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Yield stability and relationships among stability parameters in faba bean (*Vicia faba* L.) genotypes

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ABSTRACT

Sixteen faba bean genotypes were evaluated in 13 environments in Ethiopia during the main cropping season for three years (2009–2011). The objectives of the study were to evaluate the yield stability of the genotypes and the relative importance of different stability parameters for improving selection in faba bean. The study was conducted using a randomized complete block design with four replications. G × E interaction and yield stability were estimated using 17 different stability parameters. Pooled analysis of variance for grain yield showed that the main effects of both genotypes and environments, and the interaction effect, were highly significant ($P \leq 0.001$) and ($P \leq 0.01$), respectively. The environment main effect accounted for 89.27% of the total yield variation, whereas genotype and G × E interaction effects accounted for 2.12% and 3.31%, respectively. Genotypic superiority index (P_i) and FT3 were found to be very informative for selecting both high-yielding and stable faba bean genotypes. Twelve of the 17 stability parameters, including CV_i, RS, α, λ, S^2d_i, b_i, $S_i^{(2)}$, W_i, σ_i^2, EV, P^{59}, and ASV, were influenced simultaneously by both yield and stability. They should accordingly be used as complementary criteria to select genotypes with high yield and stability. Although none of the varieties showed consistently superior performance across all environments, the genotype EK 01024-1-2 ranked in the top third of the test entries in 61.5% of the test environments and was identified as the most stable genotype, with type I stability. EK 01024-1-2 also showed a 17.0% seed size advantage over the standard varieties and was released as a new variety in 2013 for wide production and named "Gora". Different stability parameters explained genotypic performance differently, irrespective of yield performance. It was accordingly concluded that assessment of G × E interaction and yield stability should not be based on a single or a few stability parameters but rather on a combination of stability parameters.

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1. Introduction

Faba bean (*Vicia faba* L., $2n = 2x = 12$) is among the most important pulse crops produced in Ethiopia. Ethiopia is the second largest producer of faba bean worldwide, after the People's Republic of China [1,2]. Currently, faba bean occupies 31% of the total area cultivated for pulses in Ethiopia, with 34% of the total annual pulse production in the country [3]. The crop grows at an altitude ranging from 1800 to 3000 m above sea level and receiving an annual rainfall of 700–1100 mm [2]. It is a crop of high economic value [4] with its edible seed serving as an important protein complement in the cereal-based Ethiopian diet, particularly for the poor who cannot afford animal protein [2]. In Ethiopia, faba bean is a suitable rotation crop with cereals [5] and should be a component of a sustainable farming system.

To maintain high agricultural productivity, the development of varieties with high yield potential is the ultimate goal of plant breeders in a crop improvement program. In recent years in faba bean breeding in Ethiopia, special focus has been placed on developing varieties with improved grain yield, large seed size, and resistance to major diseases. In addition to high yield potential, a new cultivar should have stable performance and broad adaptation over a wide range of environments. Genotype × environment (G × E) interaction is of major importance for faba bean breeders, given that phenotypic response to change in environment is different among genotypes [6]. Different authors [7,8] have reported high G × E interaction effects in faba bean genotypes grown in Ethiopia. Strong G × E interaction for quantitative traits such as seed yield can severely limit gain in selecting superior genotypes for improved cultivar development [44]. For cultivars being selected for a large group of environments, evaluating stability of performance and range of adaptation has become increasingly important. Several stability parameters have been proposed to characterize yield stability when genotypes are tested across multiple environments, with each parameter giving different results.

Joint regression of the mean performance of a genotype on an environmental index (b_i) [9] is the most popular regression approach. The deviation from regression (S^2d_i) is used as a measure of phenotypic stability of the tested genotypes in this approach. Another two-stability parameter similar to the joint regression method [9] has been proposed by Tai [10]. This method involves the partitioning of the G × E interaction effect into two parameters, α and λ, which measure linear response to environmental effects and deviation from the linear response, respectively. This method measures genotypic stability and can be considered as a special form of the regression parameters (b_i) and (S^2d_i), when the environmental index is assumed to be random [11].

An unbiased estimator (σ_i^2) [12] has also been advantageously used for simultaneous selection of high-yielding and stable genotypes [13]. The use of G × E interaction effects for each genotype, squared and summed across all environments, was proposed by Wricke [14] as a measure of stability. This statistics is termed ecovalence (W_i), and is far simpler to compute and more directly related to G × E interaction than statistics proposed by Plaisted and Peterson, 1959 [15]. Genotypes with the lowest values of the above stability parameters are considered to be stable. Francis and Kannenberg [16] measured stability by combining coefficient of variation (CV_i), mean yield, and environmental variance (EV). Genotypes with low CV_i, low environmental variance (EV), and high mean yield are considered the most desirable. Lin and Binns [17] recommended the use of the mean squared distance between genotype *i* and the genotype with the maximum yield within each environment as a genotypic superiority measure (P_i), with genotypes with small P_i values considered to be stable.

Additive main effects and multiplicative interaction (AMMI) [18,19] is gaining popularity and is currently the main alternative multivariate approach to joint regression analysis in many breeding programs [20]. Another approach called the AMMI stability value (ASV), which is based on the first and second interaction principal component axis (IPCA) scores of the AMMI model for each genotype, has also been developed more recently [21]. ASV measures the distance from the genotype coordinate point to the origin in a two-dimensional scatter diagram of IPCA2 against IPCA1 scores. Genotypes with the lowest ASV values are identified by their shortest projection from the biplot origin and considered the most stable. Other stability parameters such as genotypic desirability index (D_i) [22] and mean variance component for pairwise G × E interaction (P^{59}) [23] have also been extensively used. Estimates are made of the range of data and the homogeneity of variance when all these parametric methods are used for stability analysis.

