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Research Article

Morpho-agronomic Responses and Yield Stability of Common Bean (*Phaseolus Vulgaris L.*) Genotypes Under Contrasting Moisture Regimes

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Abstract

Moisture deficit heavily constrains common bean (*Phaseolus vulgaris L.*) production in Ethiopia, serving as a critical limitation in areas characterized by erratic rainfall. To address this challenge, forty-three common bean genotypes were evaluated in a greenhouse experiment at Hawassa University in 2022 to identify drought-tolerant materials. The trial was arranged in a Randomized Complete Block Design (RCBD) with three replications under two distinct moisture regimes: a well-watered control and a post-flowering moisture-stressed regime. Significant genotypic variation was observed for most evaluated Mopho-agronomic traits, underscoring the genetic diversity available within the germplasm. Post-flowering moisture stress severely disrupted key plant processes, resulting in a 31.6% reduction in grain yield and a 33.2% decrease in pod number per plant. Discussion points reveal that terminal moisture stress compromises carbon assimilation, triggers premature leaf senescence, and severely impairs flower retention and pod setting. Furthermore, a significant genotype × regime interaction across several parameters indicated inconsistent performance, proving that bean genotypes employ distinct adaptive mechanisms to cope with water deficits. Under non-stress conditions, variety Tatu achieved the highest production at 12.7 g plant^{-1}. Based on comprehensive selection genotypes DAB 96, SER 125, and TATU emerged as the most resilient materials. These promising genotypes are highly recommended for direct production in moisture-stressed regions and can serve as valuable donor parents in future breeding programs targeting climate-resilient agriculture in moisture-limited environments.

Keywords

Common Bean, Moisture Stress, Drought Tolerance, Genotype-By-Environment Interaction

1. Introduction

Common bean (*Phaseolus vulgaris L.*) is a vital grain legume crop on a global scale, serving as a significant source of protein, fiber, and micronutrients in human diets, particularly in developing regions [36, 46]. It is esteemed as one of the most critical food legumes, playing a substantial role in enhancing food security worldwide [52]. Notwithstanding its significance, the productivity of the common bean is profoundly jeopardized by a variety of environmental factors, with moisture stress, chiefly drought, emerging as a principal

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limitation [41]. Drought alone has the potential to inflict yield reductions that exceed 50% in common bean [10, 41].

Moisture stress negatively affects the common bean across multiple physiological, biochemical, and molecular aspects [41, 54]. On a physiological level, drought hampers plant growth and development, resulting in shorter seedlings and less biomass, as well as altered carbohydrate metabolism and restricted metabolic processes [22]. It may induce premature aging in plants, lower chlorophyll levels, and diminish photosynthetic efficiency by restricting carboxylation, heightening photorespiration, and decreasing Rubisco activity [31]. Stomatal closure, a typical plant reaction to drought aimed at conserving water, also reduces CO2 absorption, which in turn further hinders photosynthesis [40].

Drought significantly affects root systems by reducing root length and volume, both of which are essential for water uptake [46]. It also induces abnormalities in root system development [40]. At the cellular level, moisture stress impairs nutrient uptake, increases electrolyte leakage, and disrupts osmotic balance. These conditions frequently result in the generation and accumulation of reactive oxygen species (ROS), which cause oxidative stress and damage to cellular components such as chlorophyll, DNA, RNA, and proteins [44].

Plants respond to drought stress through avoidance, tolerance, and escape strategies. Avoidance includes developing deep roots, closing stomata, and leaf rolling to conserve water [31]. Tolerance involves accumulating protective solutes to maintain cell function and activating antioxidant defenses [40]. Escape strategies enable plants to accelerate their life cycle, allowing reproduction before severe drought occurs [44].

The response of common bean to moisture stress depends on genotype, with cultivars displaying varying levels of tolerance [10, 34]. Studies have identified genotypes with distinct sensitivities to both minimal and excessive soil moisture [37]. Elucidating these interactions and developing resilient varieties is essential for food and nutritional security, especially given climate change and increasing water scarcity [21]. Currently many researches aimed in identifying molecular markers and traits linked to drought resistance to support breeding of drought-tolerant common bean [4, 43, 52]. Common bean improvement in Ethiopia benefits from materials that combine acceptable yield potential with adaptation to intermittent water shortage. The diversity of released varieties and landraces evaluated here provides a useful starting point for selection and crossing. The present study used 43 common bean genotypes evaluated under well-watered and post-flowering moisture-stressed greenhouse conditions at Hawassa University which aimed to quantify morpho-agronomic and yield responses and identify genotypes with stable performance.

2. Materials and Methods

2.1. Study Site

The experiment was conducted from May to July 2022 in the greenhouse at the Hawassa University research site on the main campus, Ethiopia. The site is approximately 275 km south of Addis Ababa, at about 1,650 m above sea level, with reported annual rainfall of 900–1,100 mm and an average temperature of approximately 27 ℃. The study area supports maize, Enset, coffee and common bean production.

2.2. Plant Materials

Forty-three common bean genotypes were evaluated. The set included 35 released varieties and eight landraces collected by the Ethiopian Biodiversity Institute (appendix Table 1).

2.3. Experimental Design and Crop Management

Each moisture regime was arranged as a randomized complete block design with three replications. Nine kilograms of air-dried topsoil collected from 0–30 cm depth were placed in perforated 10L pots. Six seeds were planted per pot and thinned to four plants two weeks after emergence. NPS and urea were applied as per the recommended rates and pots were maintained weed free. The well watered treatment was irrigated until physiological maturity. In the stress treatment, water was withheld after flowering until physiological maturity. Soil moisture was monitored with a Delta-T Device HH2 moisture sensor. The two treatments were referred to as no stress (NS) and stressed (S).

2.4. Measurements and Data Collected

Agronomic observations included emergence, flowering, plant height, branches, internode length, leaf number and leaf area. Yield measurements included pods per plant, seeds per pod, and hundred-seed weight, harvest index and grain yield.

2.5. Statistical Analysis

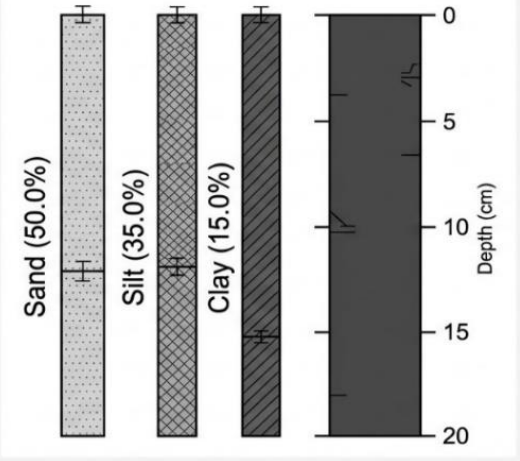
Data were analyzed using ANOVA in SAS 9.0 software. Separate and combined analyses were performed after testing homogeneity of error variances. Genotype, moisture regime and genotype × regime effects were assessed, and means were separated using LSD at $P \leq 0.05$.

3. Results

3.1. Physico-chemical Properties of the Experimental Soil

The initial soil analysis conducted to assess the necessary parameters for the study revealed that the soil at the experimental site is sandy loam, with an average composition of 15% clay, 35% silt, and 50% sand. The soil pH was found to be alkaline at 7.2. According to [51], common beans thrive in

non-acidic, well-drained soils with a pH range of 6.5 to 7.5; pH levels below 5.0 or above 8.0 are unsuitable for bean cultivation [38]. The soil's moisture content at field capacity before the experiment was recorded at 32.8%, which is within the optimal range. The ideal soil moisture content ranges from 20% to 60% [45]. The total nitrogen level at the site was measured at 0.13%, categorized as low and insufficient for common bean growth. Total nitrogen content is classified as very low (<0.1%), low (0.1% – 0.15%), medium (0.15% – 0.25%), and high (>0.25%) according to [19]. The organic carbon content was recorded at 3.25%, which is considered medium [28]. The exchange capacity (EC) of the soil was recorded at 5.04µs cm^{-1}, indicating low salinity and falling within the non-saline range as classified by USDA (2011). Overall, the physico-chemical properties of the soil suggest it is suitable for common bean production, with the exception of its nitrogen deficiency.



