Features of narrow-leaved lupin (Lupinus angustifolius) development and productivity in the application of micronutrients in the conditions of the Central Non-Chernozem zone of Russia

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Abstract. The results of three years of field research in conditions of low-fertile sod-podzolic sandy loam soil of the Kaluga region on the study of growth, development, and seed productivity of narrow-leaved lupin during foliar fertilization of plants with BorSTART, MicroStim-Marganets, and Novalon 19-19-19+2MgO+ME fertilizers are presented. The use of micronutrients increased the height of narrow-leaved lupin plants, starting from the flowering phase and the leaf area from the budding phase to the end of the vegetation of plants. The largest leaf area in the flowering phase was found in options with the treatment of plants with micro-fertilizers BorStart – 480.2 cm^2/plant and Microstim Marganets – 475.3cm^2/plant. The treatment of plants with micronutrients exceeded the control variant by weight of the aboveground mass in the phase of glaucous pods by 8.4–11.6%. The best results were obtained when treating plants with boric micro-fertilization (BorStart). Micro-fertilizers increased the yield of narrow-leaved lupin seeds in an average of 3 years from 0.16 to 0.38 t/ha compared with the control. The highest seed yield was when processing plants with chelated forms of micro-fertilizers – Novalon and MicroStim Marganets. The use of micro-fertilizers led to an increase in the content of crude ash and crude protein in lupin seeds.

1 Introduction

The increasing number of livestock in the Russian Federation further highlights the problem of a lack of animal feed, its imbalance in protein [1].

Great efforts of plant scientists and advanced practitioners are aimed at solving this problem. This is partly solved by organizational and economic methods, by increasing the area of sowing under highly productive leguminous crops, leguminous grasses and legume-cereal grass mixtures, characterized by increased grain harvest, feed mass, and quality of feed produced from them [2, 3, 4].

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Scientists often discuss the priority of saturation of crop rotations with annual leguminous crops and their mixtures or perennial crops of legumes and legume-cereal grass mixtures [5, 6].

The latter consider the low cost of cultivating perennial crops with higher energy efficiency of feed protein production to be the determining argument [7].

Nevertheless, annual leguminous crops are characterized by a high content of highly nutritious feed protein in grain and feed mass, a significant amount of atmospheric nitrogen fixed by them, which makes them indispensable precursors for other crops [8, 9].

At the same time, the seeds of grain legumes are good raw materials for the production of cereals, flour, and oil. A special place among legumes is occupied by narrow-leaved lupin. It is a relatively unpretentious crop for soil fertility, having the ability to assimilate insoluble phosphates, yielding high grain yields [10, 11, 12].

Along with lupin breeding to obtain consistently high yields, it is equally important to search and develop agrotechnical methods for obtaining high-quality crop seed yields without reducing their environmental and soil-restoring functions [13].

It seems very promising to study the issues of improving the mineral nutrition of narrow-leaved lupin on poor soils using new types of low-cost micro-fertilizers that can produce high yields of good quality grain without compromising the nitrogen-fixing ability of the crop.

2 Material sand Methods

One of the primary tasks of modern crop production in the country is to increase the grain yield of leguminous crops while maintaining a high supply of its protein. This can be achieved, among other things, through the correct selection of low-cost mineral nutrition of leguminous plants.

The purpose of the research in the field experiment was to identify the most effective types of micro-fertilizers in the cultivation of narrow-leaved lupin variety Ladny in the conditions of sod-medium podzolic sandy loam soil of the Central Non-Chernozem zone of Russia.

Research objectives.

1. To study the effect of different types of micro-fertilizers on the growth and development of narrow-leaved lupin variety Ladny.

2. To evaluate the effect of the studied fertilizers on the yield and quality of seeds of narrow-leaved lupin.

3. To calculate the economic efficiency of the use of micro-fertilizers.

To achieve this goal in the experimental field of the Kaluga branch of the RSAU-MAA named after K.A. Timiryazev in 2021-2023, a field experiment was conducted according to the following scheme:

1. Control (lupin cultivation without the use of micro-fertilizers).

2. Treatment of plants with BorStart micro-fertilizer with a rate of 2.0 l/ha.

3. Treatment of plants with micro-fertilizer MicroStim-Marganets with a rate of 1.0 l/ha.

4. Treatment of plants with micro-fertilizer Novalon 19-19-19+2MgO+ME with a norm of 3 kg/ha.

The treatment of plants with micro-fertilizers was carried out twice during the growing season, the first time – in the phase of the beginning of plant stalking, and after 10 ten days a second fertilization was carried out, control plots were sprayed with clean water with a similar rate of working fluid consumption.

