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Exploring the potential of domesticating lupins in Punjab, Pakistan

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Abstract

Studies on domestication of lupins have been lacking under agro-climatic conditions prevailing in the Indo-Gangetic Plains. To evaluate the potential of cultivating different Lupinus species/cultivars in Pakistan, a study was conducted in an alkaline calcareous soil under irrigated field conditions at Faisalabad. Maximum shoot biomass and grain yields were recorded in white lupin. Yellow and blue lupins though grew well up to flowering stage but failed to produce seed. Proteoid roots were observed in white and yellow lupins, whereas none of the tested species/cultivars produced root nodules. While the grain component of five cultivars of white lupins showed similar contents of protein and carbohydrates, cultivars significantly differed with respect to contents of seed coat, oil and micronutrients. Results suggested that white lupin (but not yellow and blue lupins) has the potential for domestication as a high-protein alternate grain legume crop in Pakistan, producing much higher grain yield as compared to some conventional grain legumes.

Keywords: *Calcareous soils, Indo-Gangetic plains, lupinus albus, lupinus luteus, lupinus angustifolius*

Introduction

The genus *Lupinus* comprises over 300 species of which only four have been domesticated. These include three 'Old World' species originating from the Mediterranean *viz. L. albus* L. (white lupin), *L. luteus* L. (yellow lupin) and *L. angustifolius* L. (blue or narrow-leaved lupin), and one "New World" species *viz. L. mutabilis* Sweet (Pearl lupin, Andean lupin or Tarwi) that belongs to South America (Yorgancilar *et al*., 2009). The major genetic improvements that lead to domestication of lupins included soft seed, non-shattering pods and low alkaloid content in seed (Blade *et al*., 2004). In contrast to bitter lupin varieties, which contain high alkaloid content (0.8-0.9%), sweet varieties contain low alkaloid content (0.01-0.03%) and thus are edible for both human and animals (Gill and Vear, 1980). Australia is the leading grower of lupins, producing over one million tons annum^{-1}, 75% of which is exported into international markets, whereas a substantial domestic market has also developed within Australia (Blade *et al*., 2004).

Next to soybean, lupins excel by protein content of up to 40% in the seed with higher protein value, and unlike beans, can successfully be fed to non-ruminants (Crowley, 2001). While major protein components in lupin seed are globulins, the amino acid profile is comparable to that of soybean thus providing most essential amino acids (Kyle, 1994). The lipid content of lupins is generally higher than that of cereals and other pulses but lower than in the oil-seed crops; the content may range from 7.6–11.8% for white lupin, 5.2–6.1% for yellow lupin and 4.9−7.0% for blue lupin (Petterson *et al*., 1997; Woods and Fearon, 2009). Due to relatively lower oil content, lupin meal does not have to be de-oiled as required for some soy-based processes. White and yellow lupins possess higher content of linolenic acid than blue lupin, whereas white lupin contains lower linoleic acid than yellow and blue lupins. The fatty acid profile of lupin seed also has excellent emollient properties for cosmetic industry (Blade *et al*., 2004). Besides, compared to soybean, lupins contain lesser levels of anti-nutritional factors like phytic acid, saponins, lectins, and trypsin inhibitors (Kyle, 1994; Petterson and Fairbrother, 1996). Therefore, raw lupins do not require extensive processing to inactivate the undesirable lectins and protease inhibitors before incorporating into feeds (Brebaum and Boland, 1995). Lupin seeds can be used as a protein-rich raw material for feed or in feeding mixtures for all categories of farm animals including ruminants (Emile *et al*., 1988), poultry (Suchý *et al*., 2010), and aquaculture (Sudaryono *et al*., 1999). Regarding nutritive value for human, lupins are considered at par with soybeans-based foods like tempo, miso, tofu, bread, cakes and pasta (Petterson and Fairbrother, 1996).