However, univariate nonparametric stability methods are not affected by data distribution. As these methods are based on rank order of genotypes, a genotype is considered stable if its ranking is relatively constant across environments [24]. Several nonparametric methods have been proposed to interpret the response of genotypes to environmental variation. Distribution-free nonparametric stability methods including $S_i^{(2)}$, $S_i^{(3)}$, and $S_i^{(6)}$ have been suggested [25]. The lowest value for each of these statistics indicates maximum stability. Kang [38] assigned ranks for mean yield, with the highest-yielding genotype receiving the rank of 1, and ranks for the stability variance (σ_i^2) of genotypes [12], with the final order of the two genotypes being decided by the sum of the two ranks. The genotype with lowest rank sum is considered the most desirable. Another nonparametric stability method is the stratified ranking technique proposed in [26], where a genotype usually found in the top third for mean performance compared to all entries tested across environments is considered to be a relatively well-adapted and stable genotype.

All of the above and several other techniques have been proposed to characterize stability of yield across a range of environments. Nonetheless, previous studies of faba bean genotypes in Ethiopia have been based either on multivariate statistics such as AMMI [27–29] or on only a few parametric methods [29], with none having used nonparametric methods. The present study was accordingly aimed at performing yield stability analysis using the 17 most commonly used univariate stability methods (12 parametric and five nonparametric), determining the association of different stability parameters, and assessing the use and relative importance of the techniques to improve varietal selection in faba bean.

2. Materials and methods

2.1. Planting materials and testing locations

Sixteen faba bean genotypes developed by hybridization were grown for three years (2009–2011) during the main cropping season (June–November) in seven locations representing different faba bean growing agro-ecological zones of Ethiopia. Each year and location was treated as a separate environment, making 13 test environments. Descriptions of the seven test locations and the 16 test genotypes are presented in Tables 1 and 2, respectively.

2.2. Experimental layout and design

The treatments were laid out in a randomized complete block design with four replications. Each plot was four rows 4 m long with a space of 40 cm between rows. Fertilizer was applied to each plot at the rate of 18 kg N and 46 kg P_2O_5 ha^{-1} in the form of diammonium phosphate at planting. Other agronomic practices were treated as non-experimental variables and applied uniformly to the entire experimental area. For data analysis, grain yield measured from a net plot size of 3.2 m^2 was converted into t ha^{-1} at 10% standard grain moisture content.

2.3. Analysis of variance

Grain yield data were subjected to analysis of variance using the SAS statistical package [30]. Variance homogeneity was tested and combined analysis of variance was performed using the general linear model (PROC GLM) procedure to partition the total variation into components due to genotype (G), environment (E) and G × E interaction effects. Genotype was treated as a fixed effect and environment as a random effect. The main effect of E was tested against the replication within environment (R/E) as error 1, the main effect of G was tested against the G × E interaction, and the G × E interaction was tested against pooled error as error 2. Multiple comparison of the main effect was performed using Duncan's multiple range test at the 5% probability level.

Table 2 – Description of 16 faba bean genotypes evaluated in 13 environments during the 2009–2011 cropping season.

No.	Genotype	Pedigree
1	MOTI	ILB4336 × MKT Illubabor
2	EK 01001-5-1	R878-3 × ILB 2717-1
3	EK 01001-8-1	R878-3 × ILB 2717-1
4	EK 01001-9-2	ILB 2717-1 × R878-3
5	EK 01001-10-5	R878-3 × ILB 2717-1
6	EK 01007-2-6	BPL 1802-1-2 × BPL 1297-1
7	EK 01006-7-1	BPL 1802-1-2 × ILB 2717-1
8	EK 01015-1-1	EH 91025-27-1 × BPL 44-1
9	EK 01019-2-1	EH 91012-23-1 × BPL 44-1
10	EK 01019-7-5	EH 91012-23-1 × BPL 44-1
11	EK 01024-1-1	EH 91026-8-2 × BPL 44-1
12	EK 01024-1-2	EH 91026-8-2 × BPL 44-1
13	EK 01002-1-1	R878-3 × ILB 1990-1
14	EK 01021-4-1	EH 91012-23-1 × Giza Blanca
15	EK 01004-2-1	R878-3 × ILB 4914-1
16	GEBELCHO	ILB4726 × 75TA26026-1-2

Twelve parametric stability methods including: the joint regression coefficient (b_i), deviation from regression (S^2d_i), ecovalence (W_i), stability variance (σ_i^2), coefficient of variation (CV_i), environmental variance (EV), Tai's alpha (α) and lambda (λ), mean variance component for a pairwise G × E interaction (P^{59}), desirability index (D_i), genotypic superiority index (P_i) and ASV; and 5 rank-based nonparametric stability parameters including $S_i^{(2)}$, $S_i^{(3)}$, $S_i^{(6)}$, RS, and FT3 were computed using a comprehensive SAS program developed by Hussein and colleagues [31]. Spearman rank correlation coefficients between yield and stability parameters were produced and a biplot analysis based on the rank correlation matrix was performed for better understanding of the relationship among all stability parameters.

