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The potential of pre-sowing treatment for the improvement of narrow-leaved lupine (*Lupinus angustifolius*) field performance in the arid conditions of North Kazakhstan

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Abstract: Narrow-leaved lupine (Lupinus angustifolius) is a high-protein legume crop with significant agricultural potential, yet its cultivation faces challenges in stand establishment under arid conditions. This study aimed to evaluate the effects of growth regulators and priming techniques on lupine seed germination, plant development, and yield under field conditions in North Kazakhstan. The experiment was conducted on the ordinary chernozem soil with low nitrogen and phosphorus content. The climate is sharply continental, with moisture as a limiting factor. The tested lupine variety, Orlovsky Kormovoy, has a low alkaloid content (0.045%) and a vegetation period of 85–90 days. Four treatments were applied: control (dry seeds), hydropriming, treatment with the growth regulator Megamix Seeds, and priming in a Megamix Seeds nutrient solution containing essential macro- and micronutrients. A preliminary experiment determined optimal soaking duration for seeds in water and nutrient solution. Field parameters assessed included seed germination, biomass accumulation, root development, photosynthetic activity, and yield. Megamix Seeds treatment increased photosynthetic activity from 16.9 to 20.4 thousand m² × days/ha and improved yield by 65% (from 8.65 to 14.28 c/ha). These findings highlight the potential of nutrient priming to enhance lupine productivity and resilience in arid regions.

Key words: lupine; growth regulators; priming; dry matter; assimilation surface, photosynthetic activity.

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1. Introduction

In recent years, protein deficiency has become a global issue, and increasing the cultivation of leguminous crops can help address this problem (Ageeva et al., 2023). Narrow-leaved lupine (*Lupinus angustifolius*) is a high-protein plant from the legume family, characterized by early maturity and cold tolerance. Achieving high yields is closely linked to seed quality. Like all leguminous crops, lupine requires a significant amount of water for germination—120-150% of its seed weight. However, the hardness of lupine seeds, a common trait among legumes, leads to slow and uneven germination (Hughes, 1915).

In Northern Kazakhstan, where soil moisture is a critical factor for field crop cultivation, techniques that promote efficient water use are essential. In recent years, one such method—pre-sowing priming—has gained attention. This process involves soaking seeds to stimulate active germination and initial growth by ensuring the high moisture levels required for germination (Waqas et al., 2019). There are several types of priming: hydropriming, osmopriming, priming with growth regulators, and biopriming. Soaking seeds in various solutions that activate enzymatic activity and enhance germination is a widely used approach (Babenko et al., 2014).

Priming is one of the effective methods to overcome challenging growing conditions, enhance seed viability, and ultimately increase yields. Studies have reported a positive effect of priming on seed quality, indicating that hormonal priming (using a nutrient solution) improves the chemical composition of seeds and increases the protein content in grain legumes. Researchers have concluded that seed priming can be a simple yet effective approach to enhancing the quality of grain legume crops (Afzal et al., 2020).

According to Ghassemi-Golezani et al. (2008), pre-sowing priming significantly increased seed germination and viability index. Additionally, plants subjected to priming outperformed the control group in terms of shoot and root dry weight.

A key challenge for agrarian science is the search for new techniques to enhance the productivity and quality of field crops. One approach to improving field germination is seed treatment, which includes dry powder or solution treatments, nutrient coating, and pelleting (Janecko et al., 2015). Growth regulators play a crucial role in increasing the productivity of field crops. However, their effectiveness depends on proper application, as studies have shown that growth regulators contribute to an increase in the number of pods only when applied correctly (Saeid, 2011).

Yagovenko T.V. et al. (2020) found that growth regulators positively affect the formation of the assimilation surface and chlorophyll content in the leaves of white lupine. Their application significantly increased yield, and when combined with pre-sowing seed treatment followed by spraying during the budding phase, a notable yield increase was observed compared to the control (+8.5–10.4%).

It can be assumed that priming and pre-sowing seed treatments serve as effective and cost-efficient approaches to alleviating abiotic stress and reducing seed hardness in lupine. Specifically, under the moisture-limited conditions prevalent in Northern Kazakhstan, pre-sowing seed soaking is expected to mitigate moisture deficits by promoting early seed development before planting. Likewise, pre-planting treatments are anticipated to enhance nutrient availability, thereby improving plant growth. Therefore, we hypothesize that seed treatment has the potential to enhance germination rates, photosynthetic activity, and dry biomass accumulation in lupine, making a significant contribution to its productivity under field conditions.