In addition to nitrogen fixation, a unique feature of white and yellow lupins grown in P-deficient soils is the formation of proteoid or cluster roots that secrete large amounts of citric and malic acids, which mobilize the sparingly soluble P from Ca-, Al-, and Fe-P and from P-adsorbed on Fe/Al humic complexes (Neumann *et al*., 2000). Particularly, white lupin is highly efficient with respect to P uptake from sparingly available sources of soil P as the amount of citric acid exuded may be as high as

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23% of the acquired carbon (Marschner, 1995). Besides, depending on species/cultivars, lupins are well adapted to diverse climatic conditions and to alkaline as well as poor acid soils. Therefore, lupins have great potential as an economic crop for marginal lands. Lupins can also play a key role in organic agriculture and livestock by improving soil fertility and providing high protein forage alternative to soybean thus reducing the risk of GMO contamination in the food chain (Hall *et al*., 2003). Lupins and lupin bi-crops with cereals have great potential as whole-crop forage for sustainable livestock production in an organic situation (Azo *et al*., 2006).

Cultivated species of lupins (*L. albus*, *L. luteus*, and *L. angustifolius*) have narrow adaptation with respect to soil type. The optimal pH for the growth of lupins is between 5 and 6, whereas the grain as well as biomass yields are depressed in alkaline calcareous soils (Tang and Thomson, 1996; Jayasundara *et al*., 1998; Liu and Tang, 1999). Although growth of lupins may be directly affected by Ca^{2+} (Jayasundara *et al*., 1998), negative effects of lime are mainly indirect, viz. through precipitation of organic acids secreted by roots to mobilize and uptake P and Fe (Dinkelaker *et al*., 1989) and through inhibition of Fe uptake by HCO_3^- (lime-induced chlorosis; Tang and Thomson, 1996). Although lupins have great potential as an economic crop due to its adaptation to infertile lands under diverse agroclimatic conditions, little is known about prospects of lupin cultivation in the Indo-Gangetic Plains of South Asia. There has been only one preliminary study conducted in the upper Punjab, Pakistan which has indicated that *L. albus*, *L. angustifolius* and *L. mutabilis* can be successfully grown under rain-fed conditions with supplemental irrigations (Chaudhary and Cheema, 1998). The present study was conducted to compare the potential of different cultivars of white, yellow and blue lupins grown in an alkaline calcareous soil under irrigated field conditions in the Central Punjab, Pakistan.

Materials and Methods

Study site

The study site (Nuclear Institute for Agriculture & Biology, Faisalabad) is located at 31º23′ 50.25″N, 73.02′ 01.31″E and is 183 m above the sea level. The area has a subtropical arid climate with a mean annual rainfall of 340 mm, most of which is received in July and August in the form of high intensity monsoon downpours. About one-third of the total rainfall is received in winter in the form of low intensity showers of long duration. The hottest months are May and June, with mean temperatures of 39.4 and 41.1°C, respectively; the daily maximum rising to 47.8°C. January is the coldest month with a mean minimum temperature of 5°C, whereas frost usually occurs for a short spell of 10–15 days in December and January. The annual excess of pan evaporation over rainfall is around 1600 mm, the greatest rainfall deficit occurring in May (203 mm) and June (314 mm). The soil (Typic Ustochrept; Hafizabad series) is a deep, well-drained sandy loam developed in a mixed calcareous medium-textured alluvium derived from Himalayas (Anonymous, 1967). The site has been under a wheat-mung bean rotation for the past 20 years. Some physicochemical properties of the field soil are given in Table 1.

