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Effect of the interrow width and plant density on the yielding of white lupin

Janusz Prusiński

Department of Agronomy, Bydgoszcz University of Science and Technology

S. Kaliskiego 7 Street, 85-796 Bydgoszcz, Poland

e-mail: janusz.prusinski@pbs.edu.pl

The study investigated a Polish white lupin ‘Butan’, and its yielding depending on the interrow width and plant density. The mean many-year lupin seed yield was 3.05 t ha^{-1} and it strongly depended on the total rainfall and total temperature over the generative plant development. The mean discrepancy in the seed yield across the research years, due to a considerable variation in the total rainfall, ranged from 1.59 t ha^{-1} to 7.43 t ha^{-1}. There was no significant effect of the factors applied on white lupin yielding. Only the number of pods per plant depended on the factors and it was significantly higher when lupin was grown in narrow rows, with the lowest plant density. Also, HI and SPAD values were significantly higher for 16 cm row width. The LAI value did not depend significantly on neither of the two factors. Content and yield of protein depended proportionally on the sum and distribution of precipitation in the following years.

Key words: yield, yield components, HI, LAI, SPAD and PC values

Introduction

White lupin seeds have been used in human nutrition and treatment for thousands of years. Over the last 20 years there have been discovered new white lupin properties used in the production of various kinds of functional foods (Prusiński 2017), including those with a lowered glycemic index (Yaver and Bilgiçli 2021). However, in the EU there is observed a decrease in legumes acreage and the favourable aftereffects of their cultivation are not considered, especially an increasing biodiversity, reducing the emissions to 50% N_2O or a favourable impact on soil and the economic benefits (Zander et al. 2016). A sustainable development in agriculture is, at present, in the centre of the agricultural policy debate in Europe. There is an agreement that a diversification of crops supports sustainable development. One of the reasons for abandoning or limiting the cultivation of legumes is a considerable yielding variation (Annicchiarico et al. 2018, Reckling et al. 2018), even though the share of legumes in the crop structure is commonly desired as it enhances succeeding crops yielding. In Brazil white lupin is considered an important alternative crop used for a recovery of degraded soils and sowing it increases succeeding crops yielding, including maize (Santi et al. 2016). According to Lucas et al. (2015), lupins, similarly as other legumes, can become an alternative for the imported soybean in Europe. Lupin cultivation in only a few EU countries is scarce and the yields – very variable. Many researchers point to a considerable effect of unfavourable weather conditions on white lupin yielding, mostly drought (Putnam et al. 1992, Šariková et al. 2011, Vadez et al. 2012, Borowska et al. 2017, Farooq et al. 2017, Annicchiarico et al. 2018, Faligowska et al. 2018). Hence, high yields of white lupine seeds can be obtained with sufficient humidity in the second half of summer (Shcherbynal at al. 2021), however, the interaction of yield and yield stability of the cultivars grown is more important (Atnaf at al. 2017).

The interrow width and white lupin sowing density are the key factors determining, next to the weather pattern, mostly the seed yield and yield components, as well as the chemical composition of the seeds. Băbuțiu and David (2010) recorded a 18% increase in white lupin seed yield together with an increase in interrow width from 25 to 50 cm. In a wider row spacing, there was also observed a decreased number of plants, accompanied by a 29% yield decrease together with an increase in row spacing from 25 to 75 cm (Koetz et al. 2015). However, Bhardway et al. (2004) and Pospišil and Pospišil (2016) did not observe any essential differences in white lupin yielding resulting from the interrow width applied, while the higher the plant density, the lower the number of pods, while the seed number and weight per pod remained unchanged. The number of pods per plant and per m^2 showed the most important impact on white lupin yielding. To compare, Putnam et al. (1992) and Faluyi et al. (2000) recorded a significantly higher seed yield when sown in narrower rows. According to Lopez-Bellido et al. (2000), a high lupin plasticity eliminates changes in seed yield components, which results from the differences in plant density, and it facilitates producing stable seed yields.

