Chapter

Legume-Rhizobium Interaction Benefits Implementation in Enhancing Faba bean (*Vicia faba* L.) Crop Yield and Economic Return

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Abstract

This study reports the interaction of rhizobium strains and varieties on yield and yield components of faba bean and the economic feasibility of the inoculant use in faba bean production. The two years field experiments used a split-plot design that involved six elite rhizobium strains as the main plot and three faba bean varieties as sub-plot treatments. Non-inoculated plants with N fertilizer and without fertilizer were included as +N (46 kg ha^{-1}) and −N controls, respectively. Phosphorus (P) was applied as triple super-phosphate at the time of sowing. Data on yield and yield components were collected and statistically analyzed. Partial budget, dominance, and marginal rate of return analysis were conducted to identify profitable rhizobial strain-variety combinations for each study location. Rhizobium strains NSFBR-15, TAL_1035 and NSFBR-12 increased grain and haulm yield of faba bean more than N fertilizer across the study locations. Location, rhizobium strain, and variety interaction influenced yield and yield components of faba bean. Economic analysis document that rhizobium inoculation for symbiotic N fixation is more profitable for supplying N to faba bean than N fertilizer application. Rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 with all faba bean varieties resulted in the highest revenue with a higher marginal rate of return at all study locations.

Keywords: faba bean, inoculation, nitrogen, strain, yield

1. Introduction

Faba bean (*Vicia faba* L) is the most important grain legume produced in Ethiopia [1]. The crop has high economic value with its edible seed serving as protein complement in the cereal-based Ethiopian diet [2], and contributes to smallholder income earnings [3]. Moreover, it has a great contribution to sustainable soil fertility improvement due to its ability in fixing N through symbiotic association with rhizobia [4] and thus can reduce the cost of inorganic fertilizer use and its negative impact on the environment [5]. Because of its nutritional and economic values, increasing the production of faba bean in sub-Saharan Africa is very important to meet the demand of the growing population [6, 7].

Despite its high socio-economic importance, the yield of faba bean (1.6 t ha^{-1}) is very low compared with its potential yield (5 t ha^{-1}) [8]. Both biotic and abiotic factors account for the low productivity of faba bean in on-farm growing conditions [9]. Declining soil fertility is a major challenge contributing to decreasing agricultural productivity in sub-Saharan Africa [10]. Available nitrogen (N) often is deficient in soils and limits faba bean productivity in Ethiopia [10]. To get optimum production, N must be adequately available to the plants [11]. Unfortunately, farmers rarely use N fertilizer in faba bean production; instead, the crop is used as a restorer of soil fertility for the subsequent cereal crop [12]. The low use of N fertilizer is because most smallholder farmers have very low financial resources to purchase inorganic fertilizers. It is, therefore, imperative to search for alternatives that can increase crop yields to satisfy the growing protein food demand while maintaining environmental safety and protection [13].

Native rhizobial populations in many soils may not be adequate or effective to symbiotically fix N [14–16]. Effective rhizobial population in the rhizosphere can be increased by inoculation [17] where natural N fixation is not optimal. Thus, there is a need for inoculation with an appropriate rhizobial strain to improve N fixation in faba bean production [18, 19].

Faba bean is one of the most efficient N_2 fixing legumes, which can fulfill most of its N requirement through symbiotic N fixation [20]. However, legume-rhizobia symbiosis is highly specific that, fitness between rhizobium strain and legume variety is very essential for successful nodulation and N fixation [21]. Faba bean usually establishes an effective symbiotic association with *Rhizobium leguminosarum* bv. viciae (Rlv) [22]. However, several studies [4, 23] have revealed that, *R. leguminosarum* bv. viciae varies in legume host-specificity and effectiveness in N fixation. Besides, the adaptability of rhizobial strain in a given soil environment should be considered as an important criterion during inoculant strain selection.

Research in sub-Saharan Africa has mainly focused on developing high-yielding varieties under optimum growing conditions and/or isolation and characterization of native rhizobia in the laboratory and under greenhouse conditions. Although promising faba bean nodulating rhizobia strains can be identified under controlled conditions [24–26], its interaction with the biophysical environment necessitates comprehensive field investigations. Thus, there is a need to identify best performing strain × variety combinations for site-specific inoculant development. This study aimed to (i) investigate the interaction effects of selected rhizobium strains on grain yield and yield component of faba bean varieties under field conditions, and (ii) evaluate the economic benefits of using rhizobial inoculants in faba bean production in southern Ethiopia.

2. Materials and methods

2.1 Description of experimental sites

Four locations were selected in two major faba bean growing agro-ecologies (cool-humid and cool sub-humid) in southern Ethiopia. Two locations, Hankomolicha and Abala-Gase, in cool humid and two locations, Haranfama and Gike-Atoye, in cool sub-humid agro-ecological zones were selected for field experiments. The experimental locations in cool humid and cool sub-humid agro-ecological zones received 1473 and 1093 mm mean annual rainfall (**Table 1**),

Year		Cool humid (location: HK and AG)			Cool sub-humid (location: HR and GA)		
		Rainfall	[a]Max. T	[b]Min. T	Rainfall	[a]Max. T	[b]Min. T
		mm	°C	°C	Mm	°C	°C
2017	June	180	14.1	7.7	128	21.3	12.9
	July	134	16.4	5.6	97	24.3	12.5
	August	182	16.3	6.1	192	22.8	11.6
	September	160	16.5	7.2	104	23.7	13.4
	Annual	1477	17.1	8.1	1303	25.2	15.1
2018	June	63	17.0	9.2	35	25.1	15.3
	July	219	15.6	5.2	161	23.3	11.9
	August	219	14.1	6.5	166	20.9	11.3
	September	206	14.0	7.8	204	19.1	10.9
	Annual	1591	17.4	9.3	1199	24.5	14.4
10 years (2009–2018)	Annual average	1473	15.4	7.1	1093	22.4	11.7

[a]*Maximum temperature.*
[b]*Minimum temperature; HM = Hankomolicha; AG = Abala-Gase; HR = Haranfama; GA = Gike-Atoye.*

Table 1.
Annual average rainfall and the mean maximum and minimum temperatures during the study period and long-term average.

respectively. The distribution of rainfall in both agro-ecologies is bimodal. A minor rainy season occurs from February to April whereas the major rainy season occurs from June to September. In each agro-ecology, experiments were conducted at selected locations during the major rainy season of 2017 and 2018.

2.2 Soil sampling and analysis

Pre-sowing soil samples were collected from each location. Samples were cored to a depth of 20 cm from 20 random locations across each experimental field and composited for the determination of soil chemical and physical properties using standard laboratory methods [27]. The results are shown in **Table 2**. The soil properties were examined to identify whether variability exists which could explain the occurrence and magnitude of treatments response. Such knowledge is important to assist in targeting technologies and to identify the need for further research on soil fertility management options. Textural classes of the surface soil of the study locations varied from clay to loam and soil pH ranged from slightly acidic (6.57) to weakly acidic (5.37–6.02) with the medium organic carbon and total N contents [28]. Cation exchange capacity (CEC) of the soils was in the range of medium to high rating (22.60–32.81 meq/100 g) which is adequate for crop production. Soil available phosphorus contents were low (5.7–12.6 mg kg^{-1}) to medium (12.6 mg kg^{-1}), suggesting that supplementary phosphorus may be required for optimum crop production.

