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Full Length Research Paper

The Potential of Rhizobium Isolates as a Biofertilizer for Common bean (*Phaseolus vulgaris* L.) Varieties Cultivated in Gurage Zone, Central Ethiopia

Kedir Shukri[1*], Nigussie Dechassa[2], Tamado Tana[2], Yonas Yohannes[3]

[1*]Department of Plant Science, College of Natural Science and Agriculture, Madda Walabu University
[2] Department of Plant Science, Haramaya University.
[3]Ethiopian Environment and Forest Research Institute, Addis Ababa

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Abstract

In Ethiopia's low and mid-altitude areas, the common bean (Phaseolus vulgaris L.) significantly contributes to food supply, smallholder farmer income, and foreign exchange earnings. Despite its importance, common bean yields are hampered by factors like poor soil fertility, particularly nitrogen deficiency, the prohibitive cost of synthetic fertilizers, and limited awareness of bio-fertilizers. To find a solution, field experiments were conducted in Ethiopia's Gurage Zone to assess the impact of rhizobia inoculation on common bean nodulation, yield-related characteristics, and overall yield. The research employed a factorial combination of four common bean varieties (Local, Awash-Melka, Awash-1, and SER-119) and five rhizobia treatments (un-inoculated control, CBR-14, CBR-J16, CBR-18, and CIAT-899), arranged in a randomized complete block design (RCBD) with three replicates. Data analysis using SAS revealed that both common bean varieties and rhizobia treatments significantly affected leaf area index ($p<0.001$), pod number per plant ($p<0.001$), hundred seed weight ($p<0.05$), above-ground dry biomass ($p<0.001$), and grain yield ($p<0.001$). Plant height ($p<0.001$), number of seeds per pod ($p<0.01$), and harvest index ($p<0.001$) were solely influenced by the bean varieties. Interactions between varieties and rhizobia, as well as their individual effects, significantly impacted plant branching and the number of total nodules ($p<0.05$), the number of effective nodules and nodule dry weight ($p<0.001$). Optimal nodulation was observed when the SER-119 variety was paired with rhizobium isolates CBR-18 or CIAT-899. SER-119 and CBR-18 independently resulted in the highest grain yields of 2935.41 kg ha-1 and 2459.2 kg ha-1, respectively, CIAT-899 performing similarly as CBR-18. Consequently, the SER-119 variety and the CBR-18 Rhizobium isolate are recommended for widespread adoption by farmers and stakeholders involved in common bean cultivation within the study region and comparable agro-ecological zones.

* *Corresponding* shikurikedir@gmail.com

1. Introduction

Common bean (*Phaseolus vulgaris* L.) is a highly variable crop cultivated globally in various environments and altitudes, from sea level up to 3000 meters above sea level (Pathania *et al*., 2014). In 2020, approximately 27.5 million tons were harvested from 34.8 million hectares (FAO, 2022). This legume can be grown as a dry bean (pulse) or as a green vegetable, utilizing its pods and leaves. Its diverse plant types and growth habits allow for cultivation in monoculture, intercropping, or crop rotation with non-leguminous species (Walelign, 2015). Furthermore, its capacity to fix atmospheric nitrogen into ammonia benefits crop rotations and enhances soil fertility by leaving residual nitrogen from residue decomposition (van der Berge, 2011).

In Ethiopia, common bean is a crop of considerable importance, serving as a lucrative cash crop, a vital protein source, and an essential emergency food in many lowland and midland regions (Amanuel and Girma, 2018). Its versatility is reflected in its consumption within traditional dishes, prepared in several ways. Dry beans are commonly prepared as 'nifro,' a dish of boiled grain mixed with sorghum or maize, or are utilized in the preparation of 'wat,' a local stew. Southern Ethiopia also features boiled and split beans mixed with 'kocho' (MoANR, 2016). The common bean's nutritional profile, boasting approximately 22% protein and 61.7% carbohydrate, makes it nutritionally comparable to cereals and other staple foods (USDA, 2021). Beyond its critical role in enhancing food security and improving the livelihoods of smallholder farmers, the common bean has a long history as an export commodity, contributing significantly to the nation's foreign exchange earnings (MoANR, 2016). More recently, it has emerged as the leading pulse crop for export, representing 41% of the total pulse export earnings (FAO, 2015). This economic significance is further highlighted by the dramatic increase in Ethiopia's foreign exchange earnings from common bean, which jumped from 31 million USD in 2016 to 624 million USD in 2020 (ERCA, 2021). Over the same period, export volumes also saw a substantial rise, increasing from 58,000 metric tons to 923,000 metric tons.

Despite its many benefits, the average productivity of common bean in Ethiopia, reported at 1.72 tons/ha by CSA (2022), significantly lags behind potential yields. For instance, Argaw *et al*. (2012) achieved 4.3 tons/ha with the Gofta variety and rhizobium inoculation, highlighting a substantial gap between farmer yields and improved variety potential under optimal conditions. This disparity is largely attributed to several production constraints, including limited adoption of improved varieties, poor soil fertility, and inadequate management practices (ATA, 2014). Soil fertility, particularly nitrogen and phosphorus levels, is a critical factor influencing common bean productivity (Bilisuma, 2019). Moreover, smallholder farmers' access to improved common bean varieties is restricted (Fistum and Belay, 2022), and they frequently neglect practices like inorganic fertilizer application and rhizobium inoculation for legumes (Argaw *et al*., 2012). The high cost of mineral fertilizers presents a significant obstacle to increasing legume and other crop production across much of Sub-Saharan Africa (Mmbaga *et al*., 2014), and Ethiopia's widespread soil fertility challenges necessitate solutions beyond mineral fertilizers alone (IFPRI, 2010). Consequently, Biological Nitrogen Fixation (BNF) emerges as an environmentally sound agricultural input (Bekere and Hailemariam, 2012) and a cost-effective alternative to inorganic fertilizers, particularly for resource-poor farmers (Hulluager *et al*., 2025).

