SOIL & CROP SCIENCES | RESEARCH ARTICLE

Impact of common bean (Phaseolus vulgaris L.) genotypes on seed yield, and seed quality at different locations of Eastern Ethiopia

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Abstract: An experiment was conducted both under field conditions (Haramaya, Babile, and Hirna) and in the laboratory during the 2018 main crop season to analyze the impact of genotype by location based on seed yield and seed quality in Common Bean varieties. Thirteen varieties of common bean were tested at three locations in a randomized complete block design with three replications under field conditions while, for seed quality traits, they were tested at a standard seed testing laboratory in a completely randomized design with four replications. Analysis of variance was computed using GenStat statistical software version 16th. Accordingly, grain yield from Ayenew (5545.82 kg ha⁻¹), and Gofta (5147.03 kg ha⁻¹) genotypes was greater than other genotypes, respectively. The maximum grain yield was obtained in the Hirna location (6040.26 kg ha⁻¹) due to its wide potential. However, location Haramaya was a representative and suitable site for the production of good quality seeds compared to other locations. The varieties Ayenew, Babile, Tinike, and Hundane yielded above the grand mean and also met the minimum (85%) national standard for germination of a common bean seed. Thus, it is better if

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PUBLIC INTEREST STATEMENT

The common bean is an early-maturing crop with good drought tolerance and is known for its high protein and other nutritional value. Currently, its yield and seed quality are affected mostly due to limited high-yielding varieties acclimatized to different environmental conditions and the selection of good agricultural practices. Since the common bean is grown over the low to mid-land regions of Ethiopia, testing the different responses of genotypes to varied environments is highly relevant, particularly for good seed production.

Therefore, the aim of this work was to test the impact of common bean varieties on seed yield and seed quality at different locations in Eastern Ethiopia. The output of this study shows that the yield and quality of common beans varied as the location changed. Therefore, seed yield and seed quality of common bean varieties are changed at different locations in Eastern Ethiopia due to genetic and environmental factors.
farmers grow these high-yielding varieties with better standard seed germination to produce high-quality seed.

**Subjects:** Agriculture & Environmental Sciences; Botany; Plant & Animal Ecology

**Keywords:** agro-environment; genotype; common bean; seed yield and quality

2. **Introduction**

The common bean (Phaseolus vulgaris L), also known as dry bean and haricot bean, is a self-pollinating crop that is a very important legume crop grown worldwide (Broughton et al., 2003; Singh et al., 2014). In east Africa, the crop is well liked by small-scale farmers, given its short growth cycle (about 70 days), which allows production when rainfall is uneven. Among major grain crops, it has the highest levels of differences in growth habit, seed characteristics such as size, shape, color, maturity period, and adaptation (Negri & Tosti, 2002). It was introduced to Ethiopia in the 16th century by the Portuguese (Wortmann & Eledu, 1997). Currently, it is one of the most widely cultivated and most economically important food crops in the country (Habtamu, 2017). It is the fast-expanding legume crops that provide an indispensable component of the everyday diet and foreign earnings for many Ethiopians. Market demand for the crop in the domestic and export markets has become the main mechanism for the growing trends in the quantity of production (Lemu, 2016). The common bean is an early-matured crop and has a reasonable degree of drought tolerance; and this has led it to play an essential role in farmers’ strategies for risk aversion in drought-prone lowland regions of the country. Common beans contain proximates like vegetable high protein, vitamins (folate), minerals such as Iron, Calcium, Copper, Manganese, Magnesium, and Zinc, and use full amino acids, all of which contribute to human nutrition and health (Acosta-Gallegos et al., 2007; Broughton et al., 2003; Reyes-Bastidas et al., 2010; Rondini et al., 2012; Rosemary et al., 2020). In Ethiopia, it is mainly produced in the Southern, Eastern, South Western, and the Rift valley areas. About 113,249.95 ha and 244,049.94 ha of area were covered by white and red common beans, respectively (CSA (Central Statistics Agency of Ethiopia), 2016). Accordingly, out of a total area of 357,299.89 ha, total production and national mean yield were only 540,238.94 tons/ha and 1600 kg/ha, indicating very low productivity (CSA (Central Statistics Agency of Ethiopia), 2016). This is mostly due to limited high-yielding varieties acclimatized to different environmental conditions and the selection of good agricultural practices.

Besides, successful crop production in any environment initially depends on the quality of the seeds sown. The term “seed quality” is used in agriculture to describe the overall value of a seed lot for its intended purpose (Hampton, 2002). In general, genetic background and the environmental conditions of the mother plant during seed development determine seed quality (Hampton et al., 2013). It is well known that the germination and viability of seeds may vary greatly from year to year and from one production site to another (Hampton, 2002). Much of this variation has been attributed to differences in environmental factors in space and time, including temperature (Egli et al., 2005; Pagamas & Nawata, 2008; Shinohara et al., 2006), soil moisture and soil nutrients (Baskin & Baskin, 2014).

Since the common bean is grown over wider agro-ecologies (low to mid-altitude regions) of Ethiopia, the genotype-by-environment interaction is highly relevant, particularly for seed production, as reported in several studies (Torga et al., 2013). Yield is an extremely complex quantitative characteristic, and its expression is the effect of genotype, environment, and their interaction. The presence of a significant genotype–environment (GE) interaction for quantitative traits such as seed yield can lead to the failure of genotypes to achieve the same relative performance in different environments (Gurmu et al., 2009). When field experiments are carried out in dissimilar agro-ecological conditions, usually 80% of the yield difference is caused by the environment, while genotype and genotype x environment interaction cause 10% of the difference each (Yan, 2001). A best genotype is one that shows stable performance in yield and high seed quality in variable environmental conditions or agro-ecologies where it is planted (Seyis et al., 2006).
In Ethiopia, common beans (*Phaseolus vulgaris* L.) describe the many types of bean varieties in the Horn of Africa country. The majority of the farmers (95%) are smallholders who produce the crop. Most of the common bean varieties grown in Ethiopia have been selected only based on their grain yield per hectare, which has resulted in poor quality of seed obtainable. Therefore, it is important to evaluate the crop varieties at diverse locations for both grain yield and seed quality (Solomon et al., 2019). However, in eastern Ethiopia, a comprehensive study on diverse genotypes under different environments is scarce for assessing quality seed production. Therefore, the general objective of this work was to study the impact of common bean (*Phaseolus vulgaris* L.) genotypes on seed yield and seed quality at different locations in Eastern Ethiopia with the following specific objectives:

1. To evaluate and identify the best varieties for yield and seed quality,
2. To identify the representative site for common bean seed production.

### 3. Materials and methods

#### 3.1. Description of the experimental site

The experiment was conducted both under field conditions (Haramaya, Babile, and Hirna) and laboratory (Haramaya University Seed Testing Laboratory) during the 2018 main crop season. These three locations were selected based on their variability of altitude, soil type, and potential for the crop. The description of test locations is given in Table 1.

#### 3.2. Plant materials and experimental design

Thirteen varieties of common bean were used in this study for their availability. They are released materials and grown at the experimental locations. They all are bush beans in growth habit. The further description of the varieties (name of variety, year of release, breeder, adaptation, seed size and color) is given below in Table 2. The experiment was laid out in a randomized complete block design (RCBD) with three replications. The distance between blocks and plots were 1 m and 0.5 m, respectively. The plot size was 2.4 m × 4 m = 9.6 m². There were six rows per plot. The central four rows were used for data collection. The distance between rows was 40 cm and the distance between plants was 10 cm. Seeds were hand drilled and covered with soil properly. The laboratory experiment was carried out in a completely randomized design (CRD) with four replications.