Parameter	Value
Organic Carbon	3.25 %
Total Nitrogen	0.13 %
pH	7.5
Electrical Conductivity	5.04 µS/cm
Field Capacity	32.5 % v/v

Figure 1. *Results of physico-chemical analysis and textural analysis of study soil.*

3.2. ANOVA of Agronomic and Yield Related Traits

Analysis of variance for the studied traits revealed presence of significant difference ($p<0.05$) among the 43 common bean genotypes tested under non-stressed conditions except for internodes length (IL) (Table 3). Similarly, there was significant difference ($p<0.05$) among the 43 genotypes for most of the traits under drought-stressed conditions except for plant height (PH), internodes length (IL), branch number $plant^{-1}$(BN) (Table 2). These results indicate the presence of genetic variability among the 43 common bean genotypes under both non-stressed and moisture stress environments for the majority of the traits studied. [3] has shown that genetic variability is crucial for the improvement of common bean cultivars, particularly under drought stress, where traits such as root length are essential for adaptation.

The result of combined ANOVA revealed significant difference ($p<0.05$) between the two environments for majority of the traits except for internode length (IL), branch number (BN), pod length (PL), seeds per pod (SPP), and harvest index (HI) (Table 4).

Table 1. *ANOVA for individual traits of common bean genotypes under moisture stress.*

TRAITS	REPLICATION	GENOTYPE	ERROR	MEAN	CV%
	DF=2	Df=42	Df=84		
EM	0.147ns	1.26**	0.052	5.78	3.94
FL	47.27**	16.82**	6.73	41.65	6.22
PH	345.37ns	218.49ns	196.05	45.69	30.64
LN	3.4ns	52.54**	4.42	12.85	16.36
LA	103.89*	502.52**	27.69	71.89	29.92

TRAITS	REPLICATION DF=2	GENOTYPE Df=42	ERROR Df=84	MEAN	CV%
IL	3.84*	1.03ns	1.17	4.52	24.03
BN	0.3ns	0.29ns	0.4	2.87	24.56
NPP	0.01ns	9.56**	0.53	4.59	15.92
PL	11.05**	4.5**	1.48	8.9	13.7
SPP	0.95ns	2.54**	0.42	4.43	14.63
HSW	18.31ns	298.09**	38.17	27.95	22.1
GY	1.46ns	9.12**	1.02	4.27	23.79
HI	56.37ns	223.31**	55.01	40.64	18.26

ns= non-significant at 5% probability, *= significant ($p < 0.05$), **= highly significant ($p< 0.01$), EM= days to 50% emergence, FL= days to 50%flowering, PH= plant height, LN=leaf number, LA= leaf area, IL=internodes length, BN= number of branches, NP=number of pods per plant, PL=pod length, SPP= seeds per pod, CT=leaf temperature, CH= chlorophyll content, GY= grain yield, HI= harvest index, HSW= hundred seed weight

Table 2. *ANOVA for individual traits of common bean genotypes under no moisture stress.*

TRAITS	REPLICATION DF=2	GENOTYPE Df=42	ERROR Df=84	MEAN	CV%
EM	0.024ns	1.34**	0.015	5.79	2.13
FL	12.85*	27.2**	3.96	43.5	4.55
PH	2.66ns	971**	21.05	56.09	8.16
LN	0.85ns	101.62**	4.24	17.99	22.4
LA	25.37ns	1070.52**	24.82	82.92	6
IL	14.3**	1.8ns	1.76	4.47	29.7
BN	1.03*	0.55*	0.32	3.25	17.5
NPP	3.54*	21**	0.98	6.88	14.35
PL	4.04ns	4.8**	1.55	9.7	12.84
SPP	2.95*	1.97**	0.46	4.77	14.23
HSW	108.94ns	410.63**	59	30.86	24.8
GY	0.78*	16.02**	0.23	6.24	7.83
HI	60.75ns	249.27**	30.23	42.39	12.97

ns= non-significant at 5% probability, *= significant ($p < 0.05$), **= highly significant ($p< 0.01$), EM= days to 50% emergence, FL= days to 50%flowering, PH= plant height, LN=leaf number, LA= leaf area, IL=internodes length, BN= number of branches, NP=number of pods per plant, PL=pod length, SPP= seeds per pod, CT=leaf temperature, CH= chlorophyll content, GY= grain yield, HI= harvest index, HSW= hundred seed weight

Table 3. ANOVA for individual traits of common bean genotypes under combined moisture environments.

Traits	Rep (ENV)	Environment	Genotype	G*E	Error	Mean	CV%
	Df= 4	Df=1	Df=42	Df=42	Df=168		
EM	0.085*	0.0038ns	2.56**	0.043ns	0.034	5.7	3.17
FL	30.05**	239.16*	38.11**	5.93ns	5.32	42.6	5.41
PH	174.01ns	6985.59*	787.88**	401.7**	108.47	50.89	20.46
LN	2.12ns	18.35.36**	99.05**	55.13**	4.33	15.52	13.4
LA	64.62*	7854.17**	959.03**	613.87**	26.26	77.4	6.62
IL	9.06**	0.082**	1.39ns	1.46ns	1.47	4.48	26.97
BN	0.66ns	9.37*	0.48ns	0.4ns	0.36	3.06	19.54
NPP	1.77ns	334.65**	22.4**	6.74**	0.76	5.74	15.15
PL	7.54**	40.57ns	8.23**	1.09ns	1.53	9.3	13.28
SPP	1.94*	7.16ns	3.78**	0.63ns	0.44	4.59	14.43
HSW	67.8ns	548.98*	640.7**	67.89ns	48.6	29.4	23.7
GY	1.11ns	252.93**	20.63**	4.5**	0.63	5.25	15.15
HI	58.55ns	198.08ns	375.46**	97.10**	42.62	41.51	15.73

ns= non-significant at 5% probability, *= significant ($p < 0.05$), **= highly significant ($p< 0.01$), EM= days to 50% emergence, FL= days to 50%flowering, PH= plant height, LN=leaf number, LA= leaf area, IL=internodes length, BN= number of branches, NP=number of pods per plant, PL=pod length, SPP= seeds per podCT=leaf temperature, CH= chlorophyll content, GY= grain yield, HI= harvest index, HSW= hundred seed weight

4. Discussion

4.1. Reduction Percentage and Contribution of Genotype Main Effect to the Total Treatment Sum Squares of Traits

The contribution of the environment to treatment (G+E+GxE) SS for these traits was minimal (0. 0 to 3.7%). Most of these traits developed before imposing moisture stress which had no effect on them (Table 6). All traits were reduced under moisture stress. The highest reductions were in number of leaves plant^{-1}(LN) (29.3%), number of pods per plant (NPP) (33.3%), and grain yield (GY) (30.6%) (Table 4).

Moisture gradient was not the main determinant of the studied traits; its contribution to Treatment SS was less than 10% for DE, IL, PL, SPP, HSW and HI, was 10 to 20% for GY, DF, PH, LA. This contribution was from 20 to 25% in LN and NPP; the highest being in CT (45.9%) and CH (51.8%), where the Environment main effect was significant only at 5% probability level while the GxE interaction was non-significant. The Genotype main effect was also non-significant in CT. Mild moisture stress was observed in LN, NPP, CH, and GY (DII 0.2 – 0.5). In all other traits the imposed moisture stress had almost minimal effect (DII< 0.2) (Table 4). [39] Also reported DII of 0.21 and 0.37 in experiments where common bean genotypes were tested under no stress and moisture stress environments. In support of the current results, [9] indicated that the moisture stress contributed less than 10% to the Treatment Sum of Squares for traits such as GY, DF, and PH. Additionally, [30] highlighted that traits such as CH were also sensitive to environmental changes, with contributions between 10% and 20%. These findings emphasize that moisture stress imposed at pod setting stage reduces many agronomic and physiological traits [8, 35] reported up to 25% contribution made by environment for the sum square of the genotype by environment interaction. The study of [24] found that grain yield was significantly affected by water stress, with reductions of up to 60% under severe-stress conditions.

Table 4. *Reduction percentage on mean performance of common bean genotypes due to moisture stress in various agronomic and yield traits.*

Traits	No stress	Moisture stress	Reduction %	DII
PH	56.0	45.6	18.5	0.19
LN	17.9	12.8	29	0.29
LA	82.9	71.8	13.3	0.13
BN	3.2	2.8	11.6	0.12
NPP	6.8	4.5	33.2	0.33
PL	9.7	8.9	8.2	0.08
SPP	4.7	4.4	7.1	0.07
CT	27.5	25.3	7.7	0.08
CH	41.4	32.2	22.2	0.22
HSW	30.8	27.9	9.4	0.09
GY	6.2	4.2	31.5	0.32
HI	42.3	40.6	4.1	0.04

PH= plant height, LN=leaf number, LA= leaf area, BN= number of branches, NPP=number of pods per plant, PL=pod length, SPP= seeds per pod, CT=canopy temperature, CH= chlorophyll content, GY= grain yield, HI= harvest index, DII= drought intensity index

The differences among the genotypes were significant for all traits except IL, BN and CT. The genotype main effect was the primary determinant for most of the traits studied, contributing more than 50% to the total Treatment Sum of Squares (SS) for 11 out of the 22 traits (Table 5). Its highest contribution was in DE (98%), DF (77%), PL (80%), SPP (83%), HSW (89%) and HI (79%) (Table 5). These traits are predominantly controlled by genetic factors indicating the possibility of developing improved varieties tolerant to drought or specifically adapted to either non-stress or stress environments from the unreleased accessions and enhancing the released varieties for drought prone areas. The lowest contributions of the genotype main effect were in CT (27.2%) and CH (33.8%) suggesting that these traits are more influenced by environmental factors or other non-genetic factors (Table 6). In agreement with this research findings, [27] found out those traits such as DE (98%), DF (77%), PL (80%), SPP (83%), HSW (89%), and HI (79%) were predominantly controlled by genetic factors, making them prime candidates for genetic improvement programs.

