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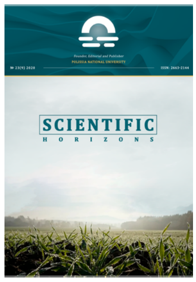

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Formation of narrow-leaved lupine productivity depending on seed inoculation and fertilization

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Abstract. Narrow-leaved lupine is characterised by valuable economic features, so it is an important source of balanced and easily digestible vegetable protein. The purpose of the study was to substantiate the effect of seed inoculation and fertiliser on the growth and development of narrow-leaved lupine plants in order to maximise the genetic potential of the variety in Polissya conditions. The following research methods were used: general scientific (induction and deduction, generalisation), special (field, measurement and weight, physiological, laboratory), and statistical (correlation and regression). Field studies were conducted during 2019-2021. The features of growth and development of narrow-leaved lupine plants of the Olimp variety in Polissya conditions were investigated. The positive effect of seed inoculation with bacterial preparations and foliar fertilization with complex fertiliser on the productivity of narrow-leaved

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lupine, which plays an important role in solving the problem of plant protein, was established. The optimal area of the leaf surface of plants was determined by optimising the elements of agricultural technology of narrow-leaved lupine. The photosynthetic potential of lupine was determined depending on seed inoculation with biological preparations and fertiliser. The studied factors increase stem density, plant survival, and improve the indicators of individual crop productivity. Inoculation of seeds with biologics and foliar application ensures the formation of the highest (2.43 t/ha) grain productivity of narrow-leaved lupine. Seed inoculation increases the yield of narrow-leaved lupine grain by 10.8-11.4%, depending on nutritional background. Foliar application of plants with complex fertiliser in phases BBCH 21-23 and BBCH 51 on a mineral background for seed inoculation provides a 2.8% increase in grain yield compared to the control. The findings can be used to improve the elements of the technology of growing narrow-leaved lupine, which will ensure high and stable grain yields

Keywords: grain yield; bacterial preparations; foliar application; BBCH scale; linear indicators; leaf surface area; photosynthetic potential

INTRODUCTION

Vegetable protein is an important component of food and feed resources. The search for reserves to increase the production of vegetable protein to ensure proper nutrition of the population is of strategic importance in economic and social aspects. Increasing the production of vegetable protein is a key area of the agricultural sector. Among the agricultural crops that are a reserve for increasing the volume of vegetable protein, legumes are the most important. The most valuable protein crops of world crop production include narrow-leaved lupine (*Lupinus angustifolius* L.), which is promising for growing on low-fertile soils. To implement the genetic potential of narrow-leaved lupine varieties, it is necessary to review the agricultural technology of the crop. Thus, the study of the effects of seed inoculation and fertiliser on field germination, plant growth and development during the growing season, and the formation of productivity elements on low-fertile Polissya soils is relevant.

Narrow-leaved lupine is unpretentious to growing conditions and is able to form a grain yield of up to 2.58-2.61 t/ha (Holodna, 2022). However, the newly created varieties of narrow-leaved lupine are not fully able to meet the maximum genetic potential due to the impact of climate change (Kotelnytska *et al.*, 2021).

The yield of narrow-leaved lupine grain significantly depends not only on weather conditions but also on elements of cultivation technology, in particular, varieties, fertilisers, seed treatment before sowing, and other factors (Szymańska *et al.*, 2017; Mazur *et al.*, 2019; Panasiewicz *et al.*, 2020). An important factor in increasing the level of grain yield of agricultural crops is the application of mineral fertilisers (Punchyshyn *et al.*, 2019; Shevnikov *et al.*, 2022). Many researchers have studied the effectiveness of applying mineral fertilisers in the cultivation technologies of narrow-leaved lupine (Tkachuk *et al.*, 2019; Holodna, 2019).

The study by H. Kotelnytska *et al.* (2021) found that the maximum yield of grain of the narrow-leaved lupine variety Peremozhets (2.26 t/ha) was obtained by complex foliar application with a mixture of fertilisers in the budding phase and applying mineral fertilisers to the soil ($N_{30}P_{60}K_{60}$). The study by Lithuanian researchers (Tripolskaja & Asakaviciute, 2019) found a 22.8% decrease in the yield of narrow-leaved lupine grain when applying nitrogen fertilisers on acidic soils. Inoculation of seeds with biologics based on nitrogen-fixing bacteria and antagonist microbes in agricultural technologies improves plant nutrition, accumulates physiologically active substances in the rhizosphere, increases plant resistance to stress factors, increases yield, and improves the quality of crop products (Nyoki & Ndakidemi, 2018; Adesemoye *et al.*, 2021; Mirriam *et al.*, 2022).

According to A.V. Holodna (2022) treatment of narrow-leaved lupine seeds with a bioinoculant (based on a strain of nitrogen-fixing bacteria of the genus *Bradirhizobium lupini* 359a) in combination with the growth stimulator Nano-Gro increases grain yield by 4.5%. Seed treatment before sowing with BTU-R and MikoHelp biologics for applying mineral fertilisers to the soil ($N_{68}P_{48}K_{66}$) and double foliar application of plants at the 2nd and 4th stages of organogenesis with Tropicel provides grain yields up to 2.58-2.61 t/ha (Holodna, 2021).

