}	0.3	3.8
Replications	9	578563^{ns}	0.9	
Error	108	805722		

Table 3. Summary of ANOVA for Additive Main effects and Multiplicative Interaction (AMMI) for seed yield (kg ha^{-1}) of red kidney bean lines grown at three locations in Kenya

Source of variation	df	MS	% CTV	% CGxE
Total	179	3666741		
Treatments (G, E, G x E)	44	13545634***	90.8	
Genotypes (G)	14	3637379***	8.5	
Environments (E)	2	252676724***	84.8	
Interactions (G x E)	28	1418969***	6.7	
IPCA1	15	2111182***	4.8	79.7
IPCA2	13	620262^{ns}	1.2	20.3
Replications	9	680006^{ns}	0.9	
Error	124	437248		

Table 4. Summary of ANOVA for Additive Main effects and Multiplicative Interaction (AMMI) for seed yield (kg ha^{-1}) of red mottled bean lines grown at three locations in Kenya

Source of variation	df	MS	% CTV	% CGxE
Total	203	4322943		
Treatments (G, E, G x E)	50	16018795***	91.3	
Genotypes (G)	16	4554833***	9.1	
Environments (E)	2	329566654***	82.3	
Interactions (G x E)	31	2223519***	8.6	
IPCA1	17	3426531***	6.6	84.5
IPCA2	15	711872^{ns}	1.2	15.5
Replications	9	865981^{ns}	0.9	
Error	139	495136		

Table 5. Summary of ANOVA for Additive Main effects and Multiplicative Interaction (AMMI) for seed yield (kg ha^{-1}) of mixed color bean lines grown at three locations in Kenya

Source of variation	df	MS	% CTV	% CGxE
Total	395	1194115		
Treatments (G, E, G x E)	98	4486728***	93.2	
Genotypes (G)	32	3260277***	23.7	
Environments (E)	2	108945864***	49.5	
Interactions (G x E)	64	1835605***	26.7	
IPCA1	33	2952261***	20.6	82.9
IPCA2	31	646908***	4.2	17.1
Replications	9	383306^{ns}	0.7	
Error	288	99050		

^{ns}, *, ** and *** = no significant, significant, highly significant and very highly significant at P-value tresholds of P>0.05, <0.05, <0.01 and <0.001, respectively; d.f. = degree of freedom; IPCA1 and IPCA2 = interaction principal component one and two, respectively; MS = mean squares; % CTV = percent of contribution to the total variation; % CGxE = percent of the contribution to the G x E interaction.

3.2. Stability Analysis

3.2.1. Pinto Bean Lines

The AMMI model showed that the highest seed yields of pinto bean lines across sites were recorded at Tigoni in the high altitude (4,347 kg ha^{-1}), followed by Kabete in medium altitude (1,388 kg ha^{-1}) whereas the lowest yields were from Mwea located in the low altitude (585.6 kg ha^{-1}) (Table 6). Across sites, the genotypes KMA13-22-21 (P5) and KMA13-22-30 (P6) were the best yielding with 2,748 kg ha^{-1} and 2,726 kg ha^{-1}, respectively, but not significantly different from the check variety GLP92 which yielded 2,543 kg ha^{-1}. All the other lines were either statistically equal or inferior to the check variety.

The AMMI stability value (ASV) of pinto bean lines showed that the check variety GLP92 was the most stable across sites (ASV=3.5). Among advanced lines, KMA13-24-6 (P11) and KMA13-21-10 (P1) were the most stable genotypes across sites with ASV of 15.6 and 45.8, respectively. KMA13-22-30 (P6) was the least stable across sites (ASV=816.7). The first four AMMI selections per environment were KMA13-21-10 (P1), GLP92, KMA13-21-19 (P2) and KMA13-22-21 (P5) for low altitudes; GLP92, KMA13-22-21 (P5), KMA13-23-18 (P9) and KMA13-23-13 (P8) for medium altitudes and KMA13-22-30 (P6), KMA13-22-21 (P5), KMA13-23-22 (P10) and KMA13-24-7 (P12) for high altitudes (Table 6).

3.2.2. Red Kidney Bean Lines

For the red kidney bean lines (Table 7), the highest seed yields across sites were recorded at Tigoni (4,642 kg ha^{-1}), much higher than Kabete (1,238 kg ha^{-1}) and Mwea (954 kg ha^{-1}). Mex54 with a mean of 3,722 kg ha^{-1} out-yielded all the advanced bean lines and the other check variety AND1062 which yielded 2,266 kg ha^{-1}. The best genotype among the advanced red kidney bean lines was KMA13-30-22 (RK13) with a seed yield of 3,226 kg ha^{-1} which was higher than all test lines and one of the check varieties, AND1062. It was not, however, significantly different from the best check variety (Mex54). Most of the red kidney bean lines were bush (Type I and II). This could explain why the cultivar Mex54 which is Type III growth habit (i.e semi-climber) had a significantly higher yield than most of the red kidney bean lines.

Table 6. Seed yield (kg ha^{-1}), ranking (in parenthesis), IPCA scores and AMMI stability values (ASV) of advanced pinto bean lines grown at three locations in Kenya.