The Genotype by Environment interaction (GxE) was statistically significant for most of the traits except for DE, DF, IL, BN, PL, SPP, CT, CH and HSW where its contribution to Treatment SS was less than 15% for most of these traits. Genotypes had inconsistent performance over the two environments in the majority of the traits (Table 5).

Table 5. *Proportion of Treatment SS accounted for by G, E and GxE for individual traits of common bean genotypes under combined moisture environments.*

Trait	G	E	GxE
GY	66.2	19.3	14.5
EM	98.2	0	1.7
FL	76.6	11.4	1.6
PH	58.1	12.3	29.6
LN	50.1	22.1	27. 9
LA	54.5	10.6	34. 9
IL	48. 9	0.1	51.1
BN	44.4	21	34.6

Trait	G	E	GxE
NPP	60.4	21.5	18.1
PL	80	9.4	10.6
SPP	82.6	3.7	13.7
HSW	88.8	1.8	9.4
HI	78.7	1	20.3

EM= days to 50% emergence, FL= days to 50%flowering, PH= plant height, LN=leaf number, LA= leaf area, IL=internodes length, BN= number of branches, NP=number of pods per plant, PL=pod length, SPP= seeds per pod, CT=leaf temperature, CH= chlorophyll content, GY= grain yield, HI= harvest index, HSW= hundred seed weight

4.2. Days to Seedling Emergence (DE) and Days to Flowering (DF)

The period for 50% of the plants to emerge ranged from 5 to 7 days. Specifically, 15 genotypes emerged within 5 days, 22 genotypes took between 5.8 and 6 days, one genotype emerged in 6.8 days, and the last five genotypes took 7 days to emerge. Among the genotypes that emerged the latest, taking 7 days, were genotypes #37-SAB 632, #34- GLP-2, #35-AWASH MELKA, #18- KAT B9 and #15- ACC 220778 showing slower initial growth (Table 6). Similarly, [50] also found significant differences among genotypes in terms of emergence days, identifying SAB 632 and KAT B9 as the latest emerging genotypes, consistent with the current study's findings.

The flowering time for the genotypes varied from 37.3 days (#16-KAT B1) to 46.5 days (#28-TABOR). Specifically, ten genotypes flowered between 37.3 and 39.8 days, another ten between 40.3 and 42.8 days, nine genotypes between 43.3 and 43.8 days, and fourteen genotypes took between 44 and 46.5 days to flower (Table 6). This diversity allows for the selection of genotypes that are better suited to specific environmental conditions or cultivation practices. The ability of different genotypes to flower at various times suggests that they may have different levels of adaptation to environmental factors [10]. Early flowered genotypes such as #16-KAT B1, #37-KAT B9 and #5-BRAZIL 2 flowering in 37.3, 37.5 and 37.8 days respectively can be advantageous in regions with shorter growing seasons or where early harvest is desired. Conversely, later flowering genotypes like #28-TABOR,#2-RED WOLAYITA and #24-DAB 107 flowering in 46.5, 46.1 and 46 days respectively (Table 6) might be better suited for areas with longer growing seasons, potentially leading to higher yields. These findings align with [53], who also observed significant differences in the days to emergence and flowering among common bean genotypes. The results also align with the results of [50] who mentioned genotypes KAT B9 and SAB 632 as early flowering varieties. Early flowering genotypes are advantageous in regions with shorter growing seasons or where early harvest is desired [6]. Additionally, [4] study on common bean genotypes with different flowering times can be selected to match specific environmental conditions and cultivation practices.

Table 6. *Means over the two environments for number of days to emergence, days to flowering, pod length (cm), seed per pod, chlorophyll content (mg cm^{-2}) and hundred seed weight (g) common bean genotypes.*

RANK	DE		DF	
	GEN	MEAN	GEN	MEAN
1	37	7.0a	28	46.5a
2	34	7.0^{a}	2	46.1^{ab}
3	35	7.0^{a}	24	46^{a-c}
4	18	7.0^{a}	29	45.8^{a-d}
5	15	7.0^{a}	8	45.8^{a-d}
6	24	6.7 ^{b}	19	45.6^{a-d}
7	1	6.0^{c}	23	45.6^{a-d}

RANK	DE		DF	
	GEN	MEAN	GEN	MEAN
8	4	6.0^{c}	25	44.6^{a-e}
9	41	6.0^{c}	27	44.5^{a-f}
10	14	6.0^{c}	40	44.5^{a-f}
11	11	6.0^{c}	32	44.1^{a-g}
12	12	6.0^{c}	31	44^{a-g}
13	29	6.0^{c}	6	44^{a-g}
14	42	6.0^{c}	30	44 $^{a-g}$
15	39	6.0^{c}	41	43.8^{b-g}
16	8	6.0^{c}	3	43.8^{b-g}
17	19	6.0^{c}	33	43.6^{b-h}
18	2	6.0^{c}	34	43.6^{b-h}
19	23	6.0^{c}	38	43.6^{b-h}
20	20	6.0^{c}	1	43.5^{c-h}
21	27	6.0^{c}	42	43.5^{c-h}
22	40	6.0^{c}	18	43.5^{c-h}
23	31	6.0^{c}	14	43.3^{d-h}
24	28	6.0^{c}	12	42.8^{e-i}
25	3	6.0^{c}	35	42.6^{e-i}
26	36	6.0^{c}	17	42.5^{e-i}
27	43	6.0^{c}	9	42.4^{e-j}
28	10	5.8^{c}	21	42^{f-k}
29	9	5.2^{d}	4	42^{f-k}
30	38	5.2^{d}	15	41.8^{g-l}
31	21	5.0^{d}	36	41.8^{g-l}
32	22	5.0^{d}	10	41.1^{h-l}
33	17	5.0^{d}	11	40.3^{i-m}
34	30	5.0^{d}	43	39.8^{j-n}
35	13	5.0^{d}	13	39.6^{k-n}
36	16	5.0^{d}	22	39.5^{k-n}
37	33	5.0^{d}	39	39.5^{k-n}
38	6	5.0^{d}	26	39.5^{k-n}
39	5	5.0^{d}	20	39.3^{l-n}
40	32	5.0^{d}	7	38.5^{mn}
41	25	5.0^{d}	5	37.8^{mn}
42	26	5.0^{d}	37	37.5^{n}
43	7	5.0^{d}	16	37.3^{n}
LSD	0.2		2.6	

RANK	DE		DF	
	GEN	MEAN	GEN	MEAN
CV%	3.1%		5.4%	

Note: means in a column with the same letter are not statistically different, GEN= Genotypes, DE= Days to seedling emergence, DF= Days to 50% flowering

4.3. Pod Length (PL), Seeds per Pod (SPP) Chlorophyll Content (CH) and Hundred Seed Weight (HSW)

Pod length varied from 8.03 to 11.7 cm. The genotypes #6-MELKE (11.7 cm), #14-BABILE (11.2 cm), #1-IBADO (11.25 cm), #29-DAB 96 (11.08 cm), and #5-BRAZIL 2 (11 cm) had the longest pods and were among the top third for pod length in both environments. However, genotypes #7-SAB 736 and #25-ROBA 1 had the longest pods only in one of the two moisture regimes showing specific adaptations to certain environmental conditions (Table 8). Significant variability among genotypes for pod length was also reported by [29, 33].

