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Agronomical and Physiological Response of Common Bean (*Phaseolus vulgaris* L.) Genotypes to Low Soil Fertility at the Southern Highland Region of Yemen

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Abstract

Production of common bean (*Phaseolus vulgaris* L.) is often limited by the low soil fertility (LF). Identification of common bean genotypes adapted to LF may be a feasible strategy to overcome the poor plant growth and production in NP-deficient soils. Eight bean genotypes samples/derived from International Center for Tropical Agriculture (CIAT) and three local common bean cultivars were evaluated in low soil fertility (LF) and recommended fertilizers (RF) at three locations representing high (Mashwarah), medium (Shaban) and low (Al-Qaidah) rainy seasons at Southern Highland Region (SHR), Ibb, Yemen in 2011, 2012 and 2013 following a completely randomized block design, arranged as split plot with either (LF) or (RF) as the main plots and the genotypes as sub plots. Three replications were used. The LF plots was absolute control, it did not receive any fertilizer (LF) and in (RF) plots, it received only 34.5 kg N and 92 kg P_2O_5 kg. The common bean genotypes varied in phenotypic, nutrient efficiency traits and low fertility tolerant indices. The genotypes G2381B, MIB-156, BFB-140, BFB-141 performed favorably under both (RF and LF) environments. These genotypes were associated with higher values of pod number/plant, seed number/plant and 100 seed weight and leaf area, root nodules mass, shoot mass and root mass, shoot mass, physiological, nutrients and recovery efficiency and geometric mean percent (GMP), mean percent (MP) and susceptible tolerant index (STI) and low values of agronomy efficiency, percent of reduction (PR), low fertility susceptible index (LFSI) and tolerant (TOL). The results also showed that high and significant positive correlation of low fertility yield (LFY) and recommended fertility yield (RFY) with seed number/plant and 100 seed weight, NP recovery and use efficiency, geometric mean percent (GMP), mean percent (MP) and susceptible tolerant index (STI) under LF or RF. These correlations indicates that direction selection for yield under LF or RF would result into improved LF tolerant genotypes. Using phenotypic, nutrient efficiency traits, low fertility tolerant indices and stability indices criteria, only G2381B, MIB-156, BFB-140, BFB-143 and BFB-144 showed high average of yields, with *b*-value of 1.00 and a very low standard deviation (s^2d) approaching zero, low ecovalence value (W) and highly significant coefficient of determination (r^2). However, the regression coefficients indicating stability (*b*'s) and residuals were highly correlated with slopes ($r = 0.943$; $P < 0.001$) and coefficient of determination ($r = 0.711$; $P < 0.001$) and equivalent value ($r = 0.809$; $P < 0.001$), respectively. Thus the data collected from three locations x three years can be used to select low fertility tolerant (or 'stable') genotypes. Such low fertility tolerant genotypes would be better suited for poor farmers in the SHR-Ibb and other similar production regions in Yemen.

Keywords: physiological and nutrients efficiency, low fertility tolerant, stability indices

1. Introduction

Low soil nitrogen and phosphorous is a widespread constraint to common bean production on tropical and sub-tropical soils in Yemen, mostly in soils that have been over cultivated with pH above 7.4. The recommendation dosages for bean are range from 69.5 to 92 P_2O_5 kg ha^{-1} and 34.5 Kg ha^{-1} in case of inoculation with local Rhizobium strain (Molaaldoila, 2008). The general symptoms of mineral deficiency or toxicity of common bean may include poor emergence; slow growth; seedling and adult plant stunting; leaf yellowing;

chlorosis; and bronzing; early seedling death; reduced overall growth and dry matter production; delayed and prolonged flowering and maturity; excessive flower and pod abortion; low harvest index; reduced seed weight; deformed and discolored seeds; and up to 100% yield loss. Root growth may also be adversely affected (Cumming et al., 1992; Fawole et al., 1982). These symptoms may vary with the type, severity, and duration of mineral stress.

Mostly soils that have little phosphorous available for the plant may contain considerable amounts of phosphorous but a large proportion is bound to different soil constituents, forming complexes of limited availability (Driessen et al., 2001; Fairhust, 1999). However, to overcome mineral deficiencies and toxicities, common bean growers must use corrective soil amendments such as lime (Fageria et al., 1995; Westermann, 1992), manure or composted manure (Tarkalson et al., 1998), and fertilizers rich in macro- and micronutrients such as N, P, B, Fe and/or Zn (Henson & Bliss, 1991). Identification and use of cultivars tolerant to mineral deficiencies and/or toxicities are essential for reducing production costs and dependence of farmers on soil amendment inputs.

Large genotypic differences in low fertility tolerance among crops also have been reported within-species variation in common bean for P (Whiteaker et al., 1976), nitrogen (Graham, 1981), Zn deficiency and response (Westermann & Singh, 2000) and Al tolerance (Foy et al., 1972; Noble et al., 1985). Genetic variability for tolerance to low phosphorous soils also has been identified in common bean (Beebe et al., 2006; Singh et al., 2003). Breeding aiming improve common bean lines with greater phosphorous acquisition and better tolerance to low phosphorous soils is a feasible strategy as shown by a range of inheritance studies. However, tolerance to low phosphorous requires maintenance of plant growth and yields in soils with limited available phosphorous and is reported to occur by two distinct routes namely acquisition efficiency and utilization efficiency (Lynch & Beebe, 1995). Acquisition efficiency is the plant's ability to extract phosphorous from the soil and is expected to be related to root system traits that increase root surface area or facilitate phosphorous acquisition (Gahoonia & Nielsen, 2003). Utilization efficiency is a function of plant growth, remobilization and physiological traits that translate phosphorous acquired by the roots into yield. Therefore phosphorus efficiency is defined as the ability of plants to produce higher biomass or yield, and/or take up more phosphorous under inadequate phosphorous conditions (Yan et al., 2006; Zhu, 2004).