3. Results and discussion

3.1. G × E interaction effects and genotypic mean performance

A combined analysis of variance for grain yield of the 16 faba bean genotypes tested across 13 environments is presented in Table 3. The main effect differences among genotypes, environments, and the interaction effects were highly significant ($P \le 0.01$). Of the total variance of grain yield, environment main effect accounted for 89.27%, whereas genotype

Table 1 – Description of the 7 locations used for evaluation of 16 faba bean genotypes during the 2009–2011 cropping season in Ethiopia.

Location	Growing season	Geographical position		Altitude (m.a.s.l.)	Average rainfall (mm)	Temperature (°C)		Agro-ecology
		Latitude	Longitude			Min.	Max.	
Asassa	2010–2011	07°06′12″N	39°11′32″E	2300	620	5.8	23.6	THMH
Kulumsa	2009 & 2011	08°01′00″N	39°09′32″E	2200	820	10.5	22.8	TSmMH
Bekoji	2009–2011	07°31′22″N	39°14′46″E	2780	1010	7.9	16.6	CHMH
Holetta	2011	09°04′12″N	38°29′45″E	2400	1044	6.05	22.4	TMMH
Koffale	2009–2011	07°04′27″N	38°46′45″E	2660	1211	7.1	18	CHMH
Jeldu	2011	09°22′40″N	37°56′38″E	2800	1200	2.06	16.9	TAMH
Adadi	2011	08°38′08″N	38°30′15″E	2050	900	NA	NA	TMMH

THMH: tepid humid mid-highland; TSmMH: tepid submoist mid-highland; CHMH: cool humid mid-highland; TMMH: tepid moist mid-highland; TAMH: tepid arid mid-highland; NA: not available.

and G × E interaction effects accounted for 2.12% and 3.31% of the total variation, respectively (Table 3). This result shows that grain yield was significantly affected by changes in environment, followed by G × E interaction and genotypic effects (Table 3). The highly significant environment effect and its high variance component (Table 3) could be attributed to the large differences among the test locations in altitude and differences in both amount and distribution of annual rainfall (Table 2). A previous report on faba bean in Ethiopia also indicated that the environmental effect accounted for the largest part of the total variation [29]. The amount of variance contributed by G × E interaction was larger than that contributed by genotype (Table 3). This result indicates that there was a marked G × E interaction effect present in these faba bean multi-environment data, leading to the presence of substantial differences in genotypic responses across the test environments and indicating, in turn, a large difference in genotypic performances and their rank orders across environments. This result is consistent with that of a previous study of faba bean in southeastern Ethiopia [29]. It is evident that selection and recommendation of new varieties would be difficult under such conditions, where G × E interaction effects are high owing to the masking effects of variable environments. Pham and Kang [34] reported that G × E interaction minimizes the utility of genotypes by confounding their yield performances. Thus, it is very important to study in depth the yield levels, adaptation patterns and stability of faba bean genotypes in multiple environments.

The average environmental grain yield across genotypes ranged from lowest at 2.31 t ha^{-1} in Bekoji 2011 to the highest at 5.24 t ha^{-1} in Koffale 2009 (Table 4). The mean grain yield of faba bean genotypes across environments varied from 3.20 t ha^{-1} for genotype EK01024-1-1 to 3.88 t ha^{-1} for EK 01024-1-2, with an overall environment mean of 3.58 t ha^{-1} (Table 4). The maximum grain yield varied from 5.16 t ha^{-1} for genotype EK01024-1-1 and EK 01024-1-2 to 6.53 t ha^{-1} for the standard cultivars Moti and EK 01001-8-1. The minimum yield ranged from 0.82 t ha^{-1} for genotype EK01001-8-1 to 2.04 t ha^{-1} for EK01004-2-1 (Table 4). The smallest yield amplitude was obtained from EK01004-2-1 (3.55 t ha^{-1}) followed by EK01015-1-1 (3.62 t ha^{-1}) revealing their consistent performance across the test environments, whereas the largest yield amplitude was recorded for EK01001-8-1 (5.70 t ha^{-1}) followed by the standard cultivar Moti (5.33 t ha^{-1}) (Table 4), indicating their inconsistent relative performance and high sensitivity to environmental variation. The standard cultivar Moti ranked first in four of the 13 environments (Kulumsa 2009, Koffale 2010, Koffale 2011, and Jeldu 2011). Similarly, two other best-performing genotypes included EK01001-5-1 (Kulumsa 2011, Bekoji 2011, and Holetta 2011) and EK01024-1-2 (Bekoji 2010, Asassa 2010 and Adadi 2011), each ranking first in three of the environments. Moti showed the best yield of 5.70 t ha^{-1} in the highest-yielding environment, Koffale 2010, whereas EK01001-5-1 showed the best yield of 2.70 t ha^{-1} in the lowest-yielding environment, Bekoji 2011 (Table 4). This differential yield ranking of genotypes across the environments showed that the G × E interaction effect was of the crossover type [46].