Number of seeds per pod varied from 3.38 to 5.97 (Table 7). This variation in seed number per pod among different genotypes highlights the presence of genetic diversity. The varieties #25-ROBA 1, #34-AWASH MELKA, #41-ACC29790, #2-RED WOLAYITA, and #23-NAZRETH 2 had the highest seed counts per pod, with 5.97, 5.94, 5.91, 5.72, and 5.72 seeds respectively. These genotypes had the largest number of seeds per plant under both environments (are in the top 1/3) indicating consistency of performance of genotypes by SPP over the two moisture regimes. These higher seed counts contribute to increased overall yield. On the other hand, the varieties #38-FEDIS FTC 1, 18-GLP 2, and #30-DEME had the lowest seed counts, with 3.38, 3.38, and 3.44 seeds per pod respectively. Similar results were also reported by [29] showing variability of genotypes in seeds per pod but the report showed significant interaction between genotypes and moisture regimes in contradict with the current study. In contrary [15] noted a significant interaction between seeds per pod and moisture levels in contradict with the current finding, indicating that moisture stress leads to a reduced number of seeds. This reduction is attributed to the plant's diminished capacity to flower and produce pods under conditions of limited water availability.

For the trait hundred seed weight genotypes #22-BATU, #3-TATU, #26-DRK, #15-SAB 632, #1-IBADO,#37-KAT B9, #18-GLP 2, #30-Deme and #29 DAB-96 had the largest seeds (largest HSW) (40.85 to 44.5 g) (Table 7). Eleven genotypes had the highest HSW under both environments (in the top 1/3) indicating consistency of performance of genotypes by HSW over the two moisture regimes. These findings are supported by similar studies of [42] in which common bean genotypes exhibited stable performance across different environmental conditions, particularly in traits like pod length and seed weight. [47] Also demonstrated that some common bean genotypes maintained stable yields and pod characteristics under varying moisture conditions, recommending these genotypes for regions with unpredictable rainfall. Additionally, [20] focused on the GxE interaction for various traits in common beans, concluding that certain genotypes showed minimal GxE interaction, indicating their stability across different environments.

Table 7. *Means over the two environments for number of days to emergence, days to flowering, pod length (cm), seed per pod, chlorophyll content (mg cm^{-2}) and hundred seed weight (g) common bean genotypes.*

RANK	PL		SPP		HSW		CH	
	GEN	MEAN	GEN	MEAN	GEN	MEAN	GEN	MEAN
1	6	11.7^{a}	25	5.97^{a}	22	44.48^{a}	13	49.4^{a}
2	14	11.2^{ab}	34	5.94^{a}	3	43.60^{ab}	43	48.08^{ab}
3	1	11.25^{ab}	41	5.91^{ab}	26	43.6^{ab}	15	41.88^{bc}
4	29	11.08^{ab}	2	5.72^{a-c}	15	43.33^{ab}	14	41.01^{dc}
5	5	11.0^{a-c}	23	5.72^{a-c}	1	42.71^{a-c}	6	40.86^{dc}
6	15	10.9^{a-d}	40	5.55^{a-d}	37	41.8^{a-d}	4	40.35^{c-e}
7	30	10.7^{a-e}	32	5.38^{a-e}	18	41.71^{a-d}	21	39.48^{c-f}

RANK	PL		SPP		HSW		CH	
	GEN	MEAN	GEN	MEAN	GEN	MEAN	GEN	MEAN
8	11	10.5^{a-f}	33	5.33^{a-e}	30	40.98^{a-d}	34	39.28^{c-f}
9	26	10.4^{a-g}	42	5.33^{a-e}	29	40.85^{a-d}	18	38.75^{c-f}
10	7	10.4^{a-g}	28	5.33^{a-e}	38	39.9^{a-e}	36	38.6^{c-f}
11	10	10.2^{b-h}	27	5.22^{a-f}	10	39.2^{a-e}	39	38.63^{c-f}
12	39	10.0^{b-i}	21	5.22^{a-f}	16	38.35^{a-e}	16	38.45^{c-g}
13	41	9.9^{b-j}	9	5.22^{a-f}	11	38.03^{a-e}	28	38.21^{c-g}
14	25	9.6^{c-k}	19	5.16^{b-f}	43	37.19^{a-f}	35	38^{c-g}
15	43	9.61^{d-l}	35	5.1^{c-f}	14	37^{a-f}	30	37.83^{c-g}
16	22	9.5^{e-l}	12	5.05^{c-g}	7	36.19^{b-f}	22	37.18^{c-g}
17	3	9.38^{e-m}	13	4.9^{d-h}	24	34.93^{c-f}	37	36.93^{c-g}
18	9	9.36^{e-m}	8	4.88^{d-h}	39	34.9^{c-f}	3	36.68^{c-g}
19	18	9.33^{f-m}	17	4.88^{d-h}	31	34.26^{d-f}	10	36.63^{c-g}
20	34	9.23^{f-n}	14	4.83^{d-i}	17	34.04^{d-g}	20	36.55^{c-g}
21	38	9.2^{f-n}	31	4.77^{e-j}	6	32.8^{e-f}	26	36.55^{c-g}
22	2	9.1^{f-o}	36	4.5^{f-k}	20	30.04^{f-h}	38	36.28^{c-g}
23	28	9.09^{f-o}	15	4.47^{f-l}	5	29.91^{f-h}	41	36.08^{c-g}
24	35	9.08^{g-o}	24	4.33^{g-m}	4	26.53^{g-i}	29	35.8^{c-h}
25	24	9.05^{g-o}	6	4.27^{h-n}	33	23.97^{h-j}	1	35.66^{c-h}
26	12	8.88^{h-o}	16	4.27^{h-n}	9	21.55^{i-k}	42	35.63^{c-h}
27	40	8.87^{i-o}	5	4.27^{h-n}	12	21.48^{i-k}	24	35.55^{c-h}
28	16	8.86^{i-o}	1	4.22^{h-n}	28	21.37^{i-k}	5	35.43^{c-h}
29	31	8.85^{i-o}	20	4.11^{i-o}	35	21.11^{i-k}	9	35.18^{c-h}
30	8	8.8^{i-o}	4	4.05^{j-o}	34	21.06^{i-l}	31	35.01^{c-h}
31	19	8.75^{i-p}	29	3.97^{k-o}	2	20.95^{i-l}	27	34.86^{d-h}
32	20	8.6^{j-q}	10	3.97^{k-o}	25	19.89^{i-l}	17	34.85^{d-h}
33	32	8.5^{l-q}	43	3.83^{k-o}	8	19.71^{i-l}	7	34.783^{d-h}
34	21	8.5^{l-q}	7	3.8^{k-o}	40	18.91^{i-l}	12	34.66^{d-h}
35	36	8.2^{l-r}	3	3.7^{l-o}	41	18.87^{i-l}	2	34.35^{d-h}
36	13	8.2^{l-r}	22	3.66^{m-o}	13	17.7^{j-l}	11	34.28^{d-h}
37	4	8.06^{m-r}	26	3.66^{m-o}	21	17.39^{j-l}	32	33.7^{e-h}
38	17	8.03^{m-r}	39	3.61^{m-o}	42	17.38^{j-l}	33	33.467^{f-h}
39	37	7.83^{n-r}	11	3.55^{no}	32	17.14^{j-l}	25	32.95^{f-h}
40	23	7.6^{o-r}	37	3.55^{no}	27	16.59^{j-l}	19	32.86^{f-h}
41	27	7.3^{p-r}	30	3.44^{no}	23	15.85^{kl}	40	31.7^{g-h}
42	33	7.2^{qr}	38	3.38^{o}	19	13.86^{kl}	8	31.61^{g-h}
43	42	7.02^{r}	18	3.38^{o}	36	13.16^{kl}	23	29.05^{h}
LSD	1.4		0.7		2.7		5.5	

RANK	PL		SPP		HSW		CH	
	GEN	MEAN	GEN	MEAN	GEN	MEAN	GEN	MEAN
CV%	13.2%		14.4%		22.1%		11.3%	

Note: means in a column with the same letter are not statistically different, GEN= Genotypes, DE= Days to seedling emergence, DF= Days to 50% flowering, PL=Pod length, SPP=seeds per pod, CH= Chlorophyll content

There were significant differences ($p< 0.05$) in chlorophyll content among the genotypes, indicating that genetic factors played a significant role. Chlorophyll content ranged from 29.05 mg cm^{-2} to 49.4 mg cm^{-2}, with higher values indicating more chlorophyll. The genotypes #15-AWASH 2, #43-HUNDANE, #15-SAB 632, #14-BABILE, #6-MELKE, and #4-SER 125 had the highest chlorophyll levels, ranging from 40.35 mg cm^{-2} to 49.4 mg cm^{-2} (Table 7). These genotypes are particularly efficient in producing chlorophyll, which could be beneficial for photosynthesis and overall plant health. In summary, while the environment did not significantly impact chlorophyll content, genetic differences among the genotypes did. The top-performing genotypes in terms of chlorophyll content could be valuable for breeding programs aimed at improving photosynthetic efficiency and crop yield. This finding aligns with research indicating that drought stress can lead to varying chlorophyll content among genotypes, with some exhibiting higher levels due to their genetic makeup, which enhances their physiological responses under stress conditions [49]. A genome-wide association study of [17] identified specific markers associated with chlorophyll content in response to drought, suggesting that certain genotypes possess inherent traits that confer resilience. Additionally, transcriptomic analyses have shown that drought-tolerant genotypes up regulate genes related to chlorophyll synthesis and stress response, further supporting the genetic basis for chlorophyll consistency across environments [48]. Thus, genetic diversity plays a crucial role in the drought tolerance of common beans, influencing chlorophyll content significantly. In contradict, the study of [25] demonstrated that moisture stress led to a significant reduction in chlorophyll content of up to 20%, which in turn decreased the amount of light absorbed.