Rhizobia, a group of soil bacteria, infect legume roots to create root nodules. Within these nodules, they convert atmospheric nitrogen into ammonia, a process known as nitrogen fixation (Herridge, 2013). These diazotrophic (nitrogen-independent) and gram-negative rods are motile and do not form spores (Baron *et al*., 1996). Rhizobia that nodulate legumes are classified within the class Alphaproteobacteria, order Hyphomicrobials, family rhizobiaceae, and genus Rhizobium. Specifically, *Rhizobium leguminosarum* is the species responsible for nodulating the common bean (Young *et al*., 2006). Rhizobia inoculants enhance soil fertility by fixing atmospheric nitrogen in legume root nodules, thus maintaining or improving soil nitrogen levels. This practice reduces the need for nitrogen fertilizer, lowering both crop production costs and environmental impact (Matny, 2015; Khan *et al*., 2020). For common bean production, bio-fertilizers offer a more economical, straightforward, and environmentally benign alternative to synthetic nitrogen fertilizers. Consequently, nitrogen fixation via bio-fertilizer application represents a sustainable, eco-friendly, and cost-effective nitrogen source for legume cultivation (Thilakarathna and Raizada, 2018). However, the efficiency of rhizobial strains in fixing nitrogen within common bean plants differs across genotypes (Pathania *et al*., 2014). The efficacy of rhizobial strains in forming nodules and fixing atmospheric nitrogen in common beans is influenced by both the specific host genotype and the bacterial strains employed (Farid and Navabi, 2015).

Research across Ethiopia has explored the effects of *Rhizobium* inoculation on common beans and other legumes, consistently revealing positive impacts on nodulation and yield. For instance, Tarekegn and Felix (2025) demonstrated that *Rhizobium* inoculation significantly boosted nodule numbers, nodule dry weight, pod counts, number of seeds per pod, hundred seed weight, and grain yield in common beans compared to un-inoculated controls. Similarly, Argaw and Muleta (2017) achieved maximum grain yields of 3800.1 kg/ha for the Kufanzik variety and 3735.6 kg/ha for the Gofta variety at Haramaya when inoculated with NSCBR-14. At Hirna, maximum yields of 3648.0 kg/ha and 3625.7 kg/ha were recorded for the Gofta variety inoculated with NSCBR-18 and NSCBR-59, respectively. Despite these findings, smallholder farmers, including those in the research area, seldom inoculate legumes like common beans or use inorganic fertilizers. This practice stems from a lack of awareness, cost concerns, and the misconception that legumes are self-sufficient in nutrient requirements. Notably, no prior research on rhizobial inoculations and common bean varieties has been conducted in the specific region of this study.

Recognizing the need for efficient and economical nutrient sources and more adaptive common bean varieties to enhance sustainable production in the Gurage Zone, Central Ethiopia, this research was undertaken. The study aimed to assess the impact of rhizobial inoculants as bio-fertilizers on nodulation, yield-contributing traits, and the yield of different various common bean varieties.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted at the Emdebir experimental field of Wolkite University in the Gurage Zone, Central Ethiopia during 2015 and 2016 main cropping seasons. Emdebir is located 33 km away to the South of Wolkite town and 185 km to the South-West of Addis Ababa at 8º 11’ 8.3” N latitude and 37º 9’ 3.6” E longitude at an altitude of 1980 meters above sea levels. The average annual rainfall of the site is 1065.7 mm. The mean annual minimum temperature is 10.8 °C and the mean annual maximum temperature is 24.8 °C. The digital soil map of the area reported by Mohammed (2014) showed that the soil was acidic with a pH of 5.1 to 5.5 and that it was deficient in nitrogen, phosphorus and sulfur. Figure 1 bellow shows the map of the experimental area.

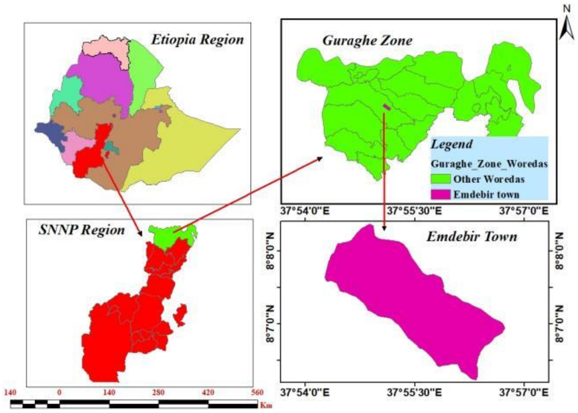

Figure 1: Map of Ethiopia and the study area (ESRI, 2020) (Source: Authors)

2.2. Soil Sampling, Processing and Analysis

Soil samples were collected from 12 spots in the experimental plots, following a zigzag pattern to a depth of 0-30 cm. After compositing, these samples were submitted to the Wolkite Soil Laboratory and Holota Agricultural Research Center for analysis of various soil parameters, such as particle size distribution, organic carbon, available phosphorus, and total nitrogen. Analytical procedures included: air-drying, grinding, and sieving sub-samples through a 2 mm sieve. Soil pH was determined using a combined glass electrode pH meter in a 1:2.5 soil: H_2O suspension (Chopra and Kanwar, 1976). Organic carbon was quantified by wet combustion (Walkely and Black, 1934), total nitrogen by the Kjeldahl procedure (Bremner and Mulvaney, 1982), available phosphorus by the Olsen method (Olsen et al., 1954), cation exchange capacity (CEC) by the ammonium acetate method (Sahlemedehin and Taye, 2000), sulfur by the turbidity method (Cottenie et al., 1979), and particle size distribution (soil texture) was determined by the Bouyoucos hydrometer method (Bouyoucos, 1951).

2.3. Source and Description of Bio-fertilizer (Rhizobium isolates) and Varieties

Three rhizobia isolate (CBR-14, CBR-J16, and CBR-18) were obtained from Haramaya University Soil Microbiology Laboratory, and one Rhizobium strain called International Center for Tropical Agriculture-899 (CIAT-899) was obtained from Holleta Agricultural Research Center. Strain CIAT-899 (*Rhizobium tropici*) is internationally used as standard check. The three isolates (CBR-14, CBR-J16, and CBR-18) were tested together with many other isolates by Haramaya University in green house and field experiments in different soil types of East and West Hararghe. The researchers reported promising results from common beans inoculated with the isolates in increasing nodulation, yield, and yield components. The researchers recommended that the isolates can to be used by common bean producers in the area, and made them available at Soil Microbiology Laboratory of Haramaya University for further study by other researchers at different locations of the country with varying agro-ecologies and soil conditions. Accordingly, these three isolates were selected based on their performance of the previous study and by considering the condition of the current study area.

