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Article

Rhizobium Inoculation and Chemical Fertilisation Improve Faba Bean Yield and Yield Components in Northwestern Ethiopia

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Abstract: The productivity of the faba bean has declined in Ethiopia, owing to poor management practices, such as blanket fertilisation. In 2018, a field experiment was conducted in a Nitisol soil during the main cropping season in Northwestern Ethiopia, to determine the amount of chemical fertiliser and Rhizobium inoculant to be used for the optimum yield within economic feasibility. The experiment consisted of a factorial combination of five rates of blended NPSZnB fertiliser (0, 60, 121, 180 and 240 kg ha^{-1}) and three rates of inoculant (0, 500 and 750 g ha^{-1}). Sole chemical fertilisation, as well as inoculation, individually produced a seed yield of 2.3–2.5 t ha^{-1}, about 1.0–1.2 t ha^{-1} more than the control. However, the maximum seed yield (3.3 t ha^{-1}) was recorded from the combined application of both the chemical fertiliser and the inoculant. The seed yield correlated closely with the number of active nodules (R^2 = 0.78 **), suggesting a substantial contribution of symbiotic N_2 fixation. Inoculation increased the N content of the seed yield by at least 30 kg ha^{-1}. Chemical fertilisation, containing at least 44 kg ha^{-1} of mineral N does not appear to have an adverse effect on N_2 fixation. The combined use of 180 kg ha^{-1} blended fertiliser with 750 g ha^{-1} inoculant, producing a maximum net profit of 72,918 birr ha^{-1} (EUR 2232), is recommended for the study area. This study emphasises that (1) inoculation alone can produce as much seed as the maximum rate of chemical fertilisation, but (2) the maximum yield was produced with a combined use of inoculant and chemical fertiliser, by promoting the vigour of the nodules and N_2 fixation.

Keywords: Rhizobium inoculant; leguminous crop; chemical fertilisation; biofertilizer; Dangla district

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1. Introduction

The faba bean (*Vicia faba* L.) is a good source of protein, starch, cellulose and minerals, and is commonly used as human food in developing countries [1]. China, Ethiopia, Egypt, and the United Kingdom are the top producers of faba beans in the world. Ethiopia produces about 56% of the total faba bean output in Africa [2]. Faba bean is the third most important pulse, in terms of cultivated area and yield in the world, after soya bean and pea, while it is the most important pulse in Ethiopia [3,4]. In the 2019/20 cropping season, about 467,000 ha of land was cultivated for faba bean in Ethiopia, and 1006,752 tonnes of grain were obtained, of which about one third was produced in the Amhara region [4].

The productivity of faba beans in Ethiopia is very low—only 2.16 t ha^{-1} [4]—and even less than 1.0 ha^{-1} in the study area, which is the Dangla district in the Amhara region. These numbers are much lower than the average yield in the rest of the world, which is approximately 4.8 t ha^{-1} [5]. The low yields in Ethiopia result from poor soil fertility management, along with other adverse factors, such as soil erosion, poor weeding practices, and the presence of different pests and diseases. Most highlands of Ethiopia are deficient in major essential nutrients, particularly nitrogen (N) and phosphorus (P).

Soil inventory data of the Ethiopian Soil Information System revealed that the soils in Ethiopia are also deficient in potassium (K), sulphur (S), boron (B), and zinc (Zn) [6]. In the Amhara region, farmers are recommended to use 121 kg ha^{-1} NPS fertiliser and 25 kg ha^{-1} urea during crop planting [7]. However, farmers utilize amounts far below this blanket recommendation rate, due to economic constraints. In the low-input cropping systems of Ethiopia, chemical fertilisers are rarely used in the production of faba bean and other pulse crops. Instead, these crops are used to restore soil fertility for the succeeding cereal crops [8,9].

In terms of N supply, leguminous crops can make use of Rhizobia, which are bacteria living symbiotically with legume crops, by fixing atmospheric N_2 [10,11]. Different leguminous crops require specific Rhizobium species for the formation of effective nodules and N_2 fixation [12], and the various strains of Rhizobium species differ in their efficiency of N_2 fixation [13]. The low level of nutrient supply and the lack of effective indigenous Rhizobium populations in soil have limited the faba bean yields [14]. Thus, the crop should be inoculated with the proper Rhizobium species and strains.

Inoculants can be regarded as biological fertilisers. They play a key role in crop productivity and may also protect the environment from pollution of leaching mineral N fertiliser residues, and serve as cost-effective inputs for farmers [15]. It has commonly been established that chemical N fertilisation of leguminous crops can substantially decrease the amount of N_2 fixed from the air [16]. However, small amounts of N fertilisation can boost the early growth of crops, allowing the delivery of more carbohydrates for N_2 fixation later in the season [17]. Diammonium phosphate (DAP) is a commonly available chemical fertiliser, so when it is used to provide the crop with P, N is inevitably made available. Moreover, urea is often included in the blanket recommendation. Scarce information is available to the agricultural extension service, regarding the integrated use of Rhizobium inoculants and chemical fertiliser. Hence, this study was designed with the following objectives: (1) to investigate the characteristics of growth that are most affected by the additions of the chemical fertiliser and Rhizobium inoculant, (2) to evaluate the effects of the chemical fertilisation and Rhizobium inoculant rates on the growth and yield of the faba bean, and (3) to identify the economically feasible, optimum rates of chemical fertiliser and inoculant use to improve the faba bean yield in the Dangla district.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in the main cropping season of 2018 at the Farmer Training Center (FTC) field of Wuftadati Kebele in the Dangila district, Awi Zone, Amhara National Regional State. The district is located 85 km southwest of Bahir Dar, the capital city of the Amhara region and 485 km northwest of Addis Ababa. The experimental site is located 10 km northwest of Dangla town, at an altitude of 2156 metres above sea level (masl) and with the geographical location at 11°14′ N latitude, 33°45′ E longitude.