The experiment was carried out four times. The placement of plots is randomized. The area of the accounting plot is 10 m^2.

Lupin crops were carried out with a manual seeder in the first decade of May with a seeding rate of 1.2 million germinating seeds per 1 ha with a row spacing of 15 cm.

The precursor crops in the experiment were: in 2021 – oat, in 2022 – barley, in 2023 – oat. Agricultural technology is generally accepted in the experiment for the Central region of Russia – in autumn, after harvesting the precursor, winter plowing was carried out to a depth of 19 cm. In spring, when the soil was physically ripe, cultivation was carried out at 12 cm and pre-sowing cultivation to a depth of 8 cm.

The soil of the experimental site is sod-medium podzolic, sandy loam on glacial deposits. The arable horizon thickness is 20 cm. The soil has a low humus content (1.18), a low content of exchangeable potassium, and a high content of mobile phosphorus, respectively 61 and 216 mg/kg of soil. The content of boron and molybdenum in the soil is 0.50 and 0.23 mg/kg, respectively. The reaction of the medium is slightly acidic (5.8).

The growing season of 2021 was characterized by abnormally high temperatures, in some periods of summer the air temperature reached 31-32.4°C. The total amount of precipitation from May to September exceeded the long-term average values, but their distribution was extremely uneven. The hydrothermal coefficient (HTC) for the period from May to August was 1.3. The vegetation period of 2022 was close to the long-term average values in terms of temperature, but almost 2 times higher than the long-term average in terms of precipitation. The HTC of the crop growing season was 2.1. In 2023, the temperature indicators of the growing season were equal to the average annual values, the amount of precipitation was slightly lower than the average. The HTC was 1.3.

Characteristics of research objects.

The narrow-leaved lupin variety Ladny is an ultra-early ripening variety created by the method of inducing and selecting mutants from the Nemchinovsky 846 variety. It is an annual plant of a self-pollinating type, up to 1.5 m tall, and with a growing season of 70-80 days. The crude protein content in the grain reaches 33-35%, alkaloids 0.001–0.015%. An intensive type variety with a high genetic potential for seed productivity, the average grain yield is 3-4 tons per hectare. The variety is recommended for cultivation in the central and adjacent northern regions of the Non-Chernozem zone of Russia for grain forage purposes [14].

BorSTART is a boron-based liquid fertilizer in a concentrated suspension for use on a leaf. BorSTART micro-fertilizer improves the distribution and penetration rate of absorbed boron, increases the amount of boron in the plant [15].

MicroStim-Marganets is a liquid, complex micro-fertilizer. The composition includes manganese (in chelated form) 50 g/l, nitrogen 40 g/l, humic substances 5.7 g/l. The preparation form is a water-soluble concentrate. It is recommended for non-root top dressing of cereals, legumes, vegetables, and fruit crops. Micro-nutrient is compatible with pesticides, growth regulators, but it is recommended to check the components for compatibility before preparing the tank mixture [16].

Novalon 19-19-19+2MgO+ME is a water-soluble complex fertilizer with trace elements in the form of chelates intended for use on various crops. It contains 19% nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), and 2% magnesium (MgO) in its composition. It also contains a number of trace elements bound by the chelating agent EDTA (ethylenediaminetetraacetic acid), such as manganese (Mn) 0.035%, copper 0.015% (Cu), iron 0.08% (Fe), zinc 0.035% (Zn), and uncomplexed trace elements – boron (B) 0.02%, sulfur (S) 1.5%, and molybdenum 0.002% (Mo) [17].

The experiment laying, observations, records, and analyses were performed according to generally accepted methods [18, 19].

3 Results and Discussion

Crop yield depends on many factors, including compliance with the recommended seeding rate for the cultivation region. With a seeding rate of 1.2 million full-fledged seedlings were obtained from germinating seeds per 1 ha (Table 1).

Table 1. The plant stand density of narrow-leaved lupin, pcs/m^2.