Common bean varieties Awash-1, Awash-Melaka, and SER-119 were released by Melkassa Agricultural Research Center in 1990, 1999 and 2014, respectively. Awash-1 and Awash Melka are canning types of varieties with small sized white colored seeds and average research field yields of 2.0-2.2 and 2.5 tons/ha, respectively. Both grows in areas receiving annual rainfall of 350-700 mm and altitude ranges of 1400-1800 and 1400-1900 m.a.s.l, respectively (MoA, 2010). SER-119 is indeterminate bush type of variety with small sized red colored seeds and average research field yield of 2.0-5.0 tons/ha. It grows in areas receiving annual rainfall of 400-1100 mm and altitudes ranging from 1000-2200 m.a.s.l . It requires 85-105 days to reach maturity (MoA, 2014). The Local variety was bought from the local market at Wolkite, while the improved varieties were obtained from Melkassa Agricultural Research Center.

2.4. Treatments, Experimental Design and Procedures

The experiment featured a factorial design, integrating four common bean varieties (Farmers' seed, Awash Melka, Awash-1, and SER-119) with five *Rhizobium* isolates (un-inoculated control, CBR-14, CBR-J16, CBR-18, and CIAT-899), resulting in a total of twenty treatments. These treatments were subjected to a randomized complete block design with three replicates. Each experimental plot had a total area of 9.6 square meters (3.2 m x 3.0 m) and comprised 8 rows. A spacing of 40 cm was implemented between rows, and plants within a row were spaced 10 cm apart. A 1-meter pathway was incorporated between blocks and between individual plots within blocks to facilitate movement for various experimental tasks and data recording.

In order to obtain appropriate seed bed plowing was done three times before sowing (twice by tractor and once by man power) and the plots were manually leveled at planting. 46 kg P_2O_5 ha^{-1} in the form of Triple Super Phosphate (TSP = $Ca(H_2PO_4)_2$, and 20 kg Nitrogen ha^{-1} (starter) in the form of urea were applied for all plots uniformly in bands and covered with soil to protect the direct contact with seeds. Except for the control, seed inoculation with *Rhizobium* inoculants was done based on the treatment.

2.5. Inoculant Preparation and Inoculation Procedures

Pure cultures of each Rhizobium isolate, sourced as slant cultures from the laboratory, were grown on yeast extract mannitol (YEM) agar. A single pure bacterial colony was then suspended in YEM broth and incubated for 7 days at 30°C with continuous shaking at 120 rpm. Subsequently, 400 cm^3 of this *Rhizobium* culture liquid was mixed with 1 kg of sterile fine filter mud (carrier) and the mixture was packed into plastic bags. These inoculants were then incubated at 28°C for 15 days. The concentration of rhizobia in the inoculants at the time of application was determined using the plate count method. To do this, 1 cm^3 of a 10^{-6} dilution of serially diluted inoculant was plated on YEM agar. After incubation at 28°C for 6 days, the resulting count indicated more than 1 x 10^9 rhizobia per gram of inocula. For each variety, the required 200 g of seeds were weighed separately and placed in a container. Lukewarm water was measured and added to a large plastic bottle, followed by a measured amount of sugar, which was thoroughly mixed to create a uniform sticker solution. The seeds were then mixed with 4 teaspoons (20 ml) of this sticker solution and 20 g of filter mud-based *Rhizobium* inoculants until evenly coated. Finally, the inoculated seeds were set aside to dry under shade for 15 minutes before sowing.

2.6. Data Collection and Measurement

2.6.1. Crop Phenology and Growth Parameters

Crop phenology and growth parameters were recorded using established procedures. These included days to 50% emergence, days to 50% flowering, days to 90% physiological maturity, plant height, Leaf Area Index (LAI), and the number of primary branches per plant. Days to emergence were counted from sowing until 50% of seeds in each plot had germinated. This emergence data was then used to calculate days to 50% flowering and days to 90% physiological maturity. Flowering was recorded as the number of days from emergence until the first flower appeared on 50% of ten randomly selected, pre-tagged plants. Physiological maturity was determined similarly, marking the number of days from emergence when 90% of these tagged plants exhibited yellow leaves and yellow or red pods. LAI was calculated by measuring the leaf area of five randomly selected plants per plot at flowering, dividing by the plant's land area, and averaging the results. The number of primary branches per plant and plant height were measured at physiological maturity from the ten pre-tagged plants in each plot. Primary branches were counted directly from the main stems and averaged. Plant height was measured from the base to the tip of the main stem and also averaged.

2.6.2. Nodulation Parameters

To determine the total number of nodules per plant, the roots of five randomly selected plants from each treatment were carefully uprooted at 50% flowering. After washing the roots with tap water on a sieve, the nodules were separated and counted. Nodules were then dissected to assess their nitrogen-fixing capacity by observing their color: pink nodules were considered effective, and cream-white nodules were deemed ineffective (Adugna *et al*., 2020). Nodule dry weight was measured using a sensitive balance after drying them in an oven at 65°C until constant weight was achieved.

2.6.3. Yield Components, Yield and Harvest Index (HI) Determination

At harvest, the total pod count from the 10 pre-tagged plants in each plot was averaged to determine pods per plant. The total seed count from these pods was then divided by the number of pods to yield seeds per pod. Hundred-seed weights (g) were recorded by counting and weighing 100 seeds from the harvested bulk of each plot. Above-ground dry biomass yield (kg ha^{-1}) was quantified. Ten randomly selected plants were harvested at physiological maturity, cut at ground level, and included the main stem, branches, leaves, petioles, pods, and seeds. These samples were oven-dried at 60°C for 72 hours and weighed. The total biomass per net plot was calculated by multiplying the average plant weight by the total number of plants within that plot, and then converted to yield per hectare. The harvest index (%) was computed as the ratio of grain yield to total above-ground dry biomass yield, multiplied by 100. Grain yield (kg ha^{-1}) was adjusted to a 10% seed moisture content. This adjustment was performed by recording the seed weight from each net plot, determining its actual moisture content (M), and applying the formula: Adjusted yield (kg) = Recorded seed weight × [(100 - M) / (100 - D)], where D is the designated moisture content (10%).

2.7. Statistical Analysis

Data analysis was conducted using SAS statistical software (SAS Institute version 9.2, 2009). Levene's test assessed homogeneity of variance across years. When variances between repeated seasons were found to be homogenous, the data were combined and analyzed using general linear procedures (Gomez and Gomez, 1984). Given this homogeneity for all traits, a combined analysis of variance (ANOVA) was performed. Significant differences between treatment means were identified using Duncan's Multiple Range Test at a 5% significance level.