At the International Center for Tropical Agriculture (CIAT), Cali, Colombia, extensive research was conducted in order to evaluated N fixation (Graham, 1981), tolerance of P deficiency (Beebe, 1997; Thung, 1990; Yan et al., 1995; Youngdahl, 1990) and Al and Mn toxicity (Ortega & Thung, 1987) in common bean. In each of these cases, large genotypic differences were found. Furthermore, there can be strong interactions among different minerals (Bache & Crooke, 1981) and other abiotic and biotic factors. Therefore, a more holistic approach was adapted at CIAT to develop two input environmentally sensitive technologies for common bean and other species (Nickel, 1987). In regard to low fertility, multiple deficient or toxic mineral stresses were applied to screen common bean germplasm (Ortega & Tbung, 1987; Singh et al., 1995) and conduct genetic (Urrea & Singh, 1989) and breeding studies (Singh et al., 1989).

Furthermore, the use of fertilizers to correct soil for nitrogen and phosphorous deficiency may not be a practical option for the small-scale farmers in developing countries because inorganic fertilizers are expensive. It was also believed that germplasm and cultivars thus developed would be better suited for poor farmers in the tropics and subtropics. Such low fertility tolerant cultivars with higher yield potential would also be valuable for environment-friendly, sustainable farming systems in other production regions and increase profit margins for growers. In addition to this, recovery of phosphorous nutrient applied as fertilizer by crop plants is also reported to be usually low, because most of the nutrient becomes unavailable due to adsorption, precipitation or conversion to organic forms (Araujo et al., 2005). Worse still, part of the applied P in intensive cropping systems can enter the waterways through runoff and erosion, contributing to pollution of surrounding lakes and marine environments (Tesfaye et al., 2007). Probably an alternative approach to all the above problems is to enhance the plant's efficiency to acquire soil phosphorous (Shenoy & Kalagudi, 2005; Lynch, 2007). Hence, the need to identify and use genotypes tolerant to phosphorous deficiency that would also reduce production costs and dependence of farmers on soil amendments.

Therefore the objective of this study was (i) to identify LF tolerance among CIAT and local common bean genotypes (ii) to identify optimal selection criterion as morpho-physiological traits that might impart "low fertility tolerance". (iii) Evaluate the response and stability of bean genotypes grown in diverse bean growing regions of Yemen using stability indices.

2. Material and Methods

2.1 Environmental Locations

Eight CIAT and three local common bean genotypes were evaluated in low soil fertility (LF) at three locations representing; L_1: high (Mashwarah), L_2: medium (Shaban) and L_3: low (Al-Qaidah) rainfed environments at the Southern Highlands Region (SHR)-Ibb Yemen in 2011, 2012 and 2013 following a completely randomized block design, arranged as split plot with both low soil fertility (LF) and recommended fertilizers (RF) as the main plots and the genotypes (Mib-156, G23818B, BFB-139, BFB-140, BFB-141, BFB-142, BFB-143, BFB-144, Taiz-304, Taiz-305, Taiz-306) as sub plots. Three replications were used. The LF plots was absolute control, it did not receive any fertilizer (LF) and in recommended or high fertility (RF) plots, it received 34.5 N kg/ha^{-1} and 92 kg P_2O_5 kg/ha^{-1}. All locations trials were treated as rain fed except at Al-Qaidah where supplemental irrigation was used twice during planting and late stage. Each plot consisted of a 6 rows of 5.0 m long and the distance between rows was 0.50 m at all location.

2.2 Plant Phenology and Production

Average leaf area of the most fully expanded top trifoliate leaf per genotype were estimated at 60 days after sawing (DAS) following the model as described by Bhatt and Chanda (2003); LA (cm^2) = 0.11 + 0.88 (L + W) where LA = Leaf area; L = Length of the leaf midrib; W = Maximum leaf width. Three rows were harvested in each plot at maturity and data were average per plot. Pods were counted, oven dried, and seed weight was determined per each row section. Total above-ground dry mailer was determined by harvesting the stover at the ground surface and by drying a 1 kg sample of each row section at 85 °C for 48 h. Total above ground biomass included pods and seed dry matter. Harvest index was calculated as the proportion of grain in total biomass.

2.3 Agronomical and Physiological Nutrients Efficiency

After (60-70 DAS) fresh weight and dry weight of the roots and shoots were taken to determine the dry materials of the freshly harvested organs (roots and shoots) after they were dried in an aerated oven at 80 °C. Successive weight was carried out until the constant dry weight of each sample reached. The dry root/shoot ratio of plant was also calculated for dry weights at each sampling stage. N was determined in shoot and root according to the method adopted by Lowry et al. (1951) and phosphorus determination was done as by Woods and Mellon (1941).