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As reported by Lopez-Bellido et al. (2000), the plant density (20–60 cm) did not have a significant impact on white lupin yielding, while Santi et al. (2016) claims that in Brazil the optimal density is 25 plants, in the Czech Republic, according to Šariková et al. (2011), 75 plants, and in Poland according to Borowska et al. (2017), Faligowska et al. (2018), Prusiński (2002) – 70–80 plants per m^2, which is slightly more than reported by Băbuțiu and David (2010) and Podleśny (2007), 50 and 60 plants more per 1 m^2, respectively. A higher plant density decreases the number of pods per plant (Podleśny 2007, Borowska et al. 2017). However, Pospišil and Pospišil (2016) did not identify any effect of plant density on white lupin yielding, however an increase in plant density exceeding 60 plants per m^2 significantly decreased the number of pods and seeds per pod and the seed weight per plant.

The aim of the present research has been to evaluate the effect of the plant density and interrow width and their interaction on plant growth, yielding and morphological traits in 'Butan' white lupin. The research hypothesis assumes that the low costs of growing white lupin resulting from a lower plant density and a narrow row spacing limiting a weed pressure will show a favourable effect on white lupin yielding.

Materials and methods

A strict two-factor field experience was experiments were made in 2016–2019 at the Experimental Station of the Bydgoszcz University of Science and Technology in Bydgoszcz, Poland, in split-plot, in 4 replications under soil conditions favourable to white lupin (Table 1). The soil type, classified according to the WRB, as Haplic Luvisols (Cutanic), was a typical lessive soil formed from light loamy sand, deposited in a shallow layer on light loam (IUSS WRB 2015). The phosphorus content was very high (90 mg kg^{-1} of soil), potassium – high (134.25 g kg^{-1} of soil), magnesium – low (28.75 mg kg^{-1} of soil). The contents of available forms of potassium and phosphorus were assayed with the Enger-Rhiem DL method and the content of magnesium – with the Schachtschabel method. The content of nitrate and ammonium ions were colometrically assayed with the Behelota and Griess-Ilosvaya reaction. The soil pH was potentiometrically measured in 1 mol l^{-1} KCl. In all the research years, the soil pH was adequate for white lupin growing (Table 1).

Table 1. Chemical properties of soil before sowing white lupin in 2016–2019

	P_2O_5	K_2O	Mg	$N\text{-}NO_3$	$N\text{-}NH_4$	pH in KCl
Years	mg 100 g^{-1} of soil			mg kg^{-1} of soil		
2016	109.0	127	30.0	9.53	5.73	6.3
2017	92.0	149	31.0	5.90	7.96	6.3
2018	82.0	112	27.0	6.12	6.97	6.8
2019	77.0	149	27.0	8.69	2.27	6.5
Mean	90.0	134	28.7	7.56	5.73	6.5

'Butan' white lupin (Hodowla Roślin Smolice, Sp. z o. o. IHAR Group, Poland) is a fodder cultivar, early and thermoneutral. Plants with short lateral shoots, a 2–14-days-shorter vegetation period, as compared with traditional cultivars, with a lowered sensitivity to *Fusarium* diseases and the content of alkaloids as compared with the earlier cultivars.

Two interrow widths (RS) were applied: 16 and 32 cm as well as three different plant densities (PD): 60, 75 and 90 plants per m^2. The forecrop in the successive years was always spring wheat. Fertilisation with N–30, P–70 and K–80 kg ha^{-1} was applied prior to sowing. The seeds were dressed with seed dressing, Vitavax 200 FS, and Sepiret 3280 Red (polymer). According to the manufacturer's guidelines, before sowing the seeds of lupin, symbiotic bacteria inoculation by *Bradyrhizobium* (Nitragina) was applied. Over the vegetation period, during the 4 research years, standard chemical treatments were used to combat dicotyledonous and monocotyledonous weeds (pre-emergence and topdressing). Weeds were selected with Afalon Dispersion 450 S.C. and Comand 480 S.C. in 2016–2018 and Stomp Aqua 455 CS in 2019. It was also necessary to control aphids (*Rhopalosiphum insertum*), seed beatle (*Bruchus pisorum* L.), and incidentally also painted-lady (*Vanessa carudi*) using the Proteus 110 OD.