2.3 Sources of strains and seeds

Six elite rhizobial strains (NSFBR-12, NSFBR-15, NSFBR-20, HUFBR-17, TAL_1035, and EAL-110), originally collected by Haremaya University, Holleta

Soil parameters		Study locations			
		Hankomolicha	Abala-Gase	Haramfama	Gike-Atoye
pH (1:2; Soil:H_2O)[a]		6.57	5.37	6.02	5.60
Available P (mg kg^{-1})[b]		12.60	5.70	8.40	6.03
Total nitrogen (%)[c]		0.17	0.17	0.16	0.22
Organic carbon (%)[d]		2.06	2.22	1.75	2.34
CEC (meq/100 g)[e]		29.40	27.56	22.60	32.81
Exchangeable bases $cmol_{(+)}$ kg^{-1}[e]	K	3.14	0.75	2.36	1.25
	Ca	13.40	15.09	12.60	17.73
	Mg	7.22	5.38	6.44	5.20
Exc. acidity ($cmol_{(+)}$ kg^{-1})[f]		0.40	0.48	0.12	0.52
Bulk density (g cm^{-3})[g]		1.24	1.21	1.35	1.25
Textural class[h]		Clay	Clay loam	Loam	Clay

Method:
[a][29]; [b][30]; [c][31]; [d][32]; [e][27]; [f][33]; [g][34]; [h][35].

Table 2.
Initial physical and chemical properties of surface soils (0–20 cm) at the study locations.

Agricultural Research Center, and National Soil Laboratory (NSL) in Ethiopia were used for the study. The inoculum was used at the concentration of approximately 10^9 cells g^{-1} in peat carrier. The purity of strain cultures was assessed in the Soil Microbiology Laboratory at Holleta Agricultural Research and Haremaya University. The sterility of the carrier was checked before mixing with the rhizobial culture. Seeds of three nationally registered faba bean varieties (Dosha (COLL 155/00–3), Moti (EH 95078–6), Gora (EKOl024–1-2) were provided by Holleta Agricultural Research Centers for use in this study.

2.4 Treatments and experimental design

The experimental design was a randomized complete block design (RCBD) in a split-plot arrangement with four replicates nested at four different locations. Main plot treatments consisted of six rhizobium strains (NSFBR-12, NSFBR-15, NSFBR-20, HUFBR-17, TAL_1035 and EAL-110). Non-inoculated plants supplied with and without N fertilizer served as +N and −N controls, respectively. Sub-plot treatments were three faba bean varieties (Moti, Dosha, and Gora).

Land preparation was done manually using a heavy hoe for primary tillage to make the field suitable for planting and divided into blocks and further into individual plots. Sub-plot size was 4 × 4 m (16 m^2). Each variety was planted in 10 rows plot of 4 m length per major plot. The inter-row and intra-row spacing were maintained at 40 and 10 cm, respectively. Spacing between sub-plots and major plots were 1 and 1.5 m, respectively. Peat carrier-based inoculant of each strain was applied at the rate of 10 g kg^{-1} seed [36]. Thus, the required quantity of inoculant was suspended in a 1:1 ratio in a 10% sugar solution in order to ensure that all the applied inoculum stuck to the seed. The thick slurry of the inoculant was gently mixed with dry seed so that all seeds received a thin coating of the inoculant. Inoculation was done just before planting under shade to maintain the viability of rhizobium.

The seed was sown at a depth of about 4 cm. Phosphorus was applied to all plots in the form of triple-superphosphate (TSP) at the recommended rate of 46 kg P_2O_5 at planting. Nitrogen fertilizer was applied two times in equal split doses to non-inoculated +N control treatment, at planting and six weeks after sowing at a recommended rate of 46 kg N ha^{-1}. All other crop management and protection practices were applied uniformly to plots.

2.5 Data collection and analysis

At physiological maturity, 10 plants were randomly sampled per plot from interior rows. Mean plant height was determined by measuring the height of each plant. Pods were counted for all ten plants and the average values were recorded as a number of pods per plant. All pods were picked from sampled plants per plot and the plants were cut at the base and removed from a plot. The straw was cut into small pieces and placed in pre-marked paper bags. The pod samples were sun-dried and threshed manually. The grain and husk were put into separate pre-labeled paper bags. The straw, grain, and husk samples were oven-dried at 70°C for 72 hours and weighed. Harvest index was calculated as a ratio of grain yield to above-ground biomass yield.

At the final harvest, the remaining plant stands were marked leaving the two border rows per plot on both sides and 0.5 m row length on both ends of all plots. Grain yield was determined from an area of 9.6 m^2 on each sub-plot. The pods were picked from all plants which were marked for harvest, and placed in pre-marked separate bags. Harvested pods were sun-dried and threshed manually. The grain was further dried and weighed. The moisture content was measured using a portable moisture tester and later adjusted to 10% standard moisture content. A hundred seeds were counted three times from the total seeds of each plot and weighed to determine the average hundred seed weight per plot.

The data were subjected to Analysis of Variance (AOV) using SAS [37] computer software (SAS Institute Inc.). Combined analysis of variance was done to assess significance among locations, rhizobium strains, faba bean varieties, and interactions among these three factors (location, strain, and variety) for all measured parameters. Mean separation and comparison were done by using Duncan's Multiple Range Test. A Pearson correlation test was conducted to determine the association among treatment means using a $p \leq 0.05$ probability level.

2.6 Economic feasibility analysis

Experimental data were organized in order to elucidate the costs and benefits of each treatment. Additional cost and benefit of each treatment were calculated relative to respective non-inoculated −N control. Extra costs incurred included purchase of inoculants and N fertilizer, inputs application, transportation, and labor. Total variable costs (TVC) comprised all variable costs for particular treatments. The average yield was adjusted 10% downward to reflect the yield expected from the same treatment under farmers' management. Additional benefits comprised revenue from additional faba bean grain yield over the control. Net benefit and benefit-cost ratio were calculated using Eqs. (1–3) as below [38].

$$\text{GFB (in USD)} = \text{AY} \times \text{FP(in USD)} \tag{1}$$

$$\text{NB (in USD)} = \text{GFB (in USD)} - \text{TVC} \tag{2}$$

$$\mathrm{BCR} = \frac{\mathrm{NB}}{\mathrm{TVC}} \tag{3}$$

Where, AY = adjusted yield; FP = field price per unit yield; GFB = Gross field benefit; NB = Net benefit; TVC = total variable cost; BCR = Benefit cost ratio.

In order to select potentially profitable treatments among the 24 treatments, the dominance analysis was employed according to CIMMYT [38]. Treatments were arranged in order of increasing variable costs and considered as dominated if its net benefit was lower than the preceding treatment. Marginal rate of return (MRR%) for each dominant treatment was calculated by using the formula [39].

$$\mathrm{MRR} = \frac{\Delta\mathrm{NB}}{\Delta\mathrm{TVC}} \times 100 \tag{4}$$

Where: MRR = marginal rate of return in percentage, ΔNB = change in net benefits and ΔTVC = change in total variable cost.

The marginal rate of return for dominant treatments is returned that can be obtained per unit of an investment expressed as a percentage. A 100% was considered as the minimum acceptable rate of return for recommendation to farmers [40]. A hundred percent (100%) MRR implies a return of one dollar for every one dollar investment in a given variable input [38].