The topography of the district is plain and the altitude ranges between 1353 and 2454 masl. Most of the Dangla district belongs to the Woinadega agro-ecological zone, which receives 700–1000 mm rainfall annually [18], and the rainfall pattern is mono-modal, extending from May to October. The mean monthly minimum and maximum temperatures are 15 °C and 21 °C, respectively. Nitisols (red soils) are prevalent in most of the district (80%), while the remaining 20% is occupied by Vertisols [18]. Soils of the Dangla district are the most degraded in the region, and they are very low in organic matter and plant nutrients, particularly N, P, K, S, B and Zn [6]. A mixed crop–livestock farming system is practiced in the area. The major crops grown in the district and the study site are cereals (maize, finger millet, teff, barley and wheat), legumes (faba bean, pea and chickpea) and oilseeds (noug, lentil and rape seed) in that order of importance [18]. During the experimental season, the mean monthly rainfall was 169 mm, while the maximum and minimum temperatures were 27.3 and 3.5 °C, respectively (Figure 1).

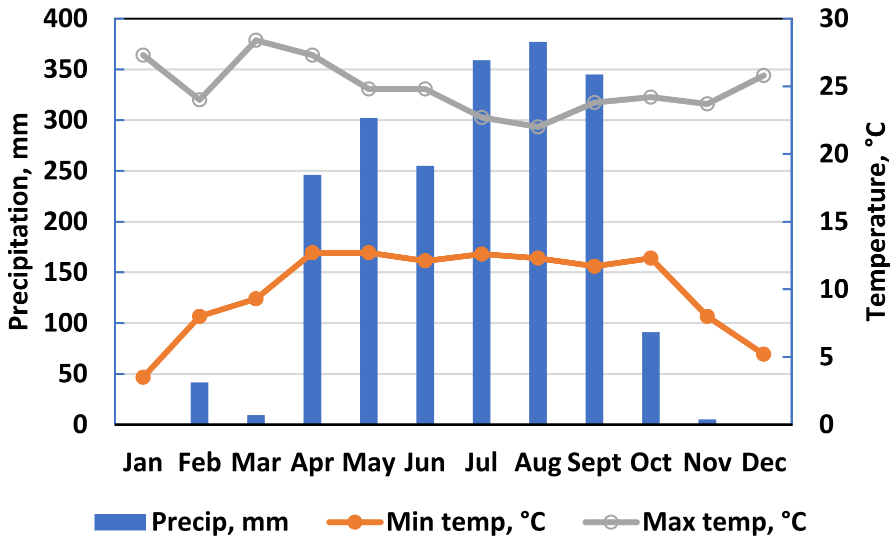

Figure 1. Mean monthly rainfall (Precip) and minimum (Min temp) and maximum temperature (Max temp) of the study area during the experimental season.

2.2. Experimental Material, Treatments, Design and Procedures

Faba bean of the Welki (EH96049-2) variety was used as the test crop. The variety was released in 2008 by the Holleta Agricultural Research Centre (HARC). It can grow at altitudes of 1900 to 2800 masl and requires 700 to 1000 mm annual rainfall. A blended chemical fertiliser with 17.8% N, 35.7% P_2O_5, 7.7% S, 2.2% Zn and 0.1% B was used in the experiment, while a uniform amount of urea (46% N) was used as an additional source of N. Inoculants of *Rhizobium leguminosarum* biovar *viceae*, strain EL110 were collected from Menagesha Biotech, Addis Ababa. Lignite is used as the carrier in this commercial inoculant. Despite knowing that K deficiency can occur in the region [6] and that abundant K can positively affect the nodulation of faba bean [19], we chose not to use K fertilisation. Potassium is not included in the blanket fertiliser recommendation in the area, and we wanted to make an experiment as close as possible to the practical farming practices. Moreover, according to the expert knowledge, the local soils have at least a moderate K status.

Factorial combinations of five blended fertiliser rates (0, 60, 121,180 and 240 kg ha^{-1}) and three inoculant rates (0, 500 and 750 g ha^{-1}), i.e., 15 treatment combinations, were laid out in a randomised complete block design (RCBD) and replicated three times (Table 1).

Table 1. Treatment combinations of the blended fertiliser and the inoculant for the experiment.

Inoculant, g ha^{-1}	**Blended Fertiliser, kg ha^{-1}**				
	0	60	121	180	240
0	0 × 0	0 × 60	0 × 121	0 × 180	0 × 240
500	500 × 0	500 × 60	500 × 121	500 × 180	500 × 240
750	750 × 0	750 × 60	750 × 121	750 × 180	750 × 240

The predetermined amount of blended fertiliser, urea and the inoculant were utilised during crop sowing. A uniform rate of urea (25 kg ha^{-1}) was applied as a starter fertiliser. The nutrients added in the chemical fertilisers are presented in Table 2.

Table 2. Amounts of nutrients, kg ha^{-1}, added at different levels in the blended chemical fertiliser and in urea.