Option of experiment	Plant stand density					
	2021		2022		2023	
	full sprouting	before harvesting	full sprouting	before harvesting	full sprouting	before harvesting
Control	107	89	105	90	109	89
BorStart	108	80	107	86	110	87
MicroStim	115	88	110	87	106	86
Novalon	107	83	108	86	107	87

Source: Compiled by the authors

The data in Table 1 indicate that in all the years of research, during the period of full germination of narrow-leaved lupin plants, a relatively equal stem was formed in the range of 106-115 plants/m^2. By the time the crop was harvested, its significant thinning had occurred. By year, it ranged from 13.1 to 23.4; 11.1 to 20.9, and from 17.8 to 20.9%, respectively, in 2021, 2022, and 2023. This did not depend on the application of the studied micro-fertilizers, but was determined by the peculiarities of agro-climatic conditions during the specified growing seasons.

The duration of interphase periods during the development of narrow-leaved lupin variety Ladny did not depend on micro-fertilizers in the experiment, but differed by years of research depending on the prevailing temperature and humidity conditions in these years. The hotter weather during the growing season of 2021 contributed to a faster passage of certain phases of crop development. The total growing season of narrow-leaved lupin variety Ladny was 81 days, compared to 87 and 88 days in 2022 and 2023, respectively.

Table 2. The duration of interphase periods during the development of narrow-leaved lupin variety Ladny according to the years of research, days.

Duration of interphase period	Years of research			On average for 3 years
	2021	2022	2023	
Sowing - shoots	10	11	12	11
Shoots - first pair of real leaves	6	8	8	7
First pair of real leaves - stooling	9	10	10	10
Stooling - budding	15	15	15	15
Budding - flowering	8	8	8	8
Flowering - glaucous pods	10	11	11	11
Glaucous pods - full ripeness	23	24	24	24
Duration of the growing season	81	87	88	86

Source: Compiled by the authors

On average, for 3 years during the growing season of narrow-leaved lupin, the longest interphase periods were "stooling - budding" - 15 days and "glaucous pods - full ripeness" - 24 days.

The dynamics of the height of narrow-leaved lupin plants on average for 2021-2023, shown in Figure 1, clearly demonstrates that double treatment of plants with the studied types of micro-fertilizers increased the height of narrow-leaved lupin plants, starting from the phase of flowering and glaucous pods. This was especially significant when treating lupin plants with MicroStim preparation in the flowering phase and Novalon preparation in the phase of glaucous pods.

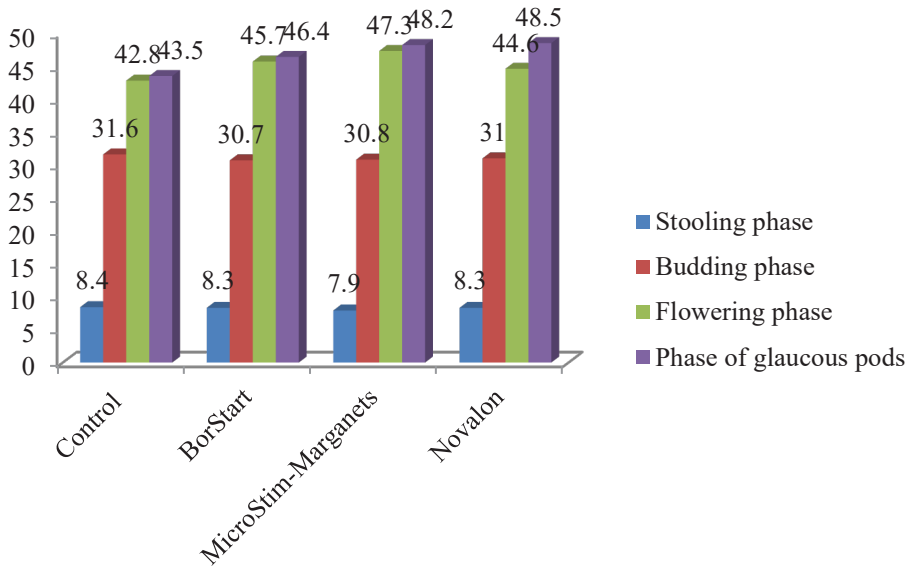

Fig. 1. Dynamics of plant height of narrow-leaved lupin on average for 2021-2023, cm.

Source: Compiled by the authors

The level of crop yield is largely determined by the photosynthetic activity of crops, while the size of the leaf surface is the main indicator. An analysis of the leaf area of narrow-leaved lupin in an average of 3 years indicates that it increased before the flowering phase in all experiment options (Table 3).