3. Results

3.1 Effect of inoculation on grain yield of faba bean

Rhizobium strain × faba bean variety interaction effect on grain yield is presented in **Table 3**. Rhizobium strains NSFBR-15 and TAL_1035 resulted in higher grain yields, whereas HUFBR-17, EAL-110, and NSFBR-20 inoculation resulted in lower grain yield relative to 46 kg ha^{-1} (**Table 3**). At Hankomolicha, NSFBR-15 × Moti and TAL_1035 × Gora produced the first and the second highest grain yield, respectively whereas TAL_1035 × Gora and NSFBR-15 × Gora produced the first and the second highest grain yield, respectively at Haramfama. NSFBR-15 × Gora produced the highest grain yield at Gike-Atoye whereas NSFBR-15 × Gora, TAL_1035 × Dosha and NSFBR-15 × Moti produced, the first, the second and the third highest grain yield, respectively at Abala-Gase.

Mean grain yields ranged from 1.89–4.28, 1.64–3.43, 1.79–3.76, and 2.12–3.88 t ha^{-1} at Hankomolicha, Haranfama, Abala-Gase, and Gike-Atoye, respectively (**Table 3**). The highest grain yield (4.28 t ha^{-1}) at Hankomolicha was obtained by Moti variety inoculated with NSFBR-15 which also resulted in the highest grain yields of 3.88 and 3.76 t ha^{-1} at Gike-Atoye and Abala-Gase, respectively for Gora variety. Variety Gora inoculated with TAL_1035 produced the highest grain yield (3.43 t ha^{-1}) at Haranfama. The lowest yields were obtained by non-inoculated −N control plants at all study locations.

There were significant ($p \le 0.05$) strain × location interaction effects for grain yield of faba bean. The highest mean grain yield among the study locations was obtained at Hankomolicha (3.05 t ha^{-1}) followed by Gike-Atoye (2.97 t ha^{-1}) whereas the least mean grain yield was recorded at Haranfama (2.50 t ha^{-1}) (**Figure 1**). Inoculation with rhizobia strains HUFBR-17, EAL-110, and NSFBR-20 resulted in lower grain yield than their respective location average whereas the grain yields obtained by TAL_1035, NSFBR-15, and

Rhizobium strains	Hankomolicha			Haranfama			Abala-Gase			Gike-Atoye		
	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora
TAL_1035	3.42^{bc}	3.47^{a}	3.93^{a}	2.76^{ab}	2.79^{ab}	3.43^{a}	3.40^{ab}	3.63^{a}	3.15^{bc}	3.37^{a}	3.22^{a}	3.51^{ab}
NSFBR-15	4.28^{a}	3.71^{a}	3.40^{b}	2.81^{a}	3.00^{a}	3.19^{a}	3.54^{a}	3.40^{ab}	3.76^{a}	3.25^{a}	3.23^{a}	3.88^{a}
HUFBR-17	2.66^{ef}	2.87^{b}	2.53^{c}	2.47^{bc}	2.03^{d}	2.09^{c}	2.07^{cd}	2.61^{c}	2.41^{e}	2.79^{bc}	3.00^{ab}	2.43^{de}
NSFBR-12	3.09^{cd}	3.40^{a}	3.54^{ab}	2.74^{ab}	2.54^{bc}	2.86^{b}	3.23^{ab}	3.41^{ab}	3.21^{bc}	3.16^{ab}	2.93^{ab}	3.27^{b}
EAL-110	3.01d^{e}	2.27^{c}	2.46^{c}	2.21^{cd}	2.28^{cd}	2.11^{c}	3.25^{ab}	2.59^{c}	2.86^{cd}	3.01^{ab}	2.98^{ab}	2.84^{c}
NSFBR-20	2.42^{f}	2.50^{bc}	2.74^{c}	2.37^{c}	2.06^{d}	1.92^{cd}	2.35^{c}	2.68^{c}	2.55^{de}	3.07^{ab}	2.66^{bc}	2.80^{cd}
+N	3.53^{b}	3.36^{a}	3.62^{ab}	2.81^{a}	2.86^{a}	2.86^{b}	3.03^{b}	3.07^{b}	3.26^{b}	3.19^{ab}	2.85^{ab}	2.79^{cd}
−N	1.89^{g}	2.42^{c}	2.75^{c}	2.03^{d}	2.28^{cd}	1.64^{d}	1.85^{d}	1.79^{d}	1.83^{f}	2.55^{c}	2.39^{c}	2.12^{e}
CV (%)		**8.5**			**8.0**			**8.4**			**8.5**	

Mean values in the same column with a different letter(s) are significantly different at $p \leq 0.05$ *probability level.*

Table 3.
Rhizobium strain × faba bean variety interaction effect on grain yield of faba bean at the study locations.

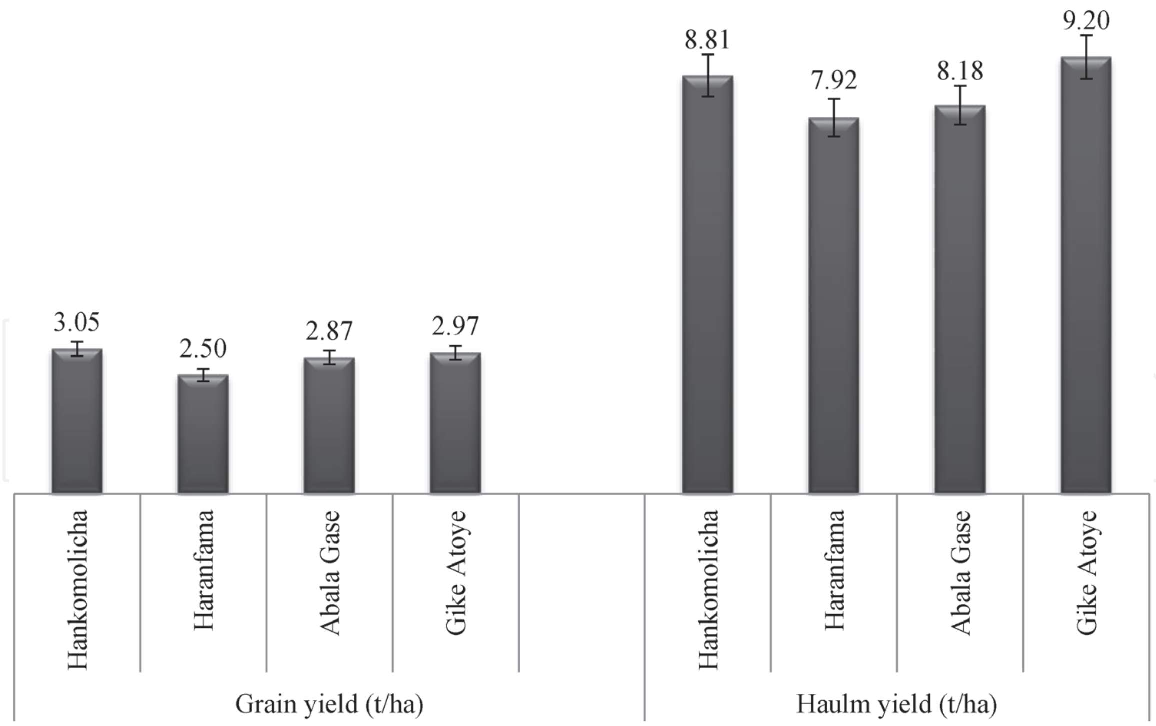

Figure 1.
Mean grain and haulm yield response to rhizobia strain inoculation at the different study locations.

NSFBR-12 inoculation were higher than that of their respective location average (**Table 3** and **Figure 1**).

