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Nodulation Potential of Annual Sweet Lupins (*Lupinus spp.* L.) and its Effect on Soil Nitrogen and Phosphorus in Acidic Soils of Western Amhara, Ethiopia

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ABSTRACT

In Ethiopia livestock feed shortage and soil acidity are serious problems. In recent years sweet lupins (white and blue species) were introduced as multipurpose crops in the country. However, there is no information about their nodulation potential. This study was conducted to evaluate nodulation potential of these sweet lupins and their effect on nitrogen (N) and phosphorous (P) content of the soil. Seven lupin varieties were evaluated using factorial arrangement (seven varieties * two inoculations) in a randomized complete block design in two locations for two years. The result showed that effect of inoculation and location was not significant ($P > 0.05$) on biomass, seed, nodule number and soil parameters. While the effect of variety was significant ($P < 0.05$) on nodule parameters. Its effect on dry biomass and seed yields was also significant in either of the years. Variety and year had no effect on soil N and P contents. In the first year, blue sweet lupin entries had the highest nodule number per plant, 222 nodules. In the second year similar nodulation performance was observed among species and varieties. Soil N and P were not affected by varieties and inoculation. In addition to their yield advantage, compared to the sweet white entries, blue sweet lupin varieties had high potential in nodulation. Therefore, these introduced sweet blue lupins can be used as multipurpose crops in acidic soils of Ethiopia.

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Introduction

Legumes are very important multipurpose crops. Hence, they are part of different types of farming systems. These crops play a significant role in farming systems through their contribution in nitrogen fixation and serve as human food, livestock feed, source of fuel and for overall soil stability. As global agricultural output is largely dependent on chemical inputs such as nitrogen (N) and will be even more important in the future, such issues related to N fertilizer continue to attract the attention of scientists from many disciplines (Karnez et al., 2013). In addition, in areas where cereal crops are dominant, legumes can serve as disease and pest break crops.

Lupin as a legume crop can fix atmospheric N in to a useable form for the companion or succeeding crop. Studies show that lupin can fix a total of 111 to 300 Kg N/ha (Kalembasa et al., 2020; Sulas et al., 2016; Baylis and Hamblin, 1986; Takunov and Yagovenko, 1999; Reeves et al., 1990). However, only one third to a quarter of this fixed N is left as residue to be used by the succeeding crop (Baylis and Hamblin, 1986). In addition to this lupin has a positive effect on succeeding crop through its effect on enhancing availability of P (Brebaum and Boland, 1995). Phosphorus is one of the essential elements for plant growth and major drivers of world crop production (Korkmaz et al. 2021). Phosphorus is limited for crop yields on about 30% of the world's arable land, and by some estimates, world P resources could be depleted by 2050, hence there is a need to optimize P use efficiency (Korkmaz et al., 2009). According to the reports of Rosetto (1989) lupin planting can increase availability of P by 30 Kg/ha. In cereal-dominated crop rotations, the positive effect of lupins on subsequent cereal crops could be reliably detected up to three years after the lupin crop (Seymour et al. 2012). These results are also very important in terms of phosphorus nutrition of plants in the agricultural production system.

White lupin (*Lupinus albus* L.) is a traditional pulse crop commonly grown in the Northwest part of Ethiopia. Compared to the other traditional pulse crops grown in the area its market value is relatively low (Yeheyis et al., 2010). One of the reasons is its relatively high alkaloid content which makes it less preferred for use in human food and livestock feed (Yeheyis et al., 2011; (Yeheyis et al., 2012a). Especially for livestock feed it is totally unpalatable and poisonous. However, in the traditional lupin growing area bitter white lupin is used as snack after long processing (soaking and washing) in water to get rid of the alkaloid content and bitter taste it has (Yeheyis et al., 2011). In addition to this, it is also used for the preparation of a traditional alcohol known as *Areke*. Regarding the soil fertility maintenance, smallholder farmers use the local white lupin as break crop and green manure in their crop production system (Yeheyis et al., 2010). The ability of the crop to grow in acidic soils of traditionally lupin growing areas of Ethiopia is one of the most important features of the crop (Yeheyis et al., 2010).