Code	Genotype	Environments			Genotype Mean	IPCAg[1] score	IPCAg[2] score	ASV
		Kabete	Mwea	Tigoni				
P1	KMA13-21-10	1,417	982	4,456	2,285 (5)	1.8	10.2	45.8
P2	KMA13-21-19	1,182	891	2,481	1,518 (13)	28.3	11.0	717.7
P3	KMA13-22-3	1,428	297	3,414	1,713 (11)	11.6	-10.8	293.5
P4	KMA13-22-7	1,160	451	3,275	1,629 (12)	13.1	1.0	331.1
P5	KMA13-22-21	1,814	609	5,820	2,748 (1)	-18.5	-9.1	469.1
P6	KMA13-22-30	1,307	435	6,436	2,726 (2)	-32.2	2.1	816.7
P7	KMA13-22-33	1,423	453	3,451	1,776 (10)	12.2	-6.3	310.5
P8	KMA13-23-13	1,450	514	4,129	2,031 (7)	3.0	-4.2	76.5
P9	KMA13-23-18	1,504	513	3,724	1,914 (9)	9.3	-6.5	235.4
P10	KMA13-23-22	1,261	593	5,226	2,360 (4)	-13.6	5.5	344.9
P11	KMA13-24-6	1,224	528	4,283	2,012 (8)	-0.6	3.1	15.6
P12	KMA13-24-7	1,006	370	5,031	2,136 (6)	-14.2	6.5	360.7
P13*	GLP92^{M}	1,868	976	4,785	2,543 (3)	-0.1	-2.5	3.5
	E Mean	1,388 (2)	586 (3)	4,347 (1)	2,107			
	IPCAe[1]	20.6	-18.1	-45.5				
	IPCAe[2]	25.0	17.0	1.1				
	ASV	521.7	633.6	1,154.7				
	$LSD_{0.05}$				722.2			

IPCA 1 and IPCA 2 = interaction principal component one and two, respectively; ASV= AMMI stability value; e=E=environment; g=genotype; P=pinto; *=check variety, M=Mesoamerican gene pool; $LSD_{0.05}$=least significant difference at 5% P-value treshold.

Table 7. Seed yield (kg ha^{-1}), ranking (in parenthesis), IPCA scores and AMMI stability values (ASV) of red kidney bean lines grown at three locations in Kenya

Code	Genotype	Environments			Genotype Mean	IPCAg[1] score	IPCAg[2] score	ASV
		Kabete	Mwea	Tigoni				
RK1	KMA13-17-25	1,403	795	4,144	2,114 (10)	8.5	3.5	33.5
RK2	KMA13-19-12	1,020	477	3,112	1,537 (15)	18.5	-1.0	72.7
RK3	KMA13-19-16	1,248	903	4,616	2,256 (7)	0.3	1.1	1.5
RK4	KMA13-20-3	806	700	4,343	1,950 (12)	-1.2	-3.0	5.6
RK5	KMA13-21-11	2,303	750	4,289	2,448 (3)	15.5	19.4	64
RK6	KMA13-25-3	553	1,079	3,827	1,819 (13)	5.6	-17.4	28.1
RK7	KMA13-25-20	1,120	885	4,514	2,173 (8)	0.4	-1.0	1.8
RK8	KMA13-26-32	1,350	1,156	4,603	2,370 (4)	2.7	-2.6	10.8
RK9	KMA13-27-31	1,120	1,114	4,173	2,136 (9)	6.5	-7.4	26.7
RK10	KMA13-28-2	1,193	883	4,878	2,318 (5)	-4.3	1.9	17.1
RK11	KMA13-29-28	727	690	3,948	1,788 (14)	3.9	-6.0	16.3
RK12	KMA13-29-30	1,226	703	4,208	2,046 (11)	5.2	2.9	20.8
RK13	KMA13-30-22	1,595	942	7,140	3,226 (2)	-33.8	18	133.9
RK14*	AND1062^{A}	1,429	763	4,605	2,266 (6)	1.7	6.8	9.5
RK15*	Mex54^{M}	1,469	2,473	7,226	3,722 (1)	-29.5	-15.3	116.8
	E Mean	1,238 (2)	954 (3)	4,642 (1)	2,278			
	IPCAe[1]	29.5	12.7	-42.2				
	IPCAe[2]	22.5	-29.4	6.9				
	ASV	22.5	29.4	6.9				
	$LSD_{0.05}$				543.2			

IPCA 1 and IPCA 2 = interaction principal component one and two, respectively; ASV= AMMI stability value; e=E=environment; g=genotype; RK=red kidney; *=check variety; A=Andean gene pool; M=Mesoamerican gene pool; $LSD_{0.05}$=least significant difference at 5% P-value treshold.

KMA13-19-16 (RK3), KMA13-25-20 (RK7), KMA13-20-3 (RK4) and AND1062 were the most stable genotypes across sites with ASV of 1.5, 1.8, 5.6 and 9.5, respectively. The high yielding genotypes KMA13-30-22 (RK13) and Mex54 were the least stable across sites. The first four AMMI selections per environment were KMA13-21-11 (RK5), KMA13-30-22 (RK13), Mex54, and AND1062 for medium altitude areas such as Kabete; Mex54, KMA13-26-32 (RK8), KMA13-27-31 (RK9), KMA13-25-3 (RK6) for low altitude agro-ecological zones such as Mwea, and Mex54, KMA13-30-22 (RK13), KMA13-28-2 (RK10), and KMA13-19-16 (RK3) for high altitude zones such as Tigoni.

