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EFFECT OF FERTILIZER RATE ON THE FORMATION OF ROOT CHICORY YIELD AND INULIN YIELD

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Problem statement. One of the key requirements of modern agricultural production is to increase the tolerance of crops to abiotic stress factors, particularly osmotic stress, the intensity of which is increasing under climate change and anthropogenic pressure on agroecosystems [6, 11]. Osmotic stress, caused by water deficit or an increased concentration of mineral compounds in the soil solution, substantially affects plant morphogenesis, growth, development, and yield formation [6].

Root crops, including root chicory, are particularly sensitive to changes in the water–osmotic regime of the soil, since the productive organ is formed directly within the zone affected by soil factors [8, 12]. In intensive farming systems, the application of mineral fertilizers, despite their positive effect on productivity, may increase the osmotic pressure of the soil solution and induce osmotic stress [5, 11], leading to morphological changes in plants and disturbances in growth processes [7, 9].

At the same time, the issue of the morphological sensitivity of root chicory to osmotic stress caused by different levels and forms of fertilization remains insufficiently studied [2, 3]. Studying the responses of plant morphological traits to such conditions is important for understanding the adaptive mechanisms and stress tolerance level of this crop [2, 6].

The practical significance of the study lies in substantiating environmentally appropriate and resource-saving fertilization systems that ensure optimal growth conditions for root chicory without excessive osmotic load [11, 12]. The obtained results may be used to improve yield stability, enhance the morphometric and quality parameters of root crops, and introduce innovative agrotechnologies into production [13].

Analysis of recent research and publications. In recent years, considerable research attention has been paid to studying plant responses to abiotic stresses, including osmotic stress, which occurs under conditions of moisture deficit or increased salt concentration in the soil solution [6, 7]. Scientific studies emphasize that osmotic stress is one of the key limiting factors of crop productivity and directly affects morphogenesis, root system growth, and yield formation [6].

Root chicory (Cichorium intybus L.) is a promising crop with high ecological plasticity; however, numerous studies confirm its sensitivity to water and osmotic stress [2, 3, 7]. Under drought conditions, chicory plants show reduced dry matter accumulation, plant height, and number of leaves, along with changes in the morphological characteristics of roots [7, 8]. At the same time, moderate water stress may induce adaptive responses associated with changes in anatomical and morphological structure and the accumulation of biologically active compounds [3].

Studies using different rates of mineral fertilizers demonstrate their positive effect on biomass and productivity indicators, but often without considering the possible osmotic load on plants [5]. At the same time, it has been shown that fertilizer application can substantially alter root system development, affecting water and nutrient uptake, especially under stress conditions [8, 11].

It has been established that the use of certain fertilizer forms and micronutrients, particularly potassium and silicon compounds, can reduce the negative effects of salt or water stress on the physiological and morphological parameters of chicory [4]. However, most of these studies focus mainly on physiological and biochemical parameters, such as chlorophyll content and antioxidant enzyme activity, whereas the morphological traits of root crops are analysed only to a limited extent [2, 9].

Thus, scientific studies cover issues related to chicory drought tolerance, the effects of salt stress, and the effectiveness of individual fertilizers. However, the complex influence of fertilization systems as a factor inducing osmotic stress on the morphological characteristics of root chicory remains insufficiently studied [2, 5]. There is a practical lack of studies tracing the relationship between levels of mineral fertilization, the osmotic status of the soil solution, and the morphometric parameters of root crops.

These unresolved aspects of the broader problem determine the relevance of studying the morphological sensitivity of root chicory to fertilizer-induced osmotic stress and define the scientific and practical focus of this research.

Purpose. To determine the effect of the fertilization system on the morphological parameters of root chicory in order to optimize the agrotechnologies for its cultivation.

Research methodology. Field studies were conducted during 2021–2024 on grey forest soils. The soil of the experimental plot was characterized by an equilibrium bulk density of 1.1–1.2 g/cm³. Total water capacity was 39–40%, field water capacity was 27.2%, capillary rupture moisture content was 19.4%, and permanent wilting moisture was 10.2%.