Thus, *the purpose of the study* was to substantiate the regularities of the formation of productivity of narrow-leaved lupine depending on seed inoculation and fertiliser on sod-podzolic sandy loamy soils of Polissya. The objectives of the study were to find out the influence of fertiliser, foliar application with complex fertiliser during critical periods of plant development, inoculation of seeds with bacterial preparations on linear indicators, individual productivity and yield of narrow-leaved lupine grain.

MATERIALS AND METHODS

Studies of the effect of fertiliser and seed inoculation on the productivity of narrow-leaved lupine were conducted during 2019-2021 on sod-medium-podzolic sandy loamy soils of Polissya. The soil of the experimental plots was characterised by the following indicators: pHsalt – 5.9, content in the arable layer of humus (according to Tyurin and Kononov) – 1.2%, easily hydrolysed nitrogen (according to Kornfield) – 63.8 mg/kg of dry soil, mobile forms of phosphorus (according to Kirsanov) – 22.7 mg/kg of dry soil, exchange potassium (according to Kirsanov) – 13.6 mg/kg of dry soil.

The field experiment scheme includes factors:

Factor A – seed treatment: 1. Control (without inoculation); 2. Rhizoactive legumes, KL, 2 l/t (seed inoculation);

Factor B – fertilization: 1. Control (without fertilisers); 2. $N_{35}P_{60}K_{16}$ – background 3. N35P60K16 (background) + YaraVita BRASSITREL PRO, KL, 3 l/ha (double foliar application).

Foliar application was carried out with microfertiliser YaraVita BRASSITREL PRO in the rosette phase at a rate of 3 l/ha and at the beginning of budding at a rate of 3 l/ha. Granular mineral fertiliser YaraMila, GR (NPK 16-27-7) at a rate of 220 kg/ha was used. The composition of the fertiliser includes: nitrogen, total (N) – 16%, nitrate (NO_3) – 11.8%, ammonium (NH_4 – 4.2%, phosphorus (P_2O_5 – 27%, potassium (K_2O) – 7%, sulphur (S) – 2% (SO_3 – 5 %), zinc (Zn) – 0.1 %. Mineral fertilisers were applied before early spring harrowing ($N_{24}P_{41}K_{11}$) and before pre-sowing cultivation ($N_{11}P_{19}K_5$). The working fluid rate – 200 l/ha. Inoculation of seeds with biologics was carried out on the day of sowing.

The narrow-leaved lupine variety Olimp was grown using the technology generally accepted for the Polissya zone. Weight of 1,000 seeds – 172 g, laboratory germination rate – 93%. The seeding rate of narrow-leaved lupine in the experiment was 1.1 million germinated seeds per 1 ha.

The area of the accounting plot in the experiment was 26 m^2. The placement of the variants in the experiment is systematic, repeated four times.

Phenological observations of plant growth and development were carried out in the following phases of plant development of narrow-leaved lupine: BBCH 11-51 (germination – budding), BBCH 51-65 (budding – flowering); BBCH 65-81 (flowering – green beans); BBCH 81-93 (green beans – full ripeness). The density of lupine grass was determined twice during the growing season: in the phase of full germination and before grain harvesting. Plant safety was determined by equation 1:

$$P = \frac{H \times 100}{S}, \qquad (1)$$

where: P – plant safety, %; H – number of plants before harvesting, units/m^2; S – number of plants at the time of full shoots, units/m^2; 100 – a number to convert to percentages (Yeshchenko *et al.*, 2005).

The assessment of photosynthetic activity of lupine plants was carried out according to the following indicators: the leaf surface area was determined by the contour method, when the leaves from the test plants laid out on paper were circled with a pencil, and then the contours were measured with a planimeter to determine the total area of the accounting leaves; photosynthetic potential (PP) was calculated according to equation 2:

$$ФП = t \times (S_1 + S_2) \div 2, \qquad (2)$$

where: t – period from germination (BBCH 11) to the green bean phase (BBCH 81), days; S_1 – leaf surface area of plants in the phase BBCH 11, thous. m2/ha; S_2 – leaf surface area of plants in the phase BBCH 81, thous. m^2/ha (Didora *et al.*, 2013).

Accounting of the yield of narrow-leaved lupine was carried out in the phase of full ripeness by harvesting each site separately and weighing the grain. Mathematical processing of the obtained results was carried out by the method of variance analysis using applied computer programmes Excel and Statistica 6.0.

RESEARCH RESULTS

Normal growth and development of lupine plants during ontogenesis is largely ensured by favourable abiotic factors and nutritional conditions. The growing season of narrow-leaved lupine is a complex dynamic process with specific critical periods defined for this crop and a well-defined morphotype for each phase of vegetation. As a result of the conducted phenological observations, indicators of the passage of the main interphase periods by plants of narrow-leaved lupine were established. Notably, over the years of research, shoots (BBCH 11) in lupine occurred on days 13-15 after sowing (Fig. 1). There is a tendency to increase the passage of interphase periods in plants during fertilization. However, the difference in phase passage in fertilised and non-fertilised areas in the germination – budding phase (BBCH 11-51) was 3-5 days (without inoculation) and 3-4 days with inoculation. The budding – flowering period (BBCH 51-65) for all variants ranged from 10-11 days, and the flowering period – green beans (BBCH 65-81) was 17-22 days. A slightly larger time difference between fertilised and non-fertilised areas was observed during the green bean – full ripeness period (BBCH 81-93). Thus, in areas without fertilization, this period was 33-34 days, with the application of $N_{35}P_{60}K_{16}$ – 35-36 days, and 38-40 days – in the option with $N_{35}P_{60}K_{16}$+ YaraVita BRASSITREL PRO, KL, which is 5-6 days longer compared to the control. In general, the growing season of narrow-leaved lupine in the control areas was 97-101 days, in areas with only mineral fertilisers – 103-108 days, and 109-115 days – with additional foliar application with YaraVita Brassitrel. Seed inoculation increased the growing season of plants by 4-6 days.