3.2. Genotypic performance stability

The results of 12 parametric and five nonparametric stability statistics are given in Table 5. The joint regression of the mean genotypic performance on the environmental index showed that results from the two stability parameters b_i and S^2d_i were not consistent in assessing the reaction of genotypes to varying environmental conditions. All genotypes showed regression coefficient (b_i) values that were nonsignificantly different from unity (Table 5) but, in contrast, some genotypes showed significant deviation from regression (S^2d_i) values of greater than zero (Table 5). Thus, based on the regression coefficients, all genotypes had an average response in all test environments. According to Becker and Leon [15], genotypes with *bi* values of unity showed an average response to changing environmental conditions. Eberhart and Russell [9] and Finlay and Wilkinson [35] found that genotypes with high mean performance, a regression coefficient of unity ($b_i = 1$), and deviation from regression of zero ($S^2d_i = 0$) showed better general adaptability across environments. Thus, six genotypes, namely EK01001-5-1, EK01019-7-5, EK01024-1-2, EK01002-1-1, EK01004-2-1, and Gebelcho, with above-average grain yield performances, regression coefficient (b_i) values nonsignificantly different from unity, and deviation from regression (S^2d_i) values nonsignificantly different from zero, were found to be more stable than the other genotypes. Four other genotypes, namely EK01006-7-1, EK01015-1-1, EK01019-2-1, and EK01024-1-1, not only were found to be among the lowest yielders but also showed poor adaptation to the test environments. Other genotypes, Moti and EK 01024-1-1, had a deviation from regression (S^2d_i) significantly greater than zero and b_i value not different from unity, indicating that these genotypes are better adapted to high-yielding environments.

Tai's [10] stability model partitions the G × E interaction effect into two components: α, which measures the linear

Table 3 – Analysis of variance of 16 faba bean genotypes tested across 13 environments.

Source	df	SS	MS	Variance component	Variance component (%)
Model	246	798.33	3.25***	0.9198	
Rep. (environment)	39	44.32	1.14***	0.0488	5.30
Environment (E)	12	645.68	53.81***	0.8211	89.27
Genotype (G)	15	22.38	1.49***	0.0195	2.12
G × E	180	85.96	0.48**	0.0305	3.31
Pooled error	585	208.11	0.36	0.3557	
CV (%) = 16.64	R^2 = 79.32		Mean = 3.58 (t ha^{-1})		

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

Table 4 – Mean minimum, maximum, and range of performance (t ha^{-1}) of 16 faba bean genotypes tested in 13 environments during the 2009–2011 cropping seasons.

Code	Genotype	Environment													Mean	Min.	Max.	Range
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13				
G1	MOTTI	3.08	5.36	3.34	5.70	4.41	3.58	3.49	5.50	2.40	2.46	3.57	2.85	3.44	3.78 ab	1.48	6.53	5.05
G2	EK 01001-5-1	3.55	4.79	2.94	5.58	4.44	3.05	3.50	5.16	2.70	2.70	3.90	3.35	2.67	3.72 abc	1.82	6.29	4.48
G3	EK 01001-8-1	3.80	4.89	3.28	5.58	4.49	3.13	3.33	4.88	2.43	2.11	3.27	3.45	1.77	3.57 bcde	0.82	6.53	5.70
G4	EK 01001-9-2	2.75	4.82	2.92	5.18	4.31	2.62	3.40	4.82	2.47	3.04	3.60	3.79	2.45	3.55 bcde	1.04	6.06	5.02
G5	EK 01001-10-5	3.02	5.20	3.75	5.11	4.30	2.98	2.39	4.61	2.33	2.72	3.53	3.28	2.80	3.54 bcde	1.15	6.18	5.04
G6	EK 01004-2-1	3.44	4.78	3.35	5.12	4.40	2.57	3.22	4.57	2.53	2.69	3.30	3.34	3.06	3.57 bcde	1.55	5.83	4.27
G7	EK 01006-7-1	3.54	5.33	3.54	5.07	3.77	3.06	2.84	4.18	2.41	2.40	2.69	3.50	2.73	3.47 cde	1.89	5.74	3.85
G8	EK 01015-1-1	3.55	4.66	3.52	4.80	3.89	2.74	2.79	4.52	2.16	2.94	2.69	3.43	2.64	3.41 def	1.73	5.35	3.62
G9	EK 01019-2-1	3.33	5.08	2.60	5.26	3.73	2.84	2.55	4.24	2.17	2.91	2.97	3.88	2.12	3.36 ef	1.38	5.48	4.11
G10	EK 01019-7-5	3.70	5.30	4.20	5.42	4.21	3.60	3.04	4.46	2.01	2.54	3.14	3.17	2.76	3.66 abcd	1.73	6.04	4.31
G11	EK 01024-1-1	2.82	4.19	2.27	4.76	4.04	3.25	2.81	4.54	1.95	2.80	2.72	3.50	2.00	3.20 f	1.02	5.16	4.14
G12	EK 01024-1-2	4.02	5.06	3.87	5.67	4.52	3.70	3.30	4.66	2.54	2.93	3.62	4.30	2.21	3.88 a	1.61	6.16	4.55
G13	EK 01002-1-1	3.43	5.29	4.14	4.78	4.31	3.17	2.98	4.29	2.49	2.98	3.38	3.83	2.53	3.66 abcd	1.79	6.20	4.41
G14	EK 01021-4-1	2.90	4.69	3.90	5.12	4.23	3.31	3.39	4.70	2.00	2.84	3.50	3.11	2.69	3.57 bcde	1.79	6.01	4.22
G15	EK 01004-2-1	4.06	4.84	4.36	5.05	4.42	3.57	3.11	4.24	2.19	2.56	3.23	3.60	3.42	3.74 ab	2.04	5.59	3.55
G16	GEBELCHO	3.62	4.87	4.49	5.57	3.93	2.48	3.09	5.17	2.14	2.66	3.59	3.61	2.54	3.67 abcd	0.88	6.21	5.33
	Mean	3.41 ef	4.95 b	3.53 e	5.24 a	4.21 d	3.10 g	3.08 g	4.66 c	2.31 i	2.70 h	3.29 fg	3.50 ef	2.61 h	3.58			
	CV (%)	12.59	9.57	22.27	8.64	10.87	25.46	18.46	11.71	14.7	24.88	16.08	22.68	25.93	16.64			