#### 3.3. Field performance evaluation of common bean varieties

##### 3.3.1. Field emergence index

The number of seedlings that emerged was counted on each day up to the seedling establishment. The field emergence index (speed of emergence) was calculated as described by Maguire (1962). The formula for the field emergence index (FIE) is given by:

\[
FIE = \frac{\text{No. of seedlings emerged at 1st day}}{\text{Days of first count}} + \ldots + \frac{\text{No. of seedlings emerged at final day}}{\text{Days of final count}}
\]

### Table 1. Altitude, soil type, latitude and longitude of the test locations

| Locations | Altitude (m a.s.l.) | Soil type | Latitude (N) | Longitude (E) |
|-----------|---------------------|-----------|--------------|--------------|
| Haramaya  | 2020                | Alluvial  | 9°26’        | 42°03’       |
| Babile    | 1650                | Sandy loam| 9°08’        | 42°21’       |
| Hirna     | 1870                | Vertisol  | 9°12’        | 41°04’       |
Table 2. Description of test common bean varieties used in the 2018 main cropping season

| No. | Variety            | Year of release | Breeder/Maintainer | Adaptation (m.a.s.l.) | Seed size | Seed color |
|-----|--------------------|-----------------|--------------------|-----------------------|-----------|------------|
| 1.  | Tinike             | 2012            | HU                 | 1500–2200             | Large     | Red        |
| 2.  | Babile             | 2012            | HU                 | 1500–2200             | Large     | Red        |
| 3.  | Awash-2            | 1999            | MARC               | 1400–2200             | Small     | White      |
| 4.  | Ayenew             | 1997            | HU                 | 1700–2000             | Large     | Pinto      |
| 5.  | Nasir              | 2003            | MARC               | 1200–1800             | Small     | Red        |
| 6.  | A-Melka            | 1999            | MARC               | 1400–2200             | Small     | White      |
| 7.  | Hundane            | 2012            | HU                 | 1500–2200             | Large     | Red mottled |
| 8.  | Awash-1            | 1990            | MARC               | 1400–2200             | Small     | White      |
| 9.  | Kufanzik           | 2007            | HU                 | 1300–2000             | Large     | Pinto      |
| 10. | Gofra              | 1997            | HU                 | 1500–2000             | Medium    | Cream      |
| 11. | Chercher           | 2006            | HU                 | 1500–2200             | Small     | White      |
| 12. | Haramaya           | 2006            | HU                 | 1500–2000             | Medium    | Cream      |
| 13. | Dursitlu           | 2007            | HU                 | 1500–2200             | Small     | Red        |

Note: HU = Haramaya University, MARC = Melkasa Agricultural Research Center
Seed source: Melkasa Agricultural Research Center and Haramaya University

3.3.2. Mean emergence time (days)
The mean emergence time was calculated by using the formula as cited in Ellis & Roberts (1980).

\[ MET = \frac{\sum_n}{t}, \text{where, } n- \text{ Number of seeds newly germinated at time } t' \text{, } t- \text{ Days from sowing, and } \sum_n \text{- Final emergence of seedlings (The total number of emerged seeds).} \]

3.3.3. Seedling establishment (%)
The seedling establishment was determined by counting the total number of seedlings planted when the emergence was completed or when there was no further addition in the total emergence.

3.3.4. Days to 50% flowering
The number of days from planting to when 50% of the plants produced flowers was recorded.

3.3.5. Days to 50% physiological maturity
This was recorded as the number of days from planting to when 50% of the plants showed yellowing of pods.

3.3.6. Plant height (cm)
The height of 10 randomly sampled plants was measured from the ground to the top of the plant at maturity and the average value was calculated by dividing by 10.

3.3.7. Number of pods per plant
The number of pods was counted on ten randomly sampled plants at maturity from each plot and the average value was calculated.

3.3.8. Number of seeds per pod
Five randomly sampled pods per plant from each ten randomly sampled plants were threshed and the number of seeds was counted, and then the total number of seeds was divided by the total number of pods to compute the average number of seeds per pod.
3.3.9. 100 seed weight (g)
This was determined by taking the weight of hundred randomly sampled seeds from each net plot area after harvest and adjusted to a 10% moisture level.

\[
100 \text{ seed weight} = \left( \frac{100 - \text{moisture content recorded}}{100 - 10} \right) \times 100 \text{ Unadjusted seed weight}
\]

3.3.10. Grain yield (kg ha\(^{-1}\))
Grain yield data were collected from the central four rows of the plot and adjusted to 10% seed moisture content using the equation (Hong and Ellis, 1996). The plot yield (considering plot size) was converted to yield per ha according to method developed by Institute of Electrical, Electronic and Engineering (IEEE, 2002).

\[
Y_{adj} = \left[ \frac{(100 - MC)}{100 - 10} \right] \times Y, \quad \text{where: } Y_{adj} \text{ was moisture adjusted yield, } Y \text{ was unadjusted yield, and } MC \text{ was measured seed moisture content (by percentage).}
\]

3.4. Seed quality test in the laboratory

3.4.1. Moisture content (%)
Seed Moisture Content (%); was done following formula indicated by (xxx, 1993); high constant temperature (130–133°C for 1 hour) oven dry method was applied.

3.4.2. Standard germination (%)
For the standard germination (SG) test, four hundred seeds from pure seed components of each sample were divided into four replicates of one hundred (100) seeds each according to the Rules of International Seed Testing Association (ISTA, 2015). Seeds were then planted in a germination box using sand substratum. The final count of germination was recorded after germination completed, and the number of normal seedlings was counted and expressed as percent germination.

3.4.3. Root length (cm), and shoot length (cm)
Root (taproot) length was measured from the five randomly taken normal seedlings taken from four replications of standard germination test and recorded in centimeters and the average was calculated (yyy, 1996).

Shoot length was measured on five randomly taken normal seedlings taken from four replications of standard germination test and recorded in centimeters and the average was calculated (yyy, 1996).

3.4.4. Seedling dry weight (mg)
Five normal seedlings taken for measuring seedling length were further kept in the oven dry for taking dry weight. These were dried at 80°C for 16 hours and then the seedling dry weight was recorded in milligram and the average weight of five seedlings was taken (yyy, 1996).

3.4.5. Seedling vigor index
Both seedling vigor indices were calculated according to the formulae suggested by Abdul-Baki & Anderson (1973) and the seed lot showing a higher seed vigor index is considered more vigorous.

\[
\text{Vigor Index – I} = \text{Standard germination(%) } \times \text{ Seedling length(cm)}
\]

Note: Seedling length = (Seedling shoot length + Seedling root length) cm

\[
\text{Vigor Index – II} = \text{Standard germination(%) } \times \text{ Seedling dry weight(mg)}
\]
3.4.6. Seed density (g/mL)

The bulk density of the bean seeds was calculated using the standard method of (Shimelis & Rakshit, 2005). One hundred grams of the sample seeds were transferred to a measuring cylinder, which had 100 mL water. Seed volume (mL/100 g of seeds) was obtained after subtracting 100 mL from the total volume (mL). The bulk density was then calculated and recorded in g/mL by using the following formula:

\[ \text{Seed density} = \frac{100 \text{g of seeds}}{\text{Volume of water displaced by seeds (mL)}} \]

3.4.7. Tetrazolium test (%)

A viability test (Moore, 1973) was conducted on four replications of 50 seeds by soaking seeds in water for 16 hours to activate dehydrogenase enzymes. After the preconditioning, the prepared seeds were stained in 1.0% tetrazolium solution (2, 3, 5-triphenyl tetrazolium chloride) for 4 hours at 30°C in petri plates. After that, seeds were washed in water and the number of seeds stained red were considered as viable seeds and expressed in percent as follows:

\[ \text{Viable seeds}(\%) = \left( \frac{\text{Number of seeds stained red}}{\text{Total number of seeds tested}} \right) \times 100 \]

3.4.8. Data analysis

Analysis of variance and AMMI analysis were computed using GenStat statistical software version 15th VSN International, 2012. The combined analysis was performed to know genotypic effects, location effects, and genotype by location effects as well as to get the estimates of environmental and genotype by location interaction variances. The least significant difference (LSD) test at 5% probability level was used for mean comparison. The accurate and appropriate AMMI model was also used and performed to select and rank the best performing common bean varieties for particular locations as indicated by, Fikere et al. (2008), which is confirmed by Halimatus & Alfian (2016).

4. Results and discussion

4.1. Field performance of test varieties

4.1.1. Seed yield

The ANOVA (analysis of variance) revealed that seed yield was highly and significantly (P < 0.001) affected by location (L), genotype (G), and genotype x location interaction (GLI). This implies that all genotype, location, and GLI effects were highly significant (P < 0.001), confirming the environmental differences and indicating the existence of genetic differences among genotypes and GxL interactions in all locations. The genotype effect depicts the variability for selection, the location effect depicts the variability between sites, while the GxL interaction effect indicates differential responses of the genotypes to environmental change.