Determination of plant growth dynamics indicates the peculiarities of grass stand development and its dependence on the studied factors. Admittedly, there was a steady tendency to increase the height of narrow-leaved lupine plants as the growing season progresses and decrease it during the development and maturation of generative organs on plants

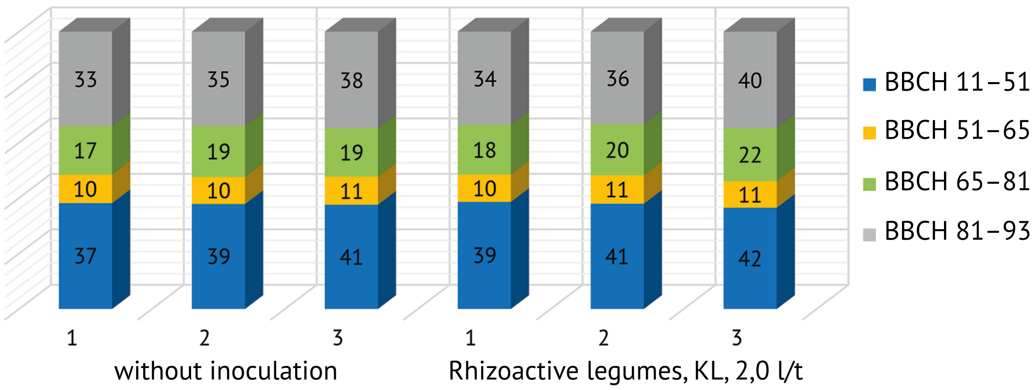

***Figure 1**. Duration of interphase periods in narrow-leaved lupine plants of the Olimp variety, depending on fertilization and inoculation of seeds, average for 2019-2021, days*

***Note:** 1 – without fertilisers (control); 2 – $N_{35}P_{60}K_{16}$; 3 – $N_{35}P_{60}K_{16}$+YaraVita BRASSITREL PRO*

***Source:** compiled by the authors*

This is conditioned by the fact that starting from the green bean phase, the inflorescence of plants dries up and the main part of the nutrients begins to be spent on the development of beans and seeds. During the budding period, the height of narrow-leaved lupine plants in non-fertilised areas was 30.3-31.8 cm and 32.4-36.3 cm in fertilised areas. During plant flowering, the height at the control increased by 15.4-15.7%, while during fertiliser application – by 16.3-16.9%, which indicates the effective use of nutrients from fertilisers. In the green bean phase, the increase in plant height was 13.7-13.9% and 12.9-13.4%, respectively. That is, the rate of increase in linear plant growth has decreased in all variants, since during this period the use of nutrients by plants for the development of generative organs and future seed yield begins. The highest height indicators of narrow-leaved lupine plants (80.0 cm) were noted during processing seeds before sowing with bioinoculant Rhizoactive legumes, KL, 2 l/t, double foliar application of crops with YaraVita BRASSITREL PRO, KL microfertiliser in the green bean phase with the background application of mineral fertilisers ($N_{35}P_{60}K_{16}$) (Table 1).

***Table 1**. Dynamics of the height of narrow-leaved lupine plants of the Olimp variety depending on fertilization and inoculation of seeds (2019-2021), M±m, cm*

Seed treatment	Fertiliser	Phases of plant growth and development			
		budding	flowering	green beans	full ripeness
without inoculation	without fertilisers (control)	30.3±3.3	46.8±3.6	64.1±4.0	58.6±4.7
	$N_{35}P_{60}K_{16}$	32.4±2.7	52.8±5.9	70.7±3.9	63.0±4.9
	$N_{35}P_{60}K_{16}$ + YaraVita BRASSITREL PRO	33.8±3.9	54.4±3.3	72.2±2.9	69.8±4.3
Rhizoactive legumes, KL, 2 l/t	without fertilisers (control)	31.8±3.0	49.9±5.0	69.2±4.4	63.3±5.0
	$N_{35}P_{60}K_{16}$	34.6±3.1	58.4±5.1	75.5±4.8	70.2±5.6
	$N_{35}P_{60}K_{16}$ + YaraVita BRASSITREL PRO	36.3±3.6	61.2±2.6	80.0±5.0	74.2±5.8

***Source:** compiled by the authors*

The intensity of the initial processes of plant growth and development plays a significant role in the formation of high productivity of narrow-leaved lupine.It was established that the density of narrow-leaved lupine plants varied depending on pre-sowing seed treatment with a bacterial preparation and double foliar application. Notably, the studied factors did not significantly affect the germination rates of narrow-leaved lupine seeds. Thus, in the control, this indicator ranged from 87.7 to 89.0%, while in fertilised areas it was 88.4-89.4%, respectively, that is, the difference was only 0.4-0.7% (Table 2). A significantly greater dependence on fertiliser was observed in plant survival rates. In areas without fertilisers, the density of plants before harvesting was 75.4-76.3 units/m^2 (the survival rate was 75.4-76.3%). The application of only mineral fertilisers increased the density indicators to 79.8-82.5 units/m^2 with a plant survival rate of 90.3-92.3%. Additional foliar application of plants with microfertilisers YaraVita BRASSITREL PRO, KL on the background of $N_{35}P_{60}K_{16}$ provided an increase in density and survival rates by another 1.1-1.6 units/m^2 and 1.3-1.8%, respectively, and by 6.0-7.3 units/m^2 (6.2-7.9%) compared to the control. Seed inoculation contributed to an increase in field germination by 1.0-1.27%.

