Received 02.06.2025 Revised 03.09.2025 Accepted 23.09.2025

Vol. 21, No. 5
2025

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 633.63:631.8:631.531:577.1

Doi: 10.31548/dopovidi/5.2025.55

Influence of nitrogen and phosphorus-potassium fertiliser on the yield and biochemical composition of common chicory (*Cichorium intybus* L.)

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Abstract. Common chicory (*Cichorium intybus* L.) is an important industrial crop, valuable due to its high content of inulin and functional bioactive compounds. Optimisation of mineral fertilisers remains key to maximising yields and improving biochemical composition in the face of climate change. The purpose of this study was to evaluate the effect of nitrogen and phosphorus-potassium fertilisers on the yield and biochemical parameters of chicory. Field studies were conducted in 2021-2023 in the Right-Bank Forest-Steppe of Ukraine on low-humus chernozem according to a two-factor scheme that included 5 variants of nitrogen fertiliser (0-200 kg/ha) and five variants of phosphorus-potassium fertiliser (0-120 kg P_2O_5 and 0-200 kg K_2O). The yield of root crops, total sugar content, inulin content, reducing sugars, and degree of polymerisation were determined using standardised biochemical and statistical methods (analysis of variance, Tukey's HSD post-hoc test, Principal Component Analysis (PCA), cluster analysis). The results of the research showed that nitrogen fertiliser affected all biochemical parameters and yield, but most of all on the content of inulin (up to 75% of dry matter) and the degree of polymerisation, while phosphorus-potassium fertilisers only on the yield and degree of polymerisation. The maximum average yield in the years of research (35.4 t/ha) was achieved with the introduction of $N_{150}P_{90}K_{150}$, while excessive application of nitrogen and phosphorus-potassium fertilisers (200 kg/ha) reduced crop productivity and yield. The total sugar and inulin content increased with

Suggested Citation:
Mazurenko, B., & Honchar, L. (2025). Influence of nitrogen and phosphorus-potassium fertiliser on the yield and biochemical composition of common chicory (*Cichorium intybus* L.). *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(5), 55-70. doi: 10.31548/dopovidi/5.2025.55.

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nitrogen application to 150 kg/ha, after which a decrease was observed. PCA confirmed the dominant role of nitrogen in the development of both yield and biochemical parameters. Optimal nitrogen standards (100-150 kg/ha) in combination with moderate levels of phosphorus-potassium fertiliser ensured stable root crop yields and high inulin content, which is important for both industrial processing and sustainable agricultural production

Keywords: correlation; inulin; sugars; Principal Component Analysis; polymerisation

Introduction

Common chicory (*Cichorium intybus L.*) is a multifunctional crop that is a source of inulin, dietary fibre, coffee substitute, and raw materials for the pharmaceutical and food industries. According to H. Akram *et al.* (2025), the acreage under chicory for inulin production in Europe exceeds 20 thousand hectares, with a tendency to increase and expand the geography of cultivation. The growing interest in functional food products and the need for high-quality raw materials leads to an increase in demand for crops with an optimal composition of biologically active substances and obtaining stable yields. In the conditions of climate change, optimisation of the mineral nutrition system is of particular importance, which allows increasing the yield and improving the quality of root crops. Nitrogen and phosphorus-potassium fertilisers directly affect the synthesis of carbohydrates, in particular inulin, and the development of root crop mass, which affects yield. The fertiliser system must meet two criteria: increase productivity and quality while minimising the negative impact on the environment. Therefore, the study of the influence of nitrogen and phosphorus-potassium fertilisers is scientifically and practically substantiated for improving the efficiency of chicory cultivation in the Forest-Steppe of Ukraine and would allow developing recommendations for improving the efficiency of growing high-quality raw materials adapted to specific varieties and growing conditions.

According to M. Hingsamer *et al.* (2022), in Europe, chicory roots are grown to produce a pre-biotic dietary fibre, inulin, which stimulates the growth of beneficial gut bacteria and stimulates the human immune system. The taproot contains an average inulin content of 17% of the raw weight, and the typical yield of the root crop is 45 tonnes per hectare. Currently, the world area of common chicory is about 14,500 hectares. Chicory roots also usually contain high amounts of sesquiterpene lactones. In the future, the food system and food supply will face various challenges, such as increasingly adverse weather conditions caused by climate change, threats of plant diseases, environmental pollution, etc. Therefore, due to its biosynthetic ability, high yield and low agronomic requirements, chicory has a high potential to become a universal industrial crop for molecular farming. M.I. Bakhmat *et al.* (2021) found that chicory plants require mineral nutrition for growth and development. The rational use of fertilisers, including nitrogen fertilisers, is an important factor in sustainable agriculture. The researchers found that nitrogen fertilisers affect plant development. According to I. Popova *et al.* (2024), plant element content is affected by stresses such as salinity, drought, extreme temperatures, and excessive or insufficient lighting. Nitrogen deficiency can reduce the yield and quality of root crops, while excess nitrogen can lead to nitrate leaching and environmental pollution. Chicory crops without fertilisers have a high agroecological resistance, but they reduce it when applying nitrogen fertilisers.