The field studies were carried out using the root chicory cultivar Tsezar. Winter wheat was the preceding crop. After harvesting the preceding crop, stubble disking was performed. Phosphorus and potassium fertilizers, in the treatments where they were included in the experimental design, were applied before the primary tillage. According to the fertilization scheme, in autumn a fertilizer mixture of triple superphosphate, containing 46% P_2O_5, was applied based on the basic rate of P_{25}, equivalent to 54.4 kg/ha of physical weight, and potassium salt, containing 60% K_2O, was applied based on the rate of K_{40}, equivalent to 66.6 kg/ha. In the remaining treatments, the application rates were increased proportionally according to the experimental design. Autumn ploughing was carried out to a depth of 25–27 cm. In spring, early spring harrowing was performed to conserve soil moisture. Nitrogen fertilizers were applied before sowing in the form of ammonium nitrate during pre-sowing cultivation, with incorporation into the 0–10 cm soil layer at a rate of 90 kg ha^{-1} of physical weight. Sowing was carried out when the soil temperature reached +6…+8 °C. The seeding rate was 150 thousand viable seeds per hectare, and the row spacing was 40 cm. Before sowing, the seeds were treated with Maxim XL 035 FS at a rate of 3 L/t of seed.

The total plot area was 32.4 m^2 (12 × 2.7 m), and the accounting plot area was 21.6 m^2 (9.0 × 2.4 m). The experiment was conducted in three replications.

To determine root mass and root yield, 10 plants were sampled, cleaned of soil, and separated into roots, which were then weighed. Plant stand density was calculated within the segment where plants were sampled for yield determination. From the roots sampled at the stage of biological maturity, five roots were selected and homogenized. The combined sample was used to determine inulin content and calculate inulin yield.

Statistical processing of the results was performed in the *R* environment, version 4.4.3, using the *ggplot2* package. Analysis of variance was conducted using a multifactorial approach, where weather conditions were included as the second factor. Tabular results present only the effect of fertilizer rate. Treatment comparisons were performed using Tukey's $HSD_{0.05}$ post hoc test.

Research results. Under normal conditions of root chicory cultivation, plant stand density is relatively stable and shows only slight variation; therefore, the main parameter affecting yield is root mass.

According to the results of analysis of variance (Table 2), weather conditions had a greater effect only on inulin content, whereas fertilizer rate had the strongest influence on root mass, yield, and inulin yield. The contribution to plant stand density was approximately similar for weather conditions and fertilizer rate, while their interaction was not significant.

Since the effects of the studied factors on inulin yield, root yield, and root mass were similar, the similarity groups among fertilizer rates were identical. The most effective treatment was the application of $N_{120}P_{100}K_{160}$, which made it possible to achieve a root mass of 249.8 g, a yield of 36.7 t/ha, and an inulin yield of 5.66 t/ha.

At the same time, adjacent fertilizer rates had different effects. With the application of $N_{90}P_{75}K_{120}$, root mass was 230.7 g, which was 19.1 g lower than in the best-performing treatment. At the $N_{150}P_{125}K_{200}$ rate, the decrease in root mass was 67.1 g, indicating a substantial negative effect of the increased fertilizer rate. With the application of $N_{180}P_{150}K_{240}$, the decrease reached 163.6 g compared with the best-performing treatment and 64.9 g compared with the unfertilized control.

The effect of fertilization on plant stand density was significant; however, all fertilizer rates within the range from $N_0P_0K_0$ to $N_{120}P_{100}K_{160}$ belonged to the same group. When the fertilizer rate increased to $N_{150}P_{125}K_{200}$ and $N_{180}P_{150}K_{240}$, plant stand density decreased to 140.36 and 136.73 thousand plants/ha, respectively.

Regarding inulin content, it gradually increased from 14.83% to 15.50% as the fertilizer rate increased up to and including $N_{105}P_{125}K_{200}$. The increase in inulin content is associated with the specific role of this compound as an osmoprotectant and a molecule that counteracts cell dehydration. However, the increase in inulin content had almost no effect on inulin yield per hectare. Therefore, the maximum value reached 5.66 t/ha, which was 2.32 t/ha higher than the value in the control treatment.