***Table 2**. Indicators of plant density of narrow-leaved lupine of Olimp variety depending on fertilization and inoculation of seeds, average for 2019-2021*

Seed treatment	Fertiliser	Number of plants per 1 m^2, units	Field germination, %	Plant density before harvesting, units/m^2	Survival rate, %
without inoculation	without fertilisers (control)	96.5	87.7	75.4	85.9
	$N_{35}P_{60}K_{16}$	97.2	88.4	79.8	90.3
	$N_{35}P_{60}K_{16}$ + YaraVita BRASSITREL PRO			81.4	92.1
Rhizoactive legumes, KL, 2 l/t	without fertilisers (control)	97.9	89.0	76.3	85.7
	$N_{35}P_{60}K_{16}$	98.3	89.4	82.5	92.3
	$N_{35}P_{60}K_{16}$ + YaraVita BRASSITREL PRO			83.6	93.6

***Source:** compiled by the authors*

According to the results of multiple linear regression analysis, there is a strong positive dependence of grain weight per plant on the number of beans per plant and the number of grains per bean (Table 3).

***Table 3**. Results of regression analysis of the dependence of grain weight from one plant on the number of beans on the plant and the number of grains in the bean, average for 2019-2021*

	Beta	Std. Err. of Beta*	B	Std.Err. of Beta	t(3)	p-level
Intercept			-2.09804	0.350663	-5.98308	0.009347
Number of beans per plant, units (X_1)	0.987428	0.028251	0.80904	0.023147	34.95253	0.000051
Number of grains per bean, units (X_2)	0.098733	0.028251	0.32695	0.093551	3.49490	0.039627

***Note:** *Std. Err. of Beta – Standart error of Beta*
***Source:** compiled by the authors*

Regression results for the dependent variable: grain weight from 1 plant (Y) R= 0.99880735,

R^2=0,99761612, Adjusted R^2=0.99602687, $F(2,3)$= =627.73, p<0.00012. The coefficient of determination is calculated based on the constructed model (R^2=0,996), which showed a significant impact of the number of beans on the plant and the number of grains in the bean on the indicator under study. Regression model for the dependence of the indicator ($\hat{Y}$) – weight of grain per plant depends on the number of beans in the plant and the number of grains in the bean is (3):

$$\hat{Y}=-2.1+0.81x_1+0.33x_2 \quad (3)$$

where $\hat{Y}$ – predicted value of grain weight per plant of narrow-leaved lupine;
X_1 – number of beans per plant, units;
X_2 – number of grains in a bean, units.

All coefficients of the equation are significant at the 5% level (p-level<0.05).

According to the findings, indicators of individual productivity of narrow-leaved lupine plants were established. The number of beans on one plant, regardless of the studied factors, ranged from 4.1-4.6 units. In general, it can be noted that with an increase in fertiliser application doses and pre-sowing seed inoculation, the indicators of individual productivity of narrow-leaved lupine increased (Table 4). In non-fertilised areas, the weight of 1,000 seeds was 161-162 g, and with the application of $N_{35}P_{60}K_{16}$ it increased to 165-166 g. Additional application of YaraVita BRASSITREL PRO, KL provided an increase in the weight of 1,000 seeds by another 2-3 g, which certainly affects the commercial quality of seeds. The largest weight of seeds from a single narrow-leaved lupine plant was observed on variant $N_{35}P_{60}K_{16}$+YaraVita BRASSITREL PRO, KL – 2.91 g.

***Table 4**. Individual productivity of narrow-leaved lupine depending on fertilization and seed inoculation, average for 2019-2021*

Seed treatment	Fertiliser	Quantity, units			Weight, g	
		beans on a plant	grains on a plant	seeds in a bean	1,000 seeds	seeds from the plant
without inoculation	without fertilisers (control)	4.1	15.1	3.7	161	2.43
	$N_{35}P_{60}K_{16}$	4.3	15.6	3.6	165	2.57
	$N_{35}P_{60}K_{16}$ + YaraVita BRASSITREL PRO	4.4	15.7	3.6	167	2.62
Rhizoactive legumes, KL, 2 l/t	without fertilisers (control)	4.3	15.9	3.7	162	2.58
	$N_{35}P_{60}K_{16}$	4.6	17.1	3.7	166	2.84
	$N_{35}P_{60}K_{16}$ + YaraVita BRASSITREL PRO	4.7	17.2	3.7	169	2.91

***Source:** compiled by the authors*

A fairly important indicator of the productivity of any crop is the leaf surface area, which directly affects the process of photosynthesis in the plant. The results of the conducted studies indicate that in the germination phase, the area of narrow-leaved lupine leaves amounted to 6.3-6.8 thousand m^2/ha on plots without fertilization. With the application of mineral fertilisers at a rate of $N_{35}P_{60}K_{16}$ this figure was 6.9-7.1 thousand m^2/ha, which is 4.5-7.9% more compared to the control, that is, starting from the germination phase of the narrow-leaved lupine plant on fertilised areas, the leaf apparatus begins to form more intensively (Fig. 2).