When individual estimates of variance components for seed yield were expressed as a percentage of the total variation, the location effect explained 68.16% of the G + L + GxL variation, followed by the genotype effects (16.13%) and the G x L effects (12.32%). The remaining 3.39% was accounted for by the error variance. The large value of the sum of squares of the location showed that the locations were varied and had a greater influence on the performance of common bean varieties regarding seed yield and contributed more to GLI when compared to that of varieties as main effects. Similarly, the magnitude of the genotype sum of squares was greater than that of the G x L interaction, indicating that varieties responded with a large variation in seed yield across locations. It occurs because different genotypes have varying genetic potential to adjust themselves to variable environments. According to the results of the current study, scholars indicated that common bean genotypes could respond differently and interact highly to environmental conditions (Bekele et al., 2016; Gebeyehu & Assefa, 2003; Kefleagn et al., 2016).
The mean seed yields of thirteen common bean varieties grown in three locations (Haramaya, Babile, and Hirna) are presented (Table 3). The mean seed yields of varieties varied significantly in all locations; they ranged from 3103.28 kg ha$^{-1}$ for Awash-1 to 5692.44 kg ha$^{-1}$ for Gofta; 603.013 kg ha$^{-1}$ for Awash-1 to 3713.96 kg ha$^{-1}$ for Hundane; and 3796.73 kg ha$^{-1}$ for Awash-1 to 8675.88 kg ha$^{-1}$ for Gofta, at Haramaya, Babile, and Hirna locations, respectively (Table 3). At Haramaya and Hirna locations, the mean values of Gofta, Ayenew, Haramaya, and Kufanzik common bean varieties exceeded the grand mean and showed the potential to produce better seed yields than other varieties. However, at the Babile location, the varieties that yielded above the grand mean were Hundane, Tinike, Babile, and Ayenew, which are large seed types. Considering the three locations, the highest average seed yield was recorded in Ayenew (5545.82 kg ha$^{-1}$). Conversely, Awash-1 exhibited a consistent low seed yield across the three locations, with an average yield of 2501.01 kg ha$^{-1}$. The overall mean seed yield was higher in the Hirna location (6040.26 kg ha$^{-1}$) than in the Haramaya location (4228.27 kg ha$^{-1}$) and Babile location (1696.85 kg ha$^{-1}$). The Hirna location, with variety Gofta, performing better, implies that the agro-ecology belongs to the location where Hirna expressed its genetic potential to give a very high yield in east Africa. The major agro-ecology of the location, like altitude of 1870, soil type of Vertisol, latitude of 9°12', longitude of 41°04', rainfall and temperature, might contribute to high grain yield, which is reported by Mondo et al. (2019), and Mashamba et al. (2021). Besides, Solomon et al. (2019) indicate another reason for the high yield of Gofta and Ayenew varieties is that they are some of the oldest varieties easily adapted to the area. Furthermore, it has been reasoned that most probably large seed size varieties could perform better and high yielding at the locations which is similarly indicated by Solomon et al. (2019). In addition, the observed difference in seed yield was probably due to the significant location effect on field emergence index, seedling establishment, and pods per plant reported by Mashamba et al. (2021).

Table 3. Mean seed yield (kg ha$^{-1}$) of thirteen common bean varieties grown in three locations (haramaya, babile, and hirna) in the 2018 main cropping season

| No. | Varieties  | Haramaya  | Babile    | Hirna   | Mean  | Rank |
|-----|------------|-----------|-----------|---------|-------|------|
| 1.  | Tinike     | 3912.89$^{ab}$ | 3481.32$^{bc}$ | 5580.88$^{c}$ | 4325.03$^{cd}$ | 6    |
| 2.  | Babile     | 4269.48$^{c}$ | 3278.70$^{b}$ | 5740.40$^{c}$ | 4429.53$^{cd}$ | 5    |
| 3.  | Awash-2    | 3858.83$^{ab}$ | 610.05$^{g}$ | 5203.92$^{cd}$ | 3224.48$^{fg}$ | 11   |
| 4.  | Ayenew     | 5458.54$^{ab}$ | 2612.48$^{c}$ | 8566.44$^{a}$ | 5545.82$^{a}$ | 1    |
| 5.  | Nasir      | 3998.68$^{cd}$ | 917.19$^{fg}$ | 5485.77$^{bc}$ | 3667.21$^{ef}$ | 9    |
| 6.  | A-Melka    | 3982.41$^{cd}$ | 1524.79$^{d}$ | 5590.30$^{c}$ | 3699.16$^{ae}$ | 8    |
| 7.  | Hundane    | 3791.08$^{ef}$ | 3713.96$^{a}$ | 5181.15$^{cd}$ | 4228.65$^{ed}$ | 7    |
| 8.  | Awash-1    | 3103.28$^{f}$ | 603.01$^{g}$ | 3796.73$^{e}$ | 2501.01$^{h}$ | 13   |
| 9.  | Kufanzik   | 4763.15$^{b}$ | 1411.22$^{de}$ | 7178.56$^{b}$ | 4450.97$^{cd}$ | 4    |
| 10. | Gofta      | 5692.44$^{a}$ | 1072.77$^{ef}$ | 8675.88$^{a}$ | 5147.03$^{b}$ | 2    |
| 11. | Chercher   | 3406.54$^{ef}$ | 787.28$^{fg}$ | 4424.79$^{de}$ | 2872.91$^{gh}$ | 12   |
| 12. | Haramaya   | 5124.19$^{ab}$ | 1147.80$^{def}$ | 7803.16$^{b}$ | 4691.71$^{bc}$ | 3    |
| 13. | Dursitu    | 3606.00$^{ef}$ | 898.46$^{fg}$ | 5295.41$^{cd}$ | 3266.60$^{fg}$ | 10   |
|     | EM         | 4228.27$^{b}$ | 1696.85$^{c}$ | 6040.26$^{a}$ | 3988.46    |      |
|     | EMS        | 231911    | 64,040.50  | 362,287.62 |         |      |
|     | CV (%)     | 11.39     | 14.91      | 10.0      |         |      |
|     | LSD (%)    | 811.53    | 426.45     | 1014.31   |         |      |

Means followed by the same letter within the same column are not significantly different from each other at 5% level of probability; LSD = least significant difference; CV = coefficient of variation; EMS = error mean of squares; EM = environmental means; EMS = error mean squares.
5. Additive main effects and multiplicative interaction (AMMI) analysis

The AMMI model considers the varieties which are characterized by means greater than the grand mean and smaller IPCA (Interaction principal components axis one) score are considered as less interacted with all environments (Mahnaz et al., 2013). However, the varieties with high mean performance and with a large value of IPCA1 score have high interaction with test environments. Similarly, by considering IPCA1 alone regardless of the positive or negative signs, varieties with large scores have high interactions, whereas varieties with small IPCA1 scores have small interactions (Mahnaz et al., 2013; Yan et al., 2007).

Accordingly, Dursitu, Awash-Melka, Nasir, Awash-2, and Chercher showed relatively smaller absolute IPCA1 scores deemed to be less interacted. However, they all yielded below-average seed yields. In another way, higher mean performance and higher IPCA1 scores were recorded for Gofta, Hundane, Haramaya, Tinike, Babile, Ayenew, and Kufanzik, and thus, they highly interacted with test locations (Table 4). The locations with higher IPCA1 scores discriminate among varieties more than environments with lower scores. Accordingly, Babile was the most discriminating location of all the others (Table 4). This suggests that their specific adaptation to specific locations, which appears to be the agro-ecology, was responsible for some of the observed variability. Although the agro-ecology (suitable altitude from 1500 to 2200) is a broad term and consists of several predictable and unpredictable factors, it was the amount of rainfall as well as the distribution of even and uneven distribution, and the associated ecology at that suitable altitude that provided the recorded variability. In the current study, potential yielding genotypes also changed their yield across locations. This indicated that Gofta, Hundane, Haramaya, Tinike, Babile, Ayenew, and Kufanzik genotypes with high genotypic yield potential were responsive to different agro-ecological factors. Thus, agro-ecological conditions tend to cause a significant yield rise. In line with the current report, similar trends were indicated by Mahnaz et al. (2013).