According to the results of the correlation analysis (Fig. 1), the relationships between most productivity components were positive. A very strong positive relationship (r > 0.9) was observed between root yield, root mass, and inulin yield per hectare. At the same time, root yield showed a strong correlation with plant stand density (r = 0.66), whereas its correlation with inulin content was

Table 1

Scheme of application of fertilizers

№	Rate	Physical weight, kg/ha		
		Ammonium nitrate	Triple superphosphate	Potassium chloride
1	$N_0P_0K_0$	0	0	0
2	$N_{30}P_{25}K_{40}$	90	54,4	66,6
3	$N_{60}P_{50}K_{80}$	180	108,8	133,2
4	$N_{90}P_{75}K_{120}$	270	163,2	199,8
5	$N_{120}P_{100}K_{160}$	360	217,6	266,4
6	$N_{150}P_{125}K_{200}$	450	272	333
7	$N_{180}P_{150}K_{240}$	540	326,4	399,6

Table 2

Analysis of variance of root chicory yield structure indicators

Effect	df	Mean squares				
		Root weight*	Plant density	Root yield	Inulin content	Inulin yield
Year (A)	3	**4496,69**	**232,89**	**159,28**	**16,19**	**5,98**
Fertilizer rate (B)	6	**34564,82**	**251,98**	**814,39**	**1,08**	**19,11**
AB	18	**1431,52**	26,77^{ns}	**33,21**	**0,91**	**0,72**
Residuals	56	26,24	39,71	0,81	0	0,02

Note. *Values shown in bold are significant at p < 0.05; ns indicates a non-significant interaction. *Root weight was determined on the 150th day of vegetation.*

Table 3

Yield structure components of root chicory

Fertilizer rate	Root weight, g	Plant desity, thou. plants/ha	Root yield, t/ha	Inulin content, %	Inulin yield, t/ha
$N_0P_0K_0$	151.1 e	148.06 ab	22.38 e	14.83 f	3.34 e
$N_{30}P_{25}K_{40}$	181.4 d	146.34 ab	26.58 d	14.90 e	3.98 d
$N_{60}P_{50}K_{80}$	195.5 c	148.31 a	29.03 c	14.75 g	4.30 c
$N_{90}P_{75}K_{120}$	230.7 b	148.28 a	34.3 b	15.05 d	5.16 b
$N_{120}P_{100}K_{160}$	249.8 a	146.78 ab	36.7 a	15.45 b	5.66 a
$N_{150}P_{125}K_{200}$	182.7 d	140.36 bc	25.65 d	15.5 a	3.97 d
$N_{180}P_{150}K_{240}$	86.2 f	136.73 c	11.73 f	15.23 c	1.78 f

Note. *Values followed by the same letters within a column do not differ significantly according to Tukey's $HSD_{0.05}$ test.*