Table 1: Some physicochemical characteristics of the field soil

Characteristic	Value
Sand (%)	63.0
Silt (%)	20.7
Clay (%)	16.3
Texture	Sandy-loam
Organic matter (%)	0.85
Maximum water-holding capacity (%)	30.5
$CaCO_3$ (%)	1.83
HCO_3^- (mg kg^{-1})	80.9
pH (1:1)	7.7
EC (1:1) (µS m^{-1})	672
CEC [cmol (+) kg^{-1}]	9.60
Total N (%)	0.07
NH_4^+-N (mg kg^{-1})	2.7
NO_3^--N (mg kg^{-1})	9.6
Olsen P (mg kg^{-1})	5.6
Extractable K (mg kg^{-1})	658

Field experiment

Five cultivars of white lupin (*Lupinus albus* L. cv. Amiga, Fortuna, Feodora, Dieta and Lublanc), three of yellow lupin (*L. luteus* L. cv. Amber, Progress and Bornal) and four of blue lupin (*L. angustifolius* L. cv. Prober, Borfgine, Bora and Borweta) were evaluated under irrigated field conditions. Seeds were obtained from Südwestsaat GbR, Rastatt, Germany (*L. albus* cv. Amiga, Fortuna and Feodora); Saatzucht Steinach GmbH, Bocksee, Germany (*L. angustifolius* cv. Prober and Borfgine; *L. luteus* cv. Bornal); Soya U.K. Ltd., Fareham, U.K. (*L. albus* cv. Dieta; *L. luteus* cv. Progress and Amber; *L. angustifolius* cv. Bora and Borweta); and from Bruno Nebelung GmbH & Co., Everswinkel, Germany (*L. albus* cv. Lublanc). Experiment was carried out in a randomized complete block design with four replicate plots (3m × 2.1m) for each cultivar. After pre-sowing irrigation (10^{th} November; 75 mm) the land was prepared on 19^{th} November and seed manually sown at 3 cm depth with row-row and plant-plant distances of 30 cm and 15 cm, respectively (30 seeds m^2; 12 rows $plot^{-1}$; 192

plants plot^{-1}). No P or K fertilizers were applied. However, N application was necessary as none of the test cultivars produced root nodules in a preliminary greenhouse experiment conducted with the same soil. Therefore, urea-N was applied at 100 kg ha^{-1} in two equal splits (incorporated at land preparation on 19th November and broadcast before 1st irrigation on 9th January). During the growing season, the crop received three (50 mm) irrigations (9th January, 26th February and 15th March). In all cultivars, flowering started in mid-February and was completed during 1st week of March, whereas the pods were mature on 10th April.

For observations on proteoid roots and to determine the overall biomass yield at flowering stage (3rd March), ten plants plot^{-1} (with intact soil) were randomly excavated from 2nd side rows of each plot. For this purpose, a PVC pipe (15 × 40 cm; diameter × depth) was pushed to a depth of 30 cm into soil around plant and the soil along with intact root system extracted. The soil along with root system was kept in water overnight and the roots carefully recovered after thorough washing with water. Shoots and roots (proteoid roots separated in case of white and yellow lupins) were dried at 70°C to a constant weight and ground (<0.5 mm) before chemical analyses. At maturity (10th April), leaving two plant rows from each side of a plot, pods were harvested (harvested area, 4.32 m^2; 96 plants plot^{-1}). Seeds were separated and oven dried at 70°C to a constant weight; in all cultivars, the seed moisture content at harvest was 5%. Seeds of white lupins were ground (<0.5 mm) before chemical analyses.

Analyses

Total N of plant material was determined by a micro-Kjeldahl method after digestion of 0.1 g of powdered material. For determination of total P, K, Fe, Zn, Mn, and Cu, 1 g of powdered plant material was digested in a 10 mL mixture of HNO_3:H_2SO_4:$HClO_4$ (10:1:4). Phosphorus was determined by vanadomolybdate method (Anonymous, 1980), K by flame photometry, and Fe, Zn, Mn and Cu by atomic absorption spectrometry. Ashing was carried out in a muffle furnace heated at 500°C for 5 h. Total carbohydrates (as glucose equivalents) of grain were determined by phenol-sulfuric acid method after hydrolyzing 0.1 g of powdered material in 0.4 mL of 12 M H_2SO_4 for 16 h (Šafařik and Šantrůčková, 1992). Oil content of seed was determined gravimetrically after Soxhlet extraction of 25 g powdered material in 200 mL of n-Hexane (Anonymous, 1970). Data were subjected to an analysis of variance using M-Stat-C software. Results are reported as means of four replicate plots and are based on oven dry weight.