E1: Kulumsa 2009; E2: Bekoji 2009; E3: Koffale 2009; E4: Koffale 2010; E5: Bekoji 2010; E6: Asassa 2010; E7: Kulumsa 2011; E8: Koffale 2011; E9: Bekoji 2011; E10: Asassa 2011; E11: Holetta 2011; E12: Adadi 2011; E13: Jeldu 2011; Min.: minimum; Max.: maximum. Means followed by similar letters are not significantly different at the 0.05 probability level based on Duncan's multiple range test (DMRT); underlined values are highest yields in each test environment.

Table 5 – Separate stability statistics values of the 16 tested genotypes and IPC scores of stability parameters.

Method	Genotype																IPC scores	
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	IPC1	IPC2
GY	3.784	3.718	3.570	3.552	3.540	3.567	3.467	3.412	3.361	3.658	3.204	3.878	3.661	3.568	3.742	3.673	−0.265	0.264
b_i	1.124	1.015	1.189	0.973	1.031	0.911	0.976	0.899	1.047	1.071	0.933	1.027	0.892	0.951	0.835	1.126	0.129	0.022
S^2d_i	0.116	0.030	0.024	0.050	−0.008	−0.033	−0.001	−0.037	0.050	0.013	0.074	0.010	−0.008	−0.006	0.065	0.064	0.206	0.293
D_i	3.994	3.908	3.793	3.734	3.733	3.738	3.650	3.58	3.557	3.859	3.379	4.071	3.828	3.746	3.899	3.884	0.265	−0.265
W_i	2.406	1.306	1.606	1.532	0.900	0.692	0.970	0.678	1.547	1.170	1.836	1.093	1.010	0.937	1.961	1.844	0.303	0.135
CV_i	29.54	26.55	31.83	27.06	27.80	24.26	27.06	25.00	30.47	28.12	29.31	25.49	23.55	25.62	22.79	29.9	0.066	0.307
EV	1.249	0.974	1.292	0.924	0.969	0.749	0.88	0.728	1.049	1.058	0.882	0.977	0.743	0.836	0.727	1.206	0.223	0.016
σ_i^2	0.221	0.116	0.144	0.137	0.077	0.057	0.084	0.056	0.139	0.103	0.166	0.096	0.088	0.081	0.178	0.167	0.303	0.135
α	0.126	0.015	0.193	−0.027	0.032	−0.091	−0.025	−0.103	0.048	0.073	−0.068	0.028	−0.110	−0.050	−0.168	0.128	0.129	0.022
λ	2.248	1.303	1.239	1.524	0.889	0.611	0.963	0.573	1.524	1.117	1.789	1.085	0.889	0.911	1.681	1.68	0.179	0.317
P_i	0.189	0.198	0.282	0.299	0.246	0.237	0.300	0.323	0.434	0.182	0.586	0.109	0.184	0.232	0.150	0.170	−0.245	0.297
ASV	0.989	0.864	0.421	0.886	0.314	0.212	0.514	0.333	0.765	0.780	0.926	0.556	0.608	0.410	1.050	0.472	0.272	0.087
P^{59}	0.167	0.118	0.131	0.128	0.100	0.090	0.103	0.090	0.128	0.112	0.141	0.108	0.105	0.101	0.147	0.142	0.279	0.190
$S_i^{(2)}$	29.06	26.17	25.40	22.40	16.53	14.69	23.42	14.64	26.94	22.26	32.27	15.26	16.69	18.42	33.94	23.69	0.244	0.269
$S_i^{(3)}$	57.8	38.57	32.17	37.22	15.63	16.69	22.39	13.56	22.42	30.42	13.82	36.04	26.62	22.89	33.13	32.43	0.291	−0.165
$S_i^{(6)}$	9.83	8.22	5.94	6.93	3.87	3.74	4.69	3.27	4.34	6.51	3.30	8.78	5.76	5.11	6.91	6.45	0.284	−0.189
FT3	61.54	46.15	38.46	46.15	15.38	15.38	7.69	7.69	15.38	38.46	0.00	61.54	38.46	23.08	38.46	46.15	−0.276	0.215
RS	18	13	20	21	15	12	18	15	26	15	29	8	12	13	18	19	0.008	0.479
% of variance accounted for																	55.37	23.52

GY: grain yield (t ha^{-1}); b_i: regression coefficient; S^2d_i: deviation from regression, W_i: Wrickes's ecovalence; σ_i^2: Shukla's stability variance; CV_i: coefficient of variation; S^2x_i: environmental variance, α and λ: Tai's alpha and lambda, P^{59}: Plaisted and Peterson's stability parameter; D_i: Hernandez desirability index, P_i: Lin and Binn's superiority index, ASV: AMMI stability value, $S_i^{(2)}$: between-ranks variance over environments; $S_i^{(3)}$: sum of the absolute deviations of the squares of ranks for each genotype; $S_i^{(6)}$: the sum of squares of ranks for each genotype relative to the mean of ranks, RS: Kang's rank sum, FT3: number of sites at which the genotype occurred in the top third of the ranks. Underlined are first-ranked (most stable) genotypes of the respective stability parameters. Name of genotypes are as defined in Table 4.