3. Results and Discussion

3.1. Soil Parameters

The soil analysis result indicated that the soil texture of the experimental field was sandy clay loam with sand, silt and clay content of 44%, 19%, and 37%, respectively; strongly acidic with a pH value of 5.2; the organic matter and organic carbon contents of 2.00%, 1.15%, respectively, which were moderate; cat ion exchange capacity (CEC) of 19.14 meq/100g, which was moderate; low total nitrogen, very low available phosphorus, and low available sulfur contents with respective values of 0.096%, 1.76 ppm, and 11.43 ppm (Table 1). The overall condition of this soil indicated that its initial fertility status was poor; suggesting successful common bean production on this field requires application of external fertilizers either from organic or inorganic sources, or both. The poor nutrient content of the soil could be due to the fact that before the field became cultivated land it has been left as bare grazing land for long period of time and most of its top soil has been eroded. In addition, after the field became cultivated land, it was used to produce only cereals such as wheat and maize, without using rotation with legumes, intercropping, cover crops, constructing soil and water conservation structures and other practices that minimize soil erosion, maintain or restore the fertility of the soil.

Table 1: Mean values for selected physic-chemical properties

Soil property	Result	Rating	Remark
pH	5.2	strongly acidic	Hazelton and Murphy (2007)
Organic Carbon%	1.15	moderate	Hazelton and Murphy (2007)
Organic Matter%	2.00	moderate	Hazelton and Murphy (2007)
Total Nitrogen%	0.096	low	Hazelton and Murphy (2007)
Available Phosphorus (ppm)	1.76	very low	Olsen et al. (1954)
Available Sulfur (ppm)	11.43	low	Ethio SIS (2014)
CEC (meq/100g soil)	19.14	moderate	Hazelton and Murphy (2007)
Sand Silt Clay	44% 19% 37%	Sandy clay loam	Bouyoucos (1951)

3.2. Crop Phenology and Growth Parameters

3.2.1. Days to 50% Seedling Emergence of Common Beans

Days to emergence were significantly ($p < 0.001$) affected by the main effect of common bean varieties, but not by the main effect *Rhizobium* inoculants and the interaction of the main effects (Table 2). Local variety took a relatively maximum number of days (8.27) to emerge, which was statistically similar with variety Awash-Melka (8.03 days) and Awash-1 (7.90 days), whereas SER-119 required a significantly shorter (7.43) days (Table 3). The early emergence of SER-119 might be attributed to the relatively large amount of food reserve stored in the endosperm due to its relatively large seed size and the existence of genetic variation among common bean varieties. The variation also might be due to the storage condition and age of the seed, which led depletion of the food reserves in the endosperm. According to Mandal *et al*. (2008), larger seeds may have an enhanced ability to penetrate ground cover and are capable of emerging from greater planting depths. Similar to our result Ndlovu (2015) indicated that a larger seed-sized cultivar emerged four days earlier than the smaller seed-sized cultivars in dry bean. Gereziher *et al*. (2017) also recorded highly significant differences among common bean varieties in days to emergence ranging between 9.33 to 11.00 days.

3.2.2. Days to 50% Flowering of Common Beans

Both the varieties and *Rhizobium* inoculants significantly impacted the number of days to reach 50% flowering ($p < 0.05$), although their interaction was not statistically significant (Table 2). The local variety took longer to flower (41.47 days), compared to SER-119, which flowered sooner (39.03 days) (Table 3). The local variety's flowering time was statistically similar to Awash-Melka (41.30 days), while SER-119 was statistically comparable to Awash-1 (39.37 days). These differences are likely attributable to genetic variations among the varieties. This finding aligns with Gereziher *et al*. (2017) and Misgana and Tadesse (2017), who observed differences of

13.67 and 7 days, respectively, between earlier and later flowering varieties. Nuru et al. (2020) and Desta et al. (2021) also reported similar influences of different common bean varieties on flowering time.

Among the tested *Rhizobium* inoculants, CBR-18 showed the longest duration to flowering at 40.83 days, though this was statistically similar to other inoculants. Conversely, the un-inoculated control flowered sooner at 39.58 days, duration statistically comparable to CBR-J16 (40.21 days) and CBR-14 (40.38 days) (Table 3). Overall, the *Rhizobium* inoculants did not significantly differ in their impact on days to 50% flowering, suggesting effective atmospheric nitrogen fixation, which is known to delay crop phenology. The variations in flowering time could be attributed to nitrogen availability from this fixation. This aligns with Havlin et al. (1999), who noted that nitrogen can delay flowering. Supporting this, Nuru and Taminew (2021) reported longer durations to 50% flowering in Rhizobium-inoculated common beans (39.59 days) compared to the un-inoculated control (38.15 days), a finding corroborated by Nuru *et al*. (2020).

Table 2: Analysis of variance for days to 50% emergence, days to 50% flowing, days to 90% physiological maturity, leaf area index (LAI) and plant height as affected by the main effects of common bean varieties and Rhizobial inoculants.

Source of variation	**DF**	**Mean square**				
		Days to 50% emergence	**Days to 50% flowering**	**Days to 90% physiological maturity**	**LAI**	**Plant height**
Block	2	0.267^{ns}	1.004^{ns}	0.950^{ns}	0.093^{ns}	59.369^{ns}
Variety	3	2.728***	24.182***	8.715***	1.425***	3905.353***
Rhizobium	4	0.115^{ns}	2.510*	4.881***	1.425***	3905.353***
Var * Rhiz	12	0.062^{ns}	0.713^{ns}	0.462^{ns}	0.026^{ns}	19.860^{ns}
Error	38	0.23^{ns}	0.855^{ns}	0.71^{ns}	0.045^{ns}	31.530^{ns}

DF = degree of freedom; *** = significant at p<0.001; ** = significant at p<0.01; * = significant at p<0.05; ns = non-significant; Var * Rhiz = Variety by Rhizobium interaction

3.2.3. Days to 90% Physiological Maturity of Common Beans

The results showed that the main effects of varieties and *Rhizobium* inoculants significantly (p <0.001) influenced the number of days required to attain 90% physiological maturity, but their interaction didn't show significant effect (Table 2), indicating the main factors were independent of each other in affecting maturity. The local variety required the maximum duration of 87.00 days to mature physiologically, which was statistically similar with SER-119 (86.80 days) (Table 3). On the other hand, Awash-1 physiologically matured relatively earlier (85.37 days) as compared to the other varieties, except Awash-Melka (85.93 days). This difference might be related with genetic variations found in common bean varieties. This outcome aligns with Nuru (2020), who observed a maturity range from a maximum of 82.56 days for the Red Wolaita variety to a minimum of 78.56 days for Nasir. Similar impacts of common bean varieties on days to maturity have also been documented by Gereziher *et al*. (2017) and Ndlovu (2015).