Results

Dry matter yield

As observed at the flowering stage, the shoot biomass of white lupin cultivars (11.4–16.6 g plant^{-1}; 3470–5070 kg ha^{-1}) was significantly higher than the biomass produced by yellow (2.0–4.8 g plant^{-1}; 590–1460 kg ha^{-1}) and blue lupins (2.2–6.8 g plant^{-1}; 655–2060 kg ha^{-1}) ($p<0.05$; Table 2). Among white lupin cultivars, the cv. Amiga and Fortuna produced significantly higher shoot dry matter (5030–5070 kg ha^{-1}) than the cv. Dieta (4220 kg ha^{-1}), Lublanc (4060 kg ha^{-1}) and Feodora (3470 kg ha^{-1}). Proteoid roots were observed in all cultivars of white as well as yellow lupins. However, averaged across cultivars, the plant^{-1} biomass of proteoid roots was almost 5-fold higher in white compared to yellow lupins. Likewise, the average ratio of proteoid/non-proteoid roots in white lupin (0.25) was also higher than that (0.16) observed in yellow lupin. Besides, averaged across cultivars, the plant biomass of non-proteoid roots in white lupin was 4 and 2 times higher than the biomass recorded for yellow and blue lupins, respectively (Table 2).

Although all the tested lupins grew well and approached the flowering stage, seed formation was recorded only in white lupin, whereas it was almost negligible in yellow and blue lupins (Table 2). Among white lupin cultivars, the seed yield was highest in the cv. Dieta (3098 kg ha^{-1}) and Fortuna (3046 kg ha^{-1}), followed closely by the cv. Amiga (2676 kg ha^{-1}), whereas minimum (1410 kg ha^{-1}) was recorded for the cv. Lublanc ($p<0.05$; Table 2). Among white lupin cultivars, the cv. Dieta showed the highest seed weight (27.9 g^{-100}) that was almost similar to that (26.3 g^{-100}) of the original seed used for sowing (Table 2). In other cultivars of white lupins, while the seed weight was only slightly lesser than that of the original lot, the seed weight of yellow and blue lupins was drastically reduced in the local environment (Table 2).

Macronutrients in roots and shoots

While N concentration was always higher in proteoid than in non-proteoid roots of white and yellow lupins, K concentration was generally higher in non-proteoid roots; no consistent trend was observed with respect to P concentration in two root types (Table 3). The concentration of N, P and K was always higher in shoots than in roots (Table 3). The shoot N concentration in different cultivars of white, yellow and blue lupins ranged from 3.31–3.56, 2.77–3.22 and 2.75–3.21%, respectively, the concentration was generally comparable in different cultivars, particularly those of white lupins (Table 3). The concentration of P in shoots ranged from 0.16–0.18%, 0.12–0.13% and 0.12–0.15% in white, yellow and