Grain yield increment due to inoculation ranged from 17.9 to 62.3% over non-inoculated −N control. Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in 62.3, 56.9, and 46.4% of grain yield increments, respectively; while 46 kg N ha^{-1} resulted in 45.8% grain yield increment over non-inoculated −N control plant (**Figure 2**). Nitrogen fertilizer application (46 kg ha^{-1}) increased grain yields of faba bean by 24.1, 16.6, and 23.5% over inoculation with HUFBR-17, EAL-110, and NSFBR-20, respectively. However, grain yields obtained by NSFBR-15, TAL_1035 and NSFBR-12 inoculation surpassed those obtained by non-inoculated +N controls (**Table 3** and **Figure 2**). Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 showed 11.3, 7.7, and 0.4% increments in grain yield compared to the non-inoculated +N control treatment, respectively.

3.2 Effect of inoculation on haulm yield of faba bean

The effect of rhizobium strains inoculation on haulm (straw + husk) yield is presented in **Table 4**. Haulm yield was significantly ($p \leq 0.01$) affected by location, rhizobium strains inoculation, strain × variety, and strain × variety × location interactions. No significant differences in haulm yields were observed among the faba bean varieties. Rhizobium strains TAL_1035, NSFBR-15, and NSFBR-12 inoculation showed a great positive response in haulm yield compared to non-inoculated −N control (**Table 4**). The mean haulm yields increased by 98.0, 91.0, and 78.7% over non-inoculated −N control treatments when inoculated with NSFBR-15, TAL_1035, and NSFBR0–12, respectively; whereas 46 kg N ha^{-1} enhanced haulm yield by 71.1% over −N control (**Figure 2**). Nitrogen fertilizer application (46 kg N ha^{-1}) also increased haulm yields by 30.9, 20.0, and 26.5% over inoculation with HUFBR-17, EAL-110, and NSFBR-20, respectively. However, haulm yield obtained by NSFBR-15, TAL_1035, and NSFBR-12 inoculation surpassed non-

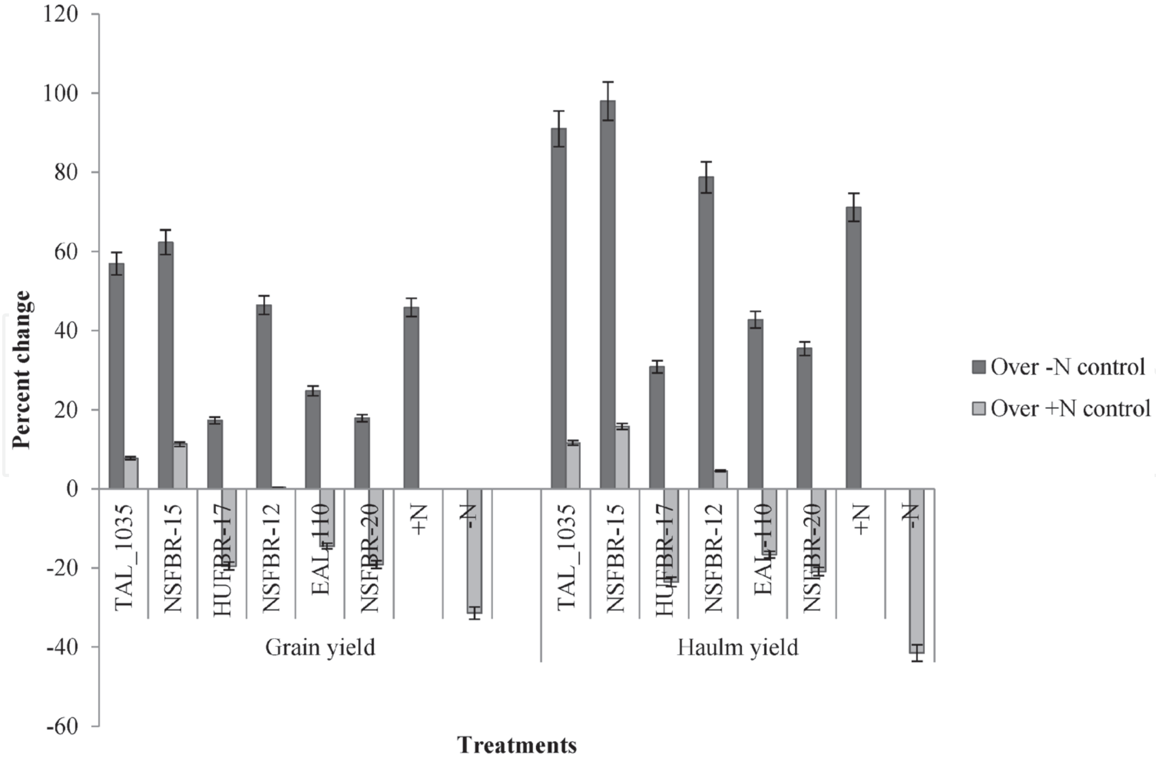

Figure 2.
Percent change in grain and haulm yields of faba bean following rhizobium strains inoculation.

inoculated +N control (**Figure 2**). Rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 inoculation resulted in 15.8, 11.6, and 4.5% increase in haulm yield over non-inoculated +N control, respectively (**Figure 2**).

Mean haulm yield varied across the study locations (**Table 4** and **Figure 1**). The highest haulm yields at Hankomolicha, Haranfama, Abala-Gase, and Gike-Atoye were 12.20, 10.52, 13.11, and 13.84 t ha^{-1} whereas the lowest haulm yields were 5.47, 5.84, 2.77, and 4.49 t ha^{-1}, respectively. Variety Gora produced the highest haulm yield (12.20 t ha^{-1}) at Hakomolicha when inoculated with NSFBR-12 and 10.52 t ha^{-1} when inoculated with TAL_1035 at Haranfama, 13.11 and 13.84 t ha^{-1} when inoculated with NSFBR-15 at Abala-Gase and Gike-Atoye, respectively. Among the study locations, the highest mean haulm yield was obtained at Gike-Atoye (9.20 t ha^{-1}) followed by Hankomolicha (8.82 t ha^{-1}) (**Figure 1**). Haulm yield increments following NSFBR-15, TAL_1035 and NSFBR-12 inoculation were consistent over the study locations. Haulm yields obtained by NSFBR-15, TAL_1035, and NSFBR-12 inoculation and 46 kg N ha^{-1} was higher than that of their respective location average. In general, the order of rhizobium strains effectiveness on yield and yield components was: NSFBR-15 > TAL_1035 > NSFBR-12 > N fertilizer.

3.3 Inoculation effect on growth and yield components

Location × strain × variety interaction had a significant ($p \leq 0.01$) effect on plant height, pods plant^{-1}, and hundred seed weight of faba bean. Rhizobium strains NSFBR-15, TAL_1035 and NSFBR-12 inoculation significantly increased plant height of faba bean varieties at all study locations relative to non-inoculated −N control (**Table 5**). Variety Gora attained the highest height (171.5 cm) at Gike-Atoye when inoculated with NSFBR-12 while variety Dosha reached the highest height of 168.3 cm at Abala-Gase when inoculated with NSFBR-15. Varieties Moti