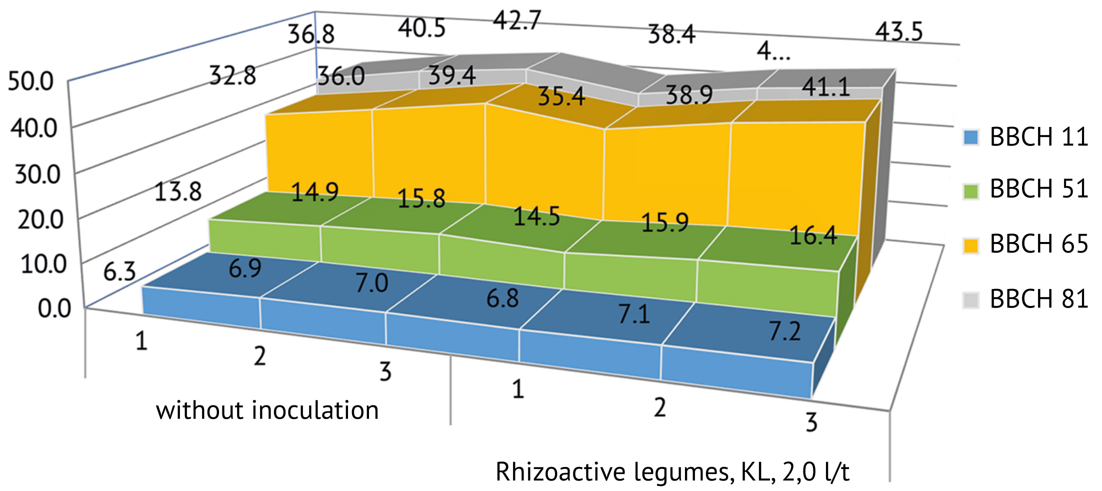

***Figure 1**. Leaf surface area of narrow-leaved lupine depending on fertiliser and seed inoculation, average for 2019-2021, thous. m^2/ha*

***Note:** 1 – without fertilisers (control); 2 – $N_{35}P_{60}K_{16}$; 3 – $N_{35}P_{60}K_{16}$+YaraVita BRASSITREL PRO, KL*

***Source:** compiled by the authors*

The tendency to increase the difference in leaf surface areas between fertilised and non-fertilised variants was also observed in later phases of vegetation of narrow-leaved lupine plants. Thus, in the green bean phase, the area of leaves in the control was 36.8-38.4 thousand m2/ha, whereas on variant $N_{35}P_{60}K_{16}$+YaraVita BRASSITREL PRO, KL – 42.7-43.5 thousand m^2/ha. Seed inoculation provided an increase in the leaf area by 0.8-1.6 thousand m^2/ha (10.2-10.4%) compared to non-inoculated plots.

Calculation of photosynthetic potential (PP) indicators of narrow-leaved lupine plants during the phases of active growth indicate that in non-fertilised areas, the PP was 1.3-1.51 million m^2/ha×day, and given the duration of the growing season (64-67 days), this is a fairly good indicator (Fig. 3).

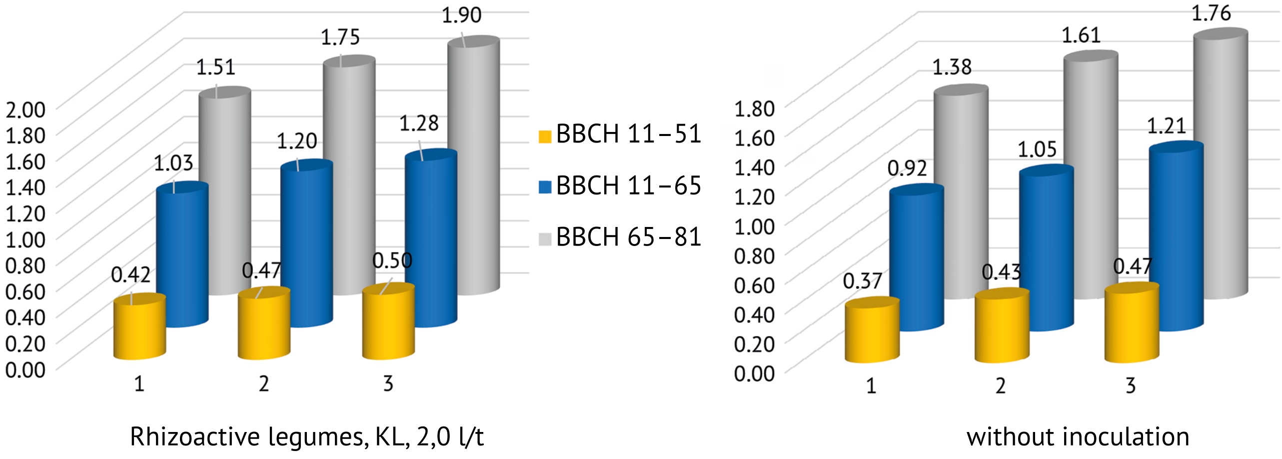

***Figure 3**. Photosynthetic potential of narrow-leaved lupine depending on the fertilization and inoculation of seeds, the average for 2019-2021, mln. m²/ha×day*

***Note:** 1 – without fertilisers (control); 2 – $N_{35}P_{60}K_{16}$; 3 – $N_{35}P_{60}K_{16}$+YaraVita BRASSITREL PRO, KL*