Table 4. AMMI analysis of genotype and location means and scores for 13 common bean varieties grown across three locations (haramaya, babile, and hirna) in the 2018 main cropping season

| No. | Varieties    | Seed yield (kg ha⁻¹) | Rank | IPC1     | IPC2     |
|-----|--------------|----------------------|------|----------|----------|
| 1.  | Tinike       | 4225.03              | 6    | -25.57206 | 11.83591 |
| 2.  | Babile       | 4429.53              | 5    | -20.8518  | 5.07420  |
| 3.  | Awash-2      | 3224.48              | 11   | 4.14730   | -11.95641|
| 4.  | Ayenew       | 5545.82              | 1    | 15.16188  | 17.76529 |
| 5.  | Nasir        | 3467.21              | 9    | 3.47471   | -8.66031 |
| 6.  | A-Melka      | 3699.16              | 8    | -2.66840  | -2.63592 |
| 7.  | Hundane      | 4228.65              | 7    | -32.14348 | 9.94512  |
| 8.  | Awash-1      | 2501.01              | 13   | -10.30547 | -16.94163|
| 9.  | Kufanzik     | 4450.97              | 4    | 14.85696  | 3.76444  |
| 10. | Gofta        | 5147.03              | 2    | 34.57304  | 3.99514  |
| 11. | Chercher     | 2872.91              | 12   | -6.04108  | -12.75760|
| 12. | Haramaya     | 4691.71              | 3    | 24.42430  | 3.62901  |
| 13. | Dursitu      | 3266.60              | 10   | 0.94750   | -3.05723 |

| Locations | Mean | Rank | IPC1 | IPC2 |
|-----------|------|------|------|------|
| 1.        | Haramaya | 4228 | 2    | 12.16677 | -28.79563|
| 2.        | Babile   | 1697 | 3    | -52.57247 | 8.74569  |
| 3.        | Hirna    | 6040 | 1    | 40.40570  | 20.04994 |

IPCA1 and IPCA2 = Interaction principal components axis one and two, respectively.
The AMMI model also selected and ranked the best-performing common bean varieties for particular locations. Hence, Gofta, Ayenew, Haramaya, and Kufanzik were the first four best-performed common bean varieties at both the Haramaya and Hirna locations. On the contrary, Hundane, Tinike, Babile, and Ayenew were the first four best-performed varieties at the Babile location (Table 5). This indicates that the genetic potential embodied by Gofta, Ayenew, Haramaya, and Kufanzik varieties has been expressed by environmental characteristics that existed at Haramaya and Hirna locations, which led to the top-ranked, best-performing common bean varieties. In agreement with the present report, Mashamba et al. (2021) indicated that the genotypes and experimental locations used have been diverse and better performed at specific and general genotype adaptability findings.

6. Yield-related traits
The combined analysis of variance for nine yield-related characters in thirteen common bean varieties in the three environments is presented. Highly significant (p < 0.01) and very highly significant (p < 0.001) genotype effects were observed (Appendix Table 1). Accordingly, the mean emergence time and seeds per pod were highly affected by the genotypes studied. Furthermore, field emergence index, seedling establishment, days to flowering, days to physiological maturity, plant height, pods per plant and, hundred seed weight were very highly affected by genotypes. This shows that the varieties have different characteristics and/or variability for phenological and agronomic traits that may affect the seed yield to different degrees. This result agrees with the findings of those who noticed a variation in the performance of different bean genotypes in their agronomic traits (Ashango et al. 2016; Tsegaye et al., 2012).

Similarly, there was a very highly significant location effect on all the characters studied except seeds per pod, in which there was a highly significant environmental effect. The combined analysis of variance further indicated that there was significant genotype x location interaction for field emergence index and very highly significant genotype x location interaction effects on all other parameters except for mean emergence time, in which there was no significant genotype x location interaction effect. In another way, there was no significant block effect in all the

| No. | Variety      | Haramaya Mean | AMMI-est. | Ranked | Babile Mean | AMMI-est. | Ranked | Hirna Mean | AMMI-est. | Ranked |
|-----|--------------|---------------|-----------|--------|-------------|-----------|--------|------------|-----------|--------|
| 1   | Tinike       | 3913          | G10       | 5692   | 3481        | G7        | 3714   | 5581       | G10       | 8676   |
| 2   | Babile       | 4269          | G4        | 5459   | 3279        | G1        | 3481   | 5740       | G4        | 8566   |
| 3   | Awash-2      | 3859          | G12       | 5124   | 610         | G2        | 3279   | 5204       | G12       | 7803   |
| 4   | Ayenew       | 5459          | G9        | 4763   | 2612        | G4        | 2612   | 8566       | G9        | 7179   |
| 5   | Nasir        | 3999          | G2        | 4269   | 917         | G6        | 1525   | 5486       | G2        | 5740   |
| 6   | A-Melka      | 3982          | G5        | 3999   | 1525        | G9        | 1411   | 5590       | G6        | 5590   |
| 7   | Hundane      | 3791          | G6        | 3982   | 3714        | G12       | 1148   | 5181       | G1        | 5581   |
| 8   | Awash-1      | 3103          | G1        | 3913   | 603         | G10       | 1073   | 3797       | G5        | 5486   |
| 9   | Kufanzik     | 4763          | G3        | 3859   | 1411        | G5        | 917    | 7179       | G13       | 5295   |
| 10  | Gofta        | 5692          | G7        | 3791   | 1073        | G13       | 898    | 8676       | G3        | 5204   |
| 11  | Chercher     | 3407          | G13       | 3606   | 787         | G11       | 787    | 4425       | G7        | 5181   |
| 12  | Haramaya     | 5124          | G11       | 3407   | 1148        | G3        | 610    | 7803       | G11       | 4425   |
| 13  | Dursitu      | 3606          | G8        | 3103   | 898         | G8        | 603    | 5295       | G8        | 3797   |

G1 = Tinike; G2 = Babile; G3 = Awash-2; G4 = Ayenew; G5 = Nasir; G6 = A-Melka; G7 = Hundane; G8 = Awash-1; G9 = Kufanzik; G10 = Gofta; G11 = Chercher; G12 = Haramaya and G13 = Dursitu varieties.
characters studied, except in mean emergence time. Other researchers have reported the presence of genotype × location interactions in yield and yield-related traits on common beans (Ashango et al., 2016; Tamene and Tadesse, 2014; Tsegaye et al., 2012). A similar result was also reported in faba bean (Karadasvut et al. 2010; Mulusew et al. 2008), in soybean (Tyagi & Khan, 2010) and in chickpea (Choudhary & Haque, 2010).

The effects of genotype and location on common bean yield-related traits are presented in (Tables 6 and 7), respectively. Field emergence index results of seeds were affected due to the locations where the tests were conducted (Table 7). Hence, varieties showed the highest (10.75) speed of emergence at Babile, the lowest (8.05) speed of emergence at Haramaya, and moderate (8.61) speed of emergence at Hirna locations (Table 7). Accordingly, the longest mean emergence time (days) was observed at Haramaya and the shortest at Babile, with means of 8.93 and 6.94 days, respectively. This means the genotypes emerged within fewer days at Babile than at the other two locations, while Babile was the poorest location for seedling establishment. This indicates the Babile site had a significant negative effect on the establishment of seedlings. However, the Haramaya and Hirna locations were better for seedling establishment. The early emergence and poor seedling establishment of genotypes at the Babile location might be due to the environmental characteristics of the Babile location like altitude of 1650 (cool environment), sandy loam soil type, and associated ecology, which could speed up the emergence of the genotype and be poor for seedling establishment. Similarly, scholars reported that location character consists of different soil types and agro-ecology can significantly speed up genotype emergence and determine seedling establishment (Dembele & Ashenafi, 2018; Mondo et al., 2019). The locations also had an influence on both the flowering and maturing of varieties. Accordingly, the

| Variety | FEI  | MET  | SE   | DF   | DPM  | PH   | PPP  | SPP  | HSW  |
|---------|------|------|------|------|------|------|------|------|------|
| 1.      | 8.75 | 8.31 | 89.38 | 45.11 | 92.44 | 75.90 | 19.70 | 4.36 | 40.00 |
| 2.      | 9.04 | 8.24 | 89.64 | 43.11 | 89.67 | 75.46 | 20.28 | 4.69 | 40.35 |
| 3.      | 9.58 | 8.07 | 80.30 | 45.22 | 92.11 | 76.40 | 25.61 | 4.68 | 19.34 |
| 4.      | 8.85 | 8.29 | 88.25 | 43.33 | 94.33 | 81.41 | 26.71 | 4.68 | 33.13 |
| 5.      | 9.63 | 7.77 | 81.55 | 50.89 | 92.00 | 65.07 | 26.04 | 4.97 | 19.40 |
| 6.      | 9.91 | 7.95 | 83.16 | 51.33 | 95.11 | 62.18 | 27.36 | 4.43 | 19.55 |
| 7.      | 8.60 | 8.32 | 89.33 | 42.89 | 91.89 | 53.79 | 20.24 | 4.14 | 39.63 |
| 8.      | 10.02 | 7.72 | 76.74 | 46.33 | 93.89 | 72.80 | 27.17 | 4.94 | 17.60 |
| 9.      | 8.89 | 8.04 | 84.58 | 38.89 | 85.89 | 82.98 | 24.57 | 4.63 | 36.74 |
| 10.     | 9.30 | 7.90 | 90.95 | 41.67 | 90.16 | 90.00 | 20.58 | 4.37 | 31.44 |
| 11.     | 6.94 | 8.24 | 77.62 | 50.59 | 95.44 | 61.00 | 29.23 | 4.92 | 21.84 |
| 12.     | 9.85 | 7.88 | 86.94 | 43.89 | 96.56 | 103.43 | 29.54 | 4.69 | 32.94 |
| 13.     | 9.42 | 7.81 | 81.47 | 50.44 | 91.56 | 63.51 | 22.53 | 4.99 | 19.21 |
| Mean    | 9.14 | 8.05 | 84.61 | 45.69 | 92.42 | 74.14 | 24.58 | 4.65 | 28.55 |
| E5      | 0.88 | 0.17 | 12.88 | 1.81 | 3.86 | 72.17 | 10.44 | 0.26 | 0.92 |
| CV (%)  | 10.28 | 12.05 | 4.24 | 7.81 | 6.04 | 24.79 | 37.58 | 12.59 | 6.44 |
| LSD 5%  | 0.88 | 0.39 | 3.37 | 1.26 | 1.84 | 7.98 | 3.03 | 0.48 | 0.90 |