Table 3. The leaf area of narrow-leaved lupin on average for 2021-2023, cm^2/plant.

Option of experiment	Crop development phase			
	stooling	budding	flowering	glaucous pods
Control	62.4	239.6	460.6	182.4
BorStart	60.0	257.6	480.2	185.2
MicroStim Marganets	62.4	263.2	475.3	184.8
Novalon	60.0	246.4	461.0	185.2

Source: Compiled by the authors

The studied types of micro-fertilizers, enhancing metabolic processes in the cells of the crop plants, contributed to an increase in the leaf area of the narrow-leaved lupin variety Ladny starting from the budding phase until the end of plant vegetation. The largest leaf

area in the flowering phase was shown by options with the treatment of plants with micro-fertilizers BorStart - 480.2 cm^2/plant and MicroStim Marganets - 475.3 cm^2/plant

To determine the optimal timing of the use of narrow-leaved lupin for forage purposes or as a sideral fertilizer, it is important to know the dynamics of the increase in the aboveground mass of plants during the growing season. Under the experiment conditions, the increase in the crop aboveground mass differed according to the years of research and the studied experiment options (Table 4).

Table 4. Dynamics of the increase in the aboveground mass of plants by years of research, g.

Option of experiment	Years of research	Plant development phase			
		stooling	budding	flowering	glaucous pods
Control	2021	2.1	9.2	13.9	22.9
	2022	1.9	9.0	13.2	22.5
	2023	2.2	8.9	13.5	22.2
	On average for 3 years	2.1	9.1	13.3	22.5
BorStart	2021	2.1	9.2	14.5	25.9
	2022	2.0	9.1	14.0	24.4
	2023	2.4	9.0	14.1	25.1
	On average for 3 years	2.2	9.1	14.1	25.1
MicroStim-Marganets	2021	2.3	8.1	15.8	24.7
	2022	2.1	8.6	15.2	24.6
	2023	2.5	8.9	15.3	23.9
	On average for 3 years	2.3	8.5	15.4	24.4
Novalon	2021	2.2	8.4	13.3	25.0
	2022	2.0	8.7	14.3	24.7
	2023	2.5	9.2	14.8	24.8
	On average for 3 years	2.2	8.8	14.1	24.8

Source: Compiled by the authors

The most active increase in the crop aboveground mass was observed in a more favorable temperature and humidity regime in 2021 in most experiment options. From the flowering phase to the phase of glaucous pods, the largest weight gain was noted. On average, over 3 years in the control option, the increase in aboveground mass during this period was 69.2%. Two-time treatment of vegetative plants of narrow-leaved lupin with the studied micro-fertilizers exceeded the control option by weight of the aboveground mass in the phase of glaucous pods, depending on the experiment option, by 8.4-11.6%. The best results were obtained when treating plants with boric micro-fertilization (BorStart).

The most important biological feature of the leguminous crops cultivation is their ability to fix atmospheric nitrogen and accumulate it in the soil. The activity of nitrogen fixation of leguminous crops is influenced by such parameters of the symbiotic apparatus as the number of nodules formed on the roots of plants and their mass. The data obtained are presented in Tables 5 and 6.

Table 5. Dynamics of the number of nodules on the roots of narrow-leaved lupin plants by years of research, pcs/plant.

Option of experiment	Years of research	Plant development phase			
		stooling	budding	flowering	glaucous pods
Control	2021	20	20	21	22
	2022	18	19	20	23
	2023	21	20	22	24
	On average for 3 years	20	20	21	23
BorStart	2021	20	20	21	30
	2022	18	18	20	25
	2023	20	20	22	24
	On average for 3 years	19	19	21	26
MicroStim Marganets	2021	20	21	22	25
	2022	17	19	21	26
	2023	21	20	23	25
	On average for 3 years	19	20	22	25
Novalon	2021	21	21	22	23
	2022	18	19	21	24
	2023	20	21	23	25
	On average for 3 years	20	20	22	24

Source: Compiled by the authors

According to the data in Table 5, the main number of nodules in all years of research on the roots of narrow-leaved lupin variety Ladnywas formed by the stooling phase - from 17 to 21 pcs/plant. In the subsequent development phases, the number of nodules on the plant increased slightly. By the phase of glaucous pods, their number increased, depending on the experiment option, to 22-30 pcs/plant. Foliar treatment of plants with micro-fertilizers did not have a noticeable effect on the number of nodules on the roots of plants. And only, by the phase of glaucous pods, on average for 3 years, the number of nodules on the treated experiment options was 24-26 pcs/plant, against 23 pcs/plant on the control option. Spraying with boron fertilizers (BorStart) showed the best result.