In the research years there were noted very variable humidity conditions and, to a smaller extent, thermal conditions (Table 2). The most favourable conditions were recorded in 2016 and 2017, when the length of the vegetation period was 152 and 150 days. In the successive two years, at a considerably higher temperature and a lower total rainfall, the vegetation period was, respectively, 118 and 133 days long, however in July 2018 the total rainfall – 86 mm must have been more favourable for lupin yielding than the total of 89.2 mm in May in 2019.

Table 2. Weather pattern in 2016–2019

	Month					
Temperature, °C	April	May	June	July	August	Mean
2016	8.3	14.7	17.7	18.3	16.4	15.1
2017	6.8	13.4	16.8	17.7	17.7	14.5
2018	12.0	16.9	18.4	20.5	19.9	17.5
2019	9.3	12.1	21.9	18.6	19.7	16.3
Rainfall, mm						Total
2016	28.7	51.4	98.1	133.8	55.3	367.3
2017	40.8	56.3	54.3	118.9	126.1	396.4
2018	40.4	14.2	26.4	86.0	23.7	190.7
2019	1.5	89.2	17.7	22.4	37.7	168.5

The experiment was 2-factorial fitted into completely randomized block design with four replications. The data was processed by ANOVA using STATISTICA version 10 (StatSoft, Tulsa, OK, U.S.). The $p < 0.05$ and $p < 0.01$ and $p < 0.001$ were set as the levels of significance. The LDS test at $p < 0.05$ was used for the difference between parameter means. Pearson's correlation coefficients were applied for the relationship between the parameters. The means in tables and charts provided with the same letters did not differ significantly.

Results

The multi-year mean white lupin plant density was 65.9 plants per m^2 (Table 3). The width of the interrows differentiated significantly neither the plant density nor the correlation between the factors applied. The real plant density for the sowing rate planned, 75 and 90 plants per m^2, did not differ significantly but it was significantly higher than for the 60 plants per square meter planned. On average for the many-year period, the plant density was 6.16%, 9.6% and 18.1% lower than planned.

Table 3. Average 4-year plant population of white lupin plants depending on row spacing and plant density

Factors		Year				Mean
		2016	2017	2018	2019	
Row spacing (RS) cm	16	67.3	63.7	63.4	65.3	64.9
	32	66.3	66.7	66.8	68.1	67.0
Plant density (PD)	60	56.6 c	56.4 b	56.0 b	56.2 c	56.3 b
	75	68.2 b	67.2 a	68.3 a	67.4 b	67.8 a
	90	75.5 a	72.1 a	70.9 a	76.4 a	73.7 a
Mean		66.8	65.2	65.1	66.3	65.9
ANOVA	RS	ns	ns	ns	ns	ns
	PD	**	**	**	**	**
	RS x PD	ns	*	ns	*	ns

Values of a parameter followed by the same letter did not differ significantly between row spacing and density (ANOVA followed by Tuckey's HDS test. $p < 0.05$). ANOVA results: ** $p < 0.01$; * $p < 0.05$; ns = not significant

The mean white lupin seed yield in 2016–2019 was 3.95 t ha^{-1} (Table 4). There were found no significant dependencies of the white lupin seed yield on row spacing and plant density. There were also no significant interactions between the examined factors, except for 2019, with the lowest seed yield and slightly worse moisture conditions in July and August.

Table 4. Effect of row spacing and plant density on white lupin yield (t ha^{-1}) in 2016–2019

Factors		Year				Mean
		2016	2017	2018	2019	
Row spacing (RS) cm	16	4.90	7.40	1.86	1.56	3.93
	32	4.92	7.47	1.88	1.62	3.97
Plant density (PD)	60	4.94	7.25	1.96	1.63	3.94
	75	4.93	7.52	1.90	1.43	3.94
	90	4.85	7.53	1.75	1.70	3.95
Mean		4.91 B	7.43 A	1.87 C	1.59 C	3.95
ANOVA	RS	ns	ns	ns	ns	ns
	PD	ns	ns	ns	ns	ns
	RS x PD	ns	ns	ns	*	ns