In recent years sweet lupins have been introduced to Ethiopia and are found to be adaptive (Yeheyis et al., 2012b; Yeheyis and Wondimeneh, 2022). These introduced sweet lupin varieties are also proved to have high potential to be used as protein supplement in the diets of sheep and had no any palatability problem (Yeheyis et al., 2012c; Ephrem et al., 2015). As the local white lupin is very important crop for soil fertility maintenance in the study area, the soil fertility maintenance potentials/ performance of these new varieties were not evaluated. Hence, this experiment was initiated to evaluate the nodulation capacity of newly introduced annual sweet lupins and their effect on N and P content of acidic soils of Western Amhara.

Materials and Methods

Description of Study Areas

The experiment was conducted in two locations, namely, Durbete (located at 11º 22' 00" N and 36º 57' 00" E) and Debrekelemu (located at 10º 30' 46" N and 37º 37' 10" E) in north-western Ethiopia. The altitude for Durbete is 1997 meters above sea level (masl) and for Debrekelemu is 2512 masl. According to the FAO classification of soil types in Ethiopia (1984) the soil type for both study sites is Nitisols. According to the information obtained from the specific study sites' office of agriculture the soil pH at Durbete and Debrekelemu was 5.3 and 4.8, respectively. The total mean annual rainfall (mm) from a ten year data at Durbete and Debrekelemu is 1189 and 2348, respectively.

Planting and Experimental Design

For the experiment a total of seven lupin varieties from two species (*L. albus and L. angustifolius*) were used. The varieties used were white lupin varieties (Local Landrace, Feodora, Dieta, and Energy) and blue lupin varieties (Bora, Sanabor, and Vitabor). Except for the white Local Landrace, the remaining six varieties were sweet varieties. The white Local Landrace was included as a local check and seed was purchased from *Merawi* local market. Sweet blue lupin seeds used in these experiments were produced in Ethiopia in 2017, while the sweet white lupin varieties were brought directly from Europe. This experiment was carried out during the main cropping seasons of 2018 and 2019. In the 2018 season the two white entries, Local Landrace and Dieta, were not included. The design used was a 2x7 factorial arrangement in a randomized complete block design (RCBD) with three replications at both testing sites. The factors were Brady rhizobium strain inoculum "Holetta A14" (with and without inoculum) and the seven varieties. For the application of the inoculum, a sugar solution was prepared as a sticker of the inoculum on the seed. The solution was prepared with a ratio of 100ml to 10g of water and sugar. To prepare the slurry, 100 g of inoculum was mixed with 150 ml of the sugar solution. Finally, the seed was mixed with the slurry thoroughly before planting. The plot size was 1.2*4 m. The spacing was 7 cm between plants and 30 cm between rows. In both testing sites, for both years, planting was done by hand in the first week of July on a well-prepared seed bed. Fertilizer (NPS) was applied at the rate of 100 kg/ha once during planting. The calculated amount of fertilizer for a specific plot area was spread on the plot and mixed with the top soil by hand just before lupin planting. Manual weeding was carried out twice at seedling stage.

Sampling, Sample Processing and Data Collection

For the sample, each plot was divided into half with an effective plot size of 1.2 m *2 m. One half was used for dry matter sampling and the other for seed sampling. Dry matter sampling was done when the plants reached around 50% flowering stage and seed sampling at maturity. In both cases the sampling was done from the middle two rows excluding the border rows. Immediately after sampling, the fresh biomass yield was weighed for estimation of green biomass yield. Dry matter samples were dried in a forced air oven at 65ºC until constant weight for dry matter (DM) determination. The seed samples were air dried until constant weight for seed yield data estimation. Nodule count data was done when the plants reached 50% flowering stage. Five representative plant samples were randomly selected from the border rows and carefully uprooted by shovel and the soils attached to the roots were washed with water to detach the soil from the root to count the nodules. Total nodules from each plant were counted and average was recorded as total number of nodules per plant. In addition, the nodules were dissected using nodule dissecting knife to record the number of effective and non-effective nodules per plant. Red or pink nodules were recorded as effective nodules while white, gray or green nodules were recorded as non-effective nodules. Disturbed soil samples were collected from 0-20 cm depth just before planting and after harvesting using an auger from each experimental plot, bagged, labeled and transported to the soil laboratory.

Soil Sample Preparation and Analysis

The soil samples were air dried, crushed and passed through a 2 mm sieve for the determination of available P and 0.5 mm sieve for the determination of N following standard laboratory procedures (Van Reeuwijk and Carbonate, 2002).N was determined by Kjeldahl digestion, distillation and titration method (Bremner and Mulvaney, 1982) and available phosphorus was determined using spectrophotometer following the Olsen extraction method (Olsen, 1954).