3.2.3. Red Mottled Bean Lines

Across environments, the highest yields for the red mottled lines were recorded from Tigoni (4,703 kg ha^{-1}), followed by Kabete (1,358 kg ha^{-1}). The lowest means were from Mwea (551 kg ha^{-1}). KMA13-29-21 (RM13) with a mean seed yield of 3,860 kg ha^{-1} out-yielded all the advanced red mottled lines and the check variety BRB191 which recorded a mean yield of 1,352 kg ha^{-1}. Among the red mottled bean lines, only KMA13-24-11 (RM6) yielded lower than the check variety but the difference was not significant (1,324.0 kg ha^{-1}) (Table 8).

Table 8. Seed yield (kg ha^{-1}), ranking (in parenthesis), IPCA scores and AMMI stability values (ASV) of red mottled bean lines grown at three locations in Kenya

Code	Genotype	Environments			Genotype	IPCAg[1]	IPCAg[2]	ASV
		Kabete	Mwea	Tigoni	Mean	Score	score	
RM1	KMA13-17-25	1,584	257	4,274	2,038 (11)	4.8	9.6	27.8
RM2	KMA13-20-3	1,239	650	3,444	1,777 (13)	16.6	-2.0	90.8
RM3	KMA13-20-14	1,038	151	4,417	1,869 (12)	-1.0	1.3	5.8
RM4*	BRB191^{A}	1,178	264	2,613	1,352 (16)	24.4	4.5	133.1
RM5	KMA13-24-5	1,551	487	5,938	2,659 (2)	-15.6	2.8	85.3
RM6	KMA13-24-11	687	594	2,691	1,324 (17)	23.0	-10.0	125.6
RM7	KMA13-24-16	1,494	350	4,637	2,160 (9)	0.2	5.9	6.0
RM8	KMA13-24-17	1,082	609	6,123	2,605 (4)	-19.9	-8.0	108.8
RM9	KMA13-22-25	1,192	292	3,429	1,638 (14)	13.9	3.1	76.0
RM10	KMA13-27-25	645	991	5,297	2,311 (8)	-8.7	-21.2	51.9
RM11	KMA13-28-3	872	492	5,739	2,368 (7)	-16.9	-9.3	92.7
RM12	KMA13-28-13	1,229	246	3,399	1,624 (15)	14.2	4.6	77.6
RM13	KMA13-29-21	3,012	939	7,630	3,860 (1)	-26.1	19.4	144.0
RM14	KMA13-29-24	1,288	792	5,839	2,640 (3)	-13.6	-6.9	74.5
RM15	KMA13-32-24	1,600	671	4,123	2,131 (10)	9.9	3.2	54.3
RM16	KMA13-32-28	1,423	1,237	5,092	2,584 (5)	0.3	-10.9	11.0
RM17	KMA13-17-17	1,968	342	5,264	2,525 (6)	-5.4	13.8	32.6
	E Mean	1,358 (3)	551 (2)	4,703 (1)	2,204			
	IPCAe[1]	22.1	28.2	-50.3				
	IPCAe[2]	29.7	27.3	-2.3				
	ASV	124.2	156.2	274.4				
	LSD$_{0.05}$				583.8			

IPCA 1 and IPCA 2 = interaction principal component one and two, respectively; ASV= AMMI stability value; e=E=environment; g=genotype; RM=red mottled; *=check variety; A=Andean gene pool; LSD$_{0.05}$=least significant difference at 5% P-value treshold.

Table 9. Seed yield (kg ha^{-1}), ranking (in parenthesis), IPCA scores and AMMI stability values (ASV) of mixed color bean lines grown at three locations in Kenya