CV = coefficient of variation; LSD = least significant difference; Means followed by the same letter within the same column are not significantly different at 5% level of probability; FEI = field emergence index; MET = mean emergence time; SE = seedling establishment; DF = days to flowering; DM = days to maturity; PH = plant height; PPP = pods per plant; SPP = seeds per pod; HSW = hundred seed weight; Var1 = Tinike; Var2 = Babile; Var3 = Awash-2; Var4 = Aynew; Var5 = Nasir; Var6 = Awash-Melka; Var7 = Hundane; Var8 = Awash-1; Var9 = Kufanzik; Var10 = Gofta; Var11 = Chercher; Var12 = Haramaya and Var13 = Dursitu.
varieties flowered and matured early at Babile and flowered and matured late at the Haramaya location. On the other hand, the tallest plant height, the largest number of pods per plant, the largest number of seeds per pod, and 100 seed weight values were recorded at the Hirna site, whilst the shortest plant height and lowest number of pods per plant were recorded at the Babile site. In general, the locations showed significant differences in parameters studied, except for non-significant differences in the number of seeds per pod and 100 seed weight for Haramaya and Babile sites, and a non-significant difference in the seedling establishment at Haramaya and Hirna locations (Table 7).

From the combined mean analysis, there was no statistically significant difference among the varieties for field emergence index, except for the Chercher variety, which was the poorest performing variety in field emergence index with the mean value of 6.94 (Table 6). This means all varieties took an equivalent number of days for emergence (mean emergence time) except the Chercher variety. In seedling establishment, the varieties Gofta, Babile, Tinike, Hundane, Ayenew, and Haramaya established better under field conditions, whereas the varieties Awash-1 and Chercher showed poor establishment in the field. The variety Kufanzik flowered early (38.89 days), whereas the longest durations of flowering were recorded for Awash-Melka, Nasir, Chercher, and Dursitu with mean values of 51.33, 50.89, 50.89, and 50.44 days, respectively. This means they were late flowering varieties. Kufanzik was also an early matured variety (85.89 days), followed by Babile (89.67 days) and Gofta (90.16 days).

The tallest (103.43 cm) and shortest (53.79 cm) plant heights were recorded from Haramaya and Hundane varieties, respectively. The number of pods per plant ranged from 19.70 (Tinike) to 29.54 (Haramaya) varieties. Similarly, the number of seeds per pod ranged from 4.14 (Hundane) to 4.99 (Dursitu). In 100 seed weight, the highest (29.14 g) and the lowest (28.06 g) value was recorded at Hirna and Haramaya locations, respectively (Table 7). Research results showed also a highly significant difference among varieties in seed weight. From the combined analysis, the mean seed weight increased from 17.60 g for Awash-1 to 40.35 g for Babile varieties (Table 6). Indeed, the different phenology traits (flowering and maturity date), and growth traits (plant height, number of pods, number of seed and 100 seed weight) responses to different location and genotypes might be due to the compatibility of the locations environmental conditions and quality genetic materials contributed for the specific traits up and down. This is previously explained by several scholars (José et al., 2016; Habtamu, 2017; Tadele et al. (2018); (Rosemary et al., 2020); Gunnabo et al., 2019); and (Solomon et al., 2019),

| Location | FEI | MET | SE | DF | DPM | PH | PPP | SPP | HSW |
|----------|-----|-----|----|----|-----|----|-----|-----|-----|
| Haramaya | 8.05 | 8.93 | 87.91 | 49.36 | 96.5 | 71.35 | 25.77 | 4.60 | 28.06 |
| Babile   | 10.75 | 6.95 | 77.51 | 42.03 | 85.51 | 56.44 | 14.60 | 4.43 | 28.48 |
| Hirna    | 8.61 | 8.28 | 88.40 | 45.70 | 95.21 | 94.64 | 33.39 | 4.92 | 29.14 |
| GM       | 9.14 | 8.05 | 84.61 | 45.69 | 92.41 | 74.14 | 24.58 | 4.65 | 28.55 |
| EMS      | 0.88 | 0.17 | 12.88 | 1.80 | 3.86 | 72.17 | 10.44 | 0.26 | 0.92 |
| CV (%)   | 16.86 | 12.05 | 4.24 | 7.81 | 6.04 | 24.79 | 37.58 | 12.59 | 6.44 |
| LSD (0.05) | 0.42 | 0.19 | 3.09 | 0.61 | 0.89 | 3.83 | 1.46 | 0.23 | 0.43 |

GM = grand mean; EMS = error mean squares; CV = coefficient of variation; LSD = least significant difference; Means followed by same letters within the same column are not significantly different from each other at 5% level of probability; FEI = field emergence index; MET = mean emergence time; SE = seedling establishment; DF = days to flowering; DM = days to maturity; PH = plant height; PPP = pods per plant; SPP = seeds per pod and HSW = hundred seed weight.
6.1. Seed quality parameters

6.1.1. Overview of laboratory tests
A combined analysis of variance for seed quality tests showed that genotype and interaction between genotype and location had very highly significant (p < 0.001) effects on all the seed quality traits studied. The location also had very highly significant (p < 0.001) effects on moisture content, seedling shoot length, VI-I, and seed density. However, the location had no significant effects on standard germination, seedling root length, seedling dry weight, VI-II, and seed viability. These seed quality parameters studied can be grouped into two categories. These are physical (seed moisture content, seed density) and physiological seed quality (germination capacity, seedling dry weight, vigor, and viability) (Appendix table 2). The mean values of seed quality parameters for thirteen common bean varieties grown at Haramaya, Babile, and Hirna locations in 2018 are shown in supplementary files of Tables 8–10, respectively, which are discussed below;

6.1.2. Status of seed moisture content
Differences in seed moisture content were significant among the varieties. Seed moisture content is the most important factor that regulates the longevity of the seeds. Higher moisture in seeds enhances seed deterioration, which ultimately reduces the planting value of seeds in the field. The seed moisture content for all varieties met the seed moisture standard for common beans in Ethiopia. However, there was a statistically significant difference among the varieties with respect to seed moisture content. In the present study, the moisture content of seeds at the Haramaya location varied from 8.15% (for Kufanzik) to 10.75% (for Haramaya) varieties (Table 8). At the Babile location, the highest seed moisture contents were recorded from Tinike and Babile varieties, whereas the lowest seed moisture contents were recorded from Gofta, Nasir, Haramaya, and