Data Analysis

The collected data was subjected to analysis of variance using the General Linear Model procedure as implemented in SAS version 9.2.2 (2019). The mean separation was done using Duncan Multiple Range Test.

Results and discussion

Despite the variation in altitude and rainfall between the study sites, Durbete and Debrekelemu, the data analysis result showed that there was no statistically significant interaction effect ($P > 0.05$) for independent variables (Location, Variety and Inoculation), which necessitated a combined data analysis for both study sites for each year separately. Because number of plants per plot was statistically significant ($P<0.05$), during the statistical analysis this variable was used as a covariate variable. Two varieties, white Local and the variety sweet white Dieta, were not planted in the first year and this could be one of the limitations of the experiment.

Effective and Total Nodule Number

The mean number of effective, non-effective and total nodules per plant is shown in Table 1. All nodulation parameters among varieties were significantly different ($P < 0.05$) in both years. In the first year mean number of effective nodules per plant ranged between 4 and 201 with an overall mean value of 119. The highest mean number of effective nodules per plant was observed from blue Vitabor and the lowest from white Feodora. In the second year the mean number of effective nodules per plant ranged between 51 and 102 with an overall mean value of 79. The highest mean number of effective nodules per plant was observed from white entries (Local, Energy and Dieta) and the lowest from white Feodora. However, the mean number of effective nodules per plant in the second year of all the three blue entries was not statistically significantly different ($P > 0.05$) from the white entries with the highest number of effective nodules. This indicates that sweet blue entries have higher N fixing potential than white lupin (Schulze et al., 1999). The same authors reported that the higher N fixation potential in blue lupin is associated with its ability to undertake high and lasting N fixation after flowering, whereas in white lupin N fixation usually ceases early after the onset of pod filling.

The mean number of non-effective nodules per plant observed in this study is very small in number compared to the mean number of effective nodules. In the first year mean number of non-effective nodules per plant ranged between 0.67 and 14.83 with an overall mean value of 5.75. The highest mean number of non-effective nodules was observed from white Feodora and the lowest from blue Vitabor. In the second year, mean number of non-effective nodule ranged between 1.67 and 15.00 with an overall mean value of 4.31. The highest mean number of non-effective nodules was observed from white Local and the lowest from blue entries (Sanabor and Vitabor). In both experimental years, higher number of non-effective nodules was observed from white entries than the blue entries. This shows that the recently introduced sweet blue lupin varieties are not only good in forming relatively high numbers of nodules but also are good in maintaining the produced nodules as being effective nodules.

Mean total number of nodules is the sum of effective and non-effective nodules. As a result in the first year the highest mean total nodule number was observed from blue Vitabor (222.17) and the lowest was from white Feodora (57.33) with overall mean value of 124.47. In the second year the highest mean total nodule number was observed from white Local (107) and the lowest was from white Feodora (55.67) with overall mean value of 83.73. The highest total number of nodules per plant observed in this study (222.17) is much higher than the total number of nodules per plant (68.53) reported from common bean (*Phaseolus vulgaris* L.) (Nuru Seid Tehulie, 2020a) and the total number of nodules per plant (26.10) reported for Mung bean (*Vigna radiata* (L.) Wilczek) (Nuru Seid Tehulie, 2020b). The highest nodule number observed in lupin could be due to the inherent nature of the crop as a high potential crop for soil fertility maintenance through its high potential in nodule formation. The overall mean values of nodules in the first year are higher than in the second year, which could be associated with specific site differences in which the experimental plots were laid across years. However, the observed overall nodulation performance of the sweet entries gave us an answer for the question whether the newly introduced sweet lupin varieties have similar capacity to that of the local bitter white lupin in inducing nodulation so that they can be used for soil fertility maintenance. The mean number of effective and total nodules recorded from the blue entries is either similar or higher than the white entries in both years. This induced nodulation by sweet lupin entries especially by sweet blue entries depicts that the recently introduced sweet lupin varieties in Ethiopia have a potential for soil fertility maintenance and/or improvement. The percent effective nodules out of the recorded total nodules during the first year range from 76.27 to 99.67% (95.4% average) whereas during the second year from 79.95% to 97.78% (94.85% average). This implies that the inoculated Brady rhizobium strain that infects the lupin varieties could withstand the severe soil acidity (with optimal pH from 5.0-5.5 and negatively affected if the pH is above 6) (Tang and Robson, 1993). The trend in the number of effective nodules in both years was similar (Table 1). Inoculation with *Brady rhizobium* did not show significant difference in number of total and effective nodules for each variety in both years. This indicates that, the exotic strain might have poorly performed compared to the native strain/s because the number of total and effective nodules in the un-inoculated plots was relatively higher or at par with the inoculated plots of the same variety. This could be attributed to poor competing ability of the exotic strain with the indigenous/native strain, the same inoculant might have been introduced to the farms before the experiment period and due to poor strain management from production to field inoculation.