2. Materials and Methods

The field experiment was conducted in the Akkaiynsky district of the North Kazakhstan region at LLP "North Kazakhstan Agricultural Experimental Station." The soil is ordinary chernozem with a humus content of 4–5% and a humus horizon thickness of 20–25 cm. The region belongs to the steppe zone, with a neutral soil reaction (pH = 6.5–7.0) and a heavy loamy texture. The nitrogen and phosphorus content in the soil is low. The climate of the region is sharply continental with arid conditions, where moisture is a limiting factor. The highest amount of precipitation typically occurs in mid-July. The object of the study was the narrow-leaved lupine (*Lupinus angustifolius*) variety Orlovsky Kormovoy, which has a low alkaloid content (0.045%). Its vegetation period lasts 85–90 days. The plants are resistant to Fusarium and exhibit high nitrogen-fixing activity (Federal Scientific Center of Grain Legumes and Cereals, 2023).

Pre-sowing seed treatment was performed using the Megamix Seeds growth regulator, which consists of two different nutrient compositions: I) MgO (22 g/l), SO_3 (145 g/l), Cu (33 g/l), Zn (31 g/l), Fe (4 g/l), Mn (3 g/l), Co (2.8 g/l, Ni (0.1 g/l); II) N (58 g/l), P_2O_5 (6 g/l), K_2O (58 g/l), B (4.6 g/l), Mo (7 g/l), Cr (0.5 g/l), Se (0.1 g/l). These two compositions were used in combination for pre-treatment and priming in the nutrient solution. The elements provided complete nutrition for seedlings at early development stages and contributed to the formation of a strong root system (Methodology for Conducting Variety Trials of Agricultural Plants, 2011). A preliminary experiment was conducted to determine the optimal soaking duration for seeds in water or nutrient solutions. In this experiment, 30 seeds were soaked in distilled water and in a 1% Megamix Seeds nutrient solution in Petri dishes under constant temperature conditions, with three replicates.

2.1 Germination Experiments (Germination Experiments)

Laboratory experiments were conducted to study *in vitro* germination, germination energy, and biometric parameters (root length, sprout height, and green mass weight) in accordance with State Standard 12038-84 "Seeds of Agricultural Crops." Seeds were germinated in Petri dishes under four treatments, each with three replications: 1) control – dry lupine seeds; 2) growth regulator treatment – dry seeds treated with the Megamix Seeds growth regulator; 3) soaking treatment – seeds soaked for 2.5 hours and then brought to a friable state; 4) seed priming – seeds primed for 2.5 hours in combination with Megamix Seeds. A four-layer filter paper was placed at the bottom of the Petri dishes and moistened with distilled water. Measurements were taken on the 3rd, 4th, 5th, 6th, and 7th days of germination. Laboratory germination was determined by calculating the percentage of normally germinated seeds, which included seedlings with a well-developed main root longer than the seed itself and a formed sprout. Seeds with minor surface damage that did not affect the tissues, as well as those with a damaged main root but well-developed lateral roots, were also classified as normally germinated. Swollen and hard seeds were categorized as ungerminated, while rotten and abnormally developed seeds were classified as non-germinating. On the 7th day, the average length of seedlings, including roots, and their weight were measured.

2.2 Seed emergence in sand

Seed emergence in sand was conducted to assess the biometric parameters of plants. For this purpose, half of the growing pots were filled with moistened calcined sand, after which the seeds were placed and covered with an additional layer of sand (State Standard 12038-84 "Seeds of agricultural crops", 1984).

Laboratory emergence was evaluated on the seventh day after seed placement. The number of emerged plants was counted, and the percentage relative to the total number of sown seeds was calculated. The average value for each treatment was then determined.

The height of each plant, measured from the base of the stem to the growing point, was recorded using a ruler, and the average value was calculated. Simultaneously, the length of the main root was measured with an accuracy of 0.1 cm. Afterward, the green biomass and root system weight were separately measured using a precision scale. The final weight was calculated per plant.

2.3 Field plot experiment

The two-year field experiment was realised to study field emergence, the dynamics of dry biomass accumulation, and photosynthetic activity during the early stages of growth and development. The field experiment was established following the methodology of Dospekhov (1985). In both years, sowing was carried out on May 5 using an SS-11 seeder with a seeding rate of 1.0 million germinated seeds per hectare at a depth of 6 cm. The experiment was arranged in a randomized design with three replications, and the area of each plot was 17 m^2. The study included four treatments: 1) control (untreated seeds); 2) dry seeds treated with Megamix Seeds (MS); 3) hydropriming (HP); 4) priming in a nutrient solution of Megamix Seeds (P+MS).

Lupine seedlings were evaluated at the appearance of seedling leaves. At the beginning of the sprouting phase, at least 10–15% of plants had entered the phase, while at least 75% had reached full sprouting. Upon full seedling emergence, plant density was determined by counting the number of plants at four different points using a 0.5–1 m^2 frame, and the average value was calculated. Field germination was determined by calculating the percentage of emerged plants relative to the total number of sown seeds.