As to the rhizobia inoculants, CBR-18 led to relatively longer duration (86.83 days) to attain maturity, whereas minimum duration of 85.38 days was recorded for the control (Table 3). All of the inoculants used in this experiment, except CBR-J16 (85.83 days), delayed maturity significantly in comparison to the control. The exception of CBR-J16 might be ascribed to its less effectiveness in fixing nitrogen; because the effectiveness of *Rhizobium* isolates to fix nitrogen differs. The observed delay in the maturity date of inoculated plots might be due to prolonged vegetative growth resulting from a better supply of nitrogen from fixation by the *Rhizobium* inoculants. According to Brady and Weil (2002), higher nitrogen levels delay crop maturity due to extended vegetative growth. This finding coincides with Nuru and Taminew (2021) who indicated longer days to maturity (80.19) from Rhizobium-inoculated common beans as compared to un-inoculated control (74.56 days). The same was also reported by Nuru (2020) in common bean.

3.2.4. Leaf Area Index (LAI) of Common Beans

Leaf area index (LAI) varied significantly ($p < 0.001$) based on the main effects of varieties and *Rhizobium* inoculants, but their interaction was not significant (Table 2), indicating the impact of one main factor on the outcome of this dependent factor (LAI) was independent of the other. Variety SER-119 yielded the highest LAI (2.71), while Awash-Melka recorded a lower value (2.00), statistically similar to the local variety (2.14) (Table 3). These differences likely stem from variations in leaf number and size, reflecting genetic differences among varieties. This aligns with the findings by Habtamu (2019), who reported a maximum LAI of 5.44 for the local variety and a minimum of 4.61 for Nasir, a trend also observed by Habtamu *et al*. (2017) in the same crop.

Regarding the *Rhizobium* inoculants, the highest LAI of 2.44 was recorded in response to CBR-18, while the lowest (2.08) was recorded from the control. The LAI from CBR-18 was statistically equal to that obtained from CIAT-899 (2.41). The control was also statistically similar to CBR-16 (2.19) and CBR-14 (Table 3). This means nitrogen supply from fixation by CBR-16 and CBR-14 was not sufficient to bring about significant increment in leaf growth as compared to the control, which might be due to their less ability to adapt the prevailed environmental condition of the area and fix atmospheric nitrogen, and make it available to the plant for growth. According to Lloyd and Farquhar (1996) nitrogen affects leaf growth by increasing the leaf area of plants. The result agrees with Habtamu (2019), who indicated a significantly larger LAI of 5.15 from Rhizobium HB-429- treated plots as compared to the un-inoculated plots (4.79). Similar effects of inoculating soybean and common bean with appropriate rhizobia were also reported by Tairo and Ndakidemi (2013) and Habtamu *et al*. (2017), respectively.

Table 3. Mean values for plant phenology (days to emergence, days to flowering, days to maturity), and growth parameters such as leaf area index (LAI), and plant height of common bean as affected by varieties and rhizobial inoculants

Parameters

Treatments	Days to 50% seedling emergence(n)	Days to 50% flowering(n)	Days to 90% physiological maturity(n)	LAI	plant height(cm)
Varieties					
Local variety	8.27^{a}	41.47^{a}	87.00^{a}	2.14^{bc}	69.59^{a}
Awash-Melka	8.03^{a}	41.30^{a}	85.93^{b}	2.00^{c}	31.77^{c}
Awash-1	7.93^{a}	39.37^{b}	85.37^{b}	2.24^{b}	44.21^{b}
SER-119	7.43^{b}	39.03^{b}	86.80^{a}	2.71^{a}	41.40^{b}
F-test	***	***	***	***	***
Rhizobial inoculants					
Un-inoculated control	8.08^{a}	39.58^{b}	85.38^{b}	2.08^{c}	45.73^{a}
CBR-14	7.88^{a}	40.38^{ab}	86.63^{a}	2.25^{bc}	45.88^{a}
CBR -J16	7.92^{a}	40.21^{ab}	85.83^{b}	2.19^{c}	45.99^{a}
CBR -18	7.88^{a}	40.83^{a}	86.83^{a}	2.44^{a}	49.99^{a}
CIAT-899	7.83^{a}	40.46^{a}	86.71^{a}	2.41^{ab}	46.12^{a}
F-test	NS	*	***	***	NS
CV	**6.08**	**2.30**	**0.98**	**9.353**	**11.75**

Means with the same letter(s) within a column are not significantly different according to DMRT at 5% level of significance; CV = Coefficient of variance; NS= non-significant; * = significantly different at P< 0.05; *** = significantly different at P< 0.001; CBR= Common Bean *Rhizobium* and n=number.

3.2.5. Plant Height of Common Beans

Analysis of variance showed that only the main effect of varieties affected plant height significantly (p <0.001) (Table 2). Significantly taller and shorter plants of 69.59 cm and 31.77 cm were recorded from the local variety and Awash-Melka, respectively. On the other hand, varieties Awash-1 and SER-119 resulted in intermediate values of 44.21 and 41.40 cm, respectively, which were statistically similar to each other (Table 3). The local variety was taller by 119.04%, 68.91%, and 57.41%, than varieties Awash-Melka, SER-119, and Awash-1, respectively. Even though the environment has an effect, common bean varieties also influence plant height, as demonstrated by Misgana and Tadesse (2017). They found that the Wajo variety produced significantly taller plants measuring 131.83 cm, while the Tatu variety yielded shorter plants at 48.93 cm, in contrast to other tested varieties. Similar outcomes have been documented by Daniel *et al*. (2014) and Kazai *et al*. (2019) for common beans.

3.2.6. The Number of Primary Branches per Plant of Common Beans

Plant branch count was significantly influenced by both the varieties and *Rhizobium* inoculants (p < 0.001), as well as their interaction (p < 0.05) (Table 4). The highest number of branches (2.63) resulted from the combination of variety SER-119 and inoculant CBR-14. This was statistically comparable to the pairing of the local variety with CBR-18 (Table 5). Conversely, the lowest branch count (1.40) was observed with the local variety and CBR-J16, a result statistically lower than most other treatments, excluding the un-inoculated control of the local variety with Awash-Melka. These variations likely stem from the synergistic relationship between varieties and *Rhizobium* inoculants in promoting branch development. These findings align with Bilisuma (2019) and Habtamu (2019), who reported that common bean varieties significantly impact the number of primary branches per plant.