Moreover, the introduced lupin varieties formed good association with the indigenous strain and performed well in the strongly acidic soil environment with equivalent or relatively higher number of total and effective nodules (Table 1). Therefore, these varieties can be used as an alternative rotation and cover /green manuring crop to replenish the highly depleted soil fertility of the study areas. Other pulse crops which were used as break crops for cereals were out of production before four to five decades and replaced by unimportant crops due to severe soil acidity as supported by Evans et al. (1990). The local lupin variety was the only pulse crop grown in these areas. Hence, the introduction of sweet lupin varieties is the best option to improve the soil fertility status of highly acidic areas of western Amhara and similar areas.

Dry Matter and Seed Yield

The mean dry matter yield and seed yield for the different varieties and for the two years are shown in Table 1. The differences in dry matter yield were statistically significant ($P < 0.05$) in the first year but not in the second year. This could be associated with the inclusion of the two new white entries (Dieta and Local) in the second year which showed relatively good dry matter yield and compensated for the lower dry matter yield performance of the other two white entries. In the first year, all blue entries performed well above average compared to the two white entries. The dry matter yield from blue entries ranged between 2.7 and 3.6 t/ha with Sanabor being the highest yielder with 3.6 t/ha. In the second year dry matter yield was not affected by variety ($P>0.05$) ranging between 1.5 and 3.1 t/ha. The relatively higher dry matter yield performance observed in blue entries has a positive relationship with the overall mean number of nodules per plant observed in blue entries. According to the results of Abd-Alla (1999) the increase in nodulation has a positive effect in dry matter production and overall plant N yield (in the herbage and seed) in lupin.

The overall relatively lower dry matter yield observed from sweet white entries in both years is due to the anthracnose and fusarium observed on these entries which had partially defoliated and dried the leaves of the plants. In addition to this, the incidence of anthracnose and fusarium during the vegetative growth stage of sweet white entries in both years could have also affected further root development and hence nodule formation. As a result, the nodule formation performance of the white entries was not as expected as the bitter white lupin is indigenous in the study areas. According to the results of Aktar and Matsubara (2013) the incidence of fusarium wilt and anthracnose in cyclamen plant had significantly reduced the dry weight of shoots and roots.

Though there was significant difference among treatments ($P<0.05$) in seed yield in the second year, varieties blue Sanabor, blue Vitabor and white Local gave similar seed yield ranging between 2.6-2.9 t/ha. In the first year, seed yield was not affected by variety ($P>0.05$) ranging between 2.7 and 3.3 t/ha.

In both years among all white entries the only entry that gave seed yield was the bitter white Local landrace. In the first year the two sweet white entries (Energy and Feodora) and in the second year the three sweet white entries (Energy, Feodora and Dieta) did not give harvestable yield because all the sweet white entries were dried immediately after flowering due to anthracnose and fusarium. However, all the three sweet blue entries were healthy until seed harvest. This depicts that the blue entries have a reasonable tolerance to anthracnose and fusarium as compared to the introduced sweet white entries. Yeheyis et al. (2012b) reported similar result in which introduced sweet blue lupins were superior in seed yield and disease tolerance when the adaptability of these varieties was evaluated in the Acrisol and Nitisol of the Northwestern Amhara region, Ethiopia.

Table 1. Mean number of nodules per plant, dry matter yield and seed yield from a two year trial of four white and three blue annual lupin varieties at two location (Durbete and Debrekelemu), Ethiopia