Blended Fertiliser, kg ha^{-1}	N	P	S	Zn	B
0	12	0	0	0	0
60	22	9	5	1.3	0.06
121	33	19	9	2.7	0.12
180	44	28	14	4.0	0.18
240	54	37	18	5.3	0.24

The gross plot size was 2.4 m × 2.4 m (5.76 m^2) while the net plot size was determined by excluding one outer row and 0.20 m of length from both sides of each plot as border effects; thus, the resulting net plot size was 2 m × 2 m (4 m^2). The spaces between blocks and plots were 1 m and 0.5 m, respectively. The crop was planted in 6 rows on each plot with inter- and intra-row spacing of 40 cm and 10 cm, respectively, and at a depth of 8 cm on 28 July 2018.

The experimental field, used recently for growing cereals, was ploughed three times by an oxen-driven local ploughing implement called maresha. The prepared land was further divided into plots as per the study design and levelled manually. The treatments were assigned randomly to the plots of each replication. The sticker material (sugar solution) was prepared by mixing 10 g of sugar with 100 mL of water. The sticker was used to evenly coat the seeds. One packet of the inoculum (125 g) was mixed with 200 mL of water to make a slurry. The seeds required for the plot were mixed in the slurry ensuring uniform coating of the inoculum over the seeds, with the target level at 10^8 Rhizobium cells per seed. The seeds were dried under shade for about 30 min and sown within 24 h. One packet of the inoculum (125 g) was sufficient to treat 10 kg of seed as per the recommendation. Weeds were controlled manually.

2.3. Soil Sampling and Analysis

Before sowing the crop, samples from the experimental soil were collected in a zigzag fashion from 9 spots at 0–30 cm depth. The subsamples were thoroughly mixed, and the composite soil sample was air dried and ground to pass through a 2 mm sieve for the analysis of texture, soil pH, available P and cation exchange capacity (CEC). To determine total N and organic carbon, the soil was pulverised further to pass through a 0.5 mm sieve. The analyses were carried out by the soil chemistry and water quality section of Amhara Design and Supervision using standard methods and procedures.

Soil pH was determined using a digital pH metre at a 1:2.5 soil-to-water ratio [20]. The organic carbon content was determined by the Walkey and Black oxidation method [21]. The texture was determined by applying the hydrometer method [20]. The total N content was estimated through the Micro-Kjeldhal method [22]. The available P was extracted with a 0.5 M $NaHCO_3$ solution, pH 8.5 [23]. The available Zn was extracted with diethylenetriaminepentaacetic acid—triethanolamine (DTPA-TEA) solution with pH 7.3 [24]. CEC was determined by extracting the soil samples utilising ammonium acetate (1 M NH_4OAc, pH 7.0) followed by repeated washing with ethanol (96%) to remove the excess ammonium (NH_4^+) ions. The adsorbed NH_4^+ in the soil was displaced with sodium chloride and then determined by steam distillation and titration using 0.1 M NaOH [25].

2.4. Data Collection and Analysis

The phenological stage, growth and yield parameters were recorded to investigate the effects of the treatments, as indicated in Table 3. The data collected from the experiment at different growth stages were subjected to statistical analysis (two-way ANOVA) as per the experimental design using SAS version 9.4. The mean separation was carried out using the least significant difference (LSD) test at $p < 0.05$ [26]. The Pearson correlation coefficients were also calculated. Normal distribution of the data was confirmed using histograms and comparing the mean and median values.

Table 3. Observations and measurements made from the crop.

	Crop Data	Procedural Method of Recording
1	Days to emergence, flowering and pod setting	50% of the plants reaching the respective state by visual observation.
2	Days to physiological maturity	90% of the plants changing from green to yellowish, senescence of leaves and pod colour turning black.
3	No. of nodules per plant	Randomly selected 5 plants per plot at 50% flowering uprooted and washed with wate; nodules remaining in soil picked by hand.
4	Effectiveness of nodules	Nodules separated from the roots assessed by the interior colour; pinkish, brown and reddish nodules considered effective while green, yellow and white classified as ineffective in N^2 fixation.
5	Nodulation rating	Examining 10 plants with intact nodules for a) nodulation in the taproot (NPTRN), b) the secondary roots close to taproot (NPNCTR), c) scattered all over the roots (PSN) and d) plants showing no nodulation (PNN); N = total number of plants; the rating was done on a scale of 1–10 and then subjected to the following formula for nodulation rating (NR) (NifTAL, 1979):NR = [(10 × NPTRN) + (5 × NPNCTR) + (1 × PSN) + (0 × PNN)]/N
6	Plant height	10 randomly selected plants of each plot measured from soil surface to the tip of the stem at 90% physiological maturity.
7	No. of leaves per plant	Counting leaves of 5 randomly selected plants at 50% flowering.
8	No. of productive tillers	Counting fertile (productive) tillers arising from main stem from randomly selected 10 plants at pod setting.
9	No. of pods per plant and seeds per pod	Counting pods and seeds of 5 randomly selected plants from the middle rows at harvest.
10	Yield (seed, biomass and straw)	After threshing, seed was adjusted to 14% moisture content and weighed; total above ground biomass from net plot was harvested and weighed; straw yield was obtained by subtracting grain yield from total biomass yield.
11	Hundred seed weight	Collecting and weighing 100 seeds from a selected plant
12	Harvest index	Ratio of dry weight of grains to total aboveground biomass.

An economic analysis was performed using the CIMMYT partial budget methodology [27]. As usual, labour costs, chemical fertilisers and the inoculant were considered in the estimation of the variable cost while the prices of faba bean seeds and straw were employed to compute the field benefit of the treatments. The average field prices of faba bean seed and straw, chemical fertilisers, inoculant and labour were collected as per the proper time schedule during the experiment season. Accordingly, during the application season the price of blended fertiliser and inoculants were 15 birr kg^{-1} (EUR 0.46 kg^{-1}) and 32 birr 100 g^{-1} (EUR 0.98 100 g^{-1}), respectively.