| Variety | MC (g/100g) | SG (mg/g) | RL (mm) | SL (mm) | SDW (g/100g) | VI-I (%) | VI-II (%) | SD (mm) | TZ (%) |
|---------|-------------|----------|---------|---------|--------------|----------|-----------|---------|--------|
| 1       | 9.80 f      | 97.04 h  | 98.33 f | 9.55 h  | 70.0 g       | 1880 d   | 6800 e    | 129.2 b | 97.3abc|
| 2       | 10.0 cde    | 95.04 ab | 10.50 bc| 11.60 de| 75.0 b       | 2099.8bc | 5220.2ab  | 121.1de | 98.75a |
| 3       | 10.1 cde    | 90.03 cd | 10.20 c | 13.43 cd| 25.0 e       | 2112.0cd | 2240.0de  | 125.9bc | 95.00de|
| 4       | 8.65 g      | 91.50 c  | 10.63 b | 12.73 de| 35.0 cd      | 2148.15f | 3220.0cd  | 137.3a  | 95.00de|
| 5       | 9.99 def    | 78.53 ef | 8.03 t  | 11.40 g | 40.0 e       | 1523.80g | 3100.0cd  | 116.9f  | 95.50cde|
| 6       | 8.20 f      | 90.56 cd | 9.25 a  | 15.08 b | 60.0 ab      | 2202.25b | 5370.0ab  | 112.4g  | 98.5ab |
| 7       | 9.88 ef     | 87.05 d  | 11.60 a | 10.93  | 1980.0 cd    | 3950.0   | 123.1 cd  | 94.00ef | 97.00d |
| 8       | 10.53      | 82.53 h  | 9.68 ab | 14.15 bc| 22.5 d       | 1969.8c  | 1845.0    | 126.5bc  | 97.00d |
| 9       | 8.15       | 81.72 m  | 9.33 ab | 10.38 gh| 60.0 ab      | 1613.6   | 4960.0    | 120.1def | 92.00fg|
| 10      | 8.40 h     | 71.27 h  | 8.28 f  | 7.28   | 40.0 e       | 1122.30 f| 2840.0    | 139.7g  | 92.00fg|
| 11      | 8.40 h     | 97.05 h  | 10.50 bc| 17.30 c | 40.0 e       | 2694.5c  | 3860.0    | 112.4g  | 99.00a |
| 12      | 10.75 d    | 78.08 ca | 10.85 b | 14.28 bc| 65.0 ab      | 1959.5c  | 5070.0    | 118.2ef | 96.30cd|
| 13      | 10.10      | 74.12 c  | 9.30 ab | 11.10 g | 35.0 cd      | 1506.45e | 2590.0    | 118.0ef | 91.5fg |
| Mean    | 9.45       | 85.65     | 9.84     | 12.24   | 45.58        | 1908.80  | 3928.1    | 123.14 | 95.21  |
| CV (%)  | 1.01       | 3.51      | 5.17     | 6.45    | 42.42        | 5.86     | 42.68     | 2.13   | 2.27   |
| LS05%   | 0.14       | 4.31      | 0.73     | 1.13    | 27.72        | 240.45   | 3.77      | 3.10   |        |

CV = coefficient of variation; LSD = least significant difference; Means followed by the same letter within the same column are not significantly different at 5% level of probability; MC = seed moisture content; SG = standard seed germination; RL = seedling root length; SL = seedling shoot length; SDW = seedling dry weight; VI-I = seedling vigor index one; VI-II = seedling vigor index two; SD = seed density; TZ = tetrazolium seed viability test; Var1 = Tinike; Var2 = Babile; Var3 = Awash-2; Var4 = Ayenew; Var5 = Nasir; Var6 = Awash-Melka; Var7 = Hundane; Var8 = Awash-1; Var9 = Kufanzik; Var10 = Gofta; Var11 = Chercher; Var12 = Haramaya and Var13 = Dursitu.
Chercher varieties (Table 9). The varieties Tinike, Babile, Nasir, Hundane, Chercher, and Dursitu met the national standard for germination at the Babile location.

In another way, the highest (9.98%) and the lowest (7.8%) seed moisture content were recorded from Ayenew and Kufanzik varieties, respectively, at the Hirna location (Table 10). In general, all varieties exhibited below the maximum (12%) national standard seed moisture content of common beans at all three tested locations. At the Hirna location, the varieties that met the national standard germination were Tinike, Awash-2, Ayenew, Awash-Melka, Hundane, Chercher, and Dursitu. In agreement with current work, the difference might be due to the presence of genetic variability in moisture content among the varieties revealed in a specific area (Kedir et al., 2014).

### 6.1.3. Seed germination results

Standard germination of seeds varies among the varieties. A seed germination test provides the ability of seeds to germinate and produce a seedling that will emerge from the soil and develop into a vigorous plant. Considering the individual locations, seven varieties, namely Tinike, Babile, Awash-2, Ayenew, Awash-Melka, Hundane, and Chercher, fulfilled the national standard germination set for common bean seeds at the Haramaya location (Table 8). The seeds produced at the Haramaya location exhibited relatively better normal germination than those produced at the other two locations (Table 11). This indicates that the Babile and Hirna locations had a negative effect on the germination capacity of varieties compared to the Haramaya location. In general, the highest (85.65%) and the lowest (82.15%) normal germination percentages were recorded at the Haramaya and Hirna locations, respectively. This varieties’ full filling of national standards at the Haramaya location might be due to the genetic makeup of the genotypes expressed at this location’s temperature and seed moisture. In line with the present study, Felipe et al. (2018),...
Table 10. Mean values of seed quality parameters for thirteen common bean varieties grown at Hirna in 2018

| Variety | MC  | SG  | RL  | SL  | SDW | VI–I | VI–II | SD  | TZ  |
|---------|-----|-----|-----|-----|-----|------|-------|-----|-----|
| 1.      | 9.75 a | 87.7 cde | 10.43 b | 8.85 h | 60 f | 167.4 e | 5210 c | 127.13 b | 93.5 cde |
| 2.      | 9.68 b | 80.05 abc | 9.85 bc | 10.65 f | 75 d | 1651.55 e | 6020 b | 127.25 b | 91 a |
| 3.      | 8.2 h | 93 ab | 10.4 a | 15.48 c | 25 f | 2405.7 ab | 2310 ab | 123.83 d | 93 de |
| 4.      | 9.98 cde | 85.5 cde | 10.13 bc | 10.38 b | 45 f | 1692.8 a | 3720 de | 126.55 bc | 98 a |
| 5.      | 9.1 c | 78.5 f | 10.08 bc | 14.13 e | 35 f | 1898.2 a | 2790 de | 123.4 a | 93 de |
| 6.      | 8.2 h | 93.5 a | 9.35 cd | 16.9 cde | 25 f | 2454.9 a | 2360 de | 129.15 ab | 95.1cd |
| 7.      | 9.45 c | 87.5 cde | 12.25 a | 12.88 a | 95 d | 2200.15 c | 8390 c | 121.55 ab | 97.5 ab |
| 8.      | 9.05 a | 79.5 f | 10.55 a | 17.85 a | 50 cd | 2258.3 c | 3960 cd | 123.53 a | 98 a |
| 9.      | 7.8 a | 64 a | 9.6 cd | 9.35 gh | 35 f | 1206.4 g | 2340 ab | 120.45 a | 96 cbc |
| 10.     | 9.23 a | 71 h | 8.38 a | 7.35 a | 40 f | 1171.4 g | 2800 de | 129.13 ab | 89.5 |
| 11.     | 8.43 a | 89 desc | 10.55 a | 16.08 ac | 30 f | 2370 abc | 2690 ac | 116.25 f | 95.50 d |
| 12.     | 8.43 a | 76 gh | 9.35 cd | 10.15 fg | 35 f | 1480.25 f | 2660 ab | 131.53 a | 89.5 |
| 13.     | 8.88 f | 86 de | 9.25 a | 12 e | 25 f | 1828.5 ab | 2160 f | 115.15 b | 97 ab |
| Mean    | 8.93 c | 82.15 c | 10.01 a | 12.46 a | 44.23 a | 1864.75 c | 3664.69 a | 124.23 ab | 94.35 |
| CV (%)  | 0.86 a | 5.31 a | 5.54 a | 12.46 a | 30.65 a | 7.09 a | 33.26 a | 1.55 a | 2.0 |
| LSD5%   | 0.11 a | 6.25 a | 0.80 a | 0.80 a | 19.44 a | 189.7 a | 1739.5 a | 2.76 a | 2.70 |

CV = coefficient of variation; LSD = least significant difference; Means followed by the same letter within the same column are not significantly different at 5% level of probability; MC = seed moisture content; SG = standard seed germination; RL = seedling root length; SL = seedling shoot length; SDW = seedling dry weight; VI–I = seedling vigor index one; VI–II = seedling vigor index two; SD = seed density; TZ = tetrazolium seed viability test; Var1 = Tinike; Var2 = Babile; Var3 = Awash; Var4 = Ayenew; Var5 = Nasir; Var6 = Awash-Mekko; Var7 = Hundane; Var8 = Awash1; Var9 = Kufanzik; Var10 = Gofta; Var11 = Chercher; Var12 = Haramaya and Var13 = Dursitu.

have reported seed germination, and vigor of different bean genotypes produced in a subtropical climate, indicating seed germination at 25°C has been reduced in genotypes with adverse water potential. Support this, Carvalho et al. (2013) show that the seed performance of common bean has been evaluated under the action of different osmotic potentials. Besides, the current report observed that the seed germination process was probably coded by genetics, resulting in