Table 2: Dry matter yield of different *Lupinus* species/cultivars

Species/Cultivar	Dry matter yield at flowering stage: Non-proteoid root	Proteoid root	Shoot	Seed yield	100-seed weight
	g plant^{-1}			kg ha^{-1}	g
White lupin					
***L. albus* cv. Amiga**	1.89 a[a]	0.41 a	16.51 a (5030 a)[b]	2675 b (2751)[c]	24.77 b
***L. albus* cv. Fortuna**	1.91 a	0.20 bc	16.64 a (5070 a)	3046 a (3131)	23.89 b
***L. albus* cv. Feodora**	0.89 c	0.31 ab	11.37 c (3470 b)	1944 c (2002)	20.60 c
***L. albus* cv. Dieta**	1.15 bc	0.40 a	13.86 b (4220 b)	3098 a (3187)	27.87 a
***L. albus* cv. Lublanc**	1.32 b	0.31 ab	13.32 b (4060 b)	1410 d (1450)	19.77 c
Yellow lupin					
***L. luteus* cv. Bornal**	0.29 d	0.07 c	2.11 f (640 d)	53 e (54)	6.98 de
***L. luteus* cv. Progress**	0.29 d	0.03 c	1.95 f (590 d)	72 e (74)	6.08 e
***L. luteus* cv. Amber**	0.58 d	0.08 c	4.78 ed (1460 cd)	145 e (149)	7.82 d
Blue lupin					
***L. angustifolius* cv. Prober**	0.97 c	Nd[e]	6.76 d (2060 c)	58 e (60)	6.58 e
***L. angustifolius* cv. Borfgine**	0.55 d	Nd	2.79 f (850 d)	3 e (3)	2.94 f
***L. angustifolius* cv. Bora**	0.54 d	Nd	2.43 f (740 d)	9 e (9)	3.39 f
***L. angustifolius* cv. Borweta**	0.39 d	Nd	2.16 f (655 d)	7 e (7)	3.79 f
LSD (*p<0.05*)	0.289	0.183	1.850 (951)	154.74	1.056
LSD (*p<0.01*)	0.388	0.253	2.486 (1278)	207.89	1.418

[a]All values are mean of four replicate plots and are based on over-dry weight; figures in a column followed by different letter are significantly different by Duncan's multiple range test ($p<0.05$); [b]Figures in parentheses represent shoot yield as kg ha^{-1}; [c]Figures in parentheses indicate seed yield on air-dry basis; [e]Not detected

blue lupins, respectively; the differences among cultivars of a given *Lupinus* species were non-significant (Table 3). The shoot K concentration ranged from 2.82–3.12%, 2.65–3.10 and 2.45–3.03% in white, yellow and blue lupins, respectively; the concentration was almost comparable in different cultivars (Table 3).

Grain composition of white lupins

The proportion of seed coat was highest in cv. Lublanc (20.1%), whereas the proportion was significantly lesser in cultivars producing highest grain yield *viz.* Dieta (15.5%) and Fortuna (17.4%) ($p<0.01$, Table 4). Highest ash content (3.43–3.68%) was observed for cv. Lublanc, Feodora and Amiga, whereas the content was significantly lesser (3.20–3.27%) in cv. Dieta and Fortuna ($P<0.05$, Table 4). The oil content was highest (11.3%) in cv. Dieta, followed closely by cv. Feodora, Fortuna and Amiga (9.5–10.5%), whereas the the cv. Lublanc showed minimum (9.0%) ($p<0.05$, Table 4). Different cultivars of white lupins did not vary with respect to carbohydrates (19.1–20.1%), crude protein (33.1–35.8%), total N (5.29–5.72%), P (0.28–0.30%), and K (1.16–1.68%). However, regarding the concentration of micronutrients (Fe, Zn, Cu and Mn) in grain, the cultivars varied significantly (Table 4). The cv. Amiga possessed significantly higher ($p<0.01$) Fe content (37.0 mg kg^{-1}) as compared to other four cultivars (22.4–28.1 mg kg^{-1}). The concentration of Zn was slightly higher ($p<0.05$) in cv. Dieta, Feodora, Amiga (31.4–31.9 mg kg^{-1}) as compared to cv. Lublanc and Fortuna (28.1–29.6 mg kg^{-1}). The concentration of Cu ranged from 6.14–7.55 mg kg^{-1}; the cv. Dieta and Amiga showing highest values (7.42–7.55 mg kg^{-1}), whereas the cv. Lublanc showed lowest ($p<0.05$). The grain Mn concentration that was much higher than other micronutrients, varied from 513–954 mg kg^{-1} with maximum and minimum values observed for the cv. Dieta and Fortuna, respectively ($p<0.01$).