Table 6 – Spearman's correlation coefficients among ranks of yield and parametric and nonparametric stability statistics for 16 faba bean genotypes tested across 13 environments.

Method	Parametric													Nonparametric			
	GY	b_i	S^2d_i	D_i	W_i	CV_i	EV	σ_i^2	α	λ	P_i	ASV	P^{59}	$S_i^{(2)}$	$S_i^{(3)}$	$S_i^{(6)}$	FT3
Parametric																	
b_i	−0.265**																
S^2d_i	−0.053	0.388															
D_i	−0.994**	0.215	0.044														
W_i	−0.365	0.382	0.700**	0.353													
CV_i	0.221	0.071	0.241	−0.176	0.479												
EV	−0.253	0.056	0.162	0.309	0.488	0.847**											
σ_i^2	−0.365	0.382	0.700**	0.353	1.000**	0.479	0.488										
α	−0.265	1.000**	0.388	0.215	0.382	0.071	0.056	0.382									
λ	0.000	0.444	0.979**	−0.015	0.685**	0.226	0.097	0.685**	0.444								
P_i	0.918**	−0.274	0.068	−0.906**	−0.212	0.326	−0.112	−0.212	−0.274	0.112							
ASV	−0.297	0.000	0.553*	0.291	0.759**	0.076	0.115	0.759**	0.000	0.547*	−0.165						
P^{59}	−0.212	0.279	0.632**	0.224	0.918**	0.759**	0.744**	0.918**	0.279	0.600*	−0.056	0.562*					
Nonparametric																	
$S_i^{(2)}$	−0.106	0.182	0.576*	0.100	0.879**	0.441	0.294	0.879**	0.182	0.597*	0.056	0.762**	0.771**				
$S_i^{(3)}$	−0.809**	0.026	0.250	0.821**	0.597*	0.065	0.447	0.597*	0.026	0.203	−0.612*	0.568*	0.521*	0.382			
$S_i^{(6)}$	−0.844**	−0.024	0.153	0.859**	0.538*	0.029	0.444	0.538*	−0.024	0.088	−0.682**	0.568*	0.462	0.315	0.976*		
FT3	0.841**	−0.047	−0.118	−0.862**	−0.426	−0.097	−0.553*	−0.426	−0.047	−0.059	0.674**	−0.332	−0.429	−0.121	−0.932**	−0.932**	
RS	0.441	0.176	0.553*	−0.447	0.629**	0.641**	0.279	0.629**	0.176	0.576*	0.500*	0.424	0.700**	0.685**	−0.038	−0.115	0.224

Symbols of both parametric and nonparametric stability statistics are as described in Table 5.

* significant at the 0.05 probability level.

** significant at the 0.01 probability level.

response to environmental effects, and λ, which measures deviation from the linear response in terms of magnitude of the error variance. According to these parameters, a perfectly stable genotype is one with an environmental effect of −1 and a deviation from linear response of +1, so that $(\alpha, \lambda) = (-1, 1)$. In this case, all of the faba bean genotypes studied except Moti showed λ values nonsignificantly different from unity, but none of them showed an α value of −1. This result indicated that none of the tested genotypes showed perfect/static stability. It could thus be assumed that genotypic performances across the environments were not consistent. Alternatively, genotypes with $(\alpha, \lambda) = (0, 1)$ showed average, those with $(\alpha, \lambda) < (0, 1)$ above-average, and those with $(\alpha, \lambda) > (0, 1)$ below-average performances for stability across test environments. Thus, two of the high-yielding faba bean genotypes, EK01001-5-1 and EK 01024-1-2, showed average performance stability; whereas eight other genotypes, namely EK01001-9-2, EK01007-2-6, EK01006-7-1, EK01015-1-1, EK01024-1-1, EK01002-1-1, EK01021-4-1, and EK01004-2-1, showed above average stability. However, some others, including EK01001-8-1, EK01001-10-5, EK01019-2-1, EK01019-7-5, and Gebelcho, with values of $\alpha > 0$ and $\lambda = 1$, showed below-average stability performances (Table 5).

According to phenotypic stability parameters (σ_i^2, W_i, and P^{59}), which measure the sums of squares contributed by each genotype to the interaction effect, and other parameters including CV_i, EV, and ASV, some low-yielding genotypes, namely EK01015-1-1, EK01007-2-6, EK01001-10-5, EK01002-1-1, and EK01021-4-1, and a high-yielding genotype, EK 01024-1-2, received the lowest values of these parameters and were found to be the most stable with respect to performance across environments. This observation means that these genotypes showed lower differential responses to the changes in the growing environment and contributed minimally to the sum of squares of the interaction effect regardless of their low yielding ability. This result suggests that selection for genotypic performance stability based on P^{59}, σ_i^2, W_i, CV_i, EV, and ASV parameters favors below-average-yielding over high yielding faba bean genotypes. Similarly, σ_i^2 and W_i discriminated stable faba bean genotypes in another study [29]. Karimizadeh et al. [36] also reported that low-yielding lentil genotypes were the most stable compared to high-yielding ones, using the same parameters. These stability (also called type I stability) parameters have been reported to be more reliable, given that they were observed to be heritable with an additive genetic mode of inheritance [37].