The labour cost for harvesting, threshing and winnowing was estimated at 100 birr per 100 kg seed yield (EUR 3.06 kg^{-1}). The cost of seed packing material and transportation was 20 birr per 100 kg of seed (EUR 0.61 $kg.^{1}$) while the cost of straw packaging and transporting was 10 birr (EUR 0.31) per 30 kg. All the costs were computed to determine the total variable cost of treatment. The economic benefits of the treatment were computed by the estimated seed price of 24 birr kg^{-1} (EUR 0.73 kg^{-1}) and straw price by 200 birr 100 kg^{-1} (EUR 6.12 100 kg^{-1}). Then, a dominance analysis was undertaken to select the most profitable treatment option. The treatments were arranged in ascending order of total variable cost from the lowest to highest cost. Moreover, the net benefit of each treatment was computed through a difference of the gross field benefit to total cost. In the year of the experiment (2018), 100 birr was equivalent to EUR 3.06 or USD 3.61.

3. Results and Discussion

3.1. Physico-Chemical Properties of the Experimental Soil

The experimental soil has a clay loam texture. The soil contained a total of 0.14% N and 11.9 mg kg^{-1} of available P, representing the lower part of the medium P level, and 1.3 mg kg^{-1} of available Zn (Table 4). The pH was close to neutral, suggesting no problem with acidity or aluminium toxicity. The CEC of the soil was significantly low, and the CEC_{clay}, which was calculated to be 20.4 cmol(+) kg^{-1}, was only half of what was reported in eight soils of the Farta district, central Ethiopia, which had an average clay content of 47% [28]. This suggests predominantly kaolinitic mineralogy in our experimental soil. The soil was tentatively classified as Eutric Nitisols according to the WRB system [29].

Table 4. Physicochemical properties of the experimental site's soil.

Soil Parameters	Unit	Value
Sand	%	17
Silt	%	22
Clay	%	61
Textural class		Clay loam
pH		6.96
Organic C	%	1.6
Total N	%	0.14
CEC	cmol(+) kg^{-1}	18.0
Available P	mg kg^{-1}	11.9
Available Zn	mg kg^{-1}	1.3

3.2. Phenological Parameters

The days to 50% emergence (data not shown) were similar for all the treatments, but the days to 50% flowering increased by 4 days at the maximum rate, with increasing amounts of blended fertiliser and inoculants (Table 5). It is noteworthy that the rate of blended fertiliser alone did not influence the early development of the faba bean and neither did the inoculation, but it was the combined application of both that had an effect. Similarly, the inoculant prolonged the days of 50% pod setting (data not shown) by about two days ($p < 0.01$), but the blended fertiliser did not have an effect. The number of days to physiological maturity was prolonged by the two treatments by four days at the maximum level (Table 5). The period between pod setting and physiological maturity was prolonged from 53 days in the control to 57 days in the plots receiving the maximum amounts of both amendments, thus allowing a few more days for pod filling.

Table 5. Days to 50% flowering and days to maturity of faba beans that received different amounts of a blended chemical fertiliser and the Rhizobium inoculant.

Blended Fertiliser, kg ha^{-1}	Days to 50% Flowering			Days to Maturity		
	Inoculant, g ha^{-1}			Inoculant, g ha^{-1}		
	0	500	750	0	500	750
0	44 ^{d}	44 ^{d}	45 ^{bcd}	129	131	130
60	44 ^{d}	45 ^{bcd}	45 ^{bcd}	128	131	129
121	44 ^{d}	46 ^{abc}	47 ^{a}	130	133	129
180	44 ^{d}	47 ^{ab}	48 ^{a}	130	131	129
240	44 ^{d}	47 ^{a}	48 ^{a}	132	129	130
LSD (p = 0.05)		1.4			14.2	
s		0.1 (0–0.6)			2.4 (0–4.0)	

LSD = Least Significant Difference at p = 0.05; s = standard deviation expressed as a mean and range within individual treatments. The mean values of days to 50% flowering marked with the same letter are not significantly different at p = 0.05. In the results of days to maturity, there were no significant differences.

The abundant supply of nutrients from the blended fertilisers likely sped up early growth, which, in turn, enhanced the N_2 fixation. Increased N supply usually delays the development of the stand and keeps it in the vegetative stage longer [30,31]. Such a positive response of shoot development, and the prolongation of the vegetative stage to inoculation and chemical N and/or P fertilisation, has also been reported for chickpea and common bean [32–34]. It has also been reported that increasing the N supply from 0 to 46 kg ha^{-1} significantly prolongs the time to physiological maturity for the common bean [35].

3.3. Vegetative Growth Parameters

3.3.1. Nodulation

The lowest numbers of nodules (54–56) were produced in plants receiving only chemical fertilisers. Even though the total nodulation did not increase with the fertiliser rate (Table 6), the number of active nodules increased from 19% to 70%. Nodulation was greatly enhanced by inoculation, and the interaction effect of the inoculant and blended fertiliser was highly significant ($p < 0.001$). The highest numbers of nodules per plant (130–140) were observed with the combined application of the inoculant and blended fertiliser at 121–240 kg ha^{-1}. However, the nodulation rating (range of 71–138 in the different treatments) was not significantly ($p > 0.05$) nor consistently influenced by any treatment. Around 60–70% nodules were active in the inoculated plants, except for the plants at a higher inoculation rate at 0 and 60 kg ha^{-1} of blended chemical fertilisation. For an unknown reason, a large number of nodules developed in these plots, but only 20 or 30% of them were active.