Values of a parameter followed by the same letter did not differ significantly between row spacing and density (ANOVA followed by Tuckey's HDS test. $p < 0.05$). ANOVA results: ** $p < 0.01$; * $p < 0.05$; ns = not significant

It was white lupin in 2017 which yielded significantly highest. The seed yield in 2018 and 2019, with considerably lower total rainfall and higher air temperature, accounted for only 25.2% and 20.6% of the maximum yield, respectively, of 2017. A significant variation in the white lupin seed yield in the successive research years resulted from essential differences in the total rainfall; high and well-distributed in 2016, especially in 2017, and low – in 2018 and 2019, which was additionally accompanied by high air temperature (Fig. 1a). The mean protein yield was 1352 kg ha^{-1} and it differed significantly in successive years, directly proportionally to a strongly varied total rainfall (Fig. 1b).

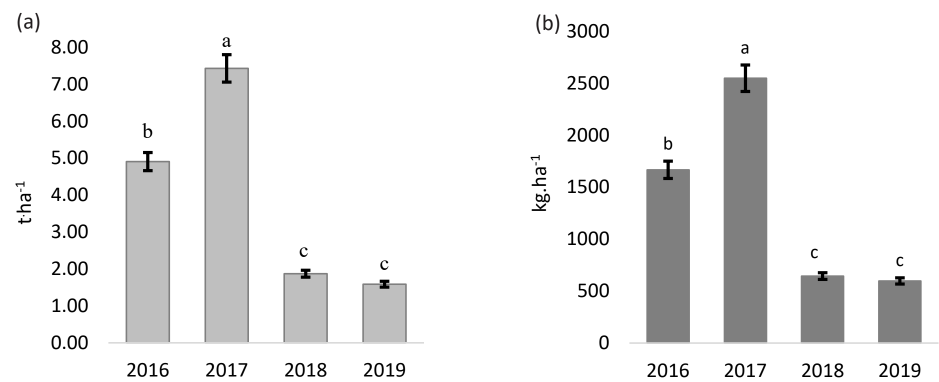

Fig. 1. Dynamics of the white lupin seed (a) and protein (b) yield in the research years. Means ± standard error followed by the same letters are not significantly different at $p < 0.05$.

There were found significant correlations between the white lupin seed yield and the total rainfall, especially in August and in June – August (Table 5).

Table 5. Pearson's correlation coefficients (r) for total rainfall in different months, for the entire vegetation period and seed yield white lupin

Month	April	May	June	July	August	June–August	April–August
R	0.537 ^{ns}	0.019 ^{ns}	0.622 ^{ns}	0.758 ^{ns}	0.937 ^{ns}	0.930 ^{ns}	0.961 *

* $p < 0.05$; ** $p < 0.01$; ns = not significant

On average for the research years, the number of pods per white lupin plant was 7.03 (Table 6). Significantly more pods were found for narrow-row sowing and the lowest plant density. In 2016–2018 the number of seeds per pod, the seed weight and 1000 seed weight were statistically similar, significantly higher than in the driest year; in 2019. The results were significantly affected neither by the width of interrows nor by plant density.

Table 6. White lupin yield components depending of row spacing and plant density in 2016–2019

Factor		Number of pods per plant	Number of seeds per pod	Seed weight per pod, g	1000 seed yield, g
Year (Y)	2016	8.26 b	3.26 a	1.046 a	321 a
	2017	12.0 a	3.32 a	1.052 a	317 a
	2018	3.92 c	3.18 a	0.992 a	313 a
	2019	3.93 c	3.07 b	0.880 b	287 b
Row spacing (RS) cm	16	7.55 a	3.18	0.981	308
	32	6.50 b	3.23	1.004	311
Plant density (PD)	70	7.82 a	3.17	0.981	310
	90	6.95 b	3.21	0.991	309
	110	6.31 b	3.24	1.005	310
Mean		7.03	3.21	0.993	309
ANOVA	Y	**	**	**	**
	R	**	ns	ns	ns
	D	**	ns	ns	ns
	Y x RS	ns	ns	ns	ns
	Y x PD	ns	ns	ns	ns
	SR x PD	ns	ns	ns	ns
	Y x RS x PD	ns	ns	ns	ns

Values of a parameter followed by the same letter did not differ significantly between year, row spacing and density (ANOVA followed by Tuckey's HDS test. $p < 0.05$). ANOVA results: ** $p < 0.01$; * $p < 0.05$; ns = not significant

The share of the seeds in the yield of white lupin seeds and straw (HI) accounted for 56.9% (Table 7) and it was significantly highest in the most humid year (2017), then in humid year 2016, and the lowest in dry vegetation periods; in 2019 and 2018.