Rhizobium strains	Hankomolicha			Haranfama			Abala-Gase			Gike-Atoye		
	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora
		(t/ha)			(t/ha)			(t/ha)			(t/ha)	
TAL_1035	8.97^{b}	10.01^{ab}	11.03^{b}	9.11^{a}	8.80^{ab}	10.52^{a}	11.89^{a}	10.75^{a}	9.53^{bc}	10.75^{a}	11.57^{a}	12.40^{ab}
NSFBR-15	10.41^{a}	10.66^{a}	9.54^{cd}	9.04^{a}	9.50^{a}	9.94^{ab}	10.74^{ab}	11.47^{a}	13.11^{a}	10.78^{a}	10.91^{ab}	13.84^{a}
HUFBR-17	8.44^{b}	8.99^{bc}	7.38^{e}	6.38^{d}	6.81^{de}	6.96^{d}	4.16^{cd}	5.88^{c}	6.83^{d}	8.27^{b}	9.49^{abc}	6.26^{d}
NSFBR-12	10.38^{a}	9.24^{bc}	12.20^{a}	7.99^{b}	8.35^{bc}	8.52^{c}	9.93^{b}	10.82^{a}	8.94^{bc}	10.39^{ab}	9.51^{abc}	11.01^{b}
EAL-110	8.27^{b}	5.82^{d}	7.40^{e}	6.74^{cd}	6.92^{de}	6.51^{de}	10.06^{b}	6.76^{c}	8.11^{cd}	9.07^{ab}	9.37^{bc}	8.59^{c}
NSFBR-20	6.56^{c}	8.40^{c}	8.56^{d}	7.58^{bc}	6.56^{e}	6.11^{de}	5.57^{c}	6.58^{c}	7.19^{d}	9.85^{ab}	8.30^{cd}	7.58^{c}
+N	10.06^{a}	10.03^{ab}	10.38^{bc}	9.04^{a}	9.16^{ab}	9.17^{bc}	9.83^{b}	9.15^{b}	10.02^{b}	9.28^{ab}	7.57^{cd}	8.57^{c}
−N	5.47^{d}	6.48^{d}	6.91^{e}	6.96^{cd}	7.65^{cd}	5.84^{e}	3.01^{d}	2.77^{d}	3.11^{e}	5.99^{c}	6.95^{d}	4.49^{d}
CV (%)		**7.8**			**7.1**			**12.2**			**14.5**	

Mean values in the same column with a different letter(s) are significantly different at $p \leq 0.05$ *probability level.*

Table 4.
Rhizobium strain × faba bean variety interaction effect on haulm yield of faba bean at the study locations.

Rhizobium strains	Hankomolicha			Haranfama			Abala-Gase			Gike-Atoye		
	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora
		(cm)			(cm)			(cm)			(cm)	
TAL_1035	157^{a}	169^{a}	165^{ab}	156^{ab}	151^{a}	167a	153^{ab}	158^{ab}	165^{a}	168^{a}	154^{ab}	169^{a}
NSFBR-15	168^{a}	160^{a}	165^{ab}	154^{ab}	159^{a}	166^{a}	168^{a}	168^{a}	161^{a}	155^{ab}	170^{a}	169^{a}
HUFBR-17	143^{b}	156^{ab}	141^{cd}	103^{e}	114^{c}	120^{b}	128^{cd}	138^{bc}	122^{b}	152^{ab}	130^{c}	131^{b}
NSFBR-12	161^{a}	165^{a}	165^{ab}	141^{bc}	152^{a}	155^{a}	149^{ab}	164^{a}	161^{a}	166^{a}	159^{ab}	172^{a}
EAL-110	141^{b}	136^{cd}	135^{d}	112^{e}	116^{c}	106^{bc}	145^{bc}	115^{d}	119^{b}	138^{bc}	143^{bc}	132^{b}
NSFBR-20	159^{a}	126^{d}	150^{bc}	132^{cd}	108^{c}	97^{c}	117^{de}	120^{cd}	132^{b}	149^{abc}	129^{c}	120^{bc}
+N	171^{a}	162^{a}	171^{a}	161^{a}	167^{a}	168^{a}	167^{a}	159^{ab}	167^{a}	154^{ab}	150^{abc}	171^{a}
−N	135^{b}	142^{bc}	159^{ab}	117^{de}	134^{b}	90^{c}	106^{e}	117^{d}	132^{b}	127^{c}	143^{bc}	103^{c}
CV (%)		**6.1**			**8.4**			**9.2**			**10.0**	

Mean values in the same column with a different letter(s) are significantly different at p ≤ *0.05 probability level.*

Table 5.
Rhizobium strain × faba bean variety interaction effect on plant height of faba bean at the study locations.

and Gora attained the highest height at Hankomolicha (171.3 cm) and Harnafama (167.8 cm), respectively when treated with 46 kg N ha^{-1}.

Rhizobium strains inoculation significantly ($p \leq 0.01$) influenced the number of pods $plant^{-1}$ of faba bean. Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in a significant increase in the number of pods $plant^{-1}$ relative to non-inoculated −N control at all study locations (**Table 6**). Rhizobium strains TAL_1035, NSFBR-15, and NSFBR-12 resulted in 77.3, 76.9, and 76.4% increment in a number of pods $plant^{-1}$ over non-inoculated −N control, respectively. The 46 kg N ha^{-1} resulted in 66.7% increase in the number of pods $plant^{-1}$ over non-inoculated −N control treatment. The number of pods $plant^{-1}$ significantly varied across the study locations (**Table 6**).

Rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 resulted in a significant increase in hundred seed weight at all study locations (**Table 7**). The highest hundred seed weights were recorded when variety Moti was inoculated with NSFBR-15 at Hankomolicha (83.7 g) and Abala-Gase (86.1 g) while variety Gora produced the highest hundred seed weight at Haranfama (71.1 g) and Gike-Atoye (78.8 g) when inoculated with TAL_1035 (**Table 7**). The lowest hundred weights were obtained from non-inoculated −N control plants of variety Moti at Hankomolicha (41.4 g) and Abala-Gase (36.5 g), and variety Gora at Haranfama (44.2 g) and Gike-Atoye (46.0 g). Inoculation with rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 resulted in 43.9, 40.3, and 33.9% increment in seed weight, respectively over non-inoculated −N control.

3.4 Correlation between yield and yield components

Correlation coefficients between the studied characters were computed (**Table 8**). Positive significant ($p \leq 0.01$) correlations were found between grain yield and haulm yield and number of pods $plant^{-1}$ and hundred seed weight. Haulm and grain yields were highly significantly correlated (R^2 = 0.97). Grain yield was significantly ($p \leq 0.01$) correlated with pods $plant^{-1}$ (R^2 = 0.73) and hundred seed weight (R^2 = 0.85).

A significantly positive ($p \leq 0.01$) correlation was also observed between haulm yield and number of pods $plant^{-1}$ (R^2 = 0.76) and hundred seed weight (R^2 = 0.80) and plant height (R^2 = 0.84). Plant height and pods $plant^{-1}$ were also positively correlated. Similarly, a number of pods $plant^{-1}$ and hundred seed weight was positively correlated.

3.5 Economic returns on inoculation

Marginal rate of returns analysis was conducted for dominant treatments (**Table 9**). Net benefits of non-inoculated +N and −N control treatments were dominated at all the study locations while the least net benefits at all locations were obtained from non-inoculated −N control treatment.

Rhizobium strain NSFBR-15 inoculation to variety Moti resulted in the highest net benefit of 2281.8 USD followed by strain TAL_1035 inoculation to variety Gora and strain NFBR-15 inoculation to variety Dosha which gave a total of 2089 and 1971 USD ha^{-1}, respectively at Hankomolicha. The net benefits of all treatments were dominated except HUFBR-17 × Dosha, EAL-110 × Moti, and combinations with strains NSFBR-15, TAL_1035, and NSFBR-12. Net benefit to cost ratio ranged from 4.6 to 4.9 for the dominant treatments whereas MRR ranged from 212.8 to 442.0% (**Table 9**) at Hankomolicha.