Discussion

Under agroclimatic conditions prevailing in the present study, all the tested *Lupinus* species/cultivars grew well up to flowering stage without apparently showing HCO_3^--induced chlorosis. However, while yellow and blue lupins failed to produce seed, the biomass yield was also reduced when compared with yields obtained in areas where these are traditional crops (Berk *et al*., 2008). The tested cultivars of white lupin significantly differed with respect to grain yield that was either slightly lower (cultivars Feodora and Lublanc) or comparable (cultivars Amiga, Fortuna and Dieta) with the yield obtained under Mediterranean climate (López-Bellido *et al*., 2000). It appears that the concentration

Table 3: Concentration of macronutrients in *Lupnus* roots and shoots harvested at flowering stage

Lupinus Species/Cultivar	Nitrogen			Phosphorus			Potassium		
	Non-proteoid root	Proteoid root	Shoot	Non-proteoid root	Proteoid root	Shoot	Non-proteoid root	Proteoid root	Shoot
	(%)								
White lupin									
***L. albus* cv. Amiga**	1.27 bcd[a]	1.97 cd	3.40 ab	0.06 ab	0.05 b	0.17 ab	1.11 a	0.52 bc	3.11 a
***L. albus* cv. Fortuna**	1.68 ab	2.31 abc	3.56 a	0.04 bc	0.06 b	0.17 ab	1.11 ab	0.57 bc	2.85 abc
***L. albus* cv. Feodora**	1.33 bcd	2.18 bcd	3.31 ab	0.04 bc	0.04 b	0.18 a	1.00 ab	0.52 bc	2.99 ab
***L. albus* cv. Dieta**	1.29 bcd	1.85 d	3.37 ab	0.01 d	0.05 b	0.17 ab	1.04 ab	0.58 bc	3.12 a
***L. albus* cv. Lublanc**	1.61 abc	2.39 ab	3.44 ab	0.05 abc	0.04 b	0.16 abc	1.16 a	0.63 bc	2.82 abcd
Yellow lupin									
***L. luteus* cv. Bornal**	1.51 abc	2.11 bcd	3.22 ab	0.04 bc	0.11 a	0.13 d	1.10 a	0.74 b	3.10 a
***L. luteus* cv. Progress**	1.81 a	2.61 a	3.10 bc	0.06 a	0.08 ab	0.13 d	0.56 c	1.15 a	2.78 abcd
***L. luteus* cv. Amber**	1.54 abc	2.22 bc	2.77 c	0.06 ab	0.06 b	0.12 d	0.74 bc	0.50 c	2.65 abc
Blue lupin									
***L. angustifolius* cv. Prober**	1.30 bcd	-	3.21 ab	0.06 abc	-	0.12 d	0.48 cd	-	2.56 cd
***L. angustifolius* cv. Borfgine**	1.30 bcd	-	3.06 bc	0.04 c	-	0.14 cd	0.55 c	-	2.90 abc
***L. angustifolius* cv. Bora**	1.21 cd	-	2.75 c	0.04 bc	-	0.15 bcd	0.49 cd	-	3.03 ab
***L. angustifolius* cv. Borweta**	1.04 d	-	3.07 bc	0.04 abc	-	0.14 bcd	0.23 d	-	2.45 d
LSD (*p<0.05*)	0.372	0.313	0.392	0.018	0.039	0.026	0.282	0.209	0.349
LSD (*p<0.01*)	0.45	0.432	0.527	0.024	0.053	0.034	0.378	0.288	0.469

[a]All values are mean of four replicate plots and are based on over-dry weight; figures in a column followed by different letter are significantly different by Duncan's multiple range test (*p<0.05*)