Table 7. HI, SPAD, LAI and PC values for white lupin depending of row spacing and plant density in 2016–2019

Factor		HI	SPAD	LAI	PC
Year (Y)	2016	58.5 b	53.0 a	3.02 ab	33.1 a
	2017	62.8 a	52.7 a	4.35 a	34.8 a
	2018	50.9 d	51.3 a	2.47 b	32.1 b
	2019	55.5 c	43.4 b	2.28 b	34.2 a
Row spacing (RS) cm	16	58.0 a	51.6 a	2.97	33.6
	32	55.9 b	48.6 b	3.09	33.6
Plant density (PD)	60	56.5	50.3	2.88	33.4
	75	57.7	50.7	3.06	33.7
	90	56.7	49.4	3.15	33.6
Mean		56.9	50.1	3.03	33.6
ANOVA	Y	**	**	**	**
	R	**	**	ns	ns
	D	ns	ns	ns	ns
	Y x RS	*	ns	ns	ns
	Y x PD	ns	ns	ns	ns
	R x PD	*	ns	ns	ns
	Y x RS x PD	**	*	ns	ns

HI = Harvest Index; SPAD = Soil-Plant Analysis Development Chlorophyll Meter; LAI = Leaf Area Index; PC = protein content. Values of a parameter followed by the same letter did not differ significantly between year, row spacing and density (ANOVA followed by Tuckey's HDS test. $p < 0.05$). ANOVA results: ** $p < 0.01$; * $p < 0.05$; ns = not significant

A narrower row spacing was accompanied by a higher HI value, however the plant density did not differentiate its value significantly. The mean SPAD value was 50.1 and it was also significantly higher in the plants grown in narrower interrows, and neither the plant density nor the interaction of both factors significantly differentiated that white lupin trait significantly. LAI did not differ significantly for the factors. In drier years, 2018 and 2019, the LAI value was significantly lower than in humid years, 2016 and 2017. The average protein content in white lupin seeds accounted for 33.6% and also did not depend neither on row spacing nor on plant density, and in 2016, 2017 and 2019 it did not differ significantly.

Discussion

White lupin yield

Legumes are commonly considered sensitive to rainfall deficit (Putnam et al. 1992, Šariková et al. 2011, Borowska et. al. 2017, Farooq at al. 2017, Faligowska et. al. 2018). According to Vadez et al. (2012), a decreased water deficit is probably the most essential challenge faced by contemporary agriculture. Very varied humidity conditions in the successive years of the present research, especially in June, July and August, also significantly determined white lupin yielding; in 2018 and 2019, with a low total rainfall, the mean seed yield was only 1.73 t ha^{-1}, whereas in the years with a high total rainfall (2016 and 2017) – as much as 6.17 t ha^{-1}; it was as much as 3.57 times higher. Annicchiarico et al. (2018) found a 79% white lupin seed yield decrease due to extreme drought. According to Vadez et al. (2012), an increase in air temperature accelerates the start of flowering and it shortens the vegetation period by increasing evapotranspiration. Similarly, in the present research a high mean air temperature in June and July 2018 (18.4 °C and 20.5 °C) and in 2019 (21.9 °C and 18.6 °C) considerably, next to a lower total rainfall, also significantly decreased white lupin yielding. It must be the reason why many authors (Lucas et al. 2015, Annicchiarico et al. 2018, Reckling et al. 2018) claimed that legumes yielding variation, including white lupin, is one of the reasons for abandoning or limiting the cultivation of legumes in Europe, in general, thus we abandon atmospheric N fixation or lowered costs of cultivating succeeding crops and an increase in succeeding crops yielding (Zander et al. 2016).