The dynamics of photosynthetic activity in narrow-leaved lupine were assessed according to the method of Nichiporovich (1961). Leaf surface area was measured using a CID Leaf Area Meter with a laser-based express method. For this purpose, plant samples consisting of 10 plants each were collected from different locations within the plots. Each plant was scanned using the laser, and the leaf area data were displayed on the screen. The average leaf area per plant and per square meter was then calculated based on these measurements.

2.4 Statistical analysis

The obtained data were analyzed using one-way analysis of variance (ANOVA) with simple treatment effect within each separate experiment followed by post-hoc Tukey HSD test at $\alpha = 0.05$. All these analyses were carried out using the STATISTICA software version 12 (StatSoft, Inc., Tulsa, Oklahoma, United States).

2.1. Subsection

When using subsections, it provides easier understanding and orientation in the text.

3. Results

According to data from the North Kazakhstan Agricultural Experimental Station (meteorological station Shagalaly), the meteorological conditions of the 2023 growing season were characterized as dry. Between May and August, total precipitation amounted to 145.4 mm, which was 75% of the long-term average (193 mm). The total precipitation during the spring-summer period was 145.4 mm, falling short of the climatic norm. However, the sum of active temperatures (2313°C) over the vegetation period was sufficient for lupine to reach full maturity.

Figure 1 illustrates the monthly mean temperatures and cumulative precipitation, which significantly influenced leaf formation. Over the two years, contrasting weather patterns had different effects on lupine growth. In 2023, moderate June temperatures (19.1°C) and 41.1 mm of rainfall supported early flower formation, but dry conditions in July limited growth, leading to reduced leaf size and assimilative surface area. In contrast, in 2024, higher precipitation, particularly in May, delayed seedling emergence but promoted vigorous vegetative growth, enhancing flowering and fruiting in July. These differences highlight the critical role of rainfall and temperature in determining lupine productivity.

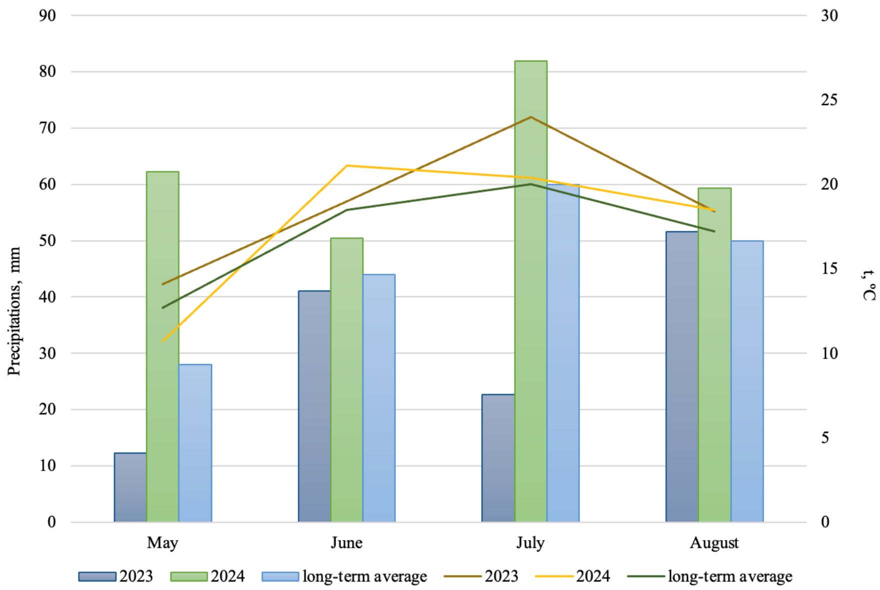


Figure 1. Temperature means and sum of precipitations for selected months in the growing seasons 2023-2024 followed by long-term means and sums

3.1 Germination Experiments

The optimal soaking duration was determined to be 2.5 hours, achieving 151% water absorption. Prolonged soaking in both water and nutrient solutions resulted in seed coat peeling and seed cracking (Table 1).