Table 11. Mean values of laboratory seed quality parameters across tested locations (haramaya, babile, and hirna) in 2018

| Locations   | MC  | SG  | RL  | SL  | SDW | VI–I | VI–II | SD  | TZ  |
|-------------|-----|-----|-----|-----|-----|------|-------|-----|-----|
| Haramaya    | 9.45 a | 85.65 a | 9.84 a | 12.24 b | 45.58 a | 1908.84 a | 3928.08 a | 123.14 a | 95.21 a |
| Babile      | 8.32 a | 83.62 a | 10.14 a | 15.02 a | 46.35 a | 2103.93 a | 3989.62 a | 113.83 b | 93.12 a |
| Hirna       | 8.93 a | 82.21 a | 10.01 a | 12.46 a | 44.23 a | 1864.75 a | 3646.92 a | 124.23 a | 94.35 ab |
| Mean        | 8.90 a | 83.81 a | 10.00 a | 13.24 a | 45.38 a | 1959.17 a | 3854.87 a | 120.40 a | 94.22 |
| EMS         | 0.01 a | 18.57 a | 0.45 a | 1.25 a | 59.61 a | 30.569.7 a | 1900.926 a | 7.51 a | 6.23 |
| CV (%)      | 11.1 a | 11.6 a | 11.9 a | 23.5 a | 52.7 a | 21.4 a | 57.5 a | 6.0 a | 4.1 |
| LSD (5%)    | 0.38 a | 3.78 a | 0.46 a | 1.21 a | 9.27 a | 162.50 a | 859.1 a | 2.82 a | 1.50 |

CV = coefficient of variation; LSD = least significant difference; EMS = error mean square; Means followed by the same letters within the same column are not significantly different from each other at 5% level of probability; MC = seed moisture content; SG = standard seed germination; RL = seedling root length; SL = seedling shoot length; SDW = seedling dry weight; VI–I = seedling vigor index one; VI–II = seedling vigor index two; SD = seed density; TZ = tetrazolium seed viability test.
a negative impact on the process of mobilization of food reserves, respiration, enzymatic activity, and the activation of physiological processes concerning germination (Peske et al., 2012).

6.1.4. Seedling root and shoot lengths
There was no statistically significant (P > 0.05) difference for mean root lengths. This shows that the root length was not significantly affected by locational conditions where seeds were produced. The longest (11.60 cm) mean root length was recorded from Hundane and the shortest (8.03 and 8.28 cm) mean values of root length were recorded for Nasir and Gofta varieties, respectively, at the Haramaya location. The longest (12.25 cm) and shortest (8.38 cm) seedling root lengths were recorded for the varieties Hundane and Gofta, respectively, at the Hirna location. The shortest and the longest average seedling shoot lengths were recorded for Gofta and Chercher, with mean values of 7.28 and 17.30 cm, respectively. At the Babile location, the mean value of seedling root length increased from 8.33 to 12.13 cm for the varieties Haramaya and Ayenew, respectively. In line with a previous report, the variability of the genotypes at different locations might be due to the availability of root elongation materials like phosphorous, resulting in root length increment at the specific location that expresses gene potential (Miller et al., 2003).

At the Hirna location, the shortest seedling shoot length was recorded for the Gofta variety, whilst the longest average seedling shoot lengths were recorded for the Awash-1, Awash-Melka, Chercher, and Awash-2 varieties. At the Babile location, average seedling shoot length varied from 9.28 cm for Tinike to 19.73 cm for Chercher varieties. For seedling shoot lengths, seeds produced at the Babile location had a relatively longer (15.02 cm) average shoot length than those produced at the Haramaya and Hirna locations (Table 11). This was due to early and uniform germination of seeds produced in the Babile location and late germination of seeds produced both in the Haramaya and Hirna locations. Furthermore, genotype variation revealed at different locations might be due to the agro-ecology, soil nutrient availability, and source of the genotype, which tends to produce more or less root length (Miller et al., 2003; Rogeerio et al.2008; Gindri et al., 2017).

6.1.5. Seedling vigor and dry weight indices
At the Haramaya location, average seedling dry weight ranged from 22.5 to 70.0 mg for Awash-1 and Tinike varieties, respectively. Seedling dry weight and seedling VI–II were not significantly affected by location conditions. The average seedling VI–II at the Haramaya location varied from 1845 to 6800 for the Awash-1 and Tinike varieties, respectively. The average VI–II increased from 2180.0 for Awash-2 to 7056.7 for Hundane varieties. Similarly, the highest (95 mg) seedling dry weight was obtained from the Hundane variety at the Hirna location. Similarly, the largest seedling VI–II value was obtained from the Hundane variety.

On the other hand, average seedling dry weight ranged from 25 mg (for Haramaya, Awash-1, Nasir, and Awash-2) varieties to 90 mg (for the Hundane variety) at the Babile location. At the Babile location, the highest and comparable values of seedling VI–II were obtained from Hundane, Tinike, and Babile varieties, whilst the lowest and comparable seedling VI–II were recorded from Gofta, Awash-1, Awash-2, Haramaya, Dursitu, and Nasir varieties.

Among the varieties, Chercher showed superiority for VI–I over other varieties, and it was followed by Awash-Melka, Hundane, Awash-1, and Awash-2. The lowest VI–I was recorded for the Gofta variety, with a mean value of 2642.7. The highest VI–I value was obtained from the Babile location, but there was no statistically significant environmental effect for VI–I between the Haramaya and Hirna locations. Considering the seedling VI–I for each variety at each location, the greatest and least values were recorded for the Chercher and Gofta varieties, respectively, at the Haramaya location. In the same way, at the Babile location, the maximum and minimum seedling VI–I values were obtained from the Chercher and Gofta varieties, respectively. The least seedling VI–I value was calculated for the Haramaya variety, but the highest seedling VI–I values were recorded for the Awash-Melka, Awash-2, Chercher, Awash-1, and Hundane varieties. In agreement
with current work, Kedar et al. (2014) and 2008 revealed that seedling dry weight and seedling vigor indices have differed significantly among varied varieties and seed sources. The significant variations observed in seedling dry weight and seed vigor might be affected by differences in seed chemical composition like protein, soluble sugar content, and starch stored in genotypes as indicated by Henning et al. (2010) and Malaaldoa & Al-Hakimi (2016). Moreover, Nedel (2003) indicates that seeds’ chemical composition has been affected by location, characterized by significant environmental variation during the formation of seed by genetic makeup.

6.1.6. Seed densities and seed viability
Considering seed density, the highest seed densities were recorded at the Hirna and Haramaya locations, but the lowest seed densities were obtained from seeds produced at the Babile location (Table 11). Higher seed densities of 139.7 and 137.23 g/mL were recorded from Gofta and Ayenew varieties, and the lower seed density of 112.4 g/mL was recorded from Chercher and Awash-Melka, respectively, at the Haramaya location. In another way, the high seed densities were recorded from Haramaya, Awash-Melka, and Gofta varieties with mean values of 131.53, 129.15, and 129.13 g/mL, respectively, while the low seed densities were recorded from Dursitu and Chercher varieties with mean values of 115.15 and 116.25 g/mL, respectively, at the Hirna location. On the contrary, the highest mean values of seed densities of 123.88 and 120.83 g/mL were obtained from Awash-2 and Ayenew, respectively, and the lowest was recorded from the Gofta variety, with a mean value of 95.23 g/mL at the Babile location.

In another way, the seed viability ranged from 86.5% for Chercher to 98% for Tinike and Hundane varieties, at the Babile location. For seed viability (Tetrazolium test), the varieties Gofta and Haramaya showed the lowest seed viability compared to other varieties, whereas there was no statistically significant difference in viability for all other varieties tested. Similarly, there was no statistically significant effect of location on the viability of seeds. The viability of seeds ranged from 89% for Kufanzik to 99% for Chercher at the Haramaya location. The current significant difference in physiological seed quality (seed density) indicates sufficient diversity to categorize genotypes and the expression of genetic potential at specific locations due to the altitude, temperature, rainfall, and soil characteristics. In contrast, Gindri et al. (2017) found variability among accessions in a study that characterized accessions for seed viability. They have also reported non-significant interaction for any of the variables between common bean accessions and years of growing (consisted varied agro-ecology).

6.1.7. Seedling dry weight and seedling vigor indices
Average seedling dry weight ranged from 22.5 to 70.0 mg for Awash-1 and Tinike varieties, respectively, at Haramaya location. Seedling dry weight and seedling VI–II were not significantly affected by location conditions. Average seedling VI–II at Haramaya location varied from 1845 to 6800 for Awassh-1 and Tinike varieties, respectively. Average VI–II increased from 2180.0 for Awash-2 to 7056.7 for Hundane varieties. Similarly, the highest (95 mg) seedling dry weight was obtained from the Hundane variety at the Hirna location. Similarly, the largest seedling VI–II value was obtained from the Hundane variety.

On the other hand, average seedling dry weight ranged from 25 mg (for Haramaya, Awash-1, Nasir, and Awash-2) varieties to 90 mg (for Hundane variety) at Babile location. At Babile location, the highest and comparable values of seedling VI–II were obtained from Hundane, Tinike, and Babile varieties, whilst the lowest and comparable seedling VI–II were recorded from Gofta, Awash-1, Awash-2, Haramaya, Dursitu, and Nasir varieties.