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Rhizobium strains	Hankomolicha			Haranfama			Abala-Gase			Gike-Atoye		
	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora
		(NPP)			(NPP)			(NPP)			(NPP)	
TAL_1035	21.7^{b}	23.6^{b}	34.9^{a}	15.7^{abc}	16.4^{abc}	26.9^{a}	19.9^{cd}	44.8^{a}	27.2^{c}	27.4^{abc}	21.1d^{e}	33.3^{ab}
NSFBR-15	17.0^{bc}	38.3^{a}	23.2^{bc}	19.2^{a}	12.8^{bc}	25.2^{ab}	25.4^{b}	27.6^{b}	40.8^{a}	23.4^{c}	23.4^{cd}	35.8^{a}
HUFBR-17	15.7^{bc}	14.5^{cde}	14.1^{d}	18.6^{ab}	15.2^{abc}	9.73^{e}	18.3^{d}	16.9^{d}	16.5^{e}	24.6^{bc}	23.5^{cd}	16.6^{e}
NSFBR-12	30.6^{a}	21.0^{bc}	19.8^{cd}	20.7^{a}	20.6^{a}	21.0^{abc}	35.8^{a}	24.6^{bc}	23.2^{d}	27.8^{ab}	36.0^{a}	30.1^{bc}
EAL-110	19.8^{b}	9.4^{e}	13.5^{d}	17.9^{ab}	9.8^{c}	12.8^{de}	23.1^{bc}	11.0^{e}	15.7^{e}	25.5^{abc}	17.7^{e}	18.2^{e}
NSFBR-20	12.1^{c}	10.8^{de}	18.5^{cd}	9.1^{c}	18.5^{ab}	15.6^{cde}	14.1^{e}	12.7^{e}	21.6^{d}	14.6^{d}	26.4^{bc}	22.3^{d}
+N	23.3^{b}	18.5^{bcd}	27.8^{b}	20.5^{a}	19.6^{ab}	18.9^{bcd}	27.2^{b}	21.5^{c}	32.5^{b}	29.3^{a}	28.0^{b}	27.0^{c}
−N	9.7^{c}	12.0^{de}	17.9^{cd}	12.2^{bc}	13.6^{abc}	11.6^{e}	11.3^{e}	14.0^{de}	20.9^{d}	17.3^{d}	19.4^{de}	16.5^{e}
CV (%)		**24.8**			**25.9**			**11.7**			**10.8**	

Mean values in the same column with a different letter(s) are significantly different at $p \leq 0.05$ *probability level. NPP = Number of pods plant*$^{-1}$.

Table 6.
Rhizobium strain × faba bean variety interaction effect on the number of pods plant^{-1} *of faba bean at the study locations.*

Rhizobium strains	Hankomolicha			Haranfama			Abala-Gase			Gike-Atoye		
	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora	Moti	Dosha	Gora
		(g)			(g)			(g)			(g)	
TAL_1035	68.5^{bc}	69.1^{a}	80.2^{a}	59.8^{b}	61.2^{a}	71.0^{a}	68.3^{bc}	69.0^{a}	82.1^{a}	65.0^{ab}	66.7^{abc}	78.8^{a}
NSFBR-15	83.7^{a}	72.6^{a}	70.5^{b}	68.4^{a}	62.0^{a}	63.0^{b}	86.1^{a}	73.0^{a}	70.7^{b}	75.5^{a}	67.8^{ab}	69.0^{ab}
HUFBR-17	54.8^{de}	58.4^{b}	54.4^{c}	49.1^{c}	50.3^{b}	56.9^{c}	52.2^{de}	56.4^{b}	51.7^{c}	52.0^{c}	53.5^{d}	61.5^{bc}
NSFBR-12	62.7^{bcd}	67.9^{a}	73.2^{ab}	63.2^{ab}	65.5^{a}	59.7^{c}	61.4^{bcd}	67.6^{a}	73.8^{ab}	69.2^{a}	72.0^{a}	65.0^{b}
EAL-110	61.1^{cd}	47.7^{c}	53.2^{c}	54.4^{c}	51.0^{b}	47.1^{d}	59.5^{cd}	43.8^{c}	50.2^{c}	58.5^{bc}	54.3^{d}	49.5^{d}
NSFBR-20	50.7^{e}	51.8^{bc}	58.4^{c}	50.1^{c}	52.4^{b}	49.3^{d}	47.4^{e}	48.6^{bc}	56.4^{c}	53.3^{c}	56.0^{cd}	52.2^{cd}
+N	70.5^{b}	67.5^{a}	74.8^{ab}	64.7^{ab}	64.4^{a}	64.7^{b}	70.6^{b}	67.1^{a}	75.7^{ab}	71.0^{a}	70.8^{a}	71.0^{ab}
−N	41.4^{f}	50.5^{bc}	58.4^{c}	50.8^{c}	54.8^{b}	44.2^{d}	36.5^{f}	47.1^{bc}	56.4^{c}	54.0^{c}	59.0^{bcd}	46.0^{d}
CV (%)		**8.5**			**6.1**			**11.5**			**11.1**	

Mean values in the same column with a different letter(s) are significantly different at $p \leq 0.05$ *probability level.*

Table 7.
Rhizobium strain × faba bean variety interaction effect on hundred seed weight of faba bean at the study locations.

Variables	Grain yield		Haulm yield		Plant height	
	r	R^2	r	R^2	r	R^2
Haul yield	0.98**	0.97	—	—	—	—
Plant height	0.92**	0.84	0.92**	0.84	—	—
Hundred seed weight	0.92**	0.85	0.90**	0.80	—	—
Pods plant^{-1}	0.85**	0.73	0.87**	0.76	0.83**	0.69

***Significant at 1% level.*

Table 8.
Correlation among grain yield and yield components of faba bean inoculated with different rhizobium strains across the study locations.

Hankomolicha				Haranfama			
Strain × variety	NB ($ ha^{-1})	B:C ratio	MRR	Strain × variety	NB ($ ha^{-1})	B:C ratio	MRR
HUFBR-17 × Dosha	1513	4.6	212.8	HUFBR-17 × Moti	1298	4.4	210.1
NSFBR-12 × Moti	1637	4.6	366.4	TAL_1035 × Moti	1455	4.5	291.3
EAL-110 × Moti	1589	4.6	356.5	NSFBR-12 × Moti	1441	4.5	285.3
TAL_1035 × Moti	1815	4.7	395.4	NSFBR-12 × Dosha	1332	4.5	126.3
TAL_1035 × Dosha	1839	4.7	346.0	TAL_1035 × Dosha	1471	4.6	236.8
NSFBR-15 × Gora	1802	4.7	276.6	NSFBR-15 × Moti	1481	4.6	302.2
NSFBR-12 × Dosha	1801	4.7	336.7	NSFBR-15 × Dosha	1584	4.6	291.6
NSFBR-12 × Gora	1875	4.7	304.2	NSFBR-12 × Gora	1510	4.6	367.7
TAL_1035 × Gora	2089	4.8	362.9	TAL_1035 × Gora	1816	4.7	412.8
NSFBR-15 × Dosha	1971	4.8	373.2	NSFBR-15 × Gora	1685	4.7	397.4
NSFBR-15 × Moti	2282	4.9	442.0				

NB = net benefit (in USD ha^{-1}); MRR = marginal rate of return (in %); B:C = benefit-cost ratio.

Table 9.
Net benefit, benefit to cost ratio, and marginal rate of return for dominant treatments at Hankomolicha and Haranfama.