Table 1. Water absorption of narrow-leaved lupine seeds at different soaking times

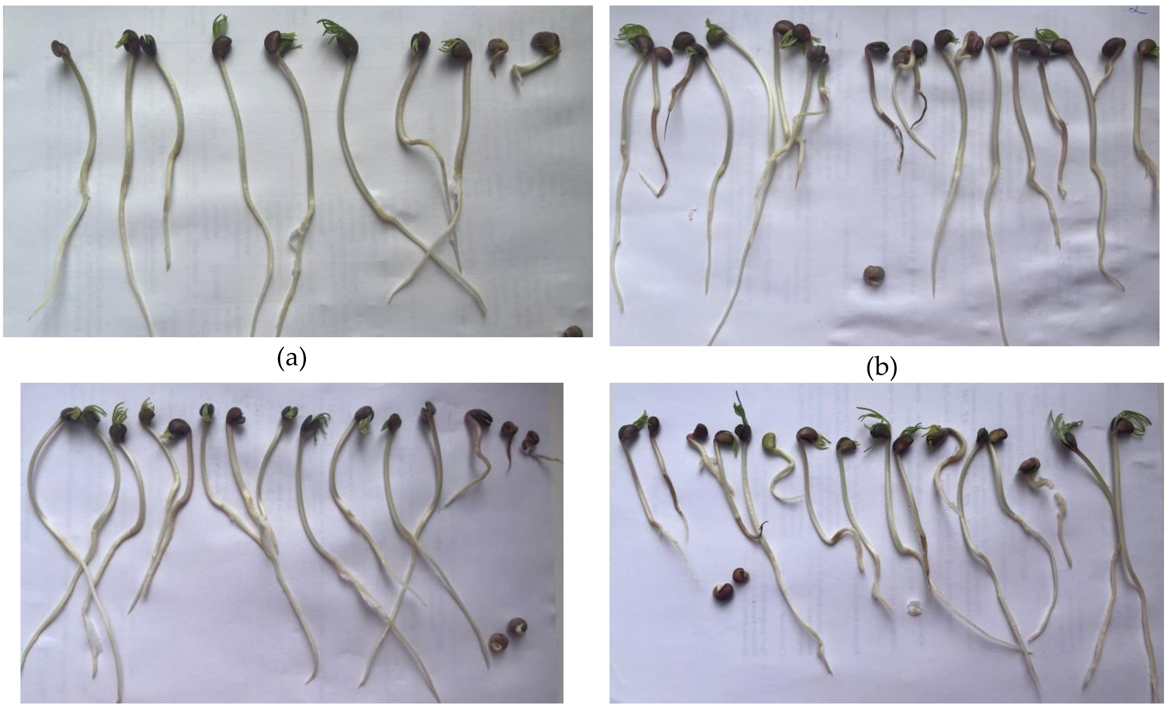
Variant (residence time in water)	Dry seed weight, g	Seed weight after priming, g	Water absorption, %
30 min	5.41[ab]	5.46[a]	110[a]

1 hour	5.56^{abc}	6.39^{ab}	115^{a}
1.5 hours	5.45^{ab}	6.59^{ab}	121^{ab}
2 hours	5.62^{c}	7.64^{bc}	136^{bc}
2.5 hours	5.39a	8.14^{bc}	151^{c}
3 hours	**5.61^{bc}**	9.37^{cd}	167^{d}
3.5 hours	5.59^{bc}	9.78^{cd}	175^{d}
4 hours	5.55^{bc}	**10^{d}**	**180^{d}**
p-value	<0.001	0.002	0.003
P-value: test probability of one-way ANOVA, different letters indicate statistical differences for Tukey HSD test at α=0,05. The maximum values are shown in bold.			

All pre-sowing treatments had a positive effect on germination dynamics under laboratory conditions. By the third day, germination rates in all treated variants were 7–9% higher than in the control. However, priming in the Megamix Seeds nutrient solution demonstrated superior results until the sixth day. By the seventh day, laboratory germination in all treated variants reached 95%, exceeding the control by 5% (Table 2). Differences in plant development are also illustrated in Figure 2.

Table 2. Dynamics of germination of narrow-leaved lupine (in %) in relation to pre-sowing treatments.

Variant	Days				
	3rd	4th	5th	6th	7th
Control	74^{a}	75^{a}	81^{a}	89^{a}	90^{b}
Dry seeds + Megamix Semena	83^{b}	85^{bc}	90^{bc}	93^{b}	**95^{a}**
Hydropriming	81^{ab}	83^{c}	88^{ab}	92^{ab}	**95^{a}**
Priming in nutrient solution Megamix Semena	**85^{c}**	**86^{b}**	**92^{c}**	**95^{c}**	**95^{a}**
p-value	0.006	<0.001	0.003	0.002	0.002
P-value: test probability of one-way ANOVA, different letters indicate statistical differences for Tukey HSD test at α=0,05. The maximum values are shown in bold.					