Agronomical efficiency (AE) was defined as the economic production obtained per unit of nutrient applied. It can be calculated as AE = (seed yield of fertilized crop in kg – seed yield of unfertilized crop in kg)/quantity of fertilizer applied in kg. *Physiological efficiency* (PE) was defined as the biological production obtained per unit of nutrient absorbed. Sometime is also known as biological efficiency or efficiency ratio. It can be calculated as PE = (total dry matter yield of fertilized crop in kg – total dry matter yield of unfertilized crop in kg)/(nutrient uptake by fertilized crop in kg – nutrient uptake by unfertilized crop in kg). *Apparent Recovery Efficiency* (ARE) was defined as the quantity of nutrient absorbed per unit of nutrient applied. It can be calculated as ARE = (nutrient uptake by fertilized crop in kg – nutrient uptake by unfertilized crop in kg)/quantity of fertilizer applied in kg) × 100. Physiological efficiency and recovery efficiency recovery efficiency can be combine to obtain *nutrient use efficiency* (NUE) that is determined as NUE = PE × ARE (Moll et al., 1982).

2.4 Low Soil Fertility Resistance Indices

Seed yields were adjusted to 140 g kg^{-1} moisture by weight, therefore, seed yields for LF environments (LFY) and LR environments (LRY) were recorded. Formulas were adopted to calculate low soil fertility intensity index (LFII) and low soil fertility susceptibility index (LFSI) from Fischer and Maurer (1978), low soil fertility tolerant index (LFTI) from Fernandez (1992), low soil fertility tolerance (LFT) from Rosielle and Hamblin (1981). Geometric mean (GM) was determined for seed yield as GM = (RF × LF). Also, percent reduction (PR) due to LF stress in relation to the (RF) environment was also determined for seed yield.

2.5 Statistical Analysis

Statistical analysis was carried out with the aid of S.A.S. statistical package (SAS institute Inc., USA) and mean comparison according to Duncan Multiple Range Test (DMRT) at $P < 0.05$. Simple correlation coefficients among different traits were also determined by using the same SAS software. For data analysis, the cropping seasons and replications were considered as random effects and (LF) versus (RF) environments and common bean genotypes as fixed effects (Mcintosh, 1983).

3. Results and Discussion

3.1 Plant Phenology and Production

The average of low soil fertility intensity index (LFII) for all genotypes, location and years ranged from 38.7% to 54.7% indicating that on the average LF stress were moderate to severe. However, genotypes differed very markedly in their response to this level of LF stress. Evidently, LF stress reduced yield to less than a half in some genotypes, while it was not reduced significantly at all in others. We can categorized genotypes into four groups; the first group were uniform superiority in both (RF and LF) conditions, these genotypes were G2381B, MIB-156, BFB-140, BFB-141 and we can consider them as LF tolerant genotypes; the second group were the genotypes that perform favorably only in LF-stressed environments, these genotypes were BFB-142, BFB-143, BFB-144; the third group were perform poorly in LF condition and those genotypes were almost the local cultivars (Taiz-304, Taiz-305 and Taiz-306) and we can consider them as LF susceptible genotypes. The genotypes from the last group are suitable only for RF conditions and in this group there is only one local cultivar, Taiz-306. Yield under LF stress of LF susceptible genotypes ranged from 1.055 to 1.413 t/ha, that corresponded with a range of 44.4% over the controls. However, the yield of LF tolerant genotypes that perform favorably in both RF and LF environments were ranged from 1.570 to 1.896 t/ha*,* that corresponded with a range of 17.2% over the controls (Table 1).

Table 1. Average yield (t/ha), Pods/plant, Seeds/plant, 100 seed weight (100SW), harvest index % (HI) of eleven common bean genotypes as affected by LF and RF environments at SHR-Yemen

Genotypes	Yield		Pods/plant		Seeds/plant		100 seed weight		Harvest index	
	LF	RF	LF	RF	LF	RF	LF	RF	LF	RF
Mib-156	2.213	1.896	28.5	21.5	113.1	97.7	25.3	22.1	40.1	45.7
G2381B	2.287	1.833	29.6	23.5	124.4	86.7	27.2	21.8	40.2	49.5
BFB-139	2.225	1.659	29.3	19.4	117.2	76.5	26.3	18.4	37.8	47.9
BFB-140	2.124	1.570	26.6	15.9	106.3	77.1	23.9	17.7	40.2	49.6
BFB-141	2.242	1.685	27.2	18.1	116.1	77.6	26.1	19.5	36.9	45.2
BFB-142	2.256	1.685	28.2	19.4	119.3	75.2	21.6	19.6	40.1	42.9
BFB-143	1.931	1.413	24.4	16.5	83.9	80.7	23.5	18.1	37.6	46.5
BFB-144	1.778	1.175	21.3	15.5	80.2	77.2	17.8	15.2	38.7	41.4
Taiz-304	1.860	1.170	17.8	14.9	74.9	50.8	19.1	10.8	39.9	33.6
Taiz-305	1.869	1.198	17.7	13.7	79.8	59	19.4	14.1	39.5	38
Taiz-306	2.133	1.055	25.6	13.3	112.7	62	25.9	14.6	38.2	36.8
Average	2.083	1.485	25.1	17.4	102.5	74.6	23.3	17.4	39.0	43.4
LSD DMRT	0.391	0.277	3.25	3.55	12.13	14.27	3.9	4.5	2.91	4.71
CV (%)	15.3	19.3	13.3	18.1	11.6	14.8	15.7	14.6	14.6	10.7

Note. CV = coefficient of variation.