Variety Gora gave the highest net benefit (1816 USD ha^{-1}) when inoculated with TAL_1035 followed by the same variety (Gora) inoculated with NSFBR-15 (1685 USD ha^{-1}) at Haranfama. The net benefits of all treatments were dominated except HUFBR-17 × Moti, and combinations with strains NSFBR-15, TAL_1035, and NSFBR-12. The net benefit-cost ratio for dominant treatments ranged from 4.4 to 4.7 while MRR ranged from 126.3 to 412.8% (**Table 9**) at Haranfama.

Rhizobium strain NSFBR-15 inoculation to variety Gora and Moti resulted in the first and third highest net benefit of 2000 and 1878 USD ha^{-1}, respectively while strain TAL_1035 inoculation to variety Dosha resulted in the second-highest net benefit (1927 USD ha^{-1}) at Abala-Gase (**Table 9**). Apart from the non-inoculated +N and −N control treatments, the net benefits of all treatments were dominant. The net benefit-cost ratio ranged from 4.3 to 4.8 for the dominant treatments, whereas MRR ranged from 99.6 to 421.6% at Abala-Gase (**Table 10**).

Abala-Gase				Gike-Atoye			
Strain × variety	NB ($ ha^{-1})	B:C ratio	MRR	Strain × variety	NB ($ ha^{-1})	B:C ratio	MRR
HUFBR-17 × Moti	1075	4.3	99.6	NSFBR-20 × Dosha	1402	4.5	137.7
HUFBR-17 × Gora	1266	4.4	256.5	HUFBR-17 × Moti	1468	4.6	111.8
NSFBR-20 × Moti	1231	4.4	232.0	HUFBR-17 × Dosha	1585	4.6	265.8
HUFBR-17 × Dosha	1371	4.5	312.2	NSFBR-12 × Dosha	1545	4.6	243.2
EAL-110 × Dosha	1362	4.5	309.0	EAL-110 × Moti	1589	4.6	217.4
NSFBR-20 × Dosha	1409	4.5	323.9	EAL-110 × Dosha	1574	4.6	260.0
NSFBR-20 × Gora	1343	4.5	289.7	EAL-110 × Gora	1499	4.6	288.9
EAL-110 × Gora	1510	4.6	343.4	NSFBR-20 × Moti	1618	4.6	234.4
TAL_1035 × Moti	1802	4.7	398.9	TAL_1035 × Moti	1783	4.7	309.5
TAL_1035 × Dosha	1927	4.7	417.1	TAL_1035 × Dosha	1705	4.7	312.3
TAL_1035 × Gora	1668	4.7	376.8	TAL_1035 × Gora	1864	4.7	382.8
NSFBR-15 × Moti	1878	4.7	407.9	NSFBR-15 × Moti	1722	4.7	286.0
NSFBR-15 × Dosha	1801	4.7	403.2	NSFBR-15 × Dosha	1709	4.7	313.7
NSFBR-12 × Moti	1711	4.7	383.8	NSFBR-12 × Moti	1672	4.7	263.5
NSFBR-12 × Dosha	1807	4.7	402.3	NSFBR-12 × Gora	1732	4.7	358.8
NSFBR-12 × Gora	1700	4.7	381.5	NSFBR-15 × Gora	2061	4.8	411.5
EAL-110 × Moti	1719	4.7	385.4				
NSFBR-15 × Gora	2000	4.8	421.6				

NB = net benefit (in USD ha^{-1}); MRR = marginal rate of return (in %); B:C = benefit-cost ratio.

Table 10.
Net benefit, benefit to cost ratio, and marginal rate of return for dominant treatments at Abala-Gase and Gike-Atoye.

Except for HUFBR-17 × Gora and non-inoculated +N and −N control treatments, the net benefits of all treatments were dominant at Gike-Atoye. The net benefit for dominant treatments (**Table 9**) ranged between 1402 and 2061 USD ha^{-1}. Rhizobium strain NSFBR-15 inoculation to variety Gora resulted in the highest net benefit (2061 USD ha^{-1}) followed by strain TAL_1035 inoculation to variety Gora and Moti which resulted in the second and third highest net benefits of 1864 and 1783 USD ha^{-1}, respectively at Gike-Atoye. The net benefit-cost ratio ranged from 4.5 to 4.8 for the dominant treatments while MRR ranged between 111.8–411.5 USD ha^{-1} at Gike-Atoye (**Table 10**).

4. Discussion

Rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 significantly ($p \le 0.01$) increased grain yield of faba bean as compared to non-inoculated −N control at all the study locations (**Table 3**). Similarly, significant effects of rhizobia inoculation on legume yield have been reported [14, 24, 41]. The grain and haulm yields increment is attributable to the increased supply of fixed N to faba bean plants as a result of inoculation.

There were variations in grain and haulm yields across the study locations (**Figure 1**). Variation in grain and haulm yield across the locations might be related to differences in fertility status of the soils (**Table 2**). Soil N, Ca, CEC and organic C status at Gike-Atoye was relatively higher than that of other study locations, whereas Haranfam had generally lower nutrients and organic carbon status among soils of the study locations, hence, the higher yield in the former following inoculation. Symbiotic N fixation is not active at the early stages of plant growth in low fertile soils [7]. Mineral nutrient deficiency limits legume N fixation, nutrient uptake, and yields of crops [42, 43].

Several studies [14, 24, 44] have shown that rhizobium strains inoculation improved the yield of faba bean. The observed yield difference in inoculated faba bean could be attributed to the variation in plant response to different rhizobium strains inoculation in N fixation. Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in 62.3, 56.9, and 46.4% grain yield increments, respectively over non-inoculated −N control (**Figure 2**). These results are in line with the findings of Denton et al. [14] and Youseif & Fayrouz [7] who reported 59–81% faba bean yield increment due to different rhizobia strain inoculation. The findings of this current study demonstrated that the increment in grain yield of faba bean depended on rhizobium strain and faba bean genotypes interaction with probably the biochemical characteristics of the soil.

Cultivation of faba bean without N fertilizer is the common practice among small holders in Ethiopia [45]. Application of N fertilizer at rates between 40 and 50 kg N ha^{-1} was reported to increase nodulation, N fixation and yield of faba bean [7, 46] and soybean [47]. In this study, 46 kg N ha^{-1} resulted in a significant haulm yield increase in faba bean over non-inoculated −N control at all the study locations (**Table 4**). The increase in haulm yield due to applied N, in turn, brought about increased grain yield. Previous studies [48, 49] revealed a strong relationship between haulm and grain yield and suggested that increasing biomass is a prerequisite for high grain yield of legumes.

In line with the finding of Albareda et al. [50] and Youseif [47] in soybean and Youseif & Fayrouz [7] in faba bean, this study revealed that response of inoculation varied among rhizobium strains. The three strains (NSFBR-15, TAL_1035, and NSFBR-12) established an effective N fixing association with faba bean, thus producing greater grain yield relative to 46 kg N ha^{-1} (**Figure 2**). This finding is in line with Albareda et al. [50] and Tena et al. [51] who reported that inoculation with effective strains resulted in significantly higher or equal grain yields as compared to non-inoculated +N controls of soybean and lentil, respectively. Youseif & Fayrouz [7] also reported that inoculation with effective rhizobium strains increased the grain yield of faba bean by 35–48% compared to 96 kg N ha^{-1}. The higher yields obtained with NSFBR-15, TAL_1035, and NSFBR-12 inoculation indicate that these strains were more efficient in supplying N to faba bean than inorganic N fertilizer application (46 kg N ha^{-1}). This result showed that inoculation of faba bean with effective rhizobium strain could reduce the need for inorganic fertilizer while achieving higher grain yield.