Based on these phenotypic stability parameters, one genotype, namely EK 01024-1-2, showed type I or static stability despite the finding that both high yield and type I stability rarely occur in multi-location variety trials [36]. Furthermore, the same genotype followed by EK01004-2-1 and Gebelcho received the lowest values of genotypic superiority index (P_i). Based on the FT3 parameter, once again, the same genotype ranked in the top third of all genotypes in the majority of the test environments (Table 5). This genotype also showed larger seed size, with 935 g 1000-seed^{-1} (data not shown). It was accordingly released as a new variety, Gora, in Ethiopia for its high yielding potential, large seed size, and wide adaptability [45].

Based on the nonparametric stability methods, namely $S_i^{(2)}$, $S_i^{(3)}$, and $S_i^{(6)}$, below-average-yielding genotypes including EK01015-1-1, EK01024-1-1, and EK01007-2-6 were found to be the most stable genotypes, whereas the best-yielding three genotypes including Moti, EK01001-5-1, and EK 01024-1-2 showed the highest values of $S_i^{(3)}$, and $S_i^{(6)}$, indicating that they were not stable for performance across the test environments (Table 5). Calculations of correlation of the values of the nonparametric stability parameters with grain yield revealed strong negative correlation coefficients between these parameters and mean grain yields (Table 6). Thus, selection of stable genotypes based on these stability parameters may not enable faba bean breeders to identify genotypes that are both high-yielding and stable. A study of durum wheat genotypes using the same stability parameters [39] also identified below-average-yielding genotypes as the most stable and the highest-yielding genotypes as more unstable. Based on the FT3 parameter [26], five genotypes (EK 01024-1-2, Moti, EK01001-5-1, EK01001-9-2, and Gebelcho) ranked in the top third of all the genotypes in several test environments (Table 5), indicating that these genotypes are stable. Kang [38] rank-sum (RS) statistics also identified some genotypes, namely EK 01024-1-2, EK01007-2-6, EK01002-1-1, and EK01001-5-1, as stable (Table 5).

3.3. Association among stability parameters

Spearman's rank correlation was computed between grain yield and stability parameters (Table 6). Significant ($P \le 0.01$) positive rank correlation coefficients were obtained between grain yield and P_i ($r = 0.92$) and FT3 ($r = 0.84$). The strong association between mean grain yield and FT3 was expected because the values of this stability parameter were high for high-yielding genotypes. Earlier reports from other studies also indicated the presence of strong positive correlations of grain yield with FT3 and P_i [39–41], including in Ethiopian bread wheat genotypes [42]. This result indicated that the use of P_i and FT3 as a tool to evaluate performance of faba bean genotypes in future selection programs would favor simultaneous development of stable and high-yielding genotypes. However, three other stability statistics, namely D_i, $S_i^{(3)}$, and $S_i^{(6)}$, showed significant positive associations with one another and strong negative rank correlations ($r = -0.81$ to -0.99) with grain yield. Thus, selection based on these stability parameters would be less useful when yield is the primary target of selection.

Significant positive rank correlation coefficients were obtained between all possible pairs of S^2d_i, W_i, σ_i^2, ASV, RS, λ, P^{59}, and $S_i^{(2)}$. The positive rank correlation coefficients between these stability parameters varied from the lowest of $r = 0.553$ ($P \le 0.05$) between S^2d_i and ASV to the highest of $r = 1.00$ ($P \le 0.01$) for σ_i^2 and W_i (Table 6). The significant positive correlation between these stability parameters suggests that these parameters would play similar roles in stability ranking of genotypes as previously reported [41].

Three of the parametric stability parameters (P^{59}, σ_i^2, and W_i) also showed strong rank correlation coefficients with Tai's λ and ASV (Table 6). This result indicated the close similarity and effectiveness of Tai's λ and ASV in detecting faba bean genotypes stable across environments. Several other investigators have also reported significant positive correlation coefficients within P^{59}, σ_i^2, and W_i, and between these stability parameters and Tai's

λ and ASV [29,33,36,39,41]. Perfect correlation was observed between the joint regression coefficient, b_i, and Tai's α. However, neither b_i nor Tai's α was significantly associated with any of the other stability parameters in the present study (Table 6). This result suggests that, compared to other stability parameters, b_i and α have a unique characteristic in ranking genotypes for stability.

Francis and Kannenberg's environmental variance (*EV*) showed significant ($P \leq 0.01$) positive correlation with P^{59} (r = 0.74) and CV_i (r = 0.85) but significant ($P \leq 0.05$) negative correlation with FT3 (r = −0.53). Moreover, the coefficient of variation (CV_i) was positively and significantly ($P \leq 0.01$) associated with P^{59} (r = 0.76) and RS (r = 0.64). The significant positive correlation observed for EV and CV_i with P^{59} shows that a substantial proportion of the phenotypic instability measured by P^{59} resulted from the G × E interaction sum of squares. The high rank correlation between EV and CV_i was in accord with reports of other investigators in field pea [33], durum wheat [32,39], bread wheat [41], and lentil [36].

3.4. *Principal component analysis of the rank correlations*

Principal component analysis based on the rank correlation matrix was performed to gain better understanding of the relationships among both parametric and nonparametric stability parameters. The first and second principal components of the rank correlation accounted for 55.37% and 23.52% of the variation, respectively, making a total of 78.89% of the original variance among the stability parameters (Fig. 1, Table 5). Similar results have been reported from other studies in faba bean and field pea [24], durum wheat [39], and barley [40].