Table 4. Analysis of variance for number of primary branches per plant, Number of total and effective nodules and nodule dry weight per plant as affected by the main effects of common bean varieties and rhizobial inoculants, and by their interaction.

Source of variation	DF	Mean square			
		NPBP	TNNP	ENNP	NDWP
Block	2	0.093^{ns}	24.379^{ns}	13.629^{ns}	0.0003^{ns}
Variety	3	0.354***	864.494***	812.471***	0.1899***
Rhizobium	4	0.331***	8243.452***	3973.754***	0.526***
Var * Rhiz	12	0.162*	75.574*	74.11***	0.016***
Error	**38**	**0.063^{ns}**	**24.506^{ns}**	**14.1^{ns}**	**0.0034^{ns}**

DF = Degree of freedom; NPBP= number of primary branch per plant; TNNP = total nodule number per plant; ENNP = effective nodule number per plant; NDWP = nodule dry weight per plant; Var * Rhiz = Variety by Rhizobium interaction.

3.3. Number of Total and Effective Nodules, and Nodule Dry Weight per Plant of Common Beans

The results showed that the main effects of varieties and *Rhizobium* inoculants and their interaction significantly influenced the number of total nodules at $p < 0.05$; and effective nodules per plant and nodule dry weight per plant at $p < 0.001$ (Table 4). The highest mean number of total and effective nodules and the dry weight of nodules of 80.67, 61.50 and 0.7668 g, respectively, were obtained when variety SER-119 was inoculated with isolate CBR-18, which were in statistical parity with respective values of 77.83, 58.83 and 0.72 g recorded from the same variety inoculated with strain CIAT-899. On the other hand, significantly minimum values for all of the nodulation parameters considered were recorded from the un-inoculated control across all of the varieties (Table 5). This might be due to unfavorable environmental conditions, such as the acidity of the soil. The variation among the varieties and the *Rhizobium* inoculants might be ascribed to genetic differences in the efficiency of making symbiotic associations between the two partners to form nodules and to fix nitrogen. In agreement with the current results, Gicharu *et al*. (2013), Khafa (2013) and Habete and Bruka (2016) reported that varieties, rhizobial inoculants, and their interaction effects significantly affected the number and dry weight of nodules per plant in common beans.

Table 5 Number of primary branches per plant, Number of total and effective nodules and nodule dry weight per plant as affected by the interaction of common bean varieties and rhizobial inoculants.

Treatments		Parameters			
Varieties	Rhizobium inoculants	NBP	TNNP	ENNP	NDWP (g)
Local variety	0 (Control)	1.77^{de}	7.000^{g}	4.000^{h}	0.0600^{i}
	CBR-14	2.10^{b-d}	55.167^{b-e}	36.500^{cd}	0.3755^{de}
	CBR-16	1.40^{e}	43.333^{f}	25.167^{g}	0.2540^{gh}
	CBR-18	2.53^{ab}	64.167^{b}	45.667^{b}	0.5427^{b}
	CIAT-899	2.17^{a-d}	54.667^{c-e}	35.333^{de}	0.3752^{de}
Awash-Melka	0 (Control)	1.80^{de}	5.667^{g}	3.000^{h}	0.0286^{i}

	CBR-14	2.07^{b-d}	46.333^{ef}	26.500^{g}	0.2258^{h}
	CBR-16	2.17^{a-d}	41.167^{f}	23.833^{g}	0.2270^{g}
	CBR-18	2.33^{a-c}	57.333^{b-d}	37.167^{b-d}	0.3855^{de}
	CIAT-899	2.20^{a-d}	53.667^{c-e}	35.333^{de}	0.3645^{de}
Awash-1	0 (Control)	1.93^{cd}	7.667^{g}	4.333^{h}	0.0471^{i}
	CBR-14	2.00^{cd}	48.333^{d-f}	29.667^{f}	0.3467^{ef}
	CBR-16	2.03^{cd}	42.833^{f}	24.333^{g}	0.2640^{f-h}
	CBR-18	2.20^{a-d}	58.667^{bc}	40.000^{b-d}	0.4657^{b-d}
	CIAT-899	2.13^{b-d}	56.833^{b-d}	38.833^{b-d}	0.4327^{c-e}
SER-119	0 (Control)	2.17^{a-d}	10.667^{g}	6.667^{h}	0.0821^{i}
	CBR-14	2.63^{a}	61.500^{bc}	43.167^{bc}	0.5278^{bc}
	CBR-16	2.37^{a-c}	61.833^{bc}	41.833^{b-d}	0.5085^{bc}
	CBR-18	2.17^{a-d}	80.667^{a}	61.500^{a}	0.7668^{a}
	CIAT-899	2.40^{a-c}	77.833^{a}	58.833^{a}	0.7190^{a}
F-test		*	*	***	***
CV		**11.750**	**10.948**	**12.409**	**17.019**

Means with the same letter(s) within a column are not significantly different according to Duncun's Multiple Range Test (DMRT) at 5% level of significance; CV = Coefficient of variance; NBP = Number of branches per plant; TNNP = Total nodule number per plant; ENN = Effective nodule number per plant; NDWP = Nodule dry weight per plant; * = Significant at $p < 0.05$; ** = Significant at $p < 0.01$; *** = Significant at $p < 0.001$; CBR= Common Bean Rhizobium.

3.4. Yield components, yield and harvest index

3.4.1. Number of pods per plant of common beans

Both bean varieties and Rhizobium inoculants significantly influenced pod number ($p<0.001$) (Table 6). This likely indicates that neither factor's impact on pod number was substantially altered by the other, potentially due to other environmental influences. The Awash-1 variety yielded the highest pod number per plant (16.21), statistically comparable to SER-119 (15.87). In contrast, Awash-Melka produced significantly fewer pods (12.61) (Table 7). These variations in pod formation are likely attributable to the genetic potential of each variety. Research by Küçük (2011), Mource and Tryphone (2012), Khafa (2013), and Morad *et al*. (2013) supports the significant influence of common bean cultivars on pod number. Similarly, Solomon *et al*. (2012) reported comparable cultivar effects on pod number in soybeans.