Rhizobium strains inoculation significantly ($p \leq 0.01$) influenced haulm yield of faba bean (**Table 4**). This finding is in line with Tena et al. [51] who reported that rhizobial strain inoculation increased the straw yield of lentil. Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in a significant increase in haulm yield compared to non-inoculated control treatments (**Table 4**). In line with this, Ali et al. [52] reported that, inoculated *Pisum sativum* L. produced significantly higher foliage yield than non-inoculated plants. An increase in haulm yield in response to rhizobium strains inoculation may be attributed to the increased supply of N through N fixation as a result of increased modulation. According to Giller [53], rhizobium strains increase N uptake and stimulate plant biomass production.

Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in a higher haulm yield of faba bean than non-inoculated +N control (**Table 4**). This shows that the rhizobium strains (NSFBR-15, TAL_1035, and NSFBR-12) were more efficient in supplying N to faba bean than inorganic N fertilizer (46 kg N ha^{-1}) in the study locations. On the other hand, inoculation with HUFBR-17, EAL-110, and NSFBR-20 resulted in lower haulm yield than non-inoculated +N control (**Table 4**). Therefore, HUFBR-17, EAL-110, and NSFBR-20 may not be the best substitute for N fertilizer for maximum haulm yield production. Hence, the study clearly showed that appropriate rhizobium strain inoculation is vital in improving plant growth and increasing haulm yield of faba bean.

Rhizobium strains and strain × variety interaction had highly significant ($p \leq 0.01$) effects on a number of pods $plant^{-1}$, hundred seed weight, and plant height (**Tables 5**–**7**) of faba bean. Rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 inoculation had a great positive effect on the number of pods $plant^{-1}$, hundred seed weight, and plant height (**Tables 5**–**7**) of faba bean as compared to non-inoculated −N control. This is in line with the findings of Solomon et al. [41]; Argaw [24]; Denton et al. [14] who reported significant improvement in yield components in faba bean with rhizobium inoculation. The positive change in the number of pods $plant^{-1}$ and hundred seed weight following NSFBR-15, TAL_1035, and NSFBR-12 inoculation contributed to the increased yield of faba bean.

Plant height was significantly ($p \leq 0.01$) affected by rhizobium inoculation (**Table 5**). In line with this result, Raza et al. [54] and Sajid et al. [55] found that rhizobium inoculation increased plant height of mung bean and groundnut, respectively. The increment in plant height might be due to supplementary N from rhizobium strains inoculation which could promote vegetative growth of the plant. Besides, rhizobium strains may synthesize growth-promoting substances (phytohormones) like auxin as secondary metabolites in inoculated plants. Gamini and Ekanayake [56] reported similar results with different strains of *Bradyrhizobium japonicum* on soybean. There was no significant variation among faba bean varieties for plant height, grain, and haulm yields of faba bean though tested varieties genetically vary in these traits [57].

Rhizobium strains inoculation and N fertilizer application significantly ($p \leq 0.01$) influenced number of pods $plant^{-1}$ of faba bean (**Table 6**). This result disagrees with that of Karasu et al. [58] who reported that inoculation of rhizobia and N fertilizer application did not affect the number of pods $plant^{-1}$. However, Anjum et al. [59] reported that inoculation of rhizobia and N fertilizer application significantly increased the number of pods $plant^{-1}$ in mung beans. The current results of this study, however, confirm that of Malik et al. [60] and Bhuiyan et al. [61] who concluded that the number of pods per plant of soybean and mung bean was significantly increased by inoculating with *Bradyrhizobium*, respectively.

Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in a higher hundred seed weight as compared to non-inoculated −N control treatment at all the study locations (**Table 7**). In line with this finding, Anjum et al. [59] revealed that hundred seed weight was significantly affected by inoculation in mung bean. Similarly, Aslam et al. [62] reported that hundred seed weight of chickpea was significantly increased by rhizobium inoculation. Zhang et al. [63] and Kazemi et al. [64] also reported that inoculation by rhizobia significantly increased hundred seed weight of soybean. A similar result was obtained by Kyei-Boahen et al. [65]. Higher seed weight was probably due to the provision of enough assimilate to fill the seeds. The variation in hundred seed weight of faba bean due to inoculation may be related to the differences in symbiotic effectiveness of rhizobium strains on the different faba varieties which could, in turn, have resulted in variation in N fixation and assimilate translocation to the grain. In grain legumes, a hundred seed weight is considered to be an indicator for the seed quality of the crop [66].

There were significant differences among the tested faba bean varieties on a number of pods per plant (**Table 6**) and hundred seed weight (**Table 7**). Significant variation among the faba bean varieties in hundred seed weight might be attributed to genetic divergences in individual varieties in pod production and seed size [57]. They noted that a number of pods plant^{-1} depended on the number of reproductive sites plant^{-1}. The result of this study indicated that tested varieties have different genetic potential in producing pods and seed size. In line with this result, Tagore et al. [67] reported that differences in seed size among chickpea varieties occurred due to differences in genotypes.

Rhizobium strains inoculation had significant effects in increasing yield components and ultimately haulm and grain yields of faba bean. Haulm yield and grain yield were highly correlated (R^2 = 0.97) (**Table 8**) indicating that haulm yield was the most important factor influencing grain yield. High biomass production in grain legumes is a prerequisite for high grain yield [48, 49]. The positive correlation of hundred seed weight (R^2 = 0.85) and the number of pods plant^{-1} (R^2 = 0.73) (**Table 8**) with grain yield indicates the importance of seed size and number of pods plant^{-1} in determining the final yield of faba bean.

Relatively, the lowest net benefit (**Tables 9** and **10**) obtained for the treatments at all the study locations was attributable to the low yields of the non-inoculated −N control treatment. Net benefits from non-inoculated both +N and −N control treatments were dominated at all study locations. A decrease in net benefits for non-inoculated +N control treatments was due to its high variable cost [38]. Whereas, the lowest net benefit for non-inoculated −N control was due to the lowest yield obtained from this treatment at all the study locations. This result indicates that inoculation with efficient rhizobium strain is sustainable and more economical in supplying N to faba bean crop than N fertilizer application (46 kg N ha^{-1}). Thus, the inclusion of appropriate rhizobium strains in faba bean production will be cost-effective in the study locations.

Inoculation with NSFBR-15, TAL_1035, and NSFBR-12 resulted in increased grain yield and profit over the control treatments which eventually resulted in a significantly greater marginal rate of returns at all the study locations (**Tables 9** and **10**). Tairo and Ndakidemi [68] revealed that rhizobia inoculation had a positive significant effect on the nutrition, growth, and economic sustainability of grain legumes. Treatments that have the highest benefit and marginal rate of return greater than the minimum acceptable marginal rate of return can be a tentative recommendation. In this current research, the marginal rates of returns for all dominant treatments were above the minimum acceptable marginal rate of return (100%) [38].

5. Conclusion

This study has shown significant location × strain × variety interaction effects on grain and haulm yields, plant height, number of pods plant^{-1}, and hundred seed weight of faba bean. Results clearly showed that rhizobium inoculation is indispensable for increasing the growth and yield of faba bean in the study locations. The economic analysis showed that efficient rhizobium strains inoculation is more economical for faba bean production than 46 kg ha^{-1} N fertilizer application. Rhizobium strains NSFBR-15, TAL_1035, and NSFBR-12 were more efficient in supplying N to faba bean as compared with the supply of 46 kg ha^{-1} N fertilizer. Thus, the result suggests the potential use of strains NSFBR-15, TAL_1035, and NSFBR-12 as a powerful alternate source for N in faba bean production in the study locations.

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