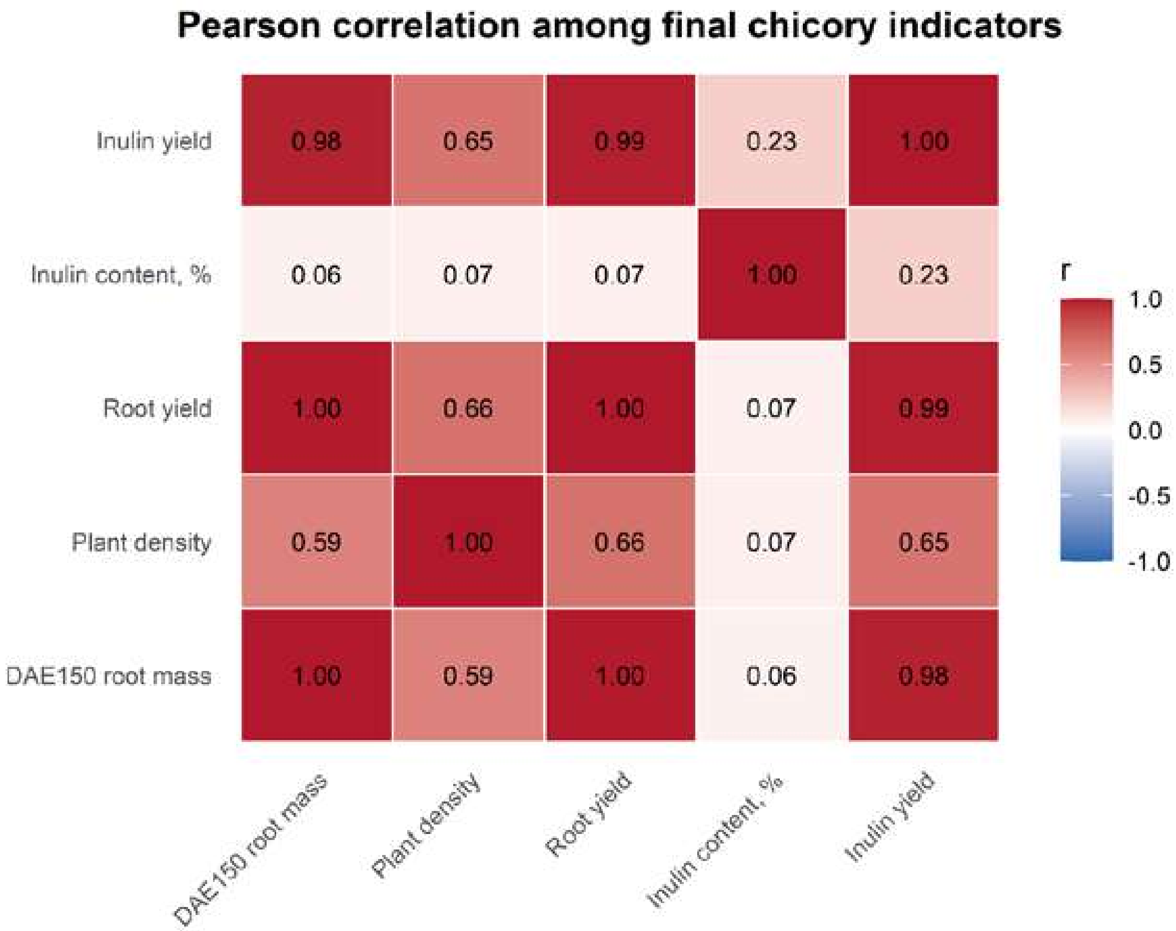

Figure 1. Correlation matrix of relationships among root chicory productivity components

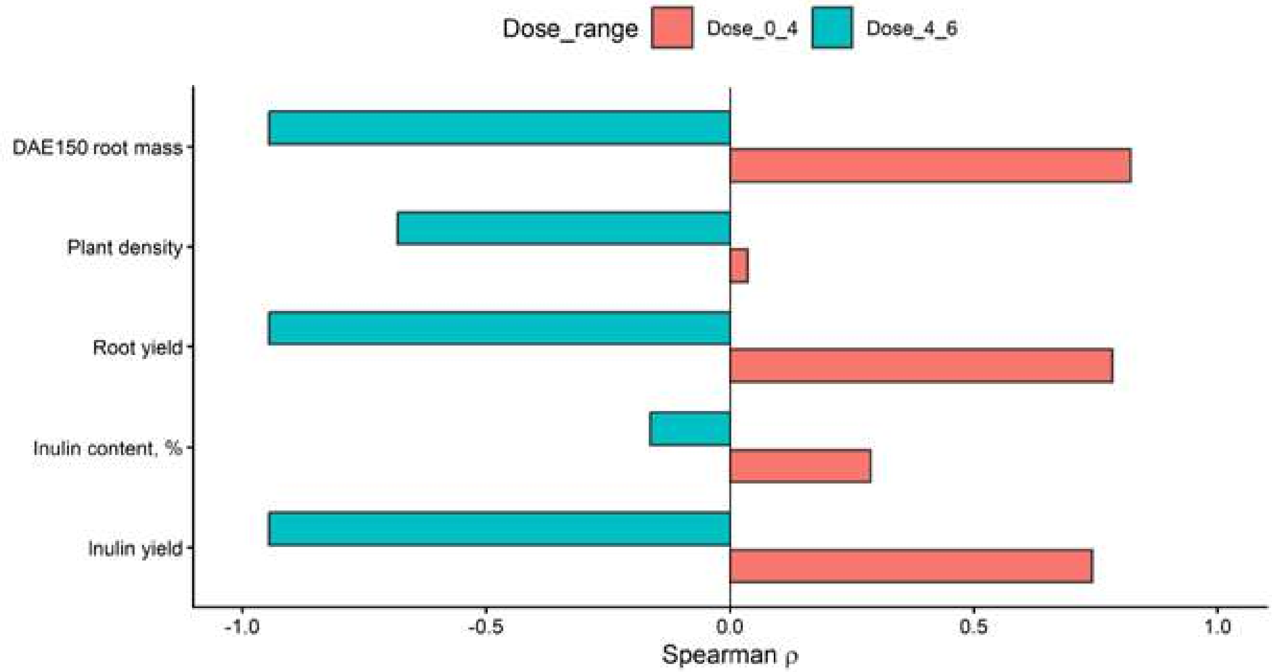

Figure 2. Spearman's correlation coefficient for the relationship between fertilizer rate and root chicory productivity components. Fertilizer rates were transformed into ranks proportionally to the basic rate of $N_{30}P_{20}K_{40}$. The range $N_0P_0K_0$–$N_{120}P_{100}K_{160}$ is shown in red, while the range $N_{120}P_{100}K_{160}$–$N_{180}P_{150}K_{240}$ is shown in turquoise