The ranks of genotypes for average number of pod per plant, seed per plant, 1000 seed weight and harvest index were identical and almost corresponded to the ranking for LFY, and RFY. In general these yield traits were reduced by LF stress to the extent of 48.0, 45.0, 43.6, 31.3, and 30.8% for the control genotype (Taiz-306), respectively (Table 1). The superior performance of these genotypes was associated with higher values of number of pod per plant, number of seed per plant, 100 seed weight and harvest index. On the other hand, harvesting index exhibited rankings different than the other indices. The harvesting index of LF tolerant genotypes was significant high at LF environment in comparison with RF environment (Table 1). Large genotypic differences in low fertility tolerance among crops also have been reported within-species variation in common bean for P (Whiteaker et al., 1976) and nitrogen (Graham, 1981).

Average leaf area (cm^2/plant), nodule mass (mg/plant), root dry weight (RDW), shoot dry weight (SDW) and root/shoot ratio (RSR) of eleven common bean genotypes as affected by LF and RF environments were shown in Table 2. LF stress strongly reduced the leaf area of bean plants but the deleterious effect were low for the LF tolerant genotypes and high for the LF susceptible genotypes implying that genotypes such as G2381B, MIB-156, BFB-140, BFB-141 observed with the highest leaf area were able to maintain their leaf growth under low nitrogen and phosphorous availability. The decrease in leaf area due to LF stress was also accompanied by decrease in root and shoot biomass. This is because when leaf expansion is reduced, there is less carbon assimilation that results into low shoot biomass. According to Trindade et al. (2010) and Namayanja et al. (2014), low phosphorus supply markedly limits leaf growth in common bean and genotypes able to maintain adequate leaf area at low P could adapt better to limited-P conditions.

Table 2. Average leaf area (cm^2/plant), nodule mass (mg/plant), root dry weight (RDW), shoot dry weight (SDW) and root/shoot ratio (RSR) of eleven common bean genotypes as affected by LF and RF environments at SHR-Yemen

Genotypes	Leaf area		Nodule mass		RDW		SDW		Harvest index	
	LF	RF	LF	RF	LF	RF	LF	RF	LF	RF
Mib-156	33.8	25.4	4.5	3.6	6.8	6.6	48.9	46.2	7.19	7.00
G2381B	35.7	26.7	4.5	3.6	6.9	6.9	48.4	43.2	7.01	6.26
BFB-139	36.3	26.5	4.4	3.9	7.1	5.7	45.4	36.7	6.39	6.44
BFB-140	66.2	25.9	4.6	4.1	7.9	4.6	45.9	34.2	5.81	7.43
BFB-141	34.5	27.2	4.1	3.3	6.3	6.8	46.2	42.4	7.33	6.24
BFB-142	32.7	17.4	4.2	4.1	7.8	6.3	44.2	41.3	5.67	6.56
BFB-143	22.2	17.2	3.3	3.6	7	5.7	37.9	33.9	5.41	5.95
BFB-144	19.6	16.3	3.8	3.1	5.8	4.5	34.7	24.3	5.98	5.4
Taiz-304	15.3	10.6	3.9	33	4	4.5	26.9	26.4	6.73	5.87
Taiz-305	16.3	12.5	3.4	3.2	5.3	5.4	33	22.9	6.23	4.24
Taiz-306	17.6	12.1	3.9	2.7	5.6	4.4	32.8	22.2	5.86	5.05
Average	30.0	19.8	4.1	6.2	6.4	5.6	40.4	34.0	6.33	6.04
DMRT	4.26	3.7	0.67	4.3	2.3	2.4	4.16	14.4	1.90	14.6
CV%	12.7	17.8	9.7	17.8	13.6	28.4	16.4	21	14.6	28.1

Therefore the genotypes had significantly difference in root, shoot mass and shoot/root ratio (SRR) as well under both LF and RF environments. The LF tolerant genotypes recorded highest root mass of 6.8–7.8 gm/plant and 5.7–6.9 gm/plant under both LF and RF environments, respectively. While the average genotypic variation for shoot mass were also highest in the LF tolerant genotypes it ranged from 42.4 to 46.2 gm/plant and 44.81–48.9 gm/plant under both LF and RF environments, respectively. However, the LF susceptible genotypes had significantly lowest values in comparison with LF tolerant genotypes. Similarly, the shoot/root ratio (SRR) of biomass did exhibited significant increase in LF environments in comparison with RF environments and was highest in LF tolerant genotypes than LF susceptible genotypes. The SRR of LF tolerant genotypes were about 5.81–7.33 gm/plant and 6.24–7.43 under both LF and RF environments, respectively. In contrast, the LF susceptible genotypes had significantly lowest values in comparison with LF tolerant genotypes. These results clearly indicated that the root mass affected more than shoot mass by LF stress. Several morphological characters including root and shoot dry weights have been identified as important to low P tolerance in common bean (Wortman et al., 1995; Namayanja et al., 2014).

High and significant increase of overall average yield and other yield traits were observed among all genotypes at high (L_1) and medium (L_2) yielding environments over low (L_3) yielding environment (Table 3). Therefore, the response of bean genotypes to LF stress depend on the severity of the water stress. Only in environments where LF stress of normal (L_1) to moderate (L_2) availability of water, the reduction in yield, p/plant, S/plant, 100 SW, HI, LA, NM, RDW and SDW were less in comparison with severe water stress (L_3). However, LF tolerant genotypes G2381B, MIB-156, BFB-140, BFB-141 performed favorably under both moderate (L_2) and severe (L_3) water stress and recorded higher values of yield and other mentioned traits in comparison with other genotypes. These observations were in accordance with the finding of Teran and Singh (2002) who found that LF tolerance, land races possess many other useful traits like high levels of resistance for drought stress.