Table 6. Total number of nodules and active nodules per plant as affected by blended fertiliser and inoculant rate.

Blended Fertiliser, kg ha^{-1}	**Total Number of Nodules**			**Number of Active Nodules**		
	Inoculant, g ha^{-1}			Inoculant, g ha^{-1}		
	0	500	750	0	500	750
0	54 ^{e}	84 ^{d}	122 ^{b}	10 ^{f}	47 ^{c}	24 ^{ef}
60	55 ^{e}	87 ^{d}	102 ^{c}	15 ^{f}	63 ^{b}	31 ^{ed}
121	56 ^{e}	130 ^{ab}	134 ^{a}	15 ^{f}	75 ^{ab}	83 ^{a}
180	58 ^{e}	133 ^{a}	136 ^{a}	40 ^{cd}	83 ^{a}	85 ^{a}
240	56 ^{e}	133 ^{a}	140 ^{a}	39 ^{cd}	85 ^{a}	89 ^{a}
LSD (p = 0.05)		11.2			14.4	
s		34 (9–58)			17 (2–30)	

LSD = Least Significant Difference at p = 0.05; s = standard deviation expressed as a mean and range within individual treatments. The mean values within a given nodulation parameter marked with the same letter are not significantly different at p = 0.05.

The inoculation of the faba bean crop has resulted in a higher number of effective nodules per plant compared to non-inoculated plants in other studies as well [34,36]. Particularly, the use of P along with the inoculant has increased the nodulation and N_2 fixation of legume crops [37–39], as well as effective nodulation [40]. On the other hand, in some studies, N fertilisation of 60 and 90 kg ha^{-1} led to decreased nodulation of the faba bean, while 30 kg ha^{-1} had a positive effect compared to the control [39]. In our study, the effects of N and P could not be distinguished because both nutrients, as well as S, Zn and B, were utilised at increasing levels, with increasing additions of the blended chemical fertiliser. It is possible that the inhibitory effect of N on nodulation has been compensated for, or even outweighed by, the boosting effect of the increasing amounts of other nutrients, most likely P, even though the level of available P in the soil was not low, but at the lower end of the medium range [22].

3.3.2. Plant Height, Number of Leaves and Biomass Yield

Plant height was significantly ($p < 0.01$) affected by the combined use of blended fertiliser and the inoculant (Table 7). The blended chemical fertiliser, when applied without inoculation, increased the plant height at the first level, but no further increase was observed with larger amounts. Notably, the inoculated plants were significantly taller than the ones without inoculation, only at the two highest levels of chemical fertilisation.

Similarly, the highest number of leaves (79) were observed in plots with the highest rates of blended fertiliser (180 and 240 kg ha^{-1}), while much fewer leaves (56) were observed in the control plot. Consequently, the total biomass yield consistently increased ($p < 0.01$), from the control (5.1 t ha^{-1}) to the two highest levels of blended fertiliser rates (7.8 and 8.3 t ha^{-1}).

Table 7. Plant height (cm) affected by combined application of blended fertiliser and the inoculant.

Blended Fertiliser	Inoculant, g ha^{-1}		
kg ha^{-1}	0	500	750
0	102 ^{f}	110 ^{ed}	102 ^{f}
60	120 ^{e}	120 ^{e}	124 ^{cde}
121	126 ^{cde}	120 ^{e}	136 ^{bcd}
180	121 ^{ed}	139 ^{bc}	151 ^{ab}
240	125 ^{cde}	156 ^{a}	157 ^{a}
LSD (p = 0.05)		15.8	
s		13.2 (5.8–35)	

LSD = Least Significant Difference at p = 0.05; s = standard deviation expressed as a mean and range within individual treatments. The means marked with the same letter do not differ significantly at p = 0.05.

3.4. Yield-Related Parameters

The number of productive tillers increased significantly ($p < 0.01$), from 1.3 to 3.0, with the increasing rate of blended fertiliser (Table 8). Rhizobium inoculation did not increase the number of productive tillers significantly, because the development stage when additional tillers are generated may have been passed before substantial N_2 fixation occurred. It is quite evident that the increase in productive tillers was conducive to the increase in pods per plant. Rhizobium inoculation did not increase the hundred seed weight, but it was rather modestly increased by the blended fertiliser at application rates of 121–240 kg ha^{-1} (Table 8).

Table 8. Number of productive tillers (NPT), pods per plant (NPP) and hundred seed weight (HSW) influenced by the main effects of the blended fertiliser and the inoculant.

Treatments	NPT	NPP	HSW
Blended fertiliser, kg ha^{-1}			
0	1.3 ^{b}	9 ^{c}	59 ^{c}
60	2.0 ^{b}	10 ^{c}	61 ^{bc}
121	2.0 ^{b}	12 ^{b}	63 ^{ab}
180	3.0 ^{a}	13 ^{ab}	67 ^{a}
240	3.0 ^{a}	14 ^{a}	64 ^{ab}
LSD (p = 0.05)	0.6	1.3	4.3
Inoculant (g ha^{-1})			
0	1.9 ^{b}	11 ^{c}	62 ^{a}
500	2.4 ^{a}	12 ^{a}	63 ^{a}
750	2.1 ^{ab}	13 ^{b}	63 ^{a}
LSD (p = 0.05)	0.5	1.0	3.3
s	0.5	2.5	4.0

LSD = Least Significant Difference at p = 0.05; s = standard deviation expressed as a mean within individual treatments. The mean values within a column marked with the same letter are not significantly different at p = 0.05. The results of the different blended fertiliser rates and inoculant rates were tested separately.