Code	Genotype	Environments			Genotype	IPCAg[1]	IPCAg[2]	ASV
		Kabete	Mwea	Tigoni	Mean	Score	score	
MC1	KMA13-21-23^{TR}	1,297	730	1,761	1,263 (29)	6.7	6.2	33.3
MC2	KMA13-22-16^{TR}	1,125	767	2,580	1,491 (21)	-3.3	11.1	19.4
MC3	KMA13-22-321^{TR}	1,912	736	2,186	1,611 (17)	4.7	-2.6	22.9
MC4	KMA13-23-9^{TR}	1,976	1,356	2,432	1,921 (8)	6.4	5.5	31.8
MC5	KMA13-23-20^{TR}	2,265	895	2,890	2,017 (5)	-0.7	-4.6	5.7
MC6	KMA13-24-10^{TR}	1,912	450	1,948	1,437 (22)	5.5	-7.1	27.4
MC7	KMA13-25-1^{TR}	2,077	1,087	2,141	1,769 (12)	8.4	-0.5	40.9
MC8	KMA13-27-13^{TR}	1,205	444	2,448	1,366 (25)	-3.6	5.1	18.2
MC9	KMA13-27-14^{TR}	1,385	838	2,965	1,729 (14)	-6.0	8.7	30.5
MC10	KMA13-27-27^{TR}	1,910	1,104	5,521	2,845 (2)	-31.3	9.2	152.2
MC11	KMA13-28-5^{TR}	2,046	1,812	1,983	1,947 (7)	15.1	9.8	74.1
MC12	KMA13-28-13^{TR}	2,467	838	2,301	1,869 (9)	6.6	-9.8	33.7
MC13	KMA13-29-21^{TR}	1,251	710	2,110	1,357 (27)	2.3	7.4	13.5
MC14	KMA13-31-61^{TB}	1,783	491	1,978	1,417 (23)	4.8	-4.4	23.7
MC15	KMA13-22-322^{TB}	1,451	928	2,481	1,620 (16)	0.5	7.9	8.3
MC16	KMA13-29-19^{TB}	1,483	902	2,967	1,784 (11)	-5.1	8.0	26.2
MC17	KMA13-30-7^{TB}	1,663	518	1,894	1,358 (26)	5.4	-2.3	26.4
MC18	KMA13-31-62^{TB}	1,435	1,626	2,906	1,989 (6)	0.4	18.7	18.8
MC19	KMA13-32-22^{TB}	1,306	507	1,408	1,074 (32)	9.3	2.3	45.2
MC20	KMA13-32-24^{BL}	1,431	52	2,184	1,222 (30)	-2.2	-4.5	11.8
MC21	KMA13-22-23^{BL}	1,268	611	3,647	1,842 (10)	-16.0	8.8	78.2
MC22	KMA13-23-10^{BL}	1,580	912	2,406	1,633 (15)	1.8	5.5	10.5
MC23	KMA13-23-11^{BL}	1,990	287	1,720	1,332 (28)	7.3	-11.0	37.2
MC24	KMA13-25-4^{BL}	1,965	784	2,009	1,586 (19)	7.3	-3.1	35.7
MC25	KMA13-27-101^{BL}	1,405	640	2,069	1,371 (24)	3.0	3.9	15.3
MC26	KMA13-27-102^{BL}	2,142	871	2,173	1,729 (13)	6.8	-4.4	33.5
MC27	KMA13-27-12^{BL}	2,491	481	3,160	2,044 (4)	-5.6	-13.4	30.5
MC28	KMA13-28-21^{BL}	3,086	657	7,412	3,718 (1)	-50.8	-11.9	247
MC29	KMA13-28-22^{BL}	2,302	248	2,121	1,557 (20)	3.9	-15.7	24.4
MC30	KMA13-28-29^{BL}	2,202	613	2,000	1,605 (18)	7.3	-9.3	36.8
MC31	KMA13-27-1^{GG}	1,350	416	1,264	1,010 (33)	10.5	0.0	51.2
MC32	KMA13-21-20^{GG}	2,610	1,027	3,348	2,329 (3)	-3.5	-7.3	18.5
MC33*	KATB1^{M}	1,547	137	1,748	1,144 (31)	3.9	-6.0	19.9
	E Mean	1,797 (2)	742 (3)	2,550 (1)	1,696			
	IPCAe[1]	22.7	34.2	-57.0				
	IPCAe[2]	-35.5	31.0	4.5				
	ASV	115.9	169.0	276.9				
	LSD$_{0.05}$				255.3			

IPCA 1 and IPCA 2 = interaction principal component one and two, respectively; ASV= AMMI stability value; e=E=environment; g=genotype; MC=mixed color; *=check variety; M=Mesoamerican gene pool; TR=tan red; TB=tan brown; BL=black; GG=greyish green; LSD$_{0.05}$=least significant difference at 5% P-value treshold.

KMA13-20-14 (RM3) and KMA13-24-16 (RM3) were the most stable genotypes across environments with ASV scores of 5.8 and 6.0, respectively. However, the best yielding line, KMA13-29-21 (RM13), was also the least stable across environments. The first four AMMI selections per environment were KMA13-24-11 (RM16), KMA13-27-25 (RM10), KMA13-29-21 (RM13) and KMA13-29-24 (RM14) for the low altitude agro-ecological zones; KMA13-29-21 (RM13), KMA13-17-17 (RM17), KMA13-32-24 (RM15), KMA13-17-25 (RM1) for the medium altitudes and KMA13-29-21 (RM13), KMA13-24-17 (RM8), KMA13-24-5 (RM5) and KMA13-29-24 (RM14) for the high altitudes (Table 8).

3.2.4. Mixed Color Bean Lines

The best yields for mixed color bean lines were obtained from Tigoni (2,550 kg ha^{-1}), followed by Kabete (1,797 kg ha^{-1}). Mwea with a mean grain yield of only 742 kg ha^{-1} was the least productive site. Among test lines, KMA13-28-21 (MC28), a black-seeded line out-yielded all the other lines and the check varieties with a mean seed yield of 3,718 kg ha^{-1}. The other high performing lines included KMA13-27-27 (MC10) with a yield of 2,845 kg ha^{-1}, KMA13-21-20 (MC32) (2,329 kg ha^{-1}), KMA13-27-12 (MC27) (2,044 kg ha^{-1}) and KMA13-23-20 (MC5) (2,017 kg ha^{-1}). The lowest yielding line was KMA13-27-1 (MC31). This line characterized by greyish green seeds had a mean yield of 1,010 kg ha^{-1}, which was lower than the greyish green-seeded check variety KATB1 which yielded 1,144 kg ha^{-1}.