3.2 Agronomical and Physiological Nutrients Efficiency

The results showed that LF susceptible genotypes have low values of nitrogen agronomical efficiency (NAE) and nitrogen physiological efficiency (NPE) and high values of nitrogen recovery efficiency (NRE) and nitrogen use efficiency (NUE). In contrast LF susceptible genotypes had high NAE and NPE and low NRE and NUE. The NAE, NPE, NRE and NUE of the LF tolerant genotypes were 13.2–16.1 and 32.8–43.8, 13.2–15.0 and 13.3–16.6 respectively, while the NAE, NPE, NRE and NUE of the LF susceptible genotypes were 19.5–28.5, 56.4–65.0, 6.6–7.1 and 3.51–4.18 respectively.

Similarly, the results revealed that LF susceptible genotypes have low values of phosphorous agronomical efficiency (PAE) and phosphorous physiological efficiency (PPE) and high values of nitrogen recovery efficiency (PRE) and phosphorous use efficiency (PUE). In contrast LF susceptible genotypes had high PAE and PPE and low PRE and PUE. The PAE, PPE, PRE and PUE of the LF tolerant genotypes were 6.58–7.63 and 2.18–3.67, 0.78–0.90 and 1.64–3.33 respectively, while the PAE, PPE, PRE and PUE of the LF susceptible genotypes were 9.13–15.62, 3.16–3.90, 0.48–0.52 and 1.65–2.33 respectively (Table 4).

Table 3. Location variation in some phenotypic traits of eleven common bean genotypes as affected by LF and RF of rainy seasons at SHR-Yemen

Locations	LFY	P/plant	S/plant	100SW	LA	HI	RNM	RDW	SDW	SRR
L_1	2.491	30.1	134.3	27.7	44.3	27.5	4.9	8.2	48.7	5.9
L_2	2.111	25.2	97.8	23.6	41.4	24.2	3.9	6.4	40.4	6.3
L_3	1.648	20	75.5	18.5	31.4	20.9	3.4	4.6	32.1	7.0
Average	2.083	25.1	102.5	23.3	39	24.2	4.1	6.4	40.4	6.4
DMRT	0.34	5.1	8	3.6	2.3	16.1	0.4	2.5	2.5	0.2
CV%	13.3	8.7	11.1	20.9	11.6	13.2	12.4	13.6	17.1	9.6
L_1	1.746	23.3	92.2	22.1	60.9	19.9	4.4	7.1	42.6	6.0
L_2	1.462	18.2	81.8	18.6	51.4	15.7	3.9	5.4	38.4	7.1
L_3	1.248	16.7	55.5	14.5	31.4	13.9	3.4	4.6	29.1	6.3
Average	1.485	17.4	74.6	17.4	42.5	15.3	6.2	5.6	34.0	6.04
DMRT	0.266	3.7	6.4	3.5	3.3	1.2	2.3	2.9	2.1	2.3
CV%	18.2	23.2	21.8	19.4	25	17.2	17.3	14.6	12.7	10.1

However, NPE and PUE were significantly high in the high (L_1) and medium (L_2) yielding environments over low (L_3) yielding environment, whereas no significant differences between locations in the other nitrogen and phosphorus efficiency traits (Table 4). Water stress is known to affect P uptake and utilization in common bean (Al-Karaki et al., 1995).

Table 4. Some nutrient efficiency traits of eleven common bean genotypes as affected by LF and RF of rainy seasons at SHR-Ibb-Yemen

Genotypes/Locations	Nitrogen efficiency traits				Phosphorous efficiency traits			
	NAE	NPE	NRE	NUE	PAE	PPE	PRE	PUE
Mib-156	15.0	43.7	13.9	5.5	7.5	3.8	0.8	2.9
G2381B	13.2	38.1	14.7	5.2	6.6	3.7	0.9	3.3
BFB-139	16.4	35.6	14.5	5.1	8.2	3.0	0.8	2.4
BFB-140	16.0	47.8	13.3	5.6	7.7	3.5	0.9	2.9
BFB-141	16.1	32.8	16.6	5.4	7.6	2.2	0.8	1.6
BFB-142	16.5	37.9	13.3	4.7	9.4	2.8	0.8	2.1
BFB-143	15.0	56.2	12.5	5.4	7.2	3.8	0.8	2.9
BFB-144	17.5	37.0	12.0	4.3	9.6	2.9	0.8	2.3
Taiz-304	20.0	64.6	7.0	4.1	9.1	5.1	0.5	2.3
Taiz-305	19.5	56.4	7.1	3.5	9.7	3.2	0.5	1.7
Taiz-306	28.5	65.0	6.6	4.2	15.6	3.9	0.5	2.0
Average	17.6	46.8	12.0	4.8	8.9	3.4	0.7	2.4
DMRT	1.7	0.4	2.2	0.8	4.0	2.4	0.2	0.8
CV%	25.8	15.7	28.4	26.3	18.2	17.3	18.6	19.7
L_1	15.9	47.1	13.0	5.5	8.0	3.9	0.8	3.0
L_2	14.1	42.4	13.3	5.3	7.1	4.0	0.9	3.7
L_3	16.6	35.0	15.0	5.2	8.3	3.0	0.9	2.6
Average	15.6	41.5	13.8	5.3	7.8	3.7	0.9	3.1
DMRT	NS	5.3	NS	NS	NS	NS	0.3	0.4
CV%	22.0	17.1	23.3	11.9	13.6	21.1	19.3	16.2