The number of seeds per pod did not increase with the blended chemical fertiliser or the inoculant individually, but it increased significantly only with the combined application of the two highest rates of chemical fertiliser and inoculant (Table 9). Thus, there was a cumulative effect of increased nutrient supply to the plants, including a higher number of productive tillers and pods, which contained more and slightly heavier seeds per pod. These increases are additive, and contributed to a higher yield.

Table 9. Number of seeds per pod at different levels of blended chemical fertiliser and the inoculant.

Blended Fertiliser, kg ha^{-1}	Inoculant, g ha^{-1}		
	0	**500**	**750**
0	2.3 ^{e}	2.7 ^{de}	2.3 ^{e}
60	2.7 ^{de}	3.3 ^{cde}	3.0 ^{de}
121	2.3 ^{e}	3.3 ^{cde}	3.3 ^{cde}
180	2.7 ^{de}	3.7 ^{cd}	4.3 ^{bc}
240	2.3 ^{e}	5.7 ^{a}	5.0 ^{bc}
LSD (p = 0.05)		1.2	
s		0.4 (0–0.6)	

LSD = least significant difference at p = 0.05; s = standard deviation expressed as a mean and range within individual treatments. The means marked with the same letter do not differ significantly at p = 0.05.

3.5. Seed and Straw Yield and Harvest Index

The seed yield (Table 10) was significantly (p < 0.01) affected by the main effects and interaction effects of the blended fertiliser and inoculant amounts (Figures 2 and 3). Blended fertiliser alone increased the yield consistently, by 89%, from the control to the highest level of application, but the effect of inoculation was less consistent. Inoculation at the rate of 500 g ha^{-1} increased the yield by 714 kg ha^{-1}, or 36% on average, compared to the yield obtained at a given level of blended fertilisation without inoculation (Figure 2). This increase can be attributed to the N provided to the plants via symbiotic N_2 fixation. Inoculation alone seemed to produce a similar grain yield as the highest rates of blended fertiliser. The combined use of 180 kg ha^{-1} blended fertiliser and 500–750 g ha^{-1} inoculant gave the maximum seed yield of 3278–3325 kg ha^{-1}, which is around 800–900 kg ha^{-1} more than with solely chemical fertilisation or inoculation.

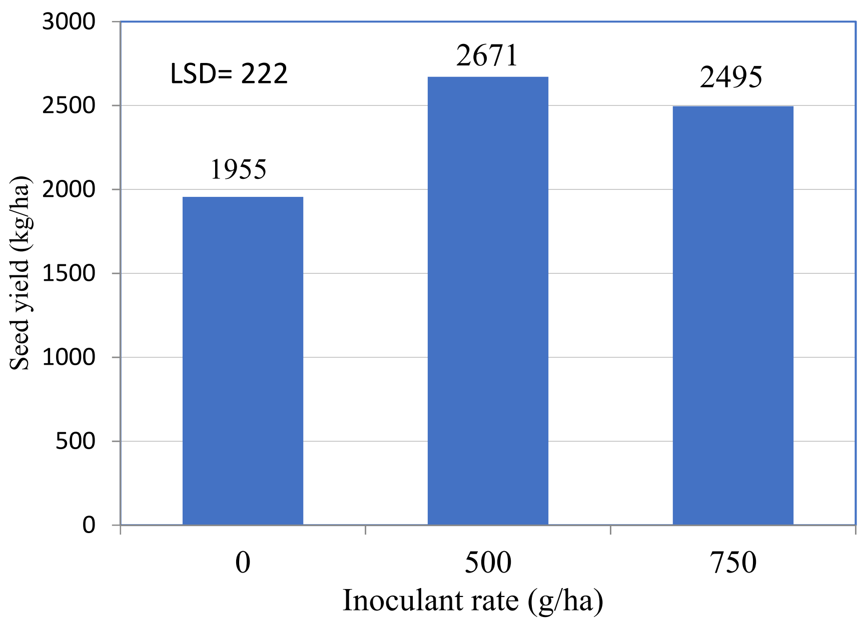

Figure 2. Effect of inoculant rates on seed yield of the faba bean.

Even though the seeds and straw were not analysed for N, we can estimate the effects of the two amendments on the N offtake by the crop, using the typical N concentrations of 3.15% for seeds and 0.82% for straw [41]. Hence, we can calculate that in the control, 69 kg ha^{-1} (28 in straw and 41 in seeds) of N was assimilated, while the yield receiving the maximum rate of blended fertiliser contained 122 kg ha^{-1} (44 in straw and 78 in seeds) of N. The yield of the inoculated plots (500 g ha^{-1}) without the blended chemical fertiliser contained 34 kg ha^{-1} (1 in straw and 33 in seeds) of N more than the control, while the maximum yield (inoculant 500 g ha^{-1} and blended fertilizer) contained 143 kg ha^{-1} (38 in straw and 105 in seeds) of N, which is 28 (−8 in straw and 36 in seeds) kg ha^{-1} of N more than in the plots at the same level of chemical fertiliser but without inoculation. This calculation suggests that inoculation commonly resulted in the accumulation of over 30 kg ha^{-1} of N more than the seed yields from the plots without inoculation.

This finding, regarding the positive effect of chemical fertilisers on grain legume yield, is similar to several earlier findings. It has been established that inoculation along with P fertiliser has had a significant impact on nodulation, shoot dry matter, and grain yield on the faba bean [42]. The application of the P fertiliser and a small amount of N has significantly increased the economic yield of the faba bean [43], and the maximum common bean seed yield (2160 kg ha^{-1}) has been obtained from the utilisation of 23 kg ha^{-1} N [33].