The most stable lines across sites were KMA13-23-20 (MC5) (ASV score of 5.7) and KMA13-22-322 (MC15) (ASV score of 8.3). KMA13-27-27 (MC10) (ASV score of 152.2) was the least stable across environments. The first four AMMI selections per environment were KMA13-28-5 (MC11), KMA13-31-62 (MC18), KMA13-23-9 (MC4) and KMA13-27-27 (MC10) for low altitudes; KMA13-28-21 (MC28), KMA13-21-20 (MC32), KMA13-27-12 (MC27), KMA13-28-13 (MC12) for medium altitudes, and KMA13-28-21 (MC28), KMA13-27-27 (MC10), KMA13-22-23 (MC21) and KMA13-21-20 (MC32) for high altitude bean growing environments (Table 9).

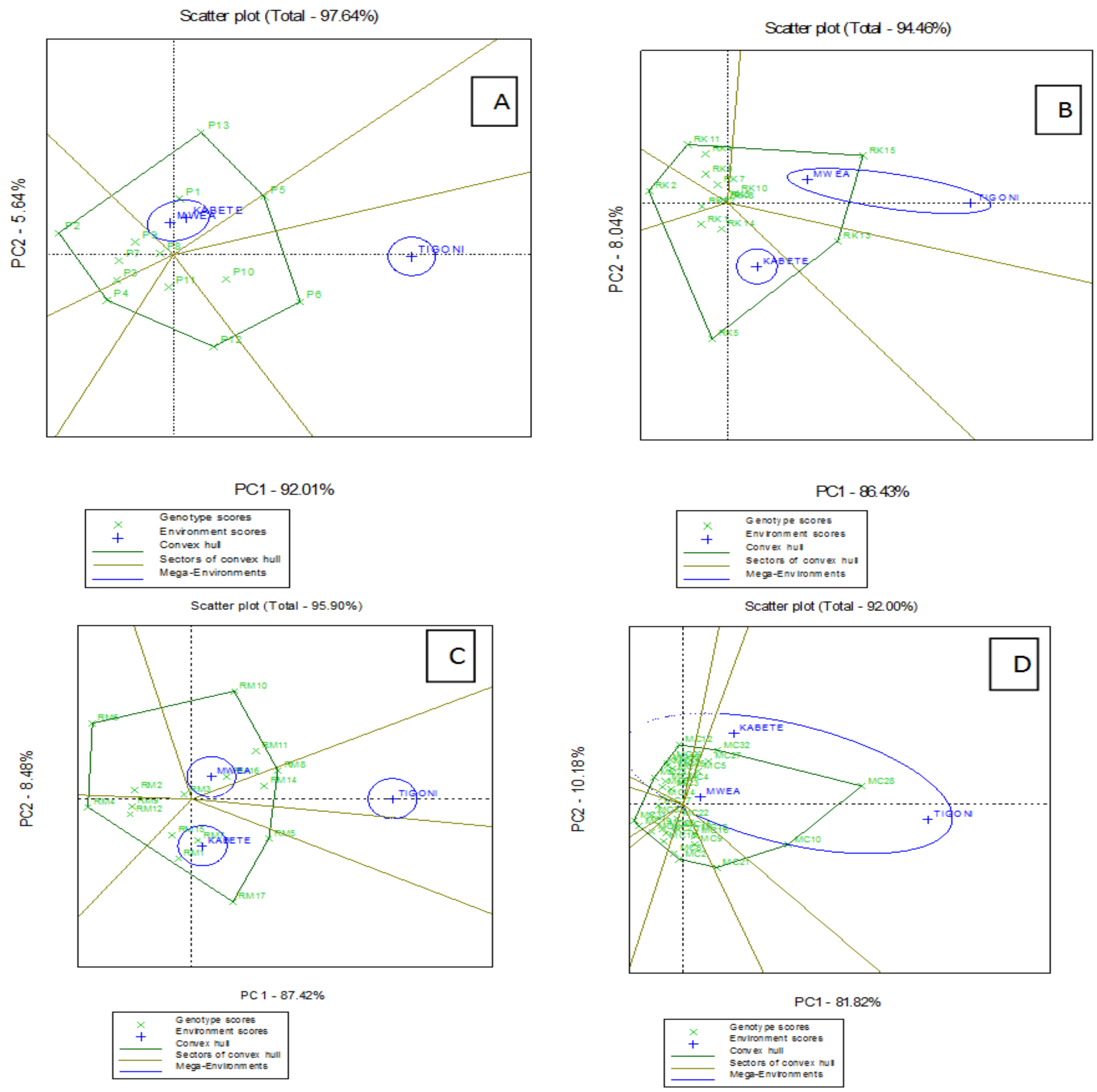

Figure 1. Polygon view of GGE biplots for best pinto (A), red kidney (B), red mottled (C), and mixed color (D) bean genotypes for seed yield across three environments in Kenya