***Source:** compiled by the authors*

There was a tendency to increase PP in interphase periods of active growth. During the germination – budding phase, the PP was 0.37-0.50 million m²/ha×day, and in the germination – flowering phase – 0.92-1.20 million m²/ha × day, that is, the increase in PP was 25.4-25.8%. Photosynthetic potential during the germination – green beans phase amounted to 1.38-1.90 million m²/ha×day , which is 14.6-15.3% more than the germination – flowering phase, that is, the rate of photosynthetic activity after the flowering phase began to decrease slightly. In general, in all fertilised areas, high indicators of lupine leaf activity were observed. According to the findings, high grain productivity of narrow-leaved lupine was established. Inoculation provided a yield increase of 0.14 t/ha on plots without fertilisers and 0.29-0.30 t/ha on fertilised ones, which in percentage terms was 10.8% and 11.4%, respectively (Fig. 4). In the control cariant, the yield was 1.83-1.97 t/ha. With the application of only mineral fertilisers in the norm $N_{35}P_{60}K_{16}$, the yield increased to 2.05-2.34 t/ha (the increase was 0.22-0.37 t/ha). Additional top dressing of plants with YaraVita BRASSITREL PRO, KL on the background of $N_{35}P_{60}K_{16}$ together with pre-sowing inoculation of seeds with bioinoculant Rhizoactive legumes, KL provided a yield of narrow-leaved lupine grain at the level of 2.43 t/ha, which is 0.60 t/ha more compared to the control.

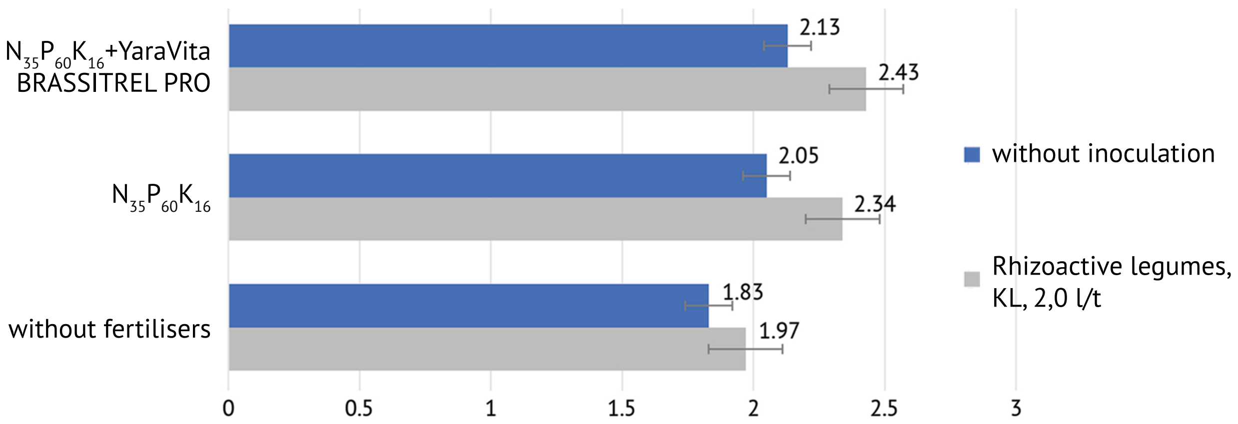

***Figure 4**. Yield of narrow-leaved lupine grain depending on fertiliser and seed inoculation, average for 2019-2021, t/ha*

***Note:** LSD=0.18 (least significant difference) to estimate the significance of the difference in partial averages; LSD=0.11 to estimate the significance of the difference in the average values for factor A; LSD=0.13 to estimate the significance of the difference in the average for the factor B and AB*

***Source:** compiled by the authors*

Based on the results of statistical analysis, indicators of the share of influence of the studied factors on the yield of narrow-leaved lupine grain were established (Fig. 5).

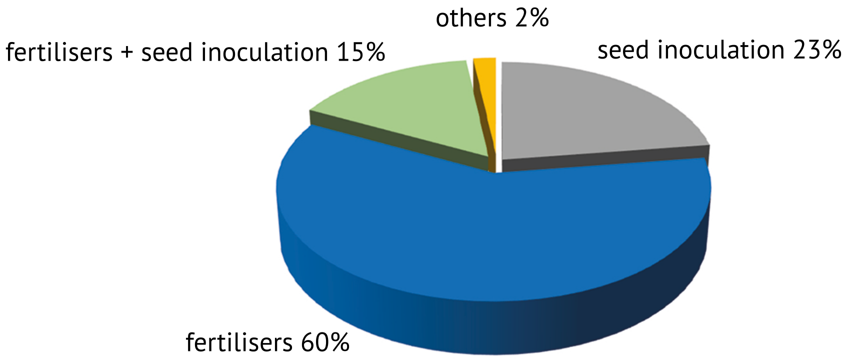

Figure 5. *The share of influence of factors on the yield of narrow-leaved lupine grain, average for 2019-2021, %*
Source: *compiled by the authors*

The "fertiliser" factor had the greatest impact on grain yield – 60%, followed by "inoculation" – 23%. The share of influence of other factors not studied was 2%. Based on the results of correlation analysis, the dependence of the yield of narrow-leaved lupine grain on the leaf surface area in the green bean phase was established (Fig. 6).