insignificant (r = 0.07). A similar trend was observed for all pairs that included the "inulin content" indicator. Only in the case of inulin yield did the correlation coefficient reach 0.23, although it was not statistically significant.

At the same time, the calculation of Pearson's pairwise correlation coefficients is appropriate when the relationship between traits remains constant throughout the entire dataset. However, in the case of increasing fertilizer rates, a negative effect is observed beyond a certain threshold, which affects yield and other biometric parameters. Since polynomial models in this case are insufficiently accurate, a more effective tool is the ranking of results and the calculation of Spearman's correlation coefficients. A specific feature of such ranking in root chicory is the division of all treatments into two groups: from the control to $N_{120}P_{100}K_{160}$, according to the criterion of increasing yield, and from $N_{120}P_{100}K_{160}$ to $N_{180}P_{150}K_{240}$, according to the criterion of decreasing yield (Fig. 2).

Therefore, according to the results of the analysis, it can be stated that a gradual increase in fertilizer rate up to $N_{120}P_{100}K_{160}$ leads to an increase in root mass, yield, and inulin yield. However, exceeding this rate results in a substantially greater decrease in these parameters. It should be noted that the effect of fertilizer rates within the first category on plant stand density was statistically insignificant, while their effect on inulin content was weakly positive. At the same time, a further increase in fertilizer rate led to a significant decrease in plant stand density and a slight reduction in inulin content.

Conclusions. Based on the complex of economically valuable traits, the most effective treatment for obtaining a high inulin yield in root chicory cultivation was the application of $N_{120}P_{100}K_{160}$, while this rate can be considered the threshold for maximizing yield. The correlation analysis indicated that root mass, root yield, and inulin yield had a very strong positive correlation, whereas the effect of mineral fertilizer rate was nonlinear.

A gradual increase in fertilizer rate up to and including $N_{120}P_{100}K_{160}$ increased root yield from 22.38 to 36.70 t/ha in an almost linear manner. However, exceeding this rate caused a substantial decrease in yield due to reductions in both plant stand density and root mass. The increase in root inulin content with increasing fertilizer rate may indicate not only improved inulin synthesis but also a protective response, since inulin acts as an osmoprotectant and helps the plant counteract osmotic stress under high fertilizer rates.

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Mazurenko B.O., Honchar L.M. Effect of fertilizer rate on the formation of root chicory yield and inulin yield

Purpose, to determine the effect of different rates of mineral fertilization on root mass formation, yield, inulin content, and inulin harvest of root chicory, as well as to identify the optimal nutrient level that ensures high productivity without a negative effect on yield and inulin accumulation. Methods. Field studies were conducted in 2021–2024 on gray forest soils using the root chicory cultivar Tsezar. The experimental design included an unfertilized control and six NPK rates, ranging from $N_{30}P_{25}K_{40}$ to $N_{180}P_{150}K_{240}$. Phosphorus and potassium fertilizers were applied before primary soil tillage, while nitrogen fertilizers were applied before sowing. At the stage of biological maturity, plant density, yield, inulin content, and inulin harvest per hectare were recorded. Statistical analysis was performed in R using multifactorial analysis of variance and Tukey's $HSD_{0.05}$ test. Results. It was established that fertilizer rate was the leading factor determining root mass, yield, and inulin harvest, whereas weather conditions had a greater effect mainly on inulin content. A gradual increase in the level of mineral nutrition up to $N_{120}P_{100}K_{160}$ promoted a stable increase in root mass during the growing season and provided the best combination of productivity and quality indicators. The highest root mass (249.8 g), yield (36.7 t/ha), and inulin harvest (5.66 t/ha) were obtained at this fertilization rate. The $N_{90}P_{75}K_{120}$ treatment also ensured high productivity, with root mass reaching 230.7 g, yield 34.3 t/ha, and inulin harvest 5.16 t/ha; however, these values were lower than those recorded for the optimal treatment. A further increase in fertilizer rate to $N_{150}P_{125}K_{200}$ led to a decline in these indicators, despite the highest inulin content of 15.5%. The most negative effect was observed at the maximum rate of $N_{180}P_{150}K_{240}$, where root mass decreased to 86.2 g, yield to 11.73 t/ha, and inulin harvest to 1.78 t/ha. This indicates that increasing the concentration of nutrients beyond the optimal level did not enhance productivity but, on the contrary, suppressed plant growth and reduced stand density. Correlation analysis confirmed a very strong positive relationship between root mass, yield, and inulin harvest, whereas the relationship between yield and inulin content was weak.