The stability parameters were separated into two stability concepts: at left, parameters that corresponded with the dynamic/agronomic stability concept were assigned. The genotypic superiority measure (P_i), number of sites at which the genotype occurred in the top third of the ranks (FT3), and grain yield (GY) were clustered in this category. At right, the remaining stability parameters corresponding with the static/biological stability concept were assigned to three subgroups (Fig. 1). This result signified that P_i and FT3 were strongly correlated with grain yield of faba bean. A previous report [24] also indicated that P_i and FT3 were strongly influenced by yield level in faba bean and field pea. In another study [17], P_i was proposed as a measure of genotypic performance that integrated both yield and stability. Thus, selection based on P_i and FT3 parameters and thus related to the dynamic concept of stability would favor selection for high-yielding faba bean genotypes with general adaptability. Becker and Leon [15] also stated that it was not a requirement that the genotypic response to changes in environmental conditions should be equal for all genotypes. Thus, these parameters could be used to identify high-yielding faba bean genotypes adapted to a wide range of conditions in Ethiopia. However, selection of stable genotypes based on these methods (P_i and FT3) may lead to discarding a genotype with low general but high specific adaptability [43].

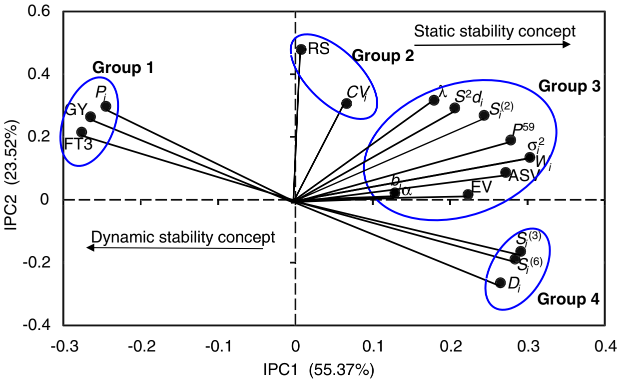

Fig. 1 – Biplot of IPC1 and IPC2 of the rank correlation matrix of the 17 univariate stability parameters with grain yield.

The biplot of the first two principal components classified the stability parameters into four major groups (Fig. 1). The parameters CV_i and RS clustered in group 2, which was positioned closer to group 3 than group 1, lay in the static/biological stability concept. Other authors [11,24] also reported that CV_i and RS statistics belonged to the static stability concept. Group 3 comprised 10 of the 17 stability parameters, including α, λ, S^2d_i, b_i, $S_i^{(2)}$, W_i, σ_i^2, EV, P^{59}, and ASV (Fig. 1). Results of the biplot of the first two principal components based on the rank correlation matrix were more or less consistent with the Spearman rank correlation coefficients (Fig. 1, Table 6). The third group was simultaneously influenced by yield and stability. Thus, like group 2, this group of stability parameters also follows a static stability concept and they could be used as alternative tools to select genotypes with better yield and high stability. Stability parameters including D_i, $S_i^{(3)}$, and $S_i^{(6)}$, which showed strong negative association with grain yield (Table 6), were clustered into group 4. It should be remembered that, based on these parameters, the low-yielding faba bean genotypes including EK01001-10-5, EK01007-2-6, EK01015-1-1, EK01019-2-1, and EK01024-1-1 were identified as the most stable (Table 5). These parameters, which identify genotypes with high phenotypic stability without due consideration of grain yield, may not be appropriate, as both breeders and farmers prefer to select high-yielding genotypes that perform consistently across environments. Similar to the current result, a strong negative rank correlation between grain yield of durum wheat and barley with $S_i^{(3)}$ and $S_i^{(6)}$ has been reported [32]. However, contrasting results indicating the presence of positive correlations between the three parameters (D_i, $S_i^{(3)}$, and $S_i^{(6)}$) and grain yield in durum wheat have been reported [39].

4. Conclusion

Several of the univariate parametric and nonparametric stability statistics employed in the present investigation quantified stability of faba bean genotypes with or without respect to yield. However, both mean yield and stability should be considered simultaneously to exploit the useful effects of G × E interaction and to make the selection of favorable genotypes more precise. In the present study, two of the stability parameters, namely P_i and FT3, were found to be strongly correlated with grain yield. This finding indicated that using P_i and FT3 to evaluate the performance stability of faba bean genotypes in future selection programs would favor the simultaneous development of stable and high yielding genotypes. Based on these stability parameters, high-yielding genotypes such as EK 01024-1-2 and EK01001-5-1 and the commercial faba bean varieties Moti and Gebelcho showed better performance stability across a range of environments. Moreover, 12 of the 17 univariate stability parameters including CV_i, RS, α, λ, S^2d_i, b_i, $S_i^{(2)}$, W_i, σ_i^2, EV, P^{59}, and ASV were found to be simultaneously influenced by both yield and stability. Perhaps they could be used as alternative tools to select genotypes with moderate yield and high stability. Though both high yield and type I stability rarely occur in multi-location trials, it was evident in this investigation that parameters such as P^{59}, $\sigma_i{}^2$, W_i, CV_i, and EV identified EK01024-1-2 as the most desirable genotype, possessing type I stability. This genotype also ranked in the top third of all genotypes in well over half of the 16 test environments. For this reason, it was released as a new variety "Gora" in 2013 for wider production for its high yield potential, large seed size, and wide adaptability. Therefore, it is advisable that selection of faba bean genotypes should consider the use of the different stability parameters described here, based on the objectives of selection.

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