These results indicated that the LF tolerant genotypes had the ability to extract or take up more nitrogen and phosphorous under inadequate NP condition efficiently and this is expected to be related to root system traits that increase root surface area or facilitate nutrients acquisition and to produce higher biomass or that reflect in the increase in plant growth and yields under LF environments. Tolerance to low phosphorous requires maintenance of plant growth and yields in soils with limited available phosphorous and is reported to occur by two distinct routes namely acquisition efficiency and utilization efficiency (Lynch & Beebe, 1995). Acquisition efficiency is the plant's ability to extract phosphorous from the soil and is expected to be related to root system traits that increase root surface area or facilitate phosphorous acquisition (Gahoonia & Nielsen, 2003). Utilization efficiency is a function of plant growth, remobilization and physiological traits that translate phosphorous acquired by the roots into yield. Therefore phosphorus efficiency is defined as the ability of plants to produce higher biomass or yield, and/or take up more phosphorous under inadequate phosphorous conditions (Yan et al., 2006).

3.3 Low Soil Fertility Tolerant Indices

The ranks of genotypes for GMP, MP and STI were identical and almost corresponded to the ranking for LFY, and RFY. On the other hand, RP, LFSI and LFT exhibited rankings different than the other indices. The tolerant indices GMP, MP and STI of the LF tolerant genotypes were significantly higher than the LF susceptible genotypes. In contrast, the tolerant indices RP, LFT and LFSI of the LF tolerant genotypes were significantly lower than the LF susceptible genotypes. The GMP, MP and STI of the LF tolerant genotypes (1.92–2.05, 1.94–2.06 and 0.44–0.50) were high in comparison the LF tolerant genotypes (1.47–1.50, 1.51–1.59 and 0.27–0.28), respectively. The LFSI of the LF tolerant genotypes were < 1 whereas the LFSI of the LF susceptible genotypes were > 1. For all genotypes tested, yield percent reduction (PR) by LF stress was also significantly affected but the magnitude of reduction was in the LF susceptible genotypes (35.9–50.5%) in comparison with the LF tolerant genotypes (19.8–25.4%). Likewise, the increments of LFT of the LF tolerant genotypes reached to the extent of (0.45–0.57) while the increments of LFT in the LF susceptible genotypes reached to the extent of (0.67–1.08) (Table 5). These results are in corresponds with the results of (Saba et al., 2001) who concluded that the ranks of parents for GMP, MP and STI were identical and almost corresponded to the ranking for Y, and Yp.

On the other hand, TOL and DSI exhibited rankings different than the other indices.

Table 5. Some low fertility tolerant indices of eleven common bean genotypes as affected by LF and RF of rainy seasons at SHR-Ibb-Yemen

Genotypes/Locations	PR	LFSI	LFT	GMP	MP	STI
Mib-156	23.4	0.78	0.52	1.94	1.95	0.45
G2381B	19.8	0.66	0.45	2.05	2.06	0.50
BFB-139	25.4	0.86	0.57	1.92	1.94	0.44
BFB-140	26.1	0.89	0.55	1.83	1.85	0.41
BFB-141	24.8	0.84	0.56	1.94	1.96	0.45
BFB-142	25.3	0.84	0.57	1.95	1.97	0.46
BFB-143	26.8	0.97	0.52	1.65	1.67	0.36
BFB-144	33.9	1.16	0.60	1.44	1.48	0.27
Taiz-304	37.1	1.26	0.69	1.47	1.51	0.27
Taiz-305	35.9	1.22	0.67	1.50	1.53	0.27
Taiz-306	50.5	1.72	1.08	1.50	1.59	0.28
Average	29.9	0.81	0.53	1.93	1.95	0.45
DMRT	9.6	0.54	0.12	0.24	0.18	0.11
CV%	17.8	22.70	21.80	23.20	19.60	16.90
L1	25.5	0.82	0.55	1.86	1.88	0.42
L2	21.5	0.69	0.49	2.01	2.03	0.48
L3	26.7	0.85	0.57	1.84	1.86	0.41
Average	24.6	0.79	0.54	1.90	1.92	0.43
DMRT	3.2	0.54	0.12	0.24	0.18	0.11

3.4 Low Fertility Stress Responses as Selection Criteria for Improvement LF Resistance

Under both RF and LF environments, the correlation coefficient of p/pant, s/plant and 100SW with RFY and LFY, was positively and highly significant while that of harvest index was high and positive with RFY and LFY under LF environment, whereas it was not significantly correlated with RFY and LFY under RF environment. However, p/pant, s/plant and 100SW were associated significantly with HI, and SDW under both RF and LF environments. Thus, these results indicating that these yield traits would be useful traits to select for low fertility tolerance genotypes under both RF and LF environments. Interestingly, RDW associated significantly with all studied traits except LA under RF environment while LA, SDW and SRR associated significantly with all studied traits except RDW under RF environment indicating that the LF stress affected SDW more than RDW (Table 6). Thus, LA, HI, SDW and SRR can be used as indirect selection criteria to select for high yielding bean genotypes for LF environments while RDW can be used as indirect selection criteria to select for high yielding bean genotypes for RF environments. Singh et al. (2003) found that seed yield, biomass and HI were positive1y associated with low soil fertility (LF) and high soil fertility (HF) and all three traits were positively correlated among themselves in both LF and HF environments. They also suggested that the three traits were interdependent and that similar mechanisms were largely involved in their expression in both LF and HF environments.