The higher rate of inoculation did not increase yield, with the application of 0 and 60 kg ha^{-1} blended fertiliser, where the number of active nodules was low for unknown reasons, and thus the level of N_2 fixation remained low. The straw yield of the crop ranged from 3.4 to 5.4 t ha $^{-1}$, and significantly ($p < 0.01$) increased with an increase in blended fertiliser; however, the other effects remained insignificant ($p > 0.05$).

Seed yield correlated positively with the days to flowering (= 0.58) and maturity (= 0.53), plant height (= 0.66), number of leaves per plant (= 0.62), productive tillers (= 0.59), pods per plant (= 0.72), and seeds per pod (= 0.55). It also correlated significantly with the total number of nodules (= 0.52), but more closely with the number of effective nodules (= 0.81) (Figure 4), indicating the important role N_2 fixation plays in the N supply to the crop in this experiment. These correlation coefficients suggest that increased vegetative growth, either attained with the help of multi-nutrient chemical fertiliser or biological N_2 fixation, contributes to higher faba bean yield. Almost all components of growth seem to be impacted.

The harvest index (Table 11) was not significantly affected by the use of the blended fertiliser, but it was affected by inoculation. The average harvest index for the inoculation rate of 500 g ha^{-1} (40.0) was significantly higher than that for chemical fertilisation alone (31.9). There were differences in the levels of inoculation (Table 11). Again, at the inoculation rate of 750 g ha^{-1}, the applications of 0 and 60 kg ha^{-1} blended fertiliser differed from the higher application rates, by having lower harvest indices. This result suggests that the increased supply of N, as indicated by the number of active nodules, increases the proportion of seeds.

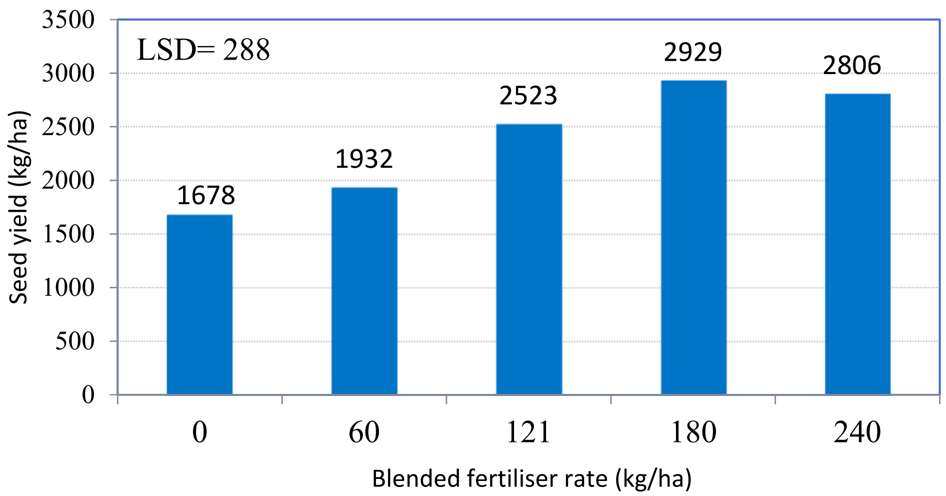

Figure 3. Effect of amounts of blended fertiliser on the faba bean seed yield.

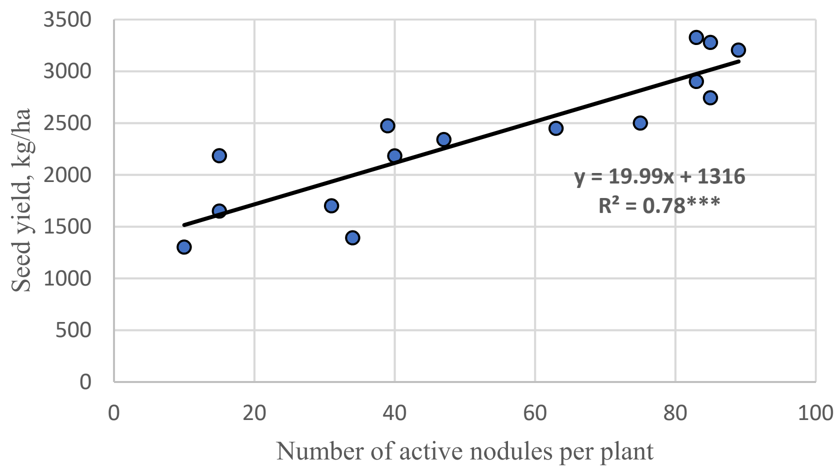

Figure 4. Relationship between the number of active nodules per plant and seed yield.

Table 10. The seed yields of faba bean receiving combed application of blended fertilizer and the inoculant.

Blended Fertilizer Rate	**Inoculant Rate, g ha^{-1}**		
kg ha^{-1}	**0**	**500**	**750**
0	1302 ^{g}	2340 ^{de}	1391 ^{g}
60	1649 ^{g}	2447 ^{cde}	1700 ^{gf}
121	2183 ^{ef}	2499 ^{cde}	2901 ^{abc}
180	2183 ^{e}	3325 ^{a}	3278 ^{a}
240	2473 ^{cde}	2743 ^{bcd}	3203 ^{ab}
LSD (p = 0.05)		498	
s		414 (300–796)	

LSD = Least Significant Difference at p = 0.05; s = standard deviation expressed as a mean and range within individual treatments. The means marked with the same letter do not differ significantly at p = 0.05.

Table 11. Harvest index as affected by combining blended fertiliser and inoculant.