(a) (b)

(c) (d)

Figure 2. Photos illustrating contrasts in plant development in the germination experiment with narrow-leaved lupine seeds: (a) control; (b) dry seeds + Megamix Seeds; (c) hydropriming; (d) priming in Megamix Seeds nutrient solution (plants at 7th day)

3.2 Effect of seed treatments on plant traits during cultivation in the sand

Megamix Seeds significantly increased the length of the sprout; when treating dry seeds, the length was 5.2 cm higher compared to the control; when adding the drug to the solution - by 6.6 cm. The maximum weight of green biomass is observed during priming in a nutrient solution - 1.06 g/plant. The increase when treating dry seeds with a regulator + 0.56 g was also significant. In the variant with hydropriming, the average weight of the sprout was 0.70 g; the increase was the smallest in the experiment, but significant when compared with the control. The same trend was observed when measuring the weight of the root system. Despite the fact that in the variant with priming in a nutrient solution the length of the root system did not change, the weight was significantly higher than the control (+0.19 g); the roots formed thick and powerful. The mass of roots in other variants was almost at the same level and exceeded the control by 46.2% (Table 3).

Table 3. Biometric indicators of narrow-leaved lupine in a laboratory experiment in relation to pre-sowing treatments.

Variant	Plant height, cm	Root system length, cm	Weight of green biomass, g/plant	Weight of root system, g/plant
Control	8.6^{b}	7.5^{a}	0.42^{bc}	0.13^{b}
Dry seeds + Megamix Semena	13.8^{a}	7.6^{a}	0.98^{ab}	0.19^{b}
Hydropriming	12.4^{a}	**9^{b}**	0.70^{c}	0.18^{b}
Priming in nutrient solution Megamix Semena	**15.2^{a}**	7.5^{a}	**1.06^{a}**	**0.32^{a}**
P-value	0.005	<0.001	0.004	0.004
P-value: test probability of one-way ANOVA, different letters indicate statistical differences for Tukey HSD test at α=0,05. The maximum values are shown in bold.				

3.3 Field experiment

Differences among seed pre-sowing treatments in plant parameters during the field experiment are presented in Table 4., where Megamix Seeds increased field emergence by 15%. The plants were formed powerful with an average weight of green biomass of 4.2-4.8 g/plant. Under increased humidity, this indicator exhibited an enhancement, showing superior results compared to other treatments. Under humidified conditions, the root mass in the Megamix Seeds treatment decreased from 33.9 g/plant to 30.1 g/plant.

In 2023, hydropriming and priming in a nutrient solution resulted in the same plant density—83 plants/m² (83%). However, in the wetter conditions of 2024, nutrient solution priming demonstrated superior performance, achieving a field germination rate of 89%. Plant height in the hydropriming treatment was 0.7–0.8 cm lower than in the control. However, due to increased branching, green biomass accumulation was 4.1–4.4 g higher (Figure 2). When priming in a nutrient solution, both plant height (14.1–14.5 cm) and green biomass (4.5–4.6 g/plant) increased. Root system development in this treatment was comparable to hydropriming, but root weight was significantly higher than in the control—30.7–32.8 g/plant (Table 4). Thus, the use of a nutrient solution can enhance moisture availability for seeds, facilitating more efficient resource utilization and improving early plant development.

Table 4. Field germination and biometric parameters of lupine plants in the full emergence stage in relation to pre-sowing treatments.

Variant	Plant stand density, pcs./m²	Field emergence, %	Plant height, cm	Weight of green biomass, g/plant	Root system length, cm	Weight of root system, g/plant
2023						
Control	72[c]	72[c]	13,5[b]	3.4[c]	20[a]	14.8[c]
Dry seeds + Megamix Seeds	**87[b]**	**87[b]**	**14.3[a]**	4.2[a]	20[a]	**33.9[ab]**
Hydropriming	83[a]	83[a]	12.8[c]	4.1[a]	19[b]	30.7[a]
Priming in nutrient solution Megamix Seeds	83[a]	83[a]	14.1[a]	**4.5[ab]**	19[b]	31.2[a]
P-value	<0.001	<0.001	0.004	0.002	0.003	0.002
2024						
Control	75[c]	75[c]	15,0[bc]	3,6[c]	**22[bc]**	20,3[c]
Dry seeds + Megamix Seeds	88[a]	88[a]	**15,8[b]**	**4,8[ab]**	21[b]	30,1[b]
Hydropriming	85[b]	85[b]	14,1[a]	4,4[a]	20[a]	32,4[a]
Priming in nutrient solution Megamix Seeds	**89[a]**	**89[a]**	14,5[a]	4,6[a]	20[a]	**32,8[a]**
P-value	0.002	0.002	0.003	<0.001	<0.001	0.003
P-value: test probability of one-way ANOVA, different letters indicate statistical differences for Tukey HSD test at α=0,05. The maximum values are shown in bold.						