Table 6. Overall average correlation coefficient of phenotypic traits of bean genotypes as affected by RF (normal Scripts) and LF (Bold Scripts) environments

Traits	RFY	LFY	P/plant	S/plant	100SW	LA	HI	RNM	RDW	SDW	SRR
LFY	1.000	0.867*	0.488*	0.630*	0.523*	0.428*	0.418*	0.229	0.357	0.340	0.294
LFY	0.867*	1.000	0.493*	0.584*	0.592*	0.466*	0.479*	0.212	0.325	0.368	0.262
P/plant	0.507*	0.461*	1.000	0.312	0.537*	0.411*	0.661*	0.187	0.387	0.590*	0.480*
S/plant	0.474*	0.536*	0.518*	1.000	0.516*	0.693*	0.491*	0.257	0.359	0.443*	0.382
100SW	0.522*	0.591*	0.530*	0.841*	1.000	0.390	0.783*	0.207	0.531*	0.627*	0.474*
LA	-0.134	-0.192	0.009	-0.470	-0.332	1.000	0.499*	0.258	0.491*	0.606*	0.513*
HI	0.331	0.373	0.560*	0.582*	0.742*	-0.101	1.000	0.211	0.479*	0.535*	0.440*
RNM	0.365	0.392	0.487*	0.342	0.565*	0.026	0.753*	1.000	0.127	0.157	0.207
RDW	0.456*	0.515*	0.541*	0.666*	0.805*	-0.192	0.672*	0.737*	1.000	0.468*	0.792*
SDW	0.312	0.335	0.488*	0.421*	0.630*	-0.090	0.734*	0.732*	0.638*	1.000	0.800*
SRR	0.036	0.070	-0.039	-0.061	-0.082	-0.028	-0.210	-0.119	0.088	-0.588*	1.000

Note. * Indicates highly significant correlation at 1% level.

RFY and LFY were also positively correlated to NRE, NUE, PRE and PUE while NAE, PAE and PPE were negatively correlated with RFY and LFY confirming the fact that, the differences of agronomical yield or total dry matter yield between RF and LF stresses to the quantity of fertilizer applied or nutrients uptake reduces in the LF tolerant genotypes in comparison with LF susceptible genotypes. However, NRE and PRE were positively correlated with NPE, NUE, PUE and with each other and negatively correlated with NAE, PAE and PPE. These could be due to the increase of nitrogen and phosphorous uptake that reflected in the increase in plant growth and yields of the LF tolerant genotypes under LF environments (Table 7). Singh et al. (2003) concluded that the type and number of minerals considered as selection criteria to identify genotypic differences and understanding the physiology of specific mineral uptake and utilization and they screened six common bean genotypes each of Andean and Middle American evolutionary origins for P deficiency tolerance, P-use efficiency, and response.

Correlation coefficients, calculated from the data obtained for bean genotypes, are presented in Table 8. GMP, MP and STI were highly correlated with each other as well as with YRL and LFY. Thus, through these indices it is possible to distinguish high yielding genotypes in either condition. However, PR was strongly correlated negatively with the above mentioned indices while that of LFT and LFI with LFY, was high and negative. According to Fernandez (1992) who concluded that MP, LFI and TOL failed to identify genotypes with both high yield and stress tolerance potentials, whereas through STI, genotypes with these attributes could be identified. However, these results indicated that indices such as SSI and TOL were not efficient to be used in selecting genotypes with high yield capacity in LF or RF environments. In contrast, STI and GMP, MP were can be used as efficient indices under both LF or RF environments.

Table 7. Correlation coefficient of overall average of nutrient efficiency and low fertility tolerant indices traits of bean genotypes as affected by LF and RF environments

Traits	RFY	LFY	NAE	NPE	NRE	NUE	PAE	PPE	PRE	PUE
RFY	1.000									
LFY	0.867*	1.000								
NAE	0.019	-0.435*	1.000							
NPE	-0.005	-0.218	0.445*	1.000						
NRE	0.390*	0.420*	-0.506*	-0.852*	1.000					
NUE	0.401*	0.351*	-0.335	-0.468*	0.775*	1.000				
PAE	0.034	-0.401*	0.879*	0.380	-0.526*	-0.412	1.000			
PPE	-0.218	-0.305*	0.294	0.294	-0.219	-0.022	0.079	1.000		
PRE	0.492*	0.652*	-0.467*	-0.269	0.405*	0.371*	-0.342*	-0.450*	1.000	
PUE	0.467*	0.623*	-0.140	0.045	0.365*	0.347*	-0.202	0.532*	0.462*	1.000

Note. * indicates highly significant correlation at 1% level.

It seemed that DSI (LFSI) and tolerant (LFT) were not useful indices to select for LF tolerant genotypes in plant breeding programs, because, LFSI exhibited negligible heritability and LFT was less heritable than other indices usually not identifying genotypes with both high yield and stress (drought) tolerance characteristics. On the other hand indices like STI were moderately heritable and are usually able to select high yielding genotypes in both environments (Saba et al., 2001). Therefore, based on the results obtained in these studies, STI seem to be useful yield-based LF tolerance indices to be employed in plant breeding programs for bean as it is highly correlated with YRL and LFY under both RF and LF environments.