Table 4: Chemical composition of grain of different cultivars of white lupin

Parameter	Cultivar					LSD	
	Amiga	**Fortuna**	**Feodora**	**Dieta**	**Lublanc**	***p<0.05***	***p<0.01***
Seed coat (%)	18.03 b[a]	17.40 b	18.14 b	15.48 c	20.08 a	1.697	2.414
Ash (%)	3.46 ab	3.27 b	3.68 a	3.20 b	3.43 ab	0.285	0.393
Protein (%)	33.06	33.46	33.82	35.01	35.76	NS	
Oil (%)	10.45 b	10.03 bc	9.53 cd	11.28 a	8.95 d	0.784	1.084
Carbohydrates (%)	20.05	19.18	19.13	19.38	19.83	NS	
Nitrogen (%)	5.29	5.35	5.41	5.60	5.72	NS	
Phosphorus (%)	0.296	0.283	0.292	0.280	0.287	NS	
Potassium (%)	1.161	1.684	1.244	1.444	1.418	NS	
Iron (mg kg^{-1})	37.02 a	24.29 b	27.11 b	28.09 b	22.40 b	5.737	8.160
Zinc (mg kg^{-1})	31.63 a	29.63 bc	31.41 ab	31.86 a	28.09 c	1.775	2.254
Copper (mg kg^{-1})	7.42 ab	6.99 b	6.88 b	7.55 a	6.14 c	0.521	0.720
Manganese (mg kg^{-1})	677 c	513 d	898 b	954 a	651 c	27.51	39.13

[a]All values are mean of four replicate plots and are based on over-dry weight; figures in a row followed by different letter are significantly different by Duncan's multiple range test (*P<0.05*)

of active lime in the mildly calcareous soil used in the present study was probably not high enough to induce toxicity in white lupin as generally reported for *Lupinus* species growing in calcareous soils (Papineau and Huyghe, 2004). Present results confirm to an earlier report indicating the adaptability of white lupin to agro-climatic conditions in the Pothwar region of Pakistan (Chaudhary and Cheema, 1998). Cultivars of white lupin viz. Amiga, Fortuna and Dieta produced substantial grain yield (2675–3098 kg ha^{-1}; Table 2), which was much higher than the yields of some high-yielding conventional grain legumes in this region e.g. chickpea (1800–1994 kg ha^{-1}; Khattak *et al*., 2007; Shah *et al*., 2010), lentil (1340 kg ha^{-1}; Sadiq *et al*., 2002) and mung bean (1962 kg ha^{-1}; Khattak *et al*., 2006). The grain protein content of white lupins cultivars tested in the present study (33–36%) is comparable with that of soybean (34–42%) but much higher than other conventional grain legumes e.g. chickpea (19–24%), pigeon pea (22%), peas (23%), mungbean (26%) and cowpea (28%) grown in Pakistan (Khan *et al*., 2001; Ali *et al*., 2007; Butt and Batool, 2010).

All the tested *Lupinus* species/cultivars were able to fulfill P requirement from the P-deficient soil used in the present study. However, application of fertilizer N was required as none of the tested species/cultivars was able to produce root nodules. The compatible *Bradyrhizobium* was probably not present in the experimental field since the tested lupins are exotic species in this region. Besides, in alkaline calcareous soils having pH above 6, a sharp decrease in nodulation is observed due to poor adaptation of *Bradyrhizobium* to alkaline soils because of insufficient iron availability, reduced recognition of host plant and reduced expression of nodulation genes (Tang and Thomson, 1996; Tang *et al*., 2006). Since large variation exists among *Bradyrhizobium* strains for their ability to produce nodulation in white lupin growing in alkaline calcareous and iron-deficient soils, the adaptation of white lupin to alkaline calcareous soils might be improved by identifying tolerant *Bradyrhizobium* strains (Annicchiaricon and Alami, 2012).

Conclusion

Results of the present study suggested that it is possible to domesticate white lupin as a high-protein alternate grain legume in the Indo-Gangetic Plains of South Asia. Since adaptation of white lupin to moderately calcareous soils could be improved by selecting lime-tolerant cultivars, detailed studies are required for screening of cultivars suitable for the local agroclimate. Detailed studies are also needed to exploit N_2-fixing potential of white lupin thus leading to its successful domestication in nutrient-poor soils of this region.

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