During the experiments, the highest dry weight of plants was reached in the variant using the Megamix Seeds regulator – 1.25-1.31 g/plant. In other treatments, the weight of dry biomass was lower, but exceeded the control by 2.1-2.8 times. Differences in dry matter mass between these options with control were proven at a 5% significance level. With such dynamics of dry matter accumulation, net photosynthetic productivity (NPP) was in the range of 10.5 – 14.6 g/m² per day. Over two years of research the pattern of NPF increase was similar to the accumulation of dry biomass.

Photosynthetic activity is directly influenced by the assimilation surface; therefore, in the field experiment, leaf surface area measurements were conducted. Under arid conditions, the largest leaf area in lupine plants was observed when priming with the Megamix Seeds nutrient solution was applied—13.5 cm²/plant. However, in humid conditions, this treatment did not enhance leaf area; instead, the greatest plant size was achieved through hydropriming.

Leaf area increased by 3.8–4.4 cm² in the Megamix Seeds treatment and by 4.2–8.2 cm² in the Priming + Megamix Seeds treatment. When evaluating assimilation area efficiency, the highest photosynthetic potential (PP) was recorded in plants subjected to nutrient solution priming—16.9–20.4 thousand m² × days/ha. Pre-sowing treatment with the Megamix Seeds regulator and hydropriming resulted in PP values of 16.7–18.3 thousand m² × days/ha and 16.3–19.6 thousand m² × days/ha, respectively (Table 5). Thus, the highest seed yield (14.1–15.4 c/ha) was achieved when priming was performed using the Megamix Seeds nutrient solution.

Table 5. Final seed yield, photosynthetic activity and productivity of narrow-leaved lupine leaves in the phase of full sprouting in relation to pre-sowing treatments.

Variant	Weight of dry biomass, g/plant	Assimilation surface, cm²/ per plant	Net photosynthetic productivity, g/m² per day	Photosynthetic potential, thousand m² x days/ha	Yield, c/ha
2023					
Control	0.29^{b}	8.4^{c}	2.5^{c}	12.5^{c}	7.0^{c}
Dry seeds + Megamix Seeds	**1.31^{c}**	12.2^{a}	**11.4^{a}**	16.7^{a}	12.5^{a}
Hydropriming	0.61^{a}	12.6^{a}	10.5^{ab}	16.3^{ab}	11.5^{a}
Priming in nutrient solution Megamix Seeds	0.76^{a}	**13.5^{b}**	11.2^{b}	**16.9^{a}**	**14.1^{b}**
P-value	0.003	0.005	0.001	0.004	0.005
2024					
Control	0.35^{c}	12.7^{c}	5.8^{c}	14.1^{c}	10.3^{b}
Dry seeds + Megamix Seeds	**1.25^{b}**	17.1^{a}	**14.6^{a}**	18.3^{ab}	15.1^{a}
Hydropriming	0.86^{a}	**20.9^{b}**	13.7^{ab}	19.6^{a}	15.1^{a}
Priming in nutrient solution Megamix Seeds	0.99^{a}	18.5^{a}	14.3^{a}	**20.4^{a}**	**15.4^{a}**
P-value	0.005	0.003	0.002	0.001	0.001
P-value: test probability of one-way ANOVA, different letters indicate statistical differences for Tukey HSD test at α=0,05. The maximum values are shown in bold.					

4. Discussion

4.1 Priming of lupine seeds

Our study demonstrates that pre-sowing soaking in water and nutrient solutions significantly enhances seed germination and plant establishment, with both hydropriming and nutrient solution priming proving to be effective methods. The results suggest that nutrient solution priming may improve the seed water balance, optimizing moisture utilization during germination. Previous research supports this, indicating that pre-sowing soaking techniques can effectively stimulate the growth of narrow-leaved lupine, leading to notable increases in aerial biomass accumulation and seed yield (Klochkova & Holodinsky, 2021). Nutrient solution priming, in particular, exhibited superior germination rates under wet conditions, aligning with findings by Smith et al. (2018), which highlight its potential to enhance seed performance across diverse environments. However, as noted by Brown et al. (2020), the correlation between laboratory and field results can be inconsistent, emphasizing the importance of field-specific assessments.

The yield increase observed with priming can be attributed to early hydration, which activates enzymatic processes essential for nutrient mobilization and seed development. This is supported by research demonstrating that hydropriming improves germination rates and biomass accumulation. Jones and Lee (2019) found that hydropriming increased green biomass accumulation by 22.6% during the flowering phase and led to a 12% rise in seed yield. Both treatments also promoted root system development, enhancing drought resilience, as confirmed by Taylor et al. (2017).