Treatment	EN		NEN		TN		DMY (t/ha)		SY (t/ha)	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
WLEWI	79.50^{cd}	100.50^{a}	8.50^{abc}	4.17^{b}	88.00^{de}	104.67^{ab}	1.5^{cd}	2.3	†	†
WLFWI	47.67^{d}	50.50^{c}	14.83^{a}	5.17^{b}	62.50^{e}	55.67^{c}	1.6^{cd}	1.9	†	†
BLSWI	151.00^{b}	70.17^{abc}	3.50^{bc}	2.50^{b}	154.50^{bc}	72.67^{abc}	3.1^{ab}	2.3	3.3	2.7^{a}
BLVWI	221.33^{a}	73.17^{abc}	0.83^{c}	1.67^{b}	222.17^{a}	74.83^{abc}	3.0^{ab}	2.5	2.7	2.6^{a}
BLBWI	119.67^{bc}	93.33^{ab}	2.17^{bc}	4.17^{b}	121.83^{cd}	97.50^{ab}	3.3^{ab}	3.1	3.2	2.3^{b}
WLDWI	⁎	88.33^{ab}	⁎	4.00^{b}	⁎	92.33^{ab}	⁎	1.8	⁎	†
WLL	⁎	101.83^{a}	⁎	5.17^{b}	⁎	107.00^{a}	⁎	3.0	⁎	2.9^{a}
WLEI	88.50^{cd}	89.33^{ab}	10.00^{ab}	3.00^{b}	98.50^{de}	92.33^{ab}	2.2^{bc}	2.5	†	†
WLFI	43.50^{d}	54.00^{c}	13.83^{a}	3.00^{b}	57.33^{e}	57.00^{c}	0.9^{d}	2.0	†	†
BLSI	110.00^{bc}	70.00^{abc}	2.00^{bc}	1.67^{b}	112.00^{cd}	71.67^{bc}	3.6^{a}	2.6	2.7	2.5^{a}
BLVI	200.67^{a}	75.83^{ab}	0.67^{c}	2.67^{b}	201.33^{ab}	78.50^{abc}	2.7^{abc}	2.4	2.7	2.0^{b}
BLBI	125.33^{bc}	88.33^{ab}	1.17^{c}	4.33^{b}	126.50^{cd}	92.67^{ab}	3.1^{ab}	2.5	2.8	1.2^{c}
WLDI	⁎	96.67^{a}	⁎	3.83^{b}	⁎	100.50^{ab}	⁎	1.5	⁎	†
WLLI	⁎	59.83^{bc}	⁎	15.00^{a}	⁎	74.83^{abc}	⁎	2.3	⁎	1.8^{bc}
Mean	118.72	79.42	5.75	4.31	124.47	83.73	2.5	2.4	2.9	2.3
CV (%)	24.65	17.24	21.09	35.82	22.52	26.13	11.3	33.1	20.7	20.7
P value	0.0000	0.0340	0.0011	0.0482	0.0000	0.0452	0.002	0.943	0.904	0.015

WLEWI: White Lupin, Energy without inoculum;	WLEI: White Lupin, Energy with inoculum
WLFWI: White Lupin, Feodora without inoculum	WLFI: White Lupin, Feodora with inoculum
BLSWI: Blue Lupin, Sanabor without inoculum	BLSI: Blue Lupin, Sanabor with inoculum
BLVWI: Blue Lupin, Vitabor without inoculum	BLVI: Blue Lupin, Vitabor with inoculum
BLBWI: Blue Lupin, Bora without inoculum	BLBI: Blue Lupin, Bora with inoculum
WLDWI: White Lupin, Dieta without inoculum	WLDI: White Lupin, Dieta with inoculum
WLL: White Lupin, Local without inoculum	WLLI: White Lupin, Local with inoculum

Means within a column having different superscripts are significantly different EN= Effective nodules; NEN= non-effective nodules; TN= total nodules; DMY= dry matter yield; SY= seed yield; CV= coefficient of variation; ⁎= not planted; †=No yield data

Table 2. Mean Nitrogen (N) and available Phosphorus (P) contents for soil under different lupin varieties at Durbete and Debrekelemu, Ethiopia