In such considerably variable temperature and rainfall conditions across the research years there was identified no significant impact of the row width on white lupin yielding, however, also the plant density, which was recorded by Lopez-Bellido et al. (2000). Many authors found, however, a significant impact of narrower interrows (Putnam et al. 1992, Faluyi et al. 2000), and others – wider (Băbuțiu and David 2010) on white lupin yielding. However, according to Bhardway et al. (2004) and to Pospišil and Pospišil (2016), similarly as in the present research, there was identified no effect of the width of interrows on white lupin yielding. Similar differences concerned also the optimal sowing density and plant density; from a lack of the effect of plant density on white lupin yielding in Spain (Lopez-Bellido et al. 2000) up to the optimal density of 25 plants per m^2 in Brazil (Santi et al. 2016), or up to 50–80 plants per m^2 in Europe (Prusiński 2002, Podleśny 2007, Băbuțiu and David 2010, Šariková et al. 2011, Borowska et al. 2017).

Yield components

The impact of total rainfall on white lupin yielding components in the successive research years concerned mostly the number of pods per plant, only in the driest years, 2019 and 2020, as well as a significantly lower number of seeds per plant, the seed weight per pod and 1000 seed weight, however only in 2019. The number of pods per plant is one of the most sensitive and variable lupin seed yield components (Lopez-Bellido et al. 2000). Only in the present study did the number of pods per plant depend on the sowing density and it was significantly highest for the lowest plant density. Also Borowska et al. (2017) and Podleśny (2007) as well as Pospišil and Pospišil (2016) observed a higher number of pods for a lower plant density. However, no such dependencies were found for the other yielding components, similarly as reported by Bhardway et al. (2004) or by Pospišil and Pospišil (2016). Neither were considerably high significant correlations between the years, the width of interrows, the plant density and white lupin seed yield components identified.

HI, LAI, SPAD and protein values

The weather pattern differentiated the HI value across the years considerably, almost similarly as the seed yield, however an increase in the plant density did not affect its value; unlike reported by other researchers (Lopez-Bellido et al. 2000), where a higher plant density was accompanied by a lower HI value, which can mean that lupins are not adapted to high yielding when accompanied by a high plant density. Importantly, however, a two-times-higher row spacing, from 16 cm to 32 cm, was accompanied by a significantly lower HI value. The Soil Plant Analysis Development chlorophyll factor (SPAD) is one of the most commonly used diagnostic tools to measure the crop nitrogen status. In the present study its mean value was 50.1 and it did not depend significantly on the plant density, and similarly as for the HI, it was significantly higher when lupin was grown in narrow rows. In dry years, with water deficit, SPAD can be considered a drought stress marker to evaluate the water use capacity in legumes (Nemeskéri et al. 2015). A significantly higher LAI value was recorded only for the white lupin plants grown in the years with a high total rainfall (2016 and 2017), however, without a significant impact of the width of interrows and the plant density on its value. Richard et al. (2013) indicate that a higher plant density in pea in humid period increases the LAI value, which was also found in the present study in white lupin, in 2016 and 2017, with a high total rainfall, the LAI value was almost 2-times higher than in the dry years 2018 and 2019. Water deficits and a significantly lower LAI value in 2018 and 2019 resulted in, according to Nadeem et al. (2019), a decrease in net photosynthesis and a nutrient absorbing capacity. A high LAI value, on the other hand, in the years with a high total rainfall, resulted from a mutual leaf overshadowing depending on raw spacing, which, however, was not identified in the present study. Similar to what is reported by Tóth (2016), there was found no significant effect of the width of interrows on the protein content in white lupin seeds. To recapitulate, the white lupin plant density did not have a significant effect on the value of any of the traits under study. Neither did the factors affect significantly the LAI and PC values and only in 2018 their values were lower than in the other years.

Conclusion

The results of the present study and those cited from various parts of Europe and the world point to a very variable effect of the width of interrows and the plant density or no such effect on white lupin yielding. A high plant plasticity facilitated producing a high seed yield with the lowest plant density and a narrow row width, what confirms assumed hypothesis. However, a white lupin growing success was mostly determined by sufficient total rainfall during the period of growth and generative development in subsequent years of research.

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