Our findings align with previous studies on seed priming in legumes, such as Afzal et al. (2016), who reported a 20-30% increase in yield following hydropriming in lentils under arid conditions. However, our results show a narrow-leaved lupine yield improvement 28-47%, which may be attributed to the specific nutrient composition of the Megamix Seeds solution. This suggests that nutrient priming could be particularly effective for lupine, a crop known for its high protein content and sensitivity to moisture stress. The superior performance of the Megamix Seeds nutrient solution can be attributed to its balanced composition of macro- and micronutrients, which are essential for early seedling development where magnesium (Mg) plays a critical role in chlorophyll synthesis, while zinc (Zn) and copper (Cu) are known to enhance enzyme activity and stress tolerance. These nutrients likely contributed to the observed increase in photosynthetic potential and root biomass, as they facilitate efficient nutrient mobilization and water uptake during the critical early stages of plant growth.

These findings raise important questions about plant adaptability to varying moisture levels. Observations indicate that under humid conditions, nutrient solution priming may outperform the Megamix Seeds regulator by promoting stronger vegetative growth. Given the uncertainty of future climatic conditions, developing adaptable seed treatment strategies will be essential for optimizing resilience and yield stability. Further research should focus on refining these treatments for effectiveness under diverse environmental conditions. As White et al. (2021) emphasized, fine-tuning priming techniques to specific environmental variables can enhance consistency in plant performance and yield outcomes across different growing conditions.

4.2 Treatment of lupine seeds with growth regulators

The Megamix Seeds solution, enriched with essential trace elements and vitamins, plays a crucial role in the initial stages of seedling development. By maintaining seed vitality and alleviating stress during germination, this combination of water and nutrients creates optimal conditions for seedling establishment. Previous studies, such as those by Jones et al. (2019), support this notion, demonstrating that pre-sowing soaking techniques can significantly enhance the physiological performance of seeds, resulting in more vigorous seedlings.

Our two-year field trials revealed a significant increase in green biomass associated with different seed treatment methods. Under arid conditions, the average green biomass ranged from 4.2 to 4.8 g per plant when dry seeds were treated with Megamix Seeds. Additionally, priming seeds in a nutrient solution further enhanced biomass accumulation, with plant weights reaching 4.5 to 4.6 g per plant. These results indicate that the macro- and microelements contained in the treatment solutions stimulated active vegetative growth. The findings align with previous studies demonstrating the positive effects of growth regulators on metabolic processes essential for germination and early development. For instance, Johnson et al. (2021) reported that the application of growth regulators not only improved germination rates but also led to significant increases in biomass and overall yield.

The Megamix Seeds solution, rich in essential trace elements and vitamins, plays a critical role in the initial stages of seedling development. By maintaining seed vitality and alleviating stress during germination, this combination of water and nutrients creates optimal conditions for seedling establishment. Previous studies, such as those by Jones et al. (2019), support this notion, showing that pre-sowing soaking techniques can significantly enhance the physiological performance of seeds, resulting in more robust seedlings. Our study indicates that the macro- and microelements contained in the regulators contributed to the active development of the vegetative mass. Additionally, the results corroborate findings from studies that demonstrate the positive effects of growth regulators on metabolic processes critical for germination and early growth stages. For example, Johnson et al. (2021) reported that the application of growth regulators not only improved germination rates but also resulted in significant increases in biomass and yield. These studies collectively reinforce the idea that optimizing nutrient availability and employing growth regulators can lead to the development of stronger, more resilient plants.

In patent RU2184434C1, a method of pre-sowing seed treatment for leguminous crops is described, which ensures green mass yield under arid conditions in the Volgograd region at the level of 5.5–6.0 t/ha, and under irrigation — 20–29 t/ha. These findings are consistent with our results, demonstrating the positive impact of pre-sowing treatment on the yield of narrow-leaved lupine in the steppe zone of Northern Kazakhstan, aligning with the aforementioned data. Our results are consistent with studies conducted by other researchers who examined the effects of pre-sowing seed treatments on the yield of leguminous crops under arid conditions. Braginets et al. (2024) investigated the influence of different pre-sowing treatments on pea seeds (Pisum sativum L.) and found that treatment with growth regulators increased biological yield by 25.2%, while hydropriming resulted in a 16% increase compared to the control. These methods also contributed to improved field emergence and enhanced structural yield components.

Unlike other studies that focused on more common legumes, such as peas or beans, our results show the effectiveness of pre-sowing treatment at the narrow-leaved lupine adapted to the unique agro-climatic conditions of Northern Kazakhstan. This contributes to a better understanding of how different types of legume plants respond to seed treatment in arid conditions, highlighting the broader application and potential impact of our work on increasing bean yields in semi-arid zones.