3.3. GGE Biplots for G x E Analysis "Which Won Where" of the Inter-racial Bean Lines across Three Locations in Kenya

Most of the variability was explained by the 2 PCs regardless of the market class (97.6%, 94.5%, 95.9%, and 92% for pinto, red kidney, red mottled and mixed color bean lines, respectively). PC1 contributed the most to that variability (92%, 86.4%, 87.4%, and 81.8% for pinto, red kidney, red mottled and mixed color genotypes, respectively). Tigoni, the high altitude site, was the best environment for most of the genotypes regardless of the market class. The variability across environment was high for the red mottled genotypes for which there are three distinct mega-environments; genotypes having performed differently in each site. The variability across environments was low for mixed color genotypes for which there is only one mega-environment suggesting that better yielding genotypes in one site were the better in the other two environments. From graphs, pinto bean lines KMA13-22-21 (P5) and GLP92 (P13) performed best at Kabete and Mwea while KMA13-22-30 (P6) was best for Tigoni. Among red kidney lines, Mex54 (RK15) was best for Mwea while KMA13-21-11 (RK5) and KMA13-30-22 (RK13) did better at Kabete. Red mottled bean lines KMA13-17-17 (RM17) and KMA13-24-5 (RM5) were suited for Kabete and KMA13-24-17 (RM8) for Mwea. KMA13-27-27 (MC10) and KMA13-28-21 (MC28) were the best mixed color bean lines for Mwea and Tigoni whereas KMA13-21-20 (MC32) and KMA13-27-12 (MC27) won at Kabete (Figure 1). From the GGE biplots, Tigoni was the most discriminative as it was far from the origin of the biplot graph regardless of the market classes. All genotypes inside the polygon, mainly those located close to the plot origin were less responsive than the vertex genotypes and not the best in any environment.

3.4. Pearson's Correlation Coefficients among Yield and Yield Components of Inter-racial Bean Lines Grown in Three Locations in Kenya

Table 10, Table 11, Table 12, and Table 13 present the Pearson's correlation coefficients among seed yield and yield-related parameters for pinto, red kidney, red mottled and mixed color bean market classes, respectively. Regardless of the market class, seed yield was positively correlated with days to flowering, days to maturity, number of pods per plant, number of seeds per pod, 100-seed mass and harvest index ($P<0.05$). It was, however, negatively correlated with seedling emergence rate and plant vigor (except the mixed color market class). This would imply that the higher the number of pods per plant and the higher the number of seeds per pod, the higher the yield was. Better yielding plants were late to reach the 50% flowering stage as they contained a large number of flowers which appeared progressively. This had also an impact on the days to maturity which was delayed compared to plant developing fewer flowers and fewer pods. As the plant vigor score varies from 1 to 9 [24] from which 1 is the best score and 9 the worst, the more a plant was vigorous, the more it could carry more flowers and more pods and consequently, the more the yield was higher. The negative correlation observed in this study between seed yield and seedling emergence rate could be largely due to extrapolation as the yield ha^{-1} was estimated on the single plant basis. If the yield per m^2 (or per plot) was considered in extrapolation regardless of the number of plants, the relationship may change. Regardless of the market class, the number of pods per plant was the most highly correlated with the seed yield, suggesting its usefulness as an indirect selection criterion for seed yield.

Looking at the correlation between growth habit and yield and yield components such as number of pods per plant, it has been observed heterogeneity among market classes. There were negative but not significant correlations between the growth habit and the seed yield ($r=-0.05^{ns}$) and between the growth habit and the number of pods per plant ($r=-0.06^{ns}$) for the pinto bean lines. However, the trend was different for other market classes for which the growth habit was positively correlated with seed yield and number of pods per plant. The growth habit was positively but not significantly correlated with seed yield ($r= 0.04^{ns}$) for red mottled market class. However, the correlation between the growth habit and number of pods per plant on red mottled market class was positive and significant (r=0.14*). The trend was the same on red kidney bean lines for which the correlations were significant and positive between the growth habit and the seed yield (r=0.20*) and between the growth habit and the number of pods per plant (r=0.24**). This study reflected the general assumption that yield increases with growth habit such that Type IVs (climbers) are the best yielding.

Table 10. Pearson's correlation coefficients among seed yield and yield components of pinto bean lines grown at three locations in Kenya

Parameters	SER	DTF	DTM	GH	PP	SP	PV	100SW	HI
DTF	-0.48***								
DTM	-0.56***	0.68***							
GH	0.15^{ns}	-0.08^{ns}	0.00^{ns}						
PP	-0.46***	0.81***	0.56***	-0.06^{ns}					
SP	-0.24**	0.52***	0.19*	-0.00^{ns}	0.58***				
PV	0.21**	-0.76***	-0.52***	-0.10^{ns}	-0.69***	-0.49***			
100SW	-0.41***	0.70***	0.74***	-0.05^{ns}	0.64***	0.26**	-0.57***		
HI	-0.16*	0.60***	0.13^{ns}	-0.16^{ns}	0.68***	0.61***	-0.58***	0.27**	
SY	-0.52***	0.79***	0.65***	-0.05ns	0.91***	0.58***	-0.68***	0.69***	0.64***

Table 11. Pearson's correlation coefficients among seed yield and yield components for red kidney bean lines grown at three locations in Kenya