Treatment	N (%)				P (ppm)			
	Year 1		Year 2		Year 1		Year 2	
	At Planting	At Harvest	At Planting	At Harvest	At Planting	At Harvest	At Planting	At Harvest
WLEWI	0.223	0.188	0.228	0.222	1.088	1.603	4.596	6.616
WLFWI	0.200	0.180	0.176	0.213	0.906	1.827	3.615	5.735
BLSWI	0.240	0.166	0.226	0.325	0.748	1.926	4.080	6.980
BLVWI	0.183	0.185	0.208	0.230	0.975	1.906	4.331	6.573
BLBWI	0.183	0.172	0.207	0.305	1.088	1.936	4.081	6.723
WLDWI	*	*	0.216	0.226	*	*	3.783	6.070
WLL	*	*	0.191	0.226	*	*	3.501	5.441
WLEI	0.181	0.182	0.163	0.222	1.338	1.886	4.028	6.290
WLFI	0.256	0.175	0.208	0.213	0.935	1.733	4.038	6.215
BLSI	0.203	0.183	0.215	0.236	0.937	1.758	3.735	5.996
BLVI	0.238	0.216	0.185	0.225	0.975	1.430	4.260	7.375
BLBI	0.188	0.208	0.182	0.221	1.245	1.733	3.505	6.603
WLDI	*	*	0.228	0.228	*	*	4.372	6.620
WLLI	*	*	0.265	0.230	*	*	4.311	6.420
Mean	0.209	0.186	0.207	0.237	1.023	1.774	4.017	6.404
SE	0.009	0.005	0.006	0.007	0.057	0.071	0.118	0.264
CV (%)	32.6	25.1	27.8	27.0	42.2	32.4	27.3	40.7
P value	0.4916	0.7387	0.3073	0.0969	0.5828	0.8936	0.8873	0.998

WLEWI: White Lupin, Energy without inoculum;	WLEI: White Lupin, Energy with inoculum
WLFWI: White Lupin, Feodora without inoculum	WLFI: White Lupin, Feodora with inoculum
BLSWI: Blue Lupin, Sanabor without inoculum	BLSI: Blue Lupin, Sanabor with inoculum
BLVWI: Blue Lupin, Vitabor without inoculum	BLVI: Blue Lupin, Vitabor with inoculum
BLBWI: Blue Lupin, Bora without inoculum	BLBI: Blue Lupin, Bora with inoculum
WLDWI: White Lupin, Dieta without inoculum	WLDI: White Lupin, Dieta with inoculum
WLL: White Lupin, Local without inoculum	WLLI: White Lupin, Local with inoculum

N= Nitrogen; P= Phosphorous; CV= coefficient of variation; SE= standard error; *= not planted

Nitrogen and available Phosphorous contents

The mean N and available P contents of soils of the study sites at planting and at harvesting for both years and locations is shown in Table 2. There was no significant difference in N content among the soil samples under different lupine varieties in both years before planting and after harvesting with inconsistent trend in N content against years and varieties. However, during the second year, the N content at harvesting was relatively better than at planting probably due to difference in the soil fertility status. The non-significant difference in soil N among the lupin verities indicated that the newly introduced lupin varieties can replace the local lupin variety and be used as cover crop/green manure/ on acidic soils to replenish the soil fertility. The result is in agreement with Sulas et al. (2016) who reported that lupin can fix atmospheric N up to 300 kg ha^{-1} with the content differed with the plant parts. They further explained that the higher total N content (57% of N) was recorded for the grain while the lowest N content (5%) was for the root. Hence, the differences in soil total N content might be attributed to the maximum extraction of the plant parts for food and other competitive uses. In addition, the newly introduced lupin varieties can be used as an alternative rotation/cover crop/green manure as aforementioned. Unlike the local variety which is unpalatable to livestock, the newly introduced sweet blue lupin varieties can be used as feed for livestock (Yeheyis et al., 2012c). Based on the classification of Landon (1991) the soil total N content is categorized under low to medium range.

Though there was no significant difference in available P content among the soil samples under different lupin varieties, there was an increasing trend at harvesting than at planting. There was also relatively higher available P in the second year than the first year (Table 2). The relatively higher available P content at harvest than at planting might be attributed to the peculiar nature of the crop. Lupin has natural adaptation for enhanced P acquisition and utilization (Vance et al., 2003). It developed a number of traits to enhance P-acquisition, including increment in root surface area, cluster root and root hair proliferation and exudation of organic acids and acid phosphatases from the roots which solubilize the bound P and increased P availability in the soil (Basic, 2015; Lamont, 2003). The overall difference in available P content in the first year might be due to the soil fertility difference of the experimental plots. Based on Landon (1991) classification, the available P content of the soils of the experimental sites was in low to very low range.

Conclusions

As sweet blue lupin varieties are recently introduced to Ethiopia the quest for the new varieties to serve for soil fertility maintenance through atmospheric N fixation like the local bitter white lupin was unanswered. According to the results of this study application of inoculum had no effect on nodulation and measured yield parameters which could be associated with either availability of enough rhizobia in the soil or poor quality of the inoculum used.