Table 8. Correlation coefficient of overall average of nutrient efficiency and low fertility tolerant indices traits of bean genotypes as affected by LF and RF environments

Traits	YRF	YLF	NAE	NPE	NRE	NUE	PAE	PPE	PRE	PUE
YRF	1.000									
YLF	0.867*	1.000								
NAE	0.019	-0.435*	1.000							
NPE	-0.005	-0.218	0.445*	1.000						
NRE	0.590*	0.320	-0.506*	-0.852*	1.000					
NUE	0.501*	0.351*	-0.335*	-0.468*	0.775*	1.000				
PAE	0.034	-0.401*	0.879*	0.380*	-0.526*	-0.412*	1.000			
PPE	-0.218	-0.305	0.294	0.294	-0.219	-0.022	0.079	1.000		
PRE	0.492*	0.652*	-0.467*	-0.269	0.305	0.371	-0.342*	-0.450*	1.000	
PUE	0.467*	0.423*	-0.140	0.045	0.065	0.347	-0.202	0.532*	0.462*	1.000

Note. * indicates highly significant correlation at 1% level.

3.5 Genotype × Environment Interaction and Stability Analysis of Seed Yield

In Ibb-Yemen although several distinct agroclimatic locations exist widely high LF tolerant genotype such as G2381B, MIB-156, BFB-140, BFB-141 are found to be high yielding far better in almost all years of testing in most of the locations than the best local cultivars and other susceptible genotypes. These results confirmed by using stability indices criteria, where these genotypes showed high overall average of yields (1.670–1.823 t/ha), with *b*-value of 1.00 and a very low standard deviation (s^2d) approaching zero, low ecovalence value (W) and highly significant coefficient of determination (r^2) between (0.426–0.829) and with relatively high average seed yields (Table 9) could be considered widely adapted and stable; they have the ability to express their yield potential in a range of environmental conditions. These genotypes could be introduced to farmers in these agro-ecological zones. According to Showemimo (2007), a genotype considered as stable should meet criteria of high average yields, with *b*-value of 1.00 and a very low standard deviation (s^2d) approaching zero, low ecovalence value (W) and highly significant coefficient of determination (r^2). Hence the conclusion has been made that the whole part of Ibb region growing seed bean during *rainy season* can be treated as one zone.

Table 9. Average yield, coefficient regression (b), coefficient of determination (r^2), standard deviation (s^2d) and ecovalence value (W) of bean genotypes for three crop three years x three locations in the SHR of Yemen (Ibb)

Genotypes	Average yield	b	S^2d	r^2	W
Mib-156	1.737	0.706	0.034	0.914	0.112
G2381B	1.823	0.294	0.007	0.735	0.085
BFB-139	1.750	0.736	0.058	0.421	0.099
BFB-140	1.670	1.111	0.102	0.421	0.123
BFB-141	1.777	0.351	0.013	0.831	0.088
BFB-142	1.749	0.462	0.046	0.586	0.544
BFB-143	1.511	2.152	0.380	0.345	0.311
BFB-144	1.328	1.430	0.247	0.289	0.239
Taiz-304	1.360	1.187	0.113	0.852	0.101
Taiz-305	1.378	2.167	0.098	0.905	0.113
Taiz-306	1.372	2.497	0.125	0.832	0.098
Average	1.634	0.937	0.111	0.599	0.184

Rank correlation values in table 10 revealed positive, low and non-significant coefficient regression (*b*) and S^2d, r^2 and W were positive and highly significantly correlated, thus indicating that the relative stability ranking of these bean genotypes when the different stability indices are used separately. The regression coefficients indicating that stability (*b*'s) and residuals were highly correlated with slopes ($r = 0.943$; $P < 0.001$) and coefficient of determination ($r = 0.711$; $P < 0.001$) and equivalent value ($r = 0.809$; $P < 0.001$), respectively. Thus the data collected from three locations × three years can be used to select low fertility tolerant (or 'stable') genotypes. Similar results were reported in common bean by Gebeyehu and Assefa (2003).

Table 10. Rank correlations between stability indices for seed yield of bean genotypes

Traits	Average yield	b	S^2d	r^2	W
Average yield	1.000				
b	0.207	1.000			
S2d	0.198	0.711*	1.000		
r2	0.288	0.943*	0.977*	1.000	
W	0.319	0.809*	0.703*	0.698*	1.000

Note. * indicates highly significant correlation at 1% level.

4. Conclusion

We can conclude that out of the studied common bean genotypes, some genotypes were more tolerant to low fertility and greatly responded to added NP than others. Generally the LF tolerant genotypes in comparison with LF susceptible genotypes appeared to have superior in LFY and RFY and yield traits (pod number/plant, seed number/plant and 100 seed weight), and had the ability for NP uptake and utilize NP efficiently. In addition LF tolerant indices (GMP, MP and STI) were high in the LF tolerant genotypes in comparison with LF susceptible genotypes. However, traits such as seed number/plant and 100 seed weight, shoot dry weight, NRE, NUE, PRE, PUE, GMP, MP and STI can be used as selection criteria to select for high yielding bean genotypes under both RF and LF environments. Using stability indices criteria, only, G2381B, MIB-156, BFB-140 showed high average of yields, with *b*-value of 1.00 and a very low standard deviation (s^2d) approaching zero, low ecovalence value (W) and highly significant coefficient of determination (r^2). Clearly, farmers with limited resources can minimize NP fertilizer application by choice these promising genotypes in LF soils-prone environments as farmers interested in stability of yield and these genotypes could be introduced to farmers in these agro-ecological zones.

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