Parameters	SER	DTF	DTM	GH	PV	PP	SP	100SW	HI
DTF	-0.39***								
DTM	-0.31***	0.90***							
GH	0.10^{ns}	0.01^{ns}	0.09^{ns}						
PV	0.21**	-0.69***	-0.70***	-0.04^{ns}					
PP	-0.43***	0.68***	0.70***	0.24**	-0.59***				
SP	-0.18*	0.16*	0.25**	0.16*	-0.29**	0.45***			
100SW	-0.07^{ns}	0.40***	0.43***	-0.05^{ns}	-0.51***	0.19*	-0.02^{ns}		
HI	-0.23**	0.64***	0.73***	0.08^{ns}	-0.50***	0.68***	0.49***	0.25***	
SY	-0.48***	0.77***	0.78***	0.20*	-0.66***	0.90***	0.44***	0.38***	0.71***

Table 12. Pearson's correlation coefficients among seed yield and yield components for red mottled bean lines grown at three locations in Kenya

Parameters	SER	DTF	DTM	GH	PV	PP	SP	100SW	HI
DTF	-0.47***								
DTM	-0.41***	0.84***							
GH	0.02^{ns}	0.00^{ns}	-0.02^{ns}						
PV	0.12^{ns}	-0.48***	-0.57***	0.06^{ns}					
PP	-0.52***	0.64***	0.70***	0.14*	-0.57***				
SP	-0.28***	0.29***	0.28***	0.37***	-0.2198**	0.3781***			
100SW	0.03^{ns}	0.23**	0.37***	-0.22**	-0.15*	0.19**	0.05^{ns}		
HI	-0.27***	0.23**	0.25***	-0.13^{ns}	-0.15*	0.30***	0.05^{ns}	0.15*	
SY	-0.52***	0.68***	0.79***	0.04^{ns}	-0.63***	0.83***	0.29***	0.35***	0.43***

Table 13. Pearson's correlation coefficients among seed yield and yield components of mixed color bean lines grown at three locations in Kenya

Parameters	SER	DTF	DTM	PV	PP	SP	100SW	HI
DTF	0.31***							
DTM	0.40***	0.82***						
PV	-0.32***	0.23***	0.14**					
PP	0.16**	0.45***	0.49***	-0.00^{ns}				
SP	0.04^{ns}	0.18***	0.18***	0.00^{ns}	0.20***			
100SW	0.28***	0.28***	0.37***	-0.08^{ns}	0.22***	-0.20***		
HI	0.33***	0.51***	0.53***	-0.01^{ns}	0.45***	0.08^{ns}	0.40***	
SY	0.28***	0.57***	0.61***	-0.05^{ns}	0.77***	0.19***	0.39***	0.62***

SER: seedling emergence rate (in %); DTF: days to flowering; DTM: days to maturity; GH: growth habit; PP: number of pods per plant; SP: number of seeds per pod; PV: plant vigor; 100SW: 100-seed mass (in g); HI: harvest index (in %); SY: seed yield (in kg ha^{-1}); *, **, ***: significant at P = 0.05, 0.01, or 0.001, respectively.

4. Discussion

4.1. Agronomic Performance of Inter-racial Bean Lines across Sites in Kenya

Effects due to interactions between the sites and the genotypes for all the traits and all the market classes were significant (*P<0.05*), implying that advanced bean lines responded differently to environmental conditions prevailing at test sites. As a result, their ranking varied significantly across the three sites. For all the traits, crops grown at Tigoni in high altitude recorded the highest means statistically superior to the other two sites namely Kabete and Mwea located in medium and low altitudes, respectively. The better performance recorded at Tigoni could be attributed to the relatively cooler conditions offered to crops; which led to slower plant growth and delayed maturity and, therefore, longer seed filling period which resulted in higher seed yields. Similar results were reported by [5]. The low yield recorded at Mwea in low altitude could be due to dry spells and erratic rainfall observed in that site during the experiment. In fact, the mean monthly temperature was 24.3°C with a total rainfall of approximately 311.4 mm for the period of September 2017 to February 2018. In addition, more than 85% of that rainfall was recorded during October and November, flooding young bean seedlings. The most critical phases (flowering and podding) experienced a dry period as no rain was recorded in January and February 2018 (0 mm), and thus, affecting negatively the grain yield. [33,34,35,36] observed that water stress during flowering, pod filling stages severely affects the harvest index and the seed yield. Seed yield losses might exceed 20% if the stress occurs during the early vegetative growth and could reach up to 50% in the early pod filling [32,37,38]. As most of test bean lines were of indeterminate growth habit, effects of water stress in low altitude Mwea site were more pronounced compared to dwarf cultivars as also reported in Malawi by [39]. [40] demonstrated that humid high altitude conditions are more conducive to indeterminate growth habit cultivars.

Seed yield and yield related components were varying significantly among genotypes and market classes. In all the market classes, there were promising genotypes for seed yield and which performed better than corresponding commercial check varieties, apart from the red kidney market class where the best yielding line was not significantly different from the best check variety (Mex54). This was probably an effect of growth habit as Mex54 is a semi-climber cultivar while most of test red kidney lines were bush lines (Type I and Type II growth habit). However, four of the 15 advanced red kidney lines were superior to the other check variety (AND1062) which is a bush cultivar. The presence of promising lines, regardless of the market class, demonstrated the effectiveness of inter-racial crosses to improve the seed yield of common bean. After studying the effects on seed yields of the Andean intra-gene pool and Andean-Middle America inter-gene pool crosses, [5] concluded that the utilization of high yielding genotypes from both gene pools which are diverse and with positive general combining ability could maximize gains from seed yield selection. [9] and [41] had previously demonstrated the superiority of the inter-racial lines over the intra-racial, suggesting the necessity to explore them as a mean to create useful genetic variations and to broaden the genetic base of commercial cultivars as well as maximizing gains from selections.