The mass of nodules on the roots of narrow-leaved lupin plants increased as the phases of crop development passed (Table 6). The greatest increase in the mass of nodules in all experiment options was noted during the period of plant flowering and glaucous pods.

Table 6. The mass of nodules on the roots of narrow-leaved lupin plants, g /plant.

Option of experiment	Years of research	Plant development phase			
		stooling	budding	flowering	glaucous pods
Control	2021	0.08	0.21	0.24	0.52
	2022	0.07	0.21	0.23	0.53
	2023	0.08	0.22	0.26	0.55
	On average for 3 years	0.08	0.21	024	0.53
BorStart	2021	0.07	0.23	0.25	0.58
	2022	0.06	0.21	0.24	0.56
	2023	0.07	0.24	0.26	0.55
	On average for	0.07	0.22	0.25	0.56

	3 years				
MicroStim Marganets	2021	0.10	0.18	0.31	0.47
	2022	0.08	0.17	0.30	0.49
	2023	0.10	0.18	0.33	0.48
	On average for 3 years	0.09	0.18	0.31	0.48
Novalon	2021	0.09	0.20	0.30	0.52
	2022	0.08	0.18	0.28	0.50
	2023	0.09	0.21	0.28	0.51
	On average for 3 years	0.09	0.20	0.26	0.51

Source: Compiled by the authors

When treating plants with boric fertilizers, the largest mass of nodules was obtained among the studied experiment options. The average for 3 years it was 0.56 g/plant. The use of other types of micron-fertilizers did not lead to an excess of nodule mass over the indicators of the control option.

The yield of seeds of the narrow-leaved lupin variety Ladny had minor differences over the years of research, but differed significantly in the studied experiment options (Table 7).

Table 7. Yield of narrow-leaved lupin seeds in the years of research, t/ha.

Option of experiment	Seed yield			
	2021	2022	2023	On average for 3 years
Control	2.23	1.98	2.01	2.07
BorStart	2.28	2.14	2.26	2.23
MicroStim Marganets	2.42	2.18	2.39	2.33
Novalon	2.58	2.34	2.42	2.45
LSD 05	0.12	0.11	0.12	

Source: Compiled by the authors

The highest seed yield was obtained in the period 2021 – in the range of 2.23-2.58 t/ha according to the experiment options and the lowest in 2022 – 1.98-2.34 t/ha. This is explained by the temperature that is more favorable for the formation and maturation of seeds and sufficient moisture in the period 2021.

The treatment of plants with micro-fertilizers contributed to an increase in the yield of lupin seeds in an average of 3 years from 0.16 to 0.38 t/ha compared with the control. The best seed yields were in options with the treatment of plants with chelated forms of micro-fertilizers - Novalon and MicroStim Marganets.

The use of the studied types of fertilizers had a positive effect on the elements of the crop structure of narrow-leaved lupin seeds (Table 8).

Table 8. The structure of the narrow-leaved lupin yield, average for 3 years.

Indicators	Experiment options			
	Control	BorStart	MicroStim-Marganets	Novalon
Number of pods, pcs/plant	8	9	9	9
Number of seeds, pcs/pod	2	2	2	3
Number of seeds,	16	17	18	27

pcs/plant				
Weight of 1000 seeds, g	120	125	126	125

Source: Compiled by the authors

On average, over 3 years, the treatment of plants with chelated forms of micro-fertilizers - MicroStim Marganets and Novalon contributed to the formation of more seeds per plant of 18 and 27 pcs and the largest weight of 1000 seeds is 126 and 125 g, respectively. The use of boron micro-fertilizer BorSTART was slightly inferior in these indicators to chelated forms of fertilizers.

Double treatment with micro-fertilizers of narrow-leaved lupin plants did not lead to an increase in crude fat and crude fiber in seeds, but increased the content of crude ash and crude protein (Table 9). To the greatest extent, the increase in quality indicators was characteristic of the micro-fertilizer MicroStim-Marganets.