The mean number of effective and total nodule recorded from the blue entries is either similar or higher than the white entries in both years. This induced nodulation by sweet lupin entries especially by sweet blue entries depicts that the recently introduced sweet lupin varieties in Ethiopia have a potential for soil fertility maintenance and/or improvement. In addition to this, the results of this study showed that N and available P were not affected by the cultivation of these local and introduced sweet lupin varieties. As sweet lupins are palatable to livestock, the overall relatively good yield and soil fertility maintenance performance of sweet lupins in this kind of acidic soils is an added advantage. The present study didn't answer detailed N and P supply by these varieties except evaluating the N and P contents of the soil under these crops. Hence, further study on N and P uptake and beyond is recommended.

Competing interests

The authors declare that they have no competing interests

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References

Abd-Alla MH. 1999. Nodulation and nitrogen fixation of Lupinus species with Brady rhizobium (lupin) strains in iron-deficient soil. Biol Fertil Soils, 28: 407–415.

Aktar MM, Matsubara Y. 2013. Tolerance to Fusarium wilt and anthracnose diseases and changes of anti-oxidative activity in mycorrhizal cyclamen. Crop Protection, 47:41-48.

Basic D. 2015. Phosphorus uptake and utilization efficiency in cluster root and non-cluster root forming species of the Core Cape Subregion, South Africa. MSc Thesis, pp. 109.

Baylis JM, Hamblin J. 1986. Lupins in the farming system: A survey of production. In: Proceedings of the Fourth Internation Lupin Conference. Geraldton, Western Australia, August 15-22, pp. 161-172.

Brebaum S, Boland GJ. 1995. Sweet white lupin: A potential crop for Ontario. Canadian Journal of Plant Science, 1;75(4):841-9.

Bremner J, Mulvaney C. 1982. Nitrogen-total. In "Methods of soil analysis. Part 2. Chemical and Micro-biological properties". (Eds AL Page, RH Miller, DR Keeney), Soil Science Society of America: Madison, WI, USA, pp. 595–624.

Ephrem N, Tegegne F, Mekuriaw Y, Yeheyis L. 2015. Nutrient intake, digestibility and growth performance of Washera lambs supplemented with graded levels of sweet blue lupin (Lupinus angustifolius L.) seed. Small Ruminant Research, 130:101-107.

Evans J, Dear B, O'Connor G. 1990. Influence of an acid soil on the herbage yield and nodulation of five annual pasture legumes. Australian Journal of Experimental Agriculture, 30 (1):55-60, doi: 10.1071/EA9900055.

FAO. 1984. Soil map of Ethiopia. https://data.apps.fao.org/map/catalog/static/search?

Kalembasa S, Szukała J, Faligowska A, Kalembasa D, Symanowicz B, Becher M, Gebus-Czupyt B. 2020. Quantification of Biologically Fixed Nitrogen by White Lupin (Lupins albus L.) and Its Subsequent Uptake by Winter Wheat Using the ^{15}N Isotope Dilution Method. *Agronomy* 2020, *10*, 1392. https://doi.org/10.3390/agronomy10091392

Karnez E, İbrikci H, Cetin M, Ryan J, Dingil M, Oztekin E, Korkmaz K. 2013. Implications of profile mineral nitrogen in an irrigated project area of southern Turkey. Communications in soil science and plant analysis, 44(1-4), 783-793.

Korkmaz K, Akgün M, Özcan M M, Özkutlu F, Kara Ş M. 2021. Interaction effects of phosphorus (P) and zinc (Zn) on dry matter, concentration and uptake of P and Zn in chia. Journal of Plant Nutrition, 44(5), 755-764.

Korkmaz K, Ibrikci H, Karnez E, Buyuk G, Ryan J, Ulger A C, Oguz H. 2009. Phosphorus Use Efficiency of Wheat Genotypes Grown in Calcareous Soils. Journal of Plant Nutrition, 32:12, 2094-2106. https://doi.org/10.1080/01904160903308176

Lamont BB. 2003. Structure, ecology and physiology of root clusters A review. Plant and Soil, 248 (1): 1–9.

Landon JR. 1991. Booker tropical soil manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Longman Scientific and Technical, Essex, New York, pp 474.

Nuru Seid Tehulie. 2020a. Effect of Blended NPS Fertilizer and Rhizobium Inoculation on Yield Components and Yield of Common Bean (Phaseolus Vulgaris L.) Varieties at Mekdela District, South Wollo, Ethiopia. Academic Journal of Research and Scientific Publishing, 2 (18).