4.4. Plant Height (PH) and Number of Pods (NPP)

The analysis of variance revealed significant differences among genotypes ($p<0.01$) and highlighted an interaction between genotypes and moisture levels (Table 3). The performance of genotypes varied under different water conditions, with plant height generally decreasing by 18.5% under moisture stress compared to non-stressed conditions (Table 3). This reduction in height may be likely due to the decreased moisture content in the root zone, which impairs leaf elongation, leaf expansion, and photosynthetic activity, ultimately inhibiting plant growth [2]. Genotypes such as #17-ACC 237078 (112 cm), #33-ACC 221728 (108.5 cm), #41-ACC 29790 85 (.7 cm), #19-ACC 28899 (75.7 cm), #25-ROBA 1 (74.9 cm), #36-ACC 235697 (74.2 cm), and #24-DAB107 (71.8 cm) exhibited the tallest plant heights without stress all except #19 and #36 also had above average PH under stress (Table 8).

Although the genotype-by-environment (GxE) interaction effect was statistically significant on plant height, 26 genotypes were consistently categorized the same way in both environments for plant height (PH), suggesting that rank changes for these traits were minimal. This indicates that the variability in the trait was largely influenced by genetic differences, with trait expression for various genotypes diverging more in more favorable environments. This variability highlights the complexity of GxE interactions, where some genotypes may be more sensitive to environmental conditions than others, leading to pronounced differences in performance [32]. The analysis indicates that moisture stress significantly impacts plant height, with a notable reduction in growth observed in most genotypes under stressed conditions. Similarly, [42] reported a 43% reduction in plant height for common bean genotypes under water deficit conditions. Previous studies of [2] also showed that water deficit typically hampers plant growth by reducing leaf elongation and photosynthesis. However, some genotypes demonstrated minimal height reduction or even slight growth under stress, suggesting these varieties may have evolved adaptive mechanisms or possess inherent drought tolerance. Understanding these differences can be crucial for selecting and breeding crops that are resilient to water stress, ensuring better yield stability under variable water availability.

Table 8. *Means of plant height (cm) and number of pods per plant of common bean genotypes under two moisture regimes.*

	PH				NPP			
	NS		S		NS		S	
RANK	GENO	MEAN	GENO	MEAN	GENO	MEAN	GENO	MEAN
1	17	112.5^{a}	42	67.1^{c-h}	34	16^{a}	36	8.7^{e-h}
2	33	108.5^{a}	18	66.8^{c-h}	36	12.3^{b}	27	8.4^{e-i}
3	41	85.7^{b}	12	64.6^{c-i}	33	11.2^{bc}	23	8.2^{e-j}
4	19	75.8b^{c}	24	62.5^{c-k}	41	11^{bc}	33	8.0^{e-l}
5	25	75.0b^{c}	29	56.6^{e-r}	23	10.2^{cd}	42	7.0^{j-r}
6	36	74.2b^{cd}	33	56.1^{e-t}	12	9.1^{de}	21	6^{p-w}
7	24	71.8^{b-e}	23	54.6^{f-u}	32	9^{d-f}	25	5.9^{q-w}
8	30	69.1^{b-f}	27	52.6^{f-x}	35	8.8^{d-g}	34	5.8^{q-x}
9	29	67.6^{d-g}	28	52.0^{g-x}	13	8.6^{e-h}	4	5.6^{r-y}
10	42	67.0^{c-h}	41	51.0^{g-z}	9	8.5^{e-i}	32	5.5^{s-z}
11	27	67.0^{c-h}	1	50.7^{i-z}	27	8.1^{e-k}	19	5.4^{s-za}
12	32	63.9^{c-j}	17	49.4^{i-za}	20	7.9^{e-m}	13	5.2^{t-zab}
13	32	63.9^{c-j}	39	48.9^{i-za}	29	7.9^{e-m}	29	5.2^{t-zab}
14	20	61.7^{c-l}	20	47.3^{j-zabc}	28	7.6^{f-n}	41	5.1^{u-za-c}
15	28	59.5^{c-k}	3	47.2^{j-zabc}	42	7.6^{f-n}	31	5.1^{u-za-c}
16	34	57.9^{d-n}	25	46.6^{k-zabc}	15	7.5^{g-n}	37	5^{u-za-d}
17	12	57.7^{d-o}	35	45.8^{k-zabc}	2	7.5^{g-o}	2	4.7^{v-za-f}
18	2	57.6^{d-p}	19	45.4^{l-zabc}	25	7.3^{h-p}	28	4.7^{v-za-f}
19	18	57.6^{d-p}	26	45.1^{l-zabc}	31	7.2^{i-q}	22	4.6^{w-za-g}
20	6	57.4^{e-p}	7	44.4^{m-zabc}	19	6.7^{k-s}	40	4.4^{x-za-h}
21	35	57.0^{e-q}	31	44.2^{m-zabc}	10	6.6^{l-s}	7	4.4^{x-za-h}
22	14	56.5^{e-s}	34	43.6^{m-zabc}	40	6.5^{m-t}	18	4.2^{za-i}
23	21	56.2^{e-t}	2	43.0^{m-zabc}	21	6.3^{n-u}	24	4.2^{za-i}
24	11	53.4^{f-v}	11	42.8^{m-zabc}	18	6.1^{o-v}	35	4.1^{a-j}
25	26	53.0f^{-w}	30	41.9^{n-zabc}	14	6^{p-w}	10	4.0^{b-k}
26	38	52.5^{f-x}	37	41.0^{o-zabc}	3	6^{p-w}	12	4.0^{b-k}
27	44	49.1^{i-z}	22	40.9^{p-zabc}	17	5.8^{q-w}	6	3.7^{c-m}
28	31	49.1^{i-za}	10	40.5^{q-zabc}	11	5.8^{q-w}	3	3.7^{c-m}
29	10	49.1^{i-za}	5	40.1^{r-zabc}	4	5.6^{r-y}	5	3.6^{d-m}
30	5	48.5^{i-za}	32	40.0^{r-zabc}	1	5.5^{s-z}	11	3.6^{d-m}
31	8	46.6^{k-zab}	38	40.0^{r-zabc}	8	5.1^{u-za-c}	17	3.5^{e-n}
32	23	45.9^{k-zab}	14	39.9^{r-zabc}	6	4.8^{v-za-d}	1	3.5^{e-n}
33	40	45.8^{l-zabc}	16	39.9^{r-zabc}	16	4.7^{v-za-f}	30	3.4^{f-n}
34	39	45.2^{l-z}	40	39.7^{s-zabc}	24	4.6^{w-za-g}	15	3.3^{g-n}
35	37	43.4^{m-z}	4	39.5^{t-zabc}	38	4.4^{x-za-h}	9	3.3^{g-n}

	PH				NPP			
	NS		S		NS		S	
RANK	GENO	MEAN	GENO	MEAN	GENO	MEAN	GENO	MEAN
36	22	42.4^{n-z}	8	39.1^{u-zabc}	39	4.3^{yza-i}	14	3.1^{h-n}
37	1	38.6^{u-z}	13	39.2^{u-zabc}	30	4.2^{za-i}	8	3.0^{i-n}
38	16	38.4^{u-z}	15	38.7^{u-zabc}	37	4.1^{a-j}	43	2.7^{j-n}
39	7	38.0^{u-z}	36	37.3^{v-zabc}	26	4^{b-k}	39	2.6^{k-n}
40	3	37.6^{v-z}	6	36.0^{xyzabc}	22	3.8^{b-l}	16	2.5^{l-n}
41	13	36.3^{w-z}	21	35.4^{yzabc}	43	3.6^{d-m}	20	2.5^{l-n}
42	15	34.8^{z}	43	34.8^{zabc}	7	3.3^{g-n}	38	2.4^{mn}
43	4	33.1^{z}	9	32.6^{zabc}	5	2.7^{j-n}	26	2.2^{n}
LSD	16.7				1.4			
CV%	20.4%				15.1%			

Note: means in a column with the same letter are not statistically different, GENO= Genotypes, PH= plant height, NPP=number of pods per plant NS= No moisture stress, S= moisture stressed

There was a 33.2% reduction in pod count under moisture stress compared to optimal conditions (Table 4). The results of the current study align with findings reported by [3], who observed a significant interaction between genotypes and moisture regimes affecting the number of pods in common beans. Their research similarly highlighted the detrimental impact of moisture deficit on pod production, reinforcing the observed variability in pod counts under different water conditions. This congruence underscores the importance of considering genotype-by-environment interactions when evaluating plant performance under stress conditions. [7] also documented significant interactions between genotypes and moisture regimes affecting pod counts in common beans, thereby reinforcing the observed variability in pod production under varying water conditions. [5] also highlighted that reductions in pod numbers during drought can lead to a loss of up to 40% in seed yield, emphasizing the critical nature of pod formation in determining overall yield.