Among the Rhizobia inoculants, CBR-18 led to the highest pod number per plant (16.60), a statistically significant increase over most treatments, with CIAT-899 (15.48) being a close second. In contrast, the un-inoculated control had a lower pod count (13.36), comparable to CBR-J16 (13.52) (Table 7). The result agrees with Girma *et al*. (2017), who obtained a higher pod number per plant of 9.10 from Rhizobia-inoculated plots, while the minimum value of 7.47 from un-inoculated control in common bean. The same was also reported by Kuçuk (2011) and Morad *et al*. (2013) in common bean; Solomon *et al*. (2012) and, Tarekegn and Kibret (2017) in soybean.

3.4.2. Number of Seeds per Pod of Common Beans

The number of seeds per pod was significantly influenced solely by the common bean varieties ($p<0.01$), with no significant effects from rhizobial inoculants or their interaction (Table 6). SER-119 exhibited the highest seed count (5.02), statistically equivalent to the local variety (4.96).

In contrast, Awash-1 recorded the lowest number of seeds (4.77), which did not differ significantly from Awash-Melka (4.83) (Table 7). These observed differences in seed production are likely attributable to the distinct responses of each common bean variety to the prevailing environmental conditions. This conclusion is supported by earlier studies by Küçük (2011), Mource and Tryphone (2012), Morad *et al*. (2013), and Habete and Buraka (2016), who also identified a significant role of varieties (cultivars) in determining the number of seeds per pod in common bean.

Table 6. Analysis of variance for pod per plant, seed per pod, hundred seed weight, above-ground biomass yield, grain yield and harvest index (HI) as affected by the main effects of common bean varieties and rhizobial inoculants.

Source of variation	DF	Mean square					
		Pod per plant	**Seeds per pod**	**Hundred seed weight(g)**	**AGDBY (kg)**	**Grain Yield (kg)**	**HI (%)**
Block	2	2.184	0.023	0.817	45066.7	900.9	2.7
Variety	3	39.57***	0.19**	170.92***	12245257.8***	4333284.2***	61.7***
Rhizobium	4	22.786***	0.062	1.798*	1668808.2***	525123.3***	5.1
Var * Rhiz	12	2.704	0.033	0.676	227532.1	73572.2	1.96
Error	38	2.479	0.035	0.589	205206.65	67013.23	2.12

DF = Degree of freedom; AGDBY = above-ground biomass yield**;** HI = harvest index; Var * Rhiz = Variety by *Rhizobium* interaction.

3.4.3. Hundred Seed Weight (g) of Common Beans

Hundred seed weight was significantly ($p<0.05$) affected by the varieties and rhizobia inoculants (Table 6). Variety SER-119 produced a significantly greater seed weight (24.97 g) followed by the local variety (20.80 g), while the lowest and similar values of 17.83 g were recorded from varieties Awash-Melka and Awash-1 (Table 7). The greater seed weight of SER-119 might be attributed to its relatively larger seed size to receive and store more assimilates in its cotyledons. According to Khafa (2013), since genotypes have different genetic potentials in producing different seed sizes, different crops or varieties of the same crop may have different seed weights. In agreement with this result, Küçük (2011), Mource and Tryphone (2012) and Morad *et al*. (2013) reported significant variations among varieties of common bean on the weight of their seed.

Inoculating with CBR-18 resulted in a maximum seed weight of 20.92 g, which was statistically similar to CIAT-899 (20.54 g) and CBR-14 (20.29 g). On the other hand, the un-inoculated control resulted in a relatively minimum seed weight of 19.92 g, which was statistically similar to other inoculants, except CBR-18 (Table 7). The observed weight difference could have resulted from differences in the Nitrogen-fixing and supplying ability of the inoculants. In line with this result, Kuçuk (2011), Tabaro (2014), Ndlovu (2015), and Habete and Buraka (2016) reported a significant increment of hundred seed weight due to inoculating common bean with rhizobia. Solomon *et al*. (2012) and Nyoki and Ndakidemi (2014) also reported similar results in soybeans and cowpeas, respectively.

3.4.4. Above-ground Dry Biomass Yield of Common Beans

The results showed that varieties and *Rhizobium* inoculants significantly ($p < 0.001$) affected above-ground dry biomass yield independently (Table 6). Accordingly, variety SER-119 resulted in the highest mean dry biomass yield (5711.5 kg/ha), whereas variety Awash-Melka produced the lowest value of 3573.7 kg/ha (Table 7). The difference between the varieties might have resulted from the observed variations in growth and yield component parameters. In line with this result, Morad *et al*. (2013) reported the highest and the lowest biomass yields of 12680 and 10750 kg/ha from varieties Bahman and Sayyad, respectively. Daniel *et al*. (2014), Dereje *et al*. (2015), Argaw and Tesso (2017), Argaw and Muleta (2018) and Tarekegn *et al*. (2018) also indicated similar effects of common bean varieties on above-ground dry biomass yield.

In the *Rhizobium* inoculant trials, CBR-18 demonstrated the highest above-ground dry biomass yield of 5057.6 kg/ha, a figure significantly exceeding that of the un-inoculated control and all other rhizobial treatments. The control group yielded the lowest biomass, 3971.1 kg/ha, which was statistically lower than all inoculated plots, with the exception of CBR-J16 (Table 7). These findings align with previous research, such as Morad et al. (2013), who observed the highest and lowest above-ground biomass yields (12490 and 11220 kg/ha) when common beans were inoculated with *Rhizobium* strains 116 and 133, respectively. Additionally, studies by Fantahun *et al*. (2013), Argaw and Muleta (2018), Tarekegn *et al*. (2018), and Nuru and Taminew (2021) have similarly reported a significant increase in above-ground dry biomass for Rhizobium-inoculated common beans compared to un-inoculated controls.

Table 7. Mean values for number of pods per plant, number of seeds per pod, hundred seed weight, above-ground dry biomass yield, grain yield, and harvest index (HI) as influenced by common bean varieties and rhizoidal inoculants.