Among the varieties, Chercher showed superiority for VI–I over other varieties and it was followed by Awash-Melka, Hundane, Awash-1, and Awash-2. The lowest VI–I was recorded for the Gofta variety having a mean value of 2642.7. The highest VI–I value was obtained from the Babile location, but there was no statistically significant environmental effect for VI–I between Haramaya and Hirna locations. Considering the seedling VI–I for each variety at each location, the greatest and least values were recorded from Chercher and Gofta varieties, respectively, at
the Haramaya location. In the same way, at Babile location the maximum and minimum seedling VI–I values were obtained from Chercher and Gofta varieties, respectively. The least seedling VI–I value was calculated for Haramaya variety, but the high seedling VI–I values were recorded from Awash-Melka, Awash-2, Chercher, Awash-1 and Hundane varieties. In agreement with current work (Kedir et al., 2014); Golezani and Oskooyi (2008) revealed that seedling dry weight, and seedling vigour indices has been differed significantly among varied varieties, and seed source. The significant variations observed on seedling dry weight, and seed vigor might be affected by differences in seed chemical composition like protein, soluble sugar content and, starch stored in genotypes as indicated by Henning et al. (2010); Molaaldoila & Al-Hakimi (2016). Moreover, Nedel (2003) indicates seeds chemical composition has been affected by location characterized by significant varied environment during formation of seed by genetic makeup.

6.1.8. Seed densities and seed viability
Considering seed density, the highest seed densities were recorded at Hirna and Haramaya locations, but the lowest seed densities were obtained from seeds produced at Babile location (Table 11). Higher seed densities of 139.7 and 137.23 g/mL were recorded from Gofta and Ayenew varieties and the lower seed density of 112.4 g/mL were recorded from Chercher and Awash-Melka, respectively, at Haramaya location. In another way, the high seed densities were recorded from Haramaya, Awash-Melka, and Gofta varieties with mean values of 131.53, 129.15, and 129.13 g/mL respectively, while the low seed densities were recorded from Dursitu and Chercher varieties with mean values of 115.15 and 116.25 g/mL, respectively, at Hirna location. On the contrary, the highest mean values of seed densities of 123.88 and 120.83 g/mL were obtained from Awash-2 and Ayenew, respectively, and the lowest was recorded from Gofta variety with a mean value of 95.23 g/mL at Babile location.

In another way, the seed viability ranged from 86.5% for Chercher to 98% for Tinike and Hundane varieties, at Babile location. For seed viability (Tetrazolium test), the varieties Gofta and Haramaya showed the lowest seed viability compared to other varieties, whereas there was no statistically significant difference in viability for all other varieties tested. Similarly, there was no statistically significant effect of locations on the viability of seeds. The viability of seeds ranged from 89% for Kufanzik to 99% for Chercher at Haramaya location. The current significant difference response of physiological seed quality (seed density) indicates sufficient diversity to categorize genotypes, and the expression of genetic potential at specific location due to the altitude, temperature, rainfall, and soil characteristics. In contrarily, study conducted elsewhere characterized accession for seed viability has been reported variability among accessions (Gindri et al., 2017). They have also reported non-significant interaction for any of the variables between common bean accessions and years of growing (consisted varied agro ecology).

7. Summary and recommendation
The production of high-quality seeds is of fundamental importance for successful crop production. However, seed yield is a complex trait that is influenced directly or indirectly by G x L interaction. This study was conducted at three locations in the Hararghe Zone, Eastern Ethiopia, in a randomized complete block design with three replications in 2018 to estimate the G x L interaction effects on yield, yield-related traits, and seed quality. The ANOVA revealed very highly significant (P ≤ 0.001) differences among locations, genotypes, and the G x L interaction. The ANOVA revealed that mean emergence time and seeds per pod were highly and significantly affected by genotype and location, respectively. Similarly, there was a very highly significant (P ≤ 0.001) effect for all the other characters.

Considering seed yield, the combined ANOVA showed that seed yield was highly and significantly (P ≤ 0.01) affected by location, genotype, and G x L interaction, and the largest proportion of the total variation in seed yield was attributed to locations. The varieties Ayenew, Gofta, Haramaya, Kufanzik, Babile, Tinike, and Hundane were the top seed-yielding varieties, with mean seed yields above the grand mean (3988.46 kg ha⁻¹) and all the other varieties yielded below the grand mean.
Among locations, the highest (6040.26 kg ha\(^{-1}\)) and lowest (1696.85 kg ha\(^{-1}\)) yields were obtained from the Hirna and Babile sites, respectively.

Regarding seed quality tests, the ANOVA revealed a very highly significant (P ≤ 0.001) effect of genotypes and G x L interaction for all traits studied. In general, common bean seeds produced in the Haramaya location had relatively better normal seed germination than those produced in the Babile and Hirna locations. Hence, Haramaya is a suitable site for the production of good quality seeds compared to the other two locations. In conclusion, among the tested varieties of common bean, the less interacted ones, namely Awash-Melka, Awash-2, Chercher, and those that yielded above the grand mean and also fulfilled the minimum national standard for seed germination (Babile, Tinike, Hundane), are better if used and dominated during production by farmers of the study locations for the production of good quality seed.

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## Appendices

### Table A1. Mean squares values of varieties and error for individual locations (haramaya, babile and hirna) for seed yield and yield related traits

| Traits | Haramaya | Babile | Hirna |
|--------|----------|--------|-------|
|        | Variety  | Error  | Variety | Error  | Variety | Error  |
| FEI    | 2.08**   | 0.64   | 5.48**  | 1.49   | 1.48*   | 0.5650 |
| MET    | 0.40***  | 0.09   | 0.08*** | 0.09   | 0.26*** | 0.28   |
| SE     | 73.87**  | 19.30  | 157.25***| 9.05   | 79.879***| 7.072  |
| DF     | 61.75*** | 1.99   | 56.03***| 1.32   | 48.58***| 1.97   |
| DPM    | 42.14*** | 3.33   | 24.81***| 4.17   | 36.09***| 4.05   |
| PH     | 559.90***| 73.95  | 294.97***| 51.28  | 1266.11***| 73.88  |
| PPP    | 180.51***| 20.99  | 55.79***| 5.09   | 67.01***| 5.58   |
| SPP    | 0.95***  | 0.15   | 0.29*** | 0.53   | 0.49**  | 0.12   |
| HSW    | 295.77***| 0.44   | 225.07***| 0.63   | 258.91***| 1.63   |
| SY     | 1904039***| 231.911| 3,961,508***| 64,040 | 7,044,514***| 362,288 |

*, **, ***; significant at 0.05, 0.01 and 0.001 level of probability, respectively; ns = non-significant; FEI = field emergence index; MET = mean emergence time; SE = seedling establishment; DF = days to flowering; DM = days to maturity; PH = plant height; PPP = pods per plant; SPP = seeds per pod; HSW = hundred seed weight and SY = seed yield.

### Table A2. Mean squares of varieties and error for individual locations (haramaya, babile and hirna) for seed quality traits

| Traits | Haramaya | Babile | Hirna |
|--------|----------|--------|-------|
|        | Variety  | Error  | Variety | Error  | Variety | Error  |
| MC     | 3.51***  | 0.01   | 6.75*** | 0.01   | 1.86*** | 0.05   |
| SG     | 303.56***| 9.01   | 416.03***| 27.67  | 291.73***| 19.00  |
| RL     | 4.14***  | 0.26   | 5.91*** | 0.81   | 3.40***  | 0.30   |
| SL     | 27.53*** | 0.62   | 36.40***| 2.46   | 45.29*** | 0.74   |
| SDW    | 917.30*  | 373.70 | 2085.90***| 199.60 | 1797.40***| 183.80 |
| VI–I   | 621646***| 12,493| 479,621.33***| 65,741.0| 805,370.0***| 17,491.0|
| VI–II  | 8573459***| 2,811,213| 21,007,541***| 1,559,380| 13,792,892***| 1,471,333|
| SD     | 287.29***| 6.90   | 204.05***| 10.32  | 97.69*** | 3.71   |
| TZ     | 37.29*** | 4.68   | 53.19***| 10.78  | 36.90*** | 3.55   |

*, **, ***; significant at 0.05, 0.01 and 0.001 level of probability, respectively; MC = seed moisture content; SG = standard seed germination; RL = seedling root length; SL = seedling shoot length; SDW = seedling dry weight; VI–I = seedling vigor index one; VI–II = seedling vigor index two; SD = seed density; TZ = tetrazolium seed viability test.