The seed yield was high for market classes with higher 100-seed mass compared to smaller seeds. While assessing effects of size of seed grown on the growth and yield of common bean, [42] concluded that sowing larger seeds improves the early-season plant growth which is advantageous for crop establishment in stressed environments. This could explain why red kidney and red mottled market classes had higher yields than pinto and mixed color market classes. The effects of seed size on yield were much more pronounced among the lines within the same market class than among market classes. This study which had both large- and small-/medium- seeded genotypes disagrees with the general observation (especially in Colombia/CIAT) that small-seeded lines yield better than large-seeded types [5]. Another key reason is that of [43] who presented evidence that large-seeded bean lines adapt better to cooler conditions from higher elevations than small-seeded counterparts.

4.2. Correlations between Seed Yield and Yield Components of Inter-racial Bean Lines grown in Three Locations in Kenya

Seed yield was significantly and positively correlated with days to flowering, days to maturity, number of pods per plant, number of seeds per pod, 100-seed mass and harvest index. The most important of these yield components regardless of the market class was the number of pods per plant, suggesting that it can be used by plant breeders as an additional and indirect selection method for seed yield. Similar results were found by [32,36,44]. This study reflected the general assumption that yield increases with growth habit such that Type IVs (climbers) are the best yielding. In fact, this study revealed a positive correlation between the growth habit and the number of pods per plant and between the growth habit and the seed yield regardless of the market class. However, the trend was opposite for the pinto bean lines for which correlations were negative but not significantly. [45] explained that in stressed environments, these climbing genotypes possess a yield compensation capacity to recover rapidly from stress.

Better yielding lines were late to reach the 50% flowering stage as they contained a large number of flowers which appeared progressively. This had also impacted the days to maturity which was delayed compared to plant developing fewer flowers and fewer pods. These findings are similar to those of [5,9,46]. However, opposite results were found in drought stress environments where higher yield was in negative correlation with days to maturity [47,48]. There were no significant correlations between the growth habit and the duration to flowering and to maturity for all market classes. This contrasts the general assumption that climbers take longer to flower and to mature compared to bush bean lines.

Significant negative correlations were detected between seed yield and plant vigor and between seed yield and seedling emergence rate. As the plant vigor score varies from 1 to 9 [24] from which 1 is the best score and 9 the worst, the more a plant was vigorous, the more it could carry more flowers and more pods and consequently, the more the yield was higher. The negative correlation existing between yield and seedling emergence rate could be attributed to extrapolation as seed yield ha^{-1} was estimated on the basis of single plants. If the yield per m^2 (or per plot) was considered in extrapolation regardless of the number of plants, the relationship may change.

4.3. Yield Stability and Genotype-environment Interaction (G x E) Effects on Seed Yield

Variability among genotypes across sites was highly significant regardless of the market class. Treatments (G, E, and G x E) contributed the most to the variability for up to 80% regardless of the market class. This showed the diversity of sites and the existence of significant genetic differences among the advanced lines for seed yield as also reported by [16] and [48]. By partitioning treatments' contribution for every market class, the environment was responsible for the largest part of the variability. Similar results were found on common bean by [39] in Malawi and [16] and [17,50] in Ethiopia. Although the environment is a very broad term and includes many factors (predictable and unpredictable); it was the temperature and the amount and distribution of rainfall that had mainly contributed to observed results. Tigoni in high altitude experienced cooler conditions (15.8°C) with a relatively well-distributed rainfall along the growing season (506 mm). Kabete experienced mean monthly temperatures of 18.2°C and an amount of rainfall of 372 mm. Mwea in low altitude was warmer (24°C) with erratic rainfall as described previously (311 mm). Other key environmental factors (e.g. soil type, nutrients, pH, etc.) were not significantly different among the three sites.

Interaction between genotype and environment was high for mixed color market class (26.7%), suggesting that test lines were not stable and thus responded differently across locations. These genotypes should, therefore, be selected and recommended to specific environments. From ASV, higher yielding lines were also the most unstable across sites. This is supporting results found by [17,50,51] showing that the stable lines are not always the better yielding. In fact, [52] demonstrated that a satisfactory Type I stability parameter (i.e., CV) is often linked with reduced yield performance.

5. Conclusion

Promising genotypes combining high seed yield potential and high stability across environments were identified from all market classes. The environment contributed the most to the variability among lines. The high altitude Tigoni site was the best environment for bean cultivation regardless of the market classes. Although the best yielding lines were not the most stable across sites, KMA13-22-21 a pinto bean line and KMA13-29-21 a red mottled line combined high yield potential and wider adaptation across the three agro-ecological conditions. Two pinto, four red kidney, 15 red mottled, and two mixed color bean lines did better than their corresponding checks with yield advantages of 7.6, 14.3, 71.5, and 34.9%, respectively. These lines should, therefore, be selected for further testing and release.

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Statement of Competing Interests

The authors do not have any competing interests.

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