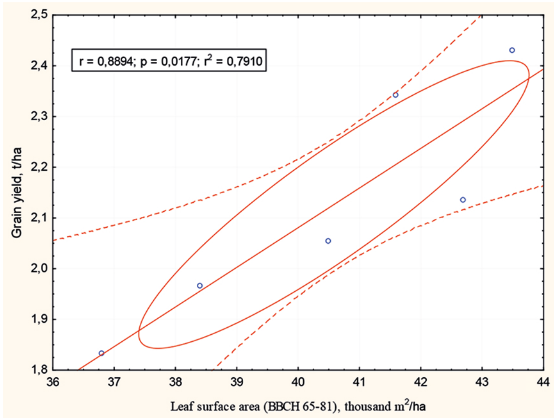

Figure 6. *Correlation between the yield of narrow-leaved lupine grain and the leaf surface area*
Source: *compiled by the authors*

Regression model of indicator dependence ($\hat{z}$) – grain yield from the leaf surface area of narrow-leaved lupine plants has the form (4):

$$\hat{Z}=-1.0469+0.0782x, \quad (4)$$

where $\hat{Z}$ – grain yield, t/ha; X – leaf surface area, thousand m^2/ha.

Therefore, it can be stated that there is a strong relationship between the grain yield of narrow-leaved lupine and the leaf area in the green bean phase (r=0.8894). The significance level did not exceed 5% (p-level=0.0177), which confirms statistical reliability. This equation applies to 79.1% of the sample.

The formation of yield and quality of narrow-leaved lupine seeds in the conditions of medium podzolic sandy loamy soils of Polissya is influenced by the duration of interphase periods by plants, the dynamics of grass stand growth, features of the use of photosynthetic active radiation (PAR), seed inoculation, and fertiliser. The study by V. Ratoshniuk and M. Havryliuk (2020) established an increase in the duration of the growing season of narrow-leaved lupine by 6-9 days with double foliar application with water-soluble complex fertilisers in the budding phase and the beginning of seed filling on a mineral background ($N_{60}R_{60}K_{60}$) compared to options without fertiliser. The obtained results of phenological observations regarding the passage of phenological phases of plants can be explained by the biological features of the Olimp variety and its reaction to the factors under study, which is consistent with the conclusions of other researchers (Pidpaly *et al.*, 2013). The dependence of lupine yield on the characteristics of a particular variety has also been noted (Mazumder *et al.*, 2021).

Optimisation of fertilization of narrow-leaved lupine contributed to the formation of maximum plant height indicators in the budding (BBCH 51), flowering (BBCH 65), and green bean (BBCH 81) phases. The studies also established the formation of the maximum height indicators of narrow-leaved lupine plants with double top dressing in the budding phase and at the beginning of seed filling with Kristallon Brown fertiliser against the background of mineral fertilization at a rate $N_{90}R_{60}K_{90}$ (Pidpaly *et al.*, 2013). A distinctive feature of lupine is the weak possibility of developing a number of side branches, which limits the formation of plant productivity (Holodna, 2021). Therefore, for the optimal supply of plants in critical periods of their development with nutrients during the growing season of narrow-leaved lupine, not only the main fertiliser, but also foliar application with liquid fertilisers have a significant impact (Holodna, 2019). The obtained experimental data are consistent with the conclusions of other researchers regarding the effectiveness of inoculation of leguminous seeds with bacterial preparations using trace elements and foliar application during the growing season. Thus, inoculation of chickpea seeds with Biomag bioinoculant and two-time foliar application of plants with microfertilisers increases stem density and plant survival (Didur & Temchenko, 2017). The positive effect of applying mineral fertilisers in combination with double foliar application on the individual productivity of narrow-leaved lupine is also confirmed by the findings of other researchers (Pidpaly *et al.*, 2013). The data obtained confirm the conclusions of other researchers (Sulas *et al.*, 2016; Tkachuk *et al.*, 2019; Bouray *et al.*, 2021) regarding the effect of inoculation of leguminous seeds with bacterial preparations and foliar application during the growing season on the indicators of individual plant productivity. Thus, inoculation of chickpea seeds with Biomag bioinoculant and two-time foliar application of plants with microfertilisers significantly improves such elements of the crop structure as the total number of beans and seeds per plant, the weight of seeds per plant and the weight of 1,000 seeds (Didur & Mordvaniuk, 2018). According to A.V. Holodna (2022), the maximum number of beans (20.2 units/plant) was obtained by treating narrow-leaved lupine seeds with a bioinoculant in combination with a Nano-Gro growth stimulator and applying mineral fertilisers ($N_{38}P_{48}K_{66}$+N_{30}).

The effect of foliar application with water-soluble complex fertilisers on increasing the leaf surface area of narrow-leaved lupine is consistent with other studies (Ratoshniuk & Havryliuk, 2020). Similar studies were conducted on other leguminous crops. Inoculation of soybean seeds with BTU bioinoculant and foliar application of plants with Helprost organo-mineral fertiliser contributed to an increase in the leaf surface area by 35.3% compared to the control (Didur, 2022). The establishment of the maximum leaf surface of soybeans under the influence of seed inoculation with bacterial preparations and foliar application with complex microfertiliser Rostok bobovi was also observed in studies by S.M. Kalenska *et al.* (2016). The indicator in the experiment, depending on the variety, increased by 17.8-29.8% compared to the control (Kalenska *et al.*, 2016). The results obtained are consistent with data from A.V. Holodna (2019) on the formation of the maximum yield of narrow-leaved lupine (2.79 and 2.80 and t/ha) with the application of mineral fertilisers ($N_{68}R_{48}K_{66}$), complex seed treatment with BTU-r and MikoHelp biologics, foliar application at the 2nd and 4th stages of plant organogenesis with Tropikel fertiliser. The study by O. Milenko (2022) found that the maximum yield of soybeans (3.11 t/ha) was formed with the combined application of mineral fertilisers ($N_{15}P_{30}K_{40}$) and double top dressing with Vuksal Microplant complex fertiliser. The formation of high grain productivity of narrow-leaved lupine can be explained by the ability of lupine to fix atmospheric nitrogen and the use of phosphorus and potassium from hard-to-reach compounds of arable and deeper horizons.