Treatments	**Parameters**					
	Number of pods per plant	**Number of seeds per pod**	**Hundred seed weight (g)**	**AGDBY (kg/ha)**	**GY (kg/ha)**	**HI (%)**
Varieties						
Local variety	14.65^{b}	4.96^{ab}	20.80^{b}	4152.2^{b}	1966.90^{b}	47.32^{b}
Awash-Melka	12.61^{c}	4.83^{bc}	17.83^{c}	3573.7^{c}	1686.96^{c}	47.07^{b}
Awash-1	16.21^{a}	4.77^{c}	17.83^{c}	4408.8^{b}	2091.12^{b}	47.34^{b}
SER-119	15.87^{a}	5.02^{a}	24.97^{a}	5111.5^{a}	2935.41^{a}	51.34^{a}
F-test	***	**	***	***	***	***
Rhizobial inoculants						
Un-inoculated control	13.36^{c}	4.84^{a}	19.92^{b}	3971.1^{c}	1905.1^{c}	47.67^{a}
CBR-14	15.23^{b}	4.81^{a}	20.29^{ab}	4485.4^{b}	2181.1^{b}	48.37^{a}
CBR-J16	13.52^{c}	4.95^{a}	20.13^{b}	4219.8^{bc}	2051.3^{bc}	48.10^{a}
CBR-18	16.60^{a}	4.98^{a}	20.92^{a}	5057.6^{a}	2459.2^{a}	48.33^{a}
CIAT-899	15.48^{ab}	4.89^{a}	20.54^{ab}	4573.8^{b}	2253.8^{ab}	48.88^{a}
F-test	***	NS	*	***	***	NS

CV	**10.613**	**3.838**	**3.768**	**10.2**	**11.95**	**3.01**

Means with the same letter(s) within a column are not significantly different according to DMRT at 5% level of significance; AGDBY = Above-ground dry biomass yield; GY = grain yield; HI = harvest index; CV = Coefficient of variance; NS= non-significant; *= significant at $p < 0.05$; **= significant at $p < 0.01$; ***= significant at $p < 0.001$; CBR= Common Bean *Rhizobium*

3.4.5. Grain Yield of Common Beans

The effect of varieties and *Rhizobium* inoculants on grain yield was significant ($p<0.001$) (Table 6). Variety SER-119 produced significantly higher grain yield (2935.41 kg/ha) than varieties Awash-1, Awash-Melka, and the local variety, used in this study. On the contrary, variety Awash-Melka resulted in the least grain yields of 1686.96 kg/ha (Table 7). The relative yield advantage from SER-119 was 74.01%, 49.24%, and 40.38% as compared to Awash-Melka, the local variety, and Awash-1, respectively. This better yield performance (yield advantage) of SER-119 could be due to better performances of the yield components, which in turn might have favored by relatively vigorous growth parameters. In agreement with the current result, many researchers have revealed that there are genotypic differences in the yield potential of common beans and other leguminous crops. For instance, Chekanai *et al*. (2018) reported the maximum yield of 3308 kg/ha from variety COS16, while the minimum yield of 2758.7 kg/ha from variety Akhtar. Kiriba *et al*. (2020), Daniel et al. (2014), Habete and Buraka (2016), Argaw and Tesso (2017), Argaw and Muleta (2018), Nuru and Taminew (2021), Tarekegn *et al*. (2018), and Yilma *et al*. (2021) also indicated similar effects of genotypes (cultivars) on common bean grain yield.

Analysis of rhizobia inoculants revealed that CBR-18 produced the maximum grain yield of 2459.2 kg/ha, a result not significantly different from CIAT-899 (2253.8 kg/ha). In contrast, the control group exhibited the lowest yield at 1905.1 kg/ha, a value statistically similar to that of CBR-J16 (2051.3 kg/ha) (Table 7). Notably, all Rhizobia inoculants demonstrated a yield advantage over the control. Specifically, CBR-18, CIAT-899, CBR-14, and CBR-J16 enhanced grain yield by 29.09%, 18.3%, 14.49%, and 7.67%, respectively, compared to the un-inoculated plants. This improvement is likely attributable to the supplementary nitrogen provided through fixation by the *Rhizobium* inoculants. Furthermore, variations in the magnitude of yield increments among the inoculants could be attributed to differences in their adaptive capabilities and nitrogen-fixing efficiency. Supporting these findings, Argaw (2016) documented a substantial yield increase of 775.5 kg/ha in common bean inoculated with NSCBR-14 when compared to the control. Similar observations have been made by Habete and Buraka (2016), Tarekegn *et al*. (2018), Abou-Shanab *et al*. (2019), Nuru and Taminew (2021), and Razafintsalama *et al*. (2022) in studies involving the same crop.

3.4.6. Harvest Index (HI) of Common Beans

The harvest index was significantly affected only by varieties ($p < 0.001$), according to the analysis of variance (Table 6). While not statistically significant, all *Rhizobium* inoculants led to a slight improvement in harvest index over the control. The maximum harvest index observed was 48.88% for CIAT-899, while the control yielded the minimum at 47.67%. Among the common bean varieties, SER-119 achieved the highest harvest index at 51.34%. Awash-Melka, with a mean value of 47.07%, showed a statistically similar harvest index to Awash-1 and the local variety (Table 7). The superior harvest index of SER-119 can be attributed to its vigorous growth and larger leaf area index (LAI), which likely allowed for greater light capture and assimilation for grain partitioning. This finding is in agreement with Morad et al. (2013), who found the highest harvest index (49.35%) in the Sayyad variety and the lowest (44.24%) in Bahman. Khafa (2013) and Nuru and Taminew (2021) also reported similar effects of common bean varieties on harvest index.

4. Conclusion and Recommendations

The study's finding revealed that, while nodulation was greatly impacted by the interaction of varieties and rhizobia inoculants, yield and yield related traits affected by the two main factors independently. The *Rhizobium* inoculants CBR-18 and common bean variety SER-119 produced the highest grain yields, 2459.2 kg/ha and 2935.41 kg/ha, respectively. However, CIAT-899 (2253.8 kg/ha) was statistically comparable to that of CBR-18. In general, SER-119 produced a higher grain yield than Awash-Melka, the local variety, and Awash-1 by 74.01%, 49.24% and 40.38%, respectively. In comparison to the un-inoculated control, *Rhizobium* CBR-18 and CIAT-899 also enhanced grain yield by 29.09% and 18.3%, respectively. Thus, farmers and other growers interested in common bean production in the study area and similar agro-ecologies are recommended to use variety SER-119 and *Rhizobium* inoculants CBR-18. By combining the inoculants with suitable mineral fertilizer supplies and rates, it is possible to take advantages of the varieties' potentials. Therefore, it is necessary to do additional research that focus on:

- Inclusion of more rhizobia isolates, common bean varieties, and different sources and rates of mineral fertilizers, repeating this study on various agro-ecologies and common bean growing regions of the nation.
- Extracting, characterization, and identifying rhizobia strains those are beneficial for enhancing common bean production.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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