Findings. The optimal fertilization rate for root chicory grown on gray forest soils is $N_{120}P_{100}K_{160}$, which provides the maximum yield and inulin harvest. Exceeding this rate causes a decrease in productivity, which may be associated with excessive osmotic stress on plants.

Key words: inulin content, correlation, Spearmen, root mass

Мазуренко Б.О., Гончар Л.М. Вплив норми добрив на формування урожайності цикорію коренеплідного та збору інуліну

Мета. Встановити вплив різних норм мінерального удобрення на формування маси коренеплодів, урожайності, вмісту та збору інуліну цикорію коренеплідного, а також визначити оптимальний рівень живлення, що забезпечує високу продуктивність без прояву негативного впливу на урожайність та збір інуліну. Методи. Польові дослідження проводили у 2021–2024 рр. на сірих лісових ґрунтах із сортом цикорію коренеплідного Цезар. Схема досліду включала контроль без удобрення та шість норм NPK: від $N_{30}P_{25}K_{40}$ до $N_{180}P_{150}K_{240}$. Фосфорні й калійні добрива вносили під основний обробіток ґрунту, а азотні перед сівбою. У фазу біологічної стиглості обліковували густоту стояння, урожайність, вміст інуліну та його збір з 1 га. Статистичну обробку виконували у середовищі R із застосуванням багатофакторного дисперсійного аналізу та тесту Tukey $HSD_{0,05}$. Результати – Установлено, що норма удобрення була провідним чинником формування маси коренеплодів, урожайності та збору інуліну, тоді як погодні умови мали більший вплив переважно на вміст інуліну. Поступове підвищення рівня мінерального живлення до $N_{120}P_{100}K_{160}$ сприяло стабільному наростанню маси коренеплодів упродовж вегетації та забезпечувало найкраще поєднання продуктивних і якісних показників. Найвищу масу коренеплоду (249,8 г), урожайність (36,7 т/га) та збір інуліну (5,66 т/га) отримано саме за цієї норми удобрення. Варіант $N_{90}P_{75}K_{120}$ також забезпечував високі показники продуктивності, оскільки маса коренеплоду становила 230,7 г, урожайність – 34,3 т/га, а збір інуліну – 5,16 т/га, однак ці значення були нижчими порівняно з оптимальним варіантом. Подальше збільшення норми добрив до $N_{150}P_{125}K_{200}$ призводило до зазначених показників, незважаючи на найвищий вміст інуліну – 15,5%. Найбільш негативний ефект відмічено за максимальної норми $N_{180}P_{150}$K240, де маса коренеплоду знижувалася до 86,2 г, урожайність – до 11,73 т/га, а збір інуліну – до 1,78 т/га. Це свідчить, що збільшення концентрації елементів живлення понад оптимальний рівень не підвищувало продуктивність, а навпаки, пригнічувало ріст рослин і зменшувало густоту стояння. Кореляційний аналіз підтвердив дуже тісний позитивний зв'язок між масою коренеплоду, урожайністю та збором інуліну, тоді як зв'язок урожайності з вмістом інуліну був слабким. Висновки. Оптимальною нормою удобрення цикорію коренеплідного на сірих лісових ґрунтах є $N_{120}P_{100}K_{160}$, яка забезпечує максимальну урожайність і збір інуліну. Перевищення цієї норми спричиняє зниження продуктивності, що може бути пов'язано з надмірним осмотичним навантаженням на рослини.

Ключові слова: вміст інуліну, кореляція, Спірмен, маса коренеплоду

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