Under non-stressed conditions, the genotypes #34-AWASH MELKA, #36- ACC 235697, #33- ACC 221728, #41- ACC 29790, and #23- NAZRETH 2 demonstrated the highest pod counts, with mean values of 16.0, 12.3, 11.2, 11.0, and 10.2 pods per plant, respectively (Table 8). However, under stress conditions, these same genotypes experienced substantial reductions in pod numbers, averaging 5.8, 8.7, 8.0, 5.1, and 8.2 pods per plant, respectively (Table 8). Among these, #34 - AWASH MELKA exhibited the most severe decline in pod formation, with a reduction rate of up to 63.8%. This agrees with previous research indicating that drought stress can severely impact pod formation and overall yield with substantial decline in pod counts under stress conditions in common beans [5]. Of all the genotypes examined, #20 - KUFAN ZIK was particularly affected by moisture stress, with an alarming decrease from 8 pods under well-watered condition to 2 pods per plant under stress (Table 8), making it the most susceptible genotype. In contrast, the #4 - SER 125 genotype showed remarkable resilience, maintaining pod numbers unchanged under stress (5.6), which corresponds to a 0% reduction and signifies exceptional stability.

24 genotypes were classified in to the same category under both environments small rank change for NPP even though there was inconsistent performance. This indicates that these genotypes are resilient to stress, as their pod production remains relatively stable despite challenging conditions. Specifically, the genotypes #27-MEXICAN 142, #42-ACC 221728, and #4-SER 125 demonstrated noteworthy resilience. These varieties maintained their pod production levels with only a minor decrease under stress, showcasing their ability to withstand and adapt to adverse conditions effectively. The identification of resilient varieties is crucial for breeding programs aimed at enhancing drought tolerance in common beans, especially as climate change continues to impact agricultural productivity [6]. This finding aligns with previous studies demonstrating that certain common bean genotypes can effectively withstand drought stress, maintaining yield components such as the number of pods per plant even when exposed to challenging conditions [11].

4.5. Leaf Number per Plant (LN) and Leaf Area per Plant (LA)

In non-stressed environment, the genotypes #27 - MEXICAN 142, #35 - ACC 220778, #33 - ACC 221728, and #17 - ACC 237078 exhibited the highest leaf counts, with values of 41.8, 28.2, 27.2, and 26.7, respectively (Table 9). However, under moisture stress, their leaf count dropped to 19, 12.3, 9, and 17.5, respectively. This discrepancy suggests that these genotypes experience accelerated leaf senescence and defoliation due to water deficit. MEXICAN 142, in particular, exhibited the most significant reduction of 54.56%, highlighting its high sensitivity to moisture stress. Likewise, AWASH 1 and ACC 221728 experienced reductions of 56.55% and 67.04%, respectively (Table 4). Some genotypes such as #4 SER 125 and # 39-SAB 626, demonstrated relatively stable performance under stress, with modest reductions in LN of 13.2 to 12.6 and 13.5 to11.0 respectively (Table 9). This stability indicates that these genotypes may possess greater resilience or adaptability to moisture stress, which could be advantageous for maintaining crop performance in variable moisture conditions. These findings align with studies conducted in by [1] highlighted that drought significantly affects physiological traits and yield parameters in various common bean varieties, reinforcing the notion that certain genotypes exhibit better resilience under moisture stress conditions.

The observed reductions in leaf number under moisture stress can be attributed to water scarcity, which often leads to reduced plant growth and leaf production. Plants may shed leaves as a survival mechanism to conserve resources and minimize transpiration [2]. Under moisture deficit conditions, leaf number (LN) dropped by 30.2% in this study (Table 4). Similarly, [15] observed a leaf number reduction of up to 24.2% under moisture stress. On the other hand, genotypes with fewer leaves under stress may experience reduced photosynthetic capacity, potentially impacting overall yield. On the other hand, genotypes with fewer leaves under stress may experience reduced photosynthetic capacity, potentially impacting overall yield. [16] Reported 19% reduction in leaf number for common bean genotypes tested against moisture stress.

Table 9. *Means of leaf number per plant and leaf area of common bean genotypes under two moisture regimes.*

	LN				LA			
	NS		S		NS		S	
RANK	GENO	MEAN	GENO	MEAN	GENO	MEAN	GENO	MEAN
1	27	41.9^{a}	34	33.5^{b}	31	142.4^{a}	9	$95.9^{e\text{-}g}$
2	35	28.2^{c}	27	$19.0^{h\text{-}k}$	38	130.4^{c}	6	$95.7^{e\text{-}g}$
3	33	27.3^{cd}	38	$18.6^{h\text{-}k}$	10	27.3^{cd}	32	$91.0^{g\text{-}j}$
4	17	26.7^{cde}	17	$17.5^{i\text{-}n}$	1	113.2^{cde}	13	$89.7^{g\text{-}j}$
5	36	24.9^{de}	42	$17.4^{i\text{-}n}$	22	24.9^{de}	16	$87.8^{g\text{-}l}$
6	32	23.9^{def}	30	$16.8^{j\text{-}o}$	16	23.9^{def}	28	$87.3^{h\text{-}m}$
7	34	23.7^{ef}	11	$16.7^{j\text{-}p}$	5	23.7^{ef}	29	$86.8^{h\text{-}n}$
8	19	23.4^{efg}	15	$15.8^{k\text{-}r}$	37	234^{efg}	3	$85.9^{h\text{-}o}$
9	21	21.4^{fgh}	41	$15.2^{l\text{-}s}$	7	214^{fgh}	11	$85.8^{h\text{-}o}$
10	41	21.3^{fgh}	12	$14.3^{n\text{-}w}$	6	213^{fgh}	4	$84.6^{j\text{-}p}$
11	42	21.3^{fgh}	31	$13.4^{p\text{-}y}$	21	213^{fgh}	40	$84.1^{j\text{-}q}$
12	29	21.2^{fgh}	3	$13.2^{q\text{-}y}$	30	212^{fgh}	22	$81.1^{k\text{-}r}$
13	12	20.3^{ghi}	28	$12.7^{q\text{-}z}$	43	203^{ghi}	31	$80.5^{k\text{-}r}$
14	28	19.5^{hij}	13	$12.7^{q\text{-}z}$	11	195^{hij}	26	$78.5^{n\text{-}s}$
15	24	$19.1^{h\text{-}k}$	4	$12.61^{r\text{-}za}$	14	$191^{h\text{-}k}$	25	$77.9^{o\text{-}t}$
16	9	$18.3^{h\text{-}k}$	16	$12.4^{s\text{-}zab}$	29	$18.3^{h\text{-}k}$	5	$75.6^{r\text{-}w}$
17	7	$18.6^{h\text{-}l}$	35	$12.3^{s\text{-}abc}$	41	$18.6^{h\text{-}l}$	39	$75.4^{r\text{-}w}$
18	23	$17.9^{i\text{-}m}$	8	$12.1^{s\text{-}zabc}$	10	$17.9^{i\text{-}m}$	33	$75.2^{r\text{-}w}$