The treatment of Megamix Seeds resulted in enhanced lupine yields, ranging from 12.5 to 15.1 c/ha under varying meteorological conditions across two years. This underscores the critical role of nutrient priming in early plant development, which is essential for establishing a robust crop capable of efficiently utilizing resources throughout its growth cycle. Future research should focus on identifying the specific nutrient interactions and mechanisms responsible for promoting plant growth. Investigating how individual nutrients contribute to seedling establishment across different crop species and environmental conditions could provide a broader scientific basis for optimizing crop management strategies.

4.3 Correlation of laboratory experiments with plot field experiments

The results of our laboratory studies, during which the influence of various methods of etching and pre-sowing treatment of seeds with the Megamix Seeds growth regulator was studied, largely coincide with the results obtained in field experiments. Our results obtained in the arid conditions of the 2023 growing season confirmed the research of Saeid H.M. et al. (2011) that priming and pre-sowing treatment are ways for plants to overcome stressful conditions.The increase in green and root biomass, especially under field conditions (4.5-4.6 g of green mass and 31.2-32.8 g of root mass), reflects findings by Afzal et al. (2016), who noted similar growth improvements in legumes following priming treatments, as well as early-stage nutrient uptake.

Moreover, the minimal difference in root length between laboratory and field conditions (around 1 cm) suggests that the early-stage benefits of priming are relatively stable across environments. These results align with findings by Farooq et al. (2017), who highlighted that seed priming facilitates rapid root establishment, enhancing the seedling's ability to access nutrients and water. However, the final yield improvements observed in our study can be attributed to pre-sowing nutrient absorption, which allowed the seeds to start developing before sowing. Similar benefits of priming for early development and yield potential have been reported by Basra et al. (2019), who found increased crop yields following nutrient-based seed treatments.

The findings from laboratory studies on various priming methods and pre-sowing treatments with the growth regulator Megamix Seeds reveal an inconsistent correlation with field outcomes. While high seed germination rates were observed in controlled laboratory conditions, this did not always translate to similar results in the field, where environmental factors can significantly influence seedling establishment. Harris et al. (2017) also reported similar discrepancies in their research on priming techniques under humid conditions. They found that while priming improved seed vigor and establishment in the lab, the same performance was not consistently replicated in the field, where additional environmental stresses altered outcomes. Their study highlights how unpredictable field conditions can disrupt the expected benefits of laboratory priming results.

Meteorological conditions represent the primary limiting factor in field experiments, emphasizing the necessity of adapting agricultural practices to local environmental conditions. In arid regions, the combination of nutrient solutions with priming may enhance plant growth and yield, whereas in moisture-sufficient environments, priming alone may be sufficient for optimal development. Future research should focus on assessing the long-term effects of these treatments, particularly in the context of climate change and increasing variability in weather patterns. To enhance plant resilience and productivity under stress, agronomists should integrate priming and pre-sowing treatments into standard cultivation practices. By tailoring these approaches to specific environmental conditions, it is possible to ensure stable crop yields and improve agricultural sustainability.

Megamix Seeds is readily available to farmers in Kazakhstan due to an established supply network. Although this nutrient solution for seeds has demonstrated high efficacy, its cost may pose a challenge for small-scale farmers in Northern Kazakhstan. However, the significant yield increase (by 28–47%) justifies the investment in seed treatment of field crops.

The application of Megamix Seeds is effective not only for lupin but also for other crops, including wheat, barley, peas, rapeseed, potatoes, and more. This versatility makes the product a valuable solution for enhancing productivity in arid regions. With a price of 5 euros per liter and a consumption rate of 1 liter per hectare, it remains a cost-effective input considering the potential yield enhancement. To facilitate wider adoption of this technology, efforts should focus on increasing its accessibility. This could be achieved through subsidies or by establishing local production of similar nutrient solutions. Such measures would enable farmers in Northern Kazakhstan to make greater use of Megamix Seeds, thereby contributing to sustainable agricultural development in the region.

5. Conclusions

Our results clearly show that pre-sowing seed treatment has the potential for significant improvement of narrow-leaved lupine growth in northern Kazakhstan, where priming seeds with Megamix Seeds nutrient solution could be considered the most effective treatment supporting crop development. This method resulted in a maximum increase in green biomass accumulation, which was 32.4% higher than the control; a root system weight that was 2.5 times greater than the control; and a photosynthetic potential that exceeded the control by 35.2%. Thus, these improvements, depending on the annual climatic conditions, result in an increase in seed yield of narrow-leaved lupine by 28-47% compared to sowing untreated seeds. The practical implications of these findings are significant, as the Megamix Seeds solution offers a cost-effective and accessible method for improving lupine productivity in arid regions. Further research is needed to optimize the effect of pre-sowing treatment of angustifolia lupine seeds under various weather conditions and to explore the long-term benefits of these treatments in different agricultural settings.

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