CONCLUSIONS

The productivity of narrow-leaved lupine in Polissya conditions is formed due to a number of factors. Thus, when applying only mineral fertilisers, the duration of the growing season of plants was 103-108 days, additional foliar application helped to increase it to 109-115 days, which is 6-7 and 12-14 days more compared to the control.

Plant density of narrow-leaved lupine for the harvesting period, regardless of fertiliser and seed inoculation, accounted for 75.4-83.6%. In fertilised areas without inoculation, this indicator was 2.2-2.7% lower compared to inoculation. The survival rate of lupine plants with fertilization ranged from 90.3 to 93.6%. The greatest individual productivity of lupine plants was recorded on the variant of combined fertilization and inoculation with the following indicators: the number of beans per plant is 4.7 units; the number of grains per plant is 17.2 units; the number of seeds in a bean – 3.7; weight of 1,000 grains – 169.0 g; weight of grain per plant – 2.91 g.

Multiple linear regression analysis showed a high positive dependence of the grain mass from one plant on the number of beans on the plant and the number of grains in the bean (R=0.99), as a result of which a regression model was constructed, and probability of the null hypothesis for the coefficients of the regression equation for all variants was less than 0.05. The best indicator of photosynthetic potential was observed in fertilised areas of narrow-leaved lupine, which in the period from germination (BBCH 11) to green bean phase (BBCH 81) with seed inoculation amounted to 1.75-1.90 million m^2/ha×days.

When applying mineral fertilisers at a rate $N_{35}P_{60}K_{16}$, the yield of narrow-leaved lupine grain was obtained at the level of 2.34 t/ha. Double fertilization of plants with YaraVita BRASSITREL PRO, KL on the background of $N_{35}P_{60}K_{16}$ together with pre-sowing treatment of narrow-leaved lupine seeds with bioinoculant Rhizoactive legumes, KL contributed to the maximum yield of the Olimp variety (2.43 t/ha). A close positive correlation was established between the leaf surface area during the flowering phase (BBCH 65-81) and the grain yield indicators of narrow-leaved lupine (*r*=0.89). Based on the obtained data, a regression equation was constructed, which is valid in 79.1% of the sample.

Crop production in modern climatic conditions requires adaptive agricultural technologies for growing field crops, which are aimed at maximising the protective reactions of the plant body to adverse environmental conditions. Further study of narrow-leaved lupine involves the selection of adaptive varieties, improvement of tillage methods, and identification of optimal sowing dates and seeding rates in order to adapt plants to abiotic environmental factors.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Формування продуктивності люпину вузьколистого залежно від інокуляції насіння та удобрення

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Анотація. Люпин вузьколистий характеризується цінними господарськими особливостями, тому є важливим джерелом збалансованого і легкозасвоюваного рослинного білка. Метою досліджень було обґрунтувати вплив інокуляції насіння та удобрення на ріст і розвиток рослин люпину вузьколистого для максимальної реалізації генетичного потенціалу сорту в умовах Полісся. Використані такі методи досліджень: загальнонаукові (гіпотеза, індукція і дедукція, узагальнення), спеціальні (польовий, вимірювальний та ваговий, фізіологічний, лабораторний), статистичний (кореляційно-регресійний). Польові дослідження проводили протягом 2019-2021 рр. Досліджено особливості росту і розвитку рослин люпину вузьколистого сорту Олімп в умовах Полісся. З'ясовано позитивний вплив інокуляції насіння бактеріальними препаратами та позакореневого підживлення комплексним добривом на продуктивність люпину вузьколистого, що відіграє важливе значення у вирішенні проблеми рослинного білка. Визначено оптимальну площу листкової поверхні рослин за рахунок оптимізації елементів агротехнології люпину вузьколистого. Встановлено фотосинтетичний потенціал люпину залежно від інокуляції насіння біопрепаратами та удобрення. Досліджувані фактори підвищують густоту стеблостою, виживаність рослин і поліпшують показники індивідуальної продуктивності культури. Інокуляція насіння біопрепаратами та позакореневе підживлення забезпечує формування найвищої (2,43 т/га) зернової продуктивності люпину вузьколистого. Інокуляція насіння підвищує на 10,8-11,4 % урожайність зерна люпину вузьколистого залежно від фону живлення. Позакореневе підживлення рослин комплексним добривом у фазах BBCH 21-23 і BBCH 51 на мінеральному фоні за інокуляції насіння забезпечує збільшення на 2,8 % урожайності зерна порівняно з контролем. Результати досліджень можуть бути використані для удосконалення елементів технології вирощування люпину вузьколистого, що забезпечить формування високих і сталих врожаїв зерна

Ключові слова: урожайність зерна; бактеріальні препарати; позакореневе підживлення; шкала BBCH; лінійні показники; площа листкової поверхні; фотосинтетичний потенціал