Table 9. The content of the main nutrients in narrow-leaved lupin seeds, depending on micro-fertilizers, on average for 3 years, %.

Option of experiment	Crude fat	Crude ash	Crude fibre	Crude protein
Control	7.47	3.71	11.79	33.22
BorStart	7.53	3.72	11.73	34.12
MicroStim-Marganets	6.92	3.75	11.59	39.68
Novalon	7.20	3.72	11.69	35.91

Source: Compiled by the authors

The calculation of the economic efficiency of obtaining narrow-leaved lupin seeds at the obtained yield level for all experiment options turned out to be cost-effective. The use of the studied micro-fertilizers indicates that the treatment with Novalon 19-19-19+2MgO+ME and MicroStim-Marganets increased the profitability of seed production by 9.9 and 8% compared to the control, respectively, but the use of boron micro-fertilizers BorSTART did not exceed the profitability of the control option due to their high cost.

The results obtained in the experiment indicate a noticeable influence of meteorological conditions on the studied indicators of growth and development of narrow-leaved lupin in the conditions of the Central Non-Chernozem zone of Russia. On average, over the 3 years of the field experiment, the total duration of the growing season of narrow-leaved lupin variety Ladny exceeded these indicators indicated by the originator of the variety by 6 days. The height of the lupin plants in the experiment was significantly inferior to the standard parameters, which is probably due to the low natural fertility of the site and the lack of use of mineral fertilizers.

Double treatment of narrow-leaved lupin plants during the growing season with the studied types of micro-fertilizers had a positive effect on the formation of the photosynthetic and symbiotic apparatus of the crop, increased seed yield by increasing the indicators of the crop structure elements - the number of pods and seeds in pods, the weight of 1000 seeds. It is known that micro-fertilizers, especially in chelated form, are

a kind of "generator" of activation of physiological and morphogenetic processes in plant tissues, with their help, these processes are regulated. This also had a positive effect on the content of crude ash and crude protein in narrow-leaved lupin plants.

Low doses of micro-fertilizers, low costs for processing plants make it economically advantageous to use them in obtaining narrow-leaved lupin seeds.

4 Conclusion

One of the promising directions for increasing the intake of feed protein is the cultivation of narrow-leaved lupin for seeds using micro-fertilizers.

As a result of three years of field research, it was proved that in the conditions of the Central Non–Chernozem zone on sod-medium podzolic, sandy loam soil, narrow-leaved lupin of the Ladny variety formed a seed yield in an average of 3 years in the range of 2.07-2.45 t/ha. Double treatment of vegetative plants with BorSTART, MicroStim-Margantes and Novalon micro-fertilizers increased the yield of lupin seeds by 0.16 to 0.38 t/ha compared with the control. Chelated forms of micro-fertilizers - Novalon and MicroStim Marganets showed the best results. The treatment of these types of micro-fertilizers of lupin plants increased the content of crude protein in the grain to 35.9 and 39.7%, respectively.

Micro-fertilizers increased the leaf area of narrow-leaved lupin. When treated with BorStart and MicroStim-Marganets, 480.2 and 475.3 cm^2/plant of leaf surface were formed, respectively.

The treatment of lupin plants with micro-fertilizers influenced the formation of the crop symbiotic apparatus. The number of nodules on the roots of the treated plants exceeded the control by 1-3 pcs/plant. Boric micro-fertilizers contributed to the formation of the largest mass of nodules - 0.56 g/plant in the phase of glaucous pods.

When treated with micro-fertilizers, the aboveground mass of plants in the phase of glaucous pods exceeded the control option by 8.4-11.6%. The best results were obtained when treating plants with boric micro-fertilization (BorStart).

The use of micro fertilizers Novalon 19-19-19+2MgO+ME and MicroStim-Marganets increased the profitability of lupin cultivation for seeds by 9.9 and 8% compared to the control, respectively.

Considering that the doses of application of the studied types of micro-fertilizers do not exceed 2 liters/ha and 3 kg/ha, and the cost of double processing of vegetative plants of narrow-leaved lupin is 2.5 times lower compared with the introduction of more expensive mineral fertilizers, while the level of crop seed yield is approaching that predicted by the variety originator, it is possible to recommend the use of the studied micro-fertilizers for narrow-leaved lupin cultivation for seeds.

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