	LN				LA			
	NS		S		NS		S	
RANK	GENO	MEAN	GENO	MEAN	GENO	MEAN	GENO	MEAN
19	22	17.8^{i-m}	19	12.1^{s-zabc}	13	17.8^{i-m}	34	74.4^{r-x}
20	8	17.3^{i-n}	34	12.1^{s-zabc}	2	17.3^{i-n}	23	74.3^{r-x}
21	13	17.2^{i-n}	7	12.0^{s-zabc}	4	17.2^{i-n}	21	73.8^{r-y}
22	2	16.8^{j-o}	22	11.9^{s-za-d}	26	16.8^{j-o}	30	73.2^{r-za}
23	30	15.9^{k-q}	9	11.9^{s-za-d}	39	15.9^{k-q}	38	71.5^{s-zabc}
24	18	15.8^{k-r}	5	11.6^{t-za-d}	28	15.8^{k-r}	12	69.5^{u-za-e}
25	11	15.2 $^{l-s}$	1	11.5^{u-za-d}	40	15.2 $^{l-s}$	18	66.8^{x-za-f}
26	43	15.2 $^{l-s}$	23	11.4^{v-za-d}	9	15.2 $^{l-s}$	35	66.5^{x-za-g}
27	25	15.1^{m-s}	20	11.1^{w-za-d}	25	15.1^{m-s}	7	65.5^{yza-h}
28	10	15.1^{l-s}	2	11.1^{w-za-d}	42	15.1^{l-s}	41	65.4^{za-h}
29	20	15.0 $^{l-s}$	39	11.0^{w-za-d}	15	15.0 $^{l-s}$	14	65.1^{a-h}
30	40	14.9^{m-t}	10	11.0^{w-za-d}	3	14.9^{m-t}	27	64.9^{a-h}
31	15	14.8^{m-u}	21	10.9^{x-za-d}	24	14.8^{m-u}	42	64.5^{c-i}
32	1	14.6^{m-v}	36	10.8^{x-za-d}	35	14.6^{m-v}	34	63.8^{c-j}
33	6	14.6^{m-v}	18	10.7^{x-za-d}	32	14.6^{m-v}	2	63.2^{d-k}
34	31	14.3^{n-w}	32	10.4^{yza-d}	12	14.3^{n-w}	1	61.4^{e-l}
35	5	13.8^{o-x}	37	10.2^{yza-d}	23	13.8^{o-x}	37	59.0^{f-m}
36	26	13.5^{o-y}	29	10.2^{yza-d}	8	13.5^{o-y}	43	58.4^{g-m}
37	39	13.5^{o-y}	6	9.7^{za-d}	20	13.5^{o-y}	8	55.9^{j-o}
38	4	13.2^{q-y}	26	9.4^{za-d}	17	13.2^{q-y}	17	55.2^{k-o}
39	37	12.56^{r-za}	14	9.3^{za-d}	33	12.56^{r-za}	20	54.3^{l-o}
40	3	12.2^{s-zabc}	40	9.3^{a-d}	27	12.2^{s-zabc}	10	54.0^{l-o}
41	38	11.4^{v-za-d}	25	9.2^{bcd}	19	11.4^{v-za-d}	19	51.4^{m-p}
42	14	11.3^{v-za-d}	33	9.0^{cd}	36	11.3^{v-za-d}	15	49.7^{n-p}
43	16	11.2^{w-za-d}	43	8.6^{d}	34	11.2^{w-za-d}	36	48.8^{op}
LSD	3.3				8.2			
CV%	13.4%				6.6%			

Note: means in a column with the same letter are not statistically different, GENO=Genotypes, LN=leaf number, LA=leaf area per plant NS= No moisture stress, S= moisture stressed

Under non-stress conditions, certain genotypes such as #31-SER 119, #38-FEDIS FTC-1, #10-MELKA DEMA, #1-IBADO, and #22-BATU exhibited the largest leaf areas, with measurements from23.9 cm ²up to 142.4 cm ²and decreasing slightly in other genotypes (Table 9). However, when subjected to moisture stress, these genotypes experienced significant reductions in leaf area. Specifically, #10-MELKA DEMA, #38-FEDIS FTC-1, and #31-SER 119 showed the most substantial decreases, with LA of 54 cm ², 71.5 cm ²and 80.5 cm ²respectively. This suggests that these genotypes are highly sensitive to moisture stress, potentially due to lower resilience or adaptability, as they lost more than 40% of their leaf area under stressed conditions. These findings are consistent with previous studies, such as those by [12, 26], which observed that water deficit typically leads to a reduction in leaf size and area. Similarly, [13] also found that moisture stress at

50% field capacity resulted in decreased leaf area due to the reduced size and expansion of young leaves. In addition, SER 125 and BELFOT LS displayed minimal reductions in leaf area, indicating a higher degree of resilience to moisture stress and a better ability to maintain their leaf area even under low moisture conditions.

Even though the GxE interaction of genotypes and moisture regimes was significant, 17 genotypes were classified in to the same category under both environments (Table 3) with small rank change for LA. Among these genotypes #31-SER 119, #32-AWASH 1, #16-KAT B1, #6- MELKE and #11-BELFOT LS were in the top third class. This indicates that these genotypes had stable performance in irrigated and stress conditions. Specifically, the genotypes#10-MELKA DEMA, #17-ACC 237078, #13-AWASH 2 and #31-SER 119demonstrated resilience by having higher leaf area or only a minor decrease under stress, showcasing their ability to withstand and adapt to adverse conditions effectively. [23] highlighted the significance of leaf area as a trait in evaluating nine common bean genotypes across different moisture regimes and genotypes with larger leaf areas were better equipped to cope with stress conditions.

4.6. Harvest Index (HI)

Under irrigated conditions genotypes #43 -HUNDANE, #41 -ACC29790, #11 -BELFOT LS, #42 – ACC 211378 and #3 –TATU had the highest HI (50.6 to 58.12%). However, these genotypes had reduction of 13.7%, 5.9%, 4.2%, 20.4% and 3.6%. With the exception of #42 the others can be declared widely adapted and stress tolerant (Table 10).

Under stress genotypes #7 -HUNDANE, #4 -ACC29790, #27 -BELFOT LS, #38 -ACC211378and #43 –TATU had the highest HI (50.14 to 56.55%). However, these genotypes had reduction of -23%, -1.6%, -26%, -3.4% and 51%. Except #43 -TATU the others had higher harvest index under stress. A except #7 – HUNDANE, #27 -BELFOT LS and #43 -TATU can be declared widely adapted and stress tolerant genotypes with minimum reduction in HI under stress (Table 10). A study by [18] found that certain varieties, like AWASH 1 are highly sensitive to moisture stress, resulting in substantial reductions in their harvest index. According to a study by [6], a high harvest index does not necessarily correlate with drought resilience. While a high harvest index indicates strong overall performance, it does not always reflect a variety's ability to withstand drought conditions.

Table 10. *Means of harvest index and grain yield (gm/plant) of common bean genotypes under two moisture regimes.*

	HI				GY			
	NS		S		NS		S	
RANK	GENO	MEAN	GENO	MEAN	GENO	MEAN	GENO	MEAN
1	43	58.12^{a}	7	51.55^{ab}	3	12.68^{a}	4	9.37^{bc}
2	41	53.31^{a}	4	51.32^{a-c}	41	12.27^{a}	17	7.8^{d-g}
3	11	51.17^{a-d}	27	50.47^{a-e}	43	10.50^{b}	29	7.75^{d-g}
4	42	51.17^{a-d}	38	50.46^{a-e}	4	10.34^{b}	34	6.77^{f-l}
5	3	50.6^{a-e}	43	50.14^{a-e}	25	8.87^{cd}	3	6.77^{f-l}
6	4	50.5^{a-e}	41	50.14^{a-e}	28	8.48^{c-e}	43	6.45^{h-o}
7	8	50.39^{a-e}	29	49.90^{a-e}	38	8.24^{c-e}	41	6.12^{i-q}
8	29	50.23^{a-e}	37	49.35^{a-e}	26	7.98^{d-f}	26	5.82^{l-u}
9	25	49.63^{a-e}	25	49.33^{a-e}	11	7.59^{d-h}	25	5.69^{l-u}
10	33	49.14^{a-e}	34	49.24^{a-e}	36	7.40^{e-i}	7	5.60^{l-v}
11	28	49.09^{a-e}	11	49.02^{a-f}	34	7.34^{e-j}	11	5.38^{m-w}
12	34	48.95^{a-g}	3	48.78^{a-g}	32	7.21^{e-k}	28	5.32^{m-x}
13	9	48.8^{a-g}	28	48.68^{a-h}	37	6.86^{f-l}	37	5.29^{n-x}
14	38	48.79^{a-g}	17	48.54^{a-h}	29	6.82^{f-l}	38	5.17^{o-y}
15	32	48.62^{a-h}	26	47.80^{a-j}	9	6.60^{g-m}	6	4.68^{t-za-c}
16	10	48.43^{a-h}	39	47.26^{b-k}	42	6.58^{g-m}	27	4.68^{u-za-c}