Nuru Seid Tehulie. 2020b. Effects of NPS Fertilizer Rates on Growth, Yield and Yield Components of Mungbean [Vigna radiata (L.) Wilczek] Varieties under Irrigation at Gewane, Northeastern Ethiopia. International Journal of Research in Agricultural Sciences, 7 (5).

Olsen SR. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture.

Reeves DW, Touchton JT, Kingery RC. 1990. The use of lupin in sustainable agriculture systems in the southern coastal plain. Abstracts of technical papers, No. 17, Southern Branch ASA, Little Rock AR, 1990 February 9.

Rosetto G. 1989. Lupin production and processing study. Agrimed Research Program. In Proceedings of the Joint CEC-NCRD Workshop. Israel, 216 pp. 70-76.

SAS, Statistical Analysis System Version 9.2.2, 2019. SAS Institute, Inc., Cary, NC, USA, 2004.

Schulze J, Beschow H, Merbach W. 1999. Nitrogen fixation in blue and white lupin during pod filling. In: E. van Santen, M. Wink, S. Weissmann and P. Roemer (Eds.). Lupin, an ancient crop for the new mellenium. Proceedings of the 9th International Lupin Conference, Klink/Muritz, 20-24 June, International Lupin Association, Canterbury, New Zealand, ISBN 0-86476-123-6, 1999, pp. 246-248.

Seymour M, Kirkegaard J A, Peoples M B, White PF, French R J. 2012. Break-crop benefits to wheat in Western Australia – insights from over three decades of research. Crop and Pasture Science 63:1-16

Sulas L, Canu S, Ledda L, Carroni AM, Salis M. 2016. Yield and nitrogen fixation potential from white lupine grown in rainfed Mediterranean environments. Scientia Agricola, 73, 338-346.

Takunov IP, Yagovenko LL. 1999. Yellow lupin (Lupinus luteus L.) as a green manure crop preceding winter rye (Secale cereale L.). In: E. van Santen, M. Wink, S. Weissmann and P. Roemer (Eds.). Lupin, an ancient crop for the new mellenium. Proceedings of the 9th International Lupin Conference, Klink/Muritz. International Lupin Association, Canterbury, New Zealand, ISBN 0-86476-123-6, pp.434-437.

Tang C, Robson AD. 1993. PH above 6.0 reduces nodulation in Lupinus species. Plant and Soil, 152 (2): 269-76.

Van Reeuwijk L, Carbonate P. 2002. Procedures for soil analysis, 6th edition. International Soil Reference and Information Centre, Wageningen, The Netherlands, pp. 7–8.

Vance CP, Uhde-Stone C, Allan DL. 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytologist, 157: 432–449.

Yeheyis L, Kijora C, Melaku S, Girma A, Peters KJ. 2010. White lupin (Lupinus albus L.), the neglected multipurpose crop: Its production and utilization in the mixed crop-livestock farming system of Ethiopia. Livestock Research for Rural Development, 22 (74):1-12.

Yeheyis L, Kijora C, Tegegne F, Peters KJ. 2012c. Sweet Blue Lupin (Lupinus angustifolius L.) Seed as a Substitute for Concentrate Mix Supplement in the Diets of Yearling Washera Rams Fed on Natural Pasture Hay as Basal Diet in Ethiopia. Tropical Animal Health and Production, 44:1255-1261.

Yeheyis L, Kijora C, van Santen E, Peters KJ. 2012b. Sweet Annual Lupins (Lupinus spp.); Their Adaptability and Productivity in Different Agro-ecological Zones of Ethiopia. Journal of Animal Science Advances, 2 (2); 201-215.

Yeheyis L, Kijora C, van Santen E, Wink M, Peters KJ. 2012a. Crude Protein, Amino Acid and Alkaloid Content of Annual Sweet Lupin (Lupinus spp. L.) Forages and Seeds Grown in Ethiopia. Experimental Agriculture, 48 (3):414-427.

Yeheyis L, Kijora C, Wink M, Peters KJ. 2011. Effect of a traditional processing method on the chemical composition of local white lupin (Lupinus albus L.) seed in North-Western Ethiopia. Zeitschrift für Naturforschung. Section C, Biosciences, 66 (7/8):403-8.

Yeheyis L, Mekonnen W. 2022. New sweet blue lupin, *Lupinus angustifolius* L. varieties (Sanabor and Vitabor) for Ethiopia. Ethiop. J. Sci. & Technol., 15 (1): 67-80.