Blended Fertiliser	**Inoculant, g ha^{-1}**		
kg ha^{-1}	**0**	**500**	**750**
0	32 ^{cdef}	40 ^{abcd}	29 ^{fg}
60	29 ^{fg}	40 ^{abc}	25 ^{g}
121	37 ^{abcdef}	37 ^{abcdef}	36 ^{bcdef}
180	30 ^{efg}	45 ^{a}	36 ^{bcdef}
240	31 ^{defg}	38 ^{abcde}	41 ^{ab}
LSD (p = 0.05)		8.5	
s		5.6 (1.7–12.1)	

LSD = Least Significant Difference at p = 0.05; s = standard deviation expressed as a mean and range within individual treatments. The means marked with the same letter do not differ significantly at p = 0.05.

3.6. Economic Analysis

The maximum net benefit of 72,918 birr ha^{-1} (EUR 2232 ha^{-1}), with an acceptable marginal rate of return (MRR) of 28%, was recorded from the combined use of 180 kg ha^{-1} blended fertiliser and 750 g ha^{-1} inoculant, followed by the combined use of 180 kg ha^{-1} blended fertiliser and 500 g ha^{-1} inoculant (72,400 birr ha^{-1}, or EUR 2216 ha^{-1}) (Table 12). The sole application of inoculants presented a lower yield as compared to the combined use of the inoculant with blended fertiliser. Thus, the combined application of 180 kg ha^{-1} blended fertiliser and 500–750 g ha^{-1} inoculant increased the net benefit the most.

Table 12. An economic analysis of the experiment.

SN	Treatmt	USeY	USwY	ASeY	ASwY	SeB	SwB	GB	TVC	NB	MRR
1	0 × 0	1302	3472	1172	3125	28,123	6250	34,373	2448	31,925	
2	0 × 750	1391	3211	1252	2890	30,046	5780	35,825	2706	33,120	5
3	0 × 500	2340	3559	2106	3203	50,544	6406	56,950	3755	53,195	19
4	60 × 0	1649	4167	1484	3750	35,618	7501	43,119	3931	39,188 ^{D}	
5	60 × 750	1700	3646	1530	3281	36,720	6563	43,283	4070	39,213 ^{D}	
6	60 × 500	2447	3646	2202	3281	52,855	6563	59,418	4797	54,621	2
7	121 × 0	2169	4514	1952	4063	46,850	8125	54,976	5512	49,464 ^{D}	
8	121 × 500	2499	3646	2249	3281	53,978	6563	60,541	5768	54,773	1
9	121 × 750	2901	4514	2611	4063	62,662	8125	70,787	6542	64,245	12
10	180 × 0	2183	5643	1965	5079	47,153	10,157	57,310	6751	50,560 ^{D}	
11	180 × 500	3325	4687	2993	4218	71,820	8437	80,257	7857	72,400	7
12	240 × 0	2473	5382	2226	4844	53,417	9688	63,104	7885	55,219 ^{D}	
13	240 × 500	2743	4861	2469	4375	59,249	8750	67,999	8181	59,818 ^{D}	
14	180 × 750	3278	5729	2950	5156	70,805	10,312	81,117	8199	72,918	28
15	240 × 750	3203	4688	2883	4219	69,185	8438	77,623	8706	68,918 ^{D}	

UseY = Unadjusted Seed Yield in kg ha^{-1}; AseY = Adjusted Seed Yield in kg ha^{-1}; USwY = Unadjusted Straw Yield in kg ha^{-1}; ASwY = Adjusted Straw Yield in kg ha^{-1}; SeB = Seed Benefit in birr ha^{-1}; SwB = Straw Benefit in birr/ha; GB = Gross Benefit in birr ha^{-1}; TVC= Total Variable Cost in birr ha^{-1}; ^{D} = Dominated treatment; NB = Net Benefit in birr ha^{-1}; MRR = Marginal Rate of Return in %.

4. Conclusions and Recommendations

Increasing amounts of blended NPSZnB fertiliser and Rhizobium inoculation, applied separately or together, had a significant influence on the yield components of the faba bean. An increase in the size of the photosynthetic machinery of the plant contributed to a higher seed yield. Higher numbers of productive tillers, tallest plants, and more nodules per plant increased the yields of seed, straw, and total biomass, indicating a positive impact of the increased nutrient supply. The seed yield was most closely correlated with the number of active nodules per plant, and there was a synergistic effect of chemical fertilisation and inoculation. Up to a level of 44 kg ha^{-1} N, we did not observe any adverse effect of mineral fertilisation on N_2 fixation. The combined application of 180 kg ha^{-1} blended fertiliser and 500–750 g ha^{-1} inoculants resulted in the highest (3278–3325 kg ha^{-1}) seed yield of the crop, which is approximately 800–900 kg ha^{-1} more than the maximum obtained with chemical fertiliser or inoculation alone. It is obvious that the currently recommended blanket rate of fertilisation is too low to produce the optimum yields of the faba bean. Inoculation increased the N offtake in seeds by approximately more than 30 kg ha^{-1}.

According to the economic analysis, the combined use of blended fertiliser (180 kg ha^{-1}) with 500 or 750 g ha^{-1} inoculant, presented the highest profit (around 73,000 birr ha^{-1}, or EUR 2234 ha^{-1}, respectively), with an acceptable MRR, and they can be recommended for local farmers.

We are aware that these results cover only one experimental year. However, they show the effects of important phenomena of plant physiology. The positive effect of the combined use of moderate applications of chemical fertilisers and Rhizobium inoculation were demonstrated, even though the magnitude of the response can vary from year to year. Further empirical studies are required across locations and over different seasons, to make a comprehensive recommendation.

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