	HI				GY			
	NS		S		NS		S	
RANK	GENO	MEAN	GENO	MEAN	GENO	MEAN	GENO	MEAN
17	26	48.31^{a-h}	6	46.93^{b-l}	8	6.52^{g-n}	39	4.58^{u-za-c}
18	36	47.96^{a-h}	21	45.67^{b-n}	33	6.40^{h-o}	42	4.26^{w-za-f}
19	37	47.91^{a-i}	16	41.43^{c-t}	27	6.19^{i-p}	33	4.26^{w-za-f}
20	5	47.72^{a-k}	36	41.03^{c-t}	35	6.18^{i-p}	5	3.84z^{a-h}
21	22	45.79^{b-m}	5	40.78^{d-u}	5	6.10^{j-q}	40	3.67^{a-i}
22	23	44.17^{b-o}	42	40.75^{d-u}	6	6.05^{k-r}	16	3.62^{a-i}
23	6	43.94^{b-p}	8	38.47^{g-v}	22	6.02^{k-s}	2	3.52^{b-i}
24	35	43.09^{b-q}	30	38.18^{h-v}	7	5.96^{k-t}	21	3.4^{c-i}
25	16	42.76^{c-r}	33	37.42^{i-w}	10	5.79^{l-u}	30	3.26^{d-j}
26	7	42.04^{c-s}	13	37.32^{j-w}	23	5.78^{l-u}	36	3.13^{d-k}
27	31	41.534^{c-t}	24	37.21^{k-w}	2	5.23^{o-x}	19	3.1^{d-k}
28	27	40.12^{e-u}	19	36.72^{l-w}	12	5.10^{p-z}	22	3.05^{d-k}
29	39	38.50^{f-v}	18	36.57^{l-w}	20	5.01^{p-z}	32	3.03^{e-k}
30	2	38.49^{f-v}	40	36.33^{m-w}	17	4.84^{q-za}	18	3.01^{e-k}
31	20	36.69^{l-w}	22	35.44^{m-x}	39	4.79^{r-zab}	1	2.98^{f-k}
32	40	35.73^{m-x}	2	35.13^{o-x}	1	4.78^{r-zab}	9	2.98^{f-k}
33	1	35.24^{n-x}	10	35.05^{o-x}	31	4.7$^{4s-za-c}$	24	2.93^{g-k}
34	13	34.13^{o-x}	31	33.55^{p-x}	16	4.58^{u-za-c}	13	2.92^{g-k}
35	18	33.87^{o-x}	9	32.93^{q-x}	19	4.58^{u-za-c}	20	2.90^{g-k}
36	19	33.50^{p-x}	1	32.83^{q-x}	24	4.33^{v-za-d}	23	2.88^{g-k}
37	17	33.11^{q-x}	32	32.33^{r-x}	30	4.27^{w-za-e}	10	2.82^{g-k}
38	12	32.86^{q-x}	15	31.69^{s-x}	40	4.06^{x-za-g}	8	2.82^{g-k}
39	24	31.21^{t-x}	20	31.36^{t-x}	18	3.92^{yza-h}	31	2.77^{h-k}
40	30	31.18^{t-x}	35	30.37^{u-x}	13	3.92^{yza-h}	35	2.49^{i-l}
41	21	28.36^{v-x}	23	30.26^{u-x}	21	3.28^{d-j}	12	2.18^{j-l}
42	15	25.46^{x}	12	27.01^{x}	15	2.71^{h-k}	15	2.09^{j-l}
43	14	11.92^{y}	14	12.43^{y}	14	1.40^{l}	14	1.86^{kl}
LSD		10.5				1.2		
CV%		15.7%				15.1%		

Note: means in a column with the same letter are not statistically different, GENO= Genotypes, NS= No moisture stress, S= moisture stressed, HI= Harvest index, GY= Grain yield

4.7. Grain Yield

Under irrigated conditions genotypes #3 -TATU, #41 – ACC29790, #43 -HUNDANE, #4 -SER 125and #25 -ROBA 1 had the highest GY (8.87 to 12.68 g plant^{-1}). However, these genotypes had reduction of 47, 50, 39, 9 and 36%. With the exception of #4-SER 125 (reduction of 9%) the others had dramatic reduction (36 to 50%) in GY under moisture stress (Table 4). These four genotypes were specifically adapted to no

stress environment and were very susceptible to drought stress (Table 10). Under stress genotypes #4 -SER 125, #17 –ACC237078, #29 -DAB 96, #34 -AWASH MELKA and #3 –TATU had the highest GY (6.77 to 9.37g lant^{-1}). However, these genotypes had reduction of 9, -61, -14, 8 and 47%. #17 –ACC237078 and #29 -DAB 96 had higher grain yield under stress (reduction of -61 and -14%). #4 -SER 125, #29 -DAB 96 and #34 -AWASH MELKA can be declared widely adapted and drought tolerant genotypes having lower reduction under stress (Table 10). Out of the genotypes #4 -SER 125, #3 -TATU, #41 -ACC29790, #43 -HUNDANE and #29 -DAB 96 had the highest mean grain yield over the two environments. All except #29-DAB 96(-14%) had positive reduction (8 to 50%). Genotypes #4-SER 125 (9%), #34 -AWASH MELKA (9%) and #29 -DAB 96 (-14%) can be declared as widely adapted and drought tolerant genotypes. [4] Also found that TATU and SER 125 exhibited superior drought tolerance, with yields of 10.1 and 9.0 grams per plant, respectively, under water-limited conditions. Specific varieties can exhibit significant yield advantages under drought stress conditions that emphasize the importance of selecting genotypes with high genetic potential for grain yield under varying water availability [14].

5. Conclusion

Defining traits based on a target environment is very critical in any breeding program to know the influence of a trait on yield and the exact genetic potential of the plant. This experiment was made to assess response of common bean genotypes under water stressed and non-stressed conditions for various agronomic and physiological traits along with statistical methods to observe the association and relationship between yield and other traits. Moisture stress reduced plant growth and yield, consistent with the dependence of pod formation and seed filling on water supply. The significant genotype × regime effects indicate that some genotypes were specifically adapted, while others were relatively stable. DAB 96, SER 125 and Tatu merit multi-location validation, but recommendations should remain provisional until field performance, farmer preference and stability across seasons are confirmed. Future work should combine replicated field testing with molecular characterization, root-system measurements, farmer-preferred traits and multi-location stability analysis. Candidate genotypes should be evaluated under several stress timings because post-flowering stress responses may differ from early-season or terminal drought responses.

Abbreviations

ANOVA	Analysis of Variance
DF	Days to Flowering
DII	Drought Intensity Index
EBI	Ethiopian Biodiversity Institute
EC	Exchange Capacity
FAO	Food and agricultural organization of the United Nations
LSD	Least Significant Difference
MARC	Melkassa Agricultural Research Center
MASL	Meters above Sea Level
SARI	South Agricultural Research Institute
SAS	Statistical Analysis System
SEDPSZ	Socio Economic and Demographic Profile of Sidama Zone

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Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Table 12. *List of common bean genotypes that were used for the experiment.*

ENTRY	GENOTYPES	YEAR OF RELEASE	BREEDER MAINTAINER
1	IBADO	2003	SARI
2	RED WOLAYITA	1974	Melkassa
3	TATU	2014	SARI
4	SER 125	2014	Melkassa

ENTRY	GENOTYPES	YEAR OF RELEASE	BREEDER MAINTAINER
5	BRAZIL 2	2017	Melkassa
6	MELKE	1998	Melkassa
7	SAB 736	2014	Melkassa
8	DIMTU	2007	Melkassa
9	HAWASSADUME	2008	SARI
10	MELKADEMA	2006	Melkassa
11	BELFOT LS	2017	Melkassa
12	NASIR	2003	Melkassa
13	AWASH 2	2013	Melkassa
14	BABILE	2012	Haremaya
15	SAB 632	2015	Melkassa
16	KAT B1	2013	Melkassa
17	ACC237078		EBI
18	GLP 2	2011	Melkassa
19	ACC28899		EBI
20	KUFAN ZIK	2008	Haremaya
21	29557		EBI
22	BATU	2008	Melkassa
23	NAZRETH 2	2005	Melkassa
24	DAB 107	2009	Melkassa
25	ROBA 1	1990	Melkassa
26	DRK	1987	Melkassa
27	MEXICAN 142	1973	Melkassa
28	TABOR	1999	SARI
29	DAB 96	2017	Melkassa
30	DEME	2008	Melkassa
31	SER 119	2014	Melkassa
32	AWASH 1	1990	Melkassa
33	ACC221728		EBI
34	AWASH MELKA	1999	Melkassa
35	ACC220778		EBI
36	ACC235697		EBI
37	KAT B9	2013	Melkassa
38	FEDISFTC 1	2012	Haremaya
39	SAB 626	2018	Haremaya
40	DINKINESH	2007	Melkassa
41	ACC29790		EBI
42	ACC211378		EBI

ENTRY	GENOTYPES	YEAR OF RELEASE	BREEDER MAINTAINER
43	HUNDANE	2012	Haremaya

Note: SARI= South agricultural research institute, EBI=Ethiopian biodiversity institute

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