In previous studies, D. Alves *et al.* (2024) noted that the reasons for the decrease in yield with an increase in fertiliser rates can be not only an imbalance of nutrients, but also subsequent damage to leaf diseases, which, in turn, reduces assimilation activity. Sodium (Na) helps to regulate osmotic pressure in cells, thereby supporting water absorption and retention. Weather conditions and the sensitivity of varieties to fertilisers also affect the crop productivity, in particular, the weight of root crops. O. Tkach *et al.* (2023) have shown that excessive rates of nitrogen fertilisers, especially when the maximum possibility of sowing them was absorbed, lead to a decrease in the size and weight of the root crop. Growing conditions are a key factor in the development of the chicory crop, which was confirmed by the findings of H. Zhang *et al.* (2023), where the variation can reach 83.9% due to weather factors alone. According to A. Buchelt *et al.* (2020), in the context of potassium deficiency, chicory (*Cichorium endivia* L.) shows a decrease in the leaf area and their number, and therefore, a smaller area of photosynthesis and a smaller dry weight of shoots and roots. The reduced potassium content in cells acts as a switch that suppresses anabolic responses and stimulates catabolic processes, which leads to interruptions in plant growth and redirects available energy to deal with stress-related damage.

Numerous studies by X. Zhao *et al.* (2021) found the effect of macro- and microelements, including phosphorus and iron, on the quality and quantity of primary and secondary metabolites. Phosphorus as a macronutrient is the main component of biomolecules such as phospholipids and nucleic acids, in case of deficiency or defects in assimilation of which the plant faces a decrease in yield. M. Ebrahimi & M. Gholami (2025) found that in order to adapt and increase phosphorus reabsorption under phosphate stress, plants inhibit the growth of shoots and roots, the development of root hairs, demonstrating various physiological responses such as changes in the rate of glycolysis, the production of primary and secondary metabolites such as organic acids, sugars, and flavonoids. Iron deficiency, on the other hand, affected many of chicory's vital functions and led to reduced root length.

The study of chicory root by S. Tabatabaee *et al.* (2021) found that an increase in phosphorus content in the culture medium resulted in more crude mass and less inulin. Accumulation of inulin with a polysaccharide structure under conditions of phosphorus deficiency was associated with a decrease in biomass production, although an increase in root length was also observed under these conditions. This phenomenon may be related to the numerous functions of phosphorus in plant photochemical reactions.

The purpose of the study was to establish the regularities of the influence of various norms of nitrogen and phosphorus-potassium fertilisers on the yield and biochemical parameters of chicory roots.

Materials and Methods

Research area, soil and weather conditions

The field experiment was carried out during 2021-2023 on a site located in the Obukhov District of the Kyiv Oblas (49°46' N, 30°44' E) in the typical conditions of the Right-Bank Forest-Steppe of Ukraine. The soil of the experimental site was low-humus chernozem with an organic matter content of 4.36-4.53% in a layer of 0-20 cm, pH_{KCl} – 7.2-7.6, the content of easily hydrolysed nitrogen (according to Cornfield) – 152-164 mg/kg of soil, mobile phosphorus (according to Cornfield) – 152-161 mg/kg of soil, exchange potassium (according to Chirikov) – 148-157 mg/kg of soil.

In 2021-2023, the average monthly air temperature in most months consistently exceeded long-term indicators, which reflects the general trend of the last decade. In April, the average temperature was 7.5°C in 2021, and in 2023 it reached 9.6°C, exceeding the long-term average (8.4°C). Similar deviations were observed in August and September, when average temperatures were also higher than long-term values. Precipitation was characterised by significant variability over the years: in 2023, their total amount (422.7 mm) slightly exceeded the long-term figure (409 mm), while in other years the amount of precipitation was significantly lower. This indicates both the instability of seasonal conditions and a gradual trend towards an increase in temperature and a decrease in precipitation during certain periods.

The distribution of precipitation during the growing season significantly affected the growth of chicory. In 2021, sufficient precipitation in May (78.7 mm) provided favourable conditions for seed germination, but further shortages in June (23.7 mm) and July (62.7 mm) limited the development of root crops. Lower rainfall in May 2022 (34.2 mm) created stressful conditions for early plant development, while moderate rainfall in June (41 mm) and July (53.3 mm) remained below long-term average, which could limit the accumulation of biomass. The growing season of 2023 was characterised by sharp fluctuations: extremely dry May (1 mm) delayed initial growth, but heavy precipitation in June (87.6 mm) and especially in July (136.1 mm) led to excessive soil moisture. This uneven distribution of precipitation probably caused an imbalance in the development of the root system and affected the crop development. The study was conducted in accordance with the principles of Convention on Biological Diversity (1992).

Research conditions

The field experiment involved the study of two factors: phosphorus-potassium (ratio P_2O_5:K_2O – 3:5) and nitrogen fertiliser (Table 1).

Table 1. *Field experiment scheme*

Factor A Phosphorus-potassium fertiliser	Factor B Nitrogen fertiliser
A1. Without phosphorous-potassium fertilisers (control)	B1. Nitrogen-free fertilisers (control)
A2. $P_{30}K_{50}$	B2. N_{50}
A3. $P_{60}K_{100}$	B3. N_{100}
A4. $P_{90}K_{150}$	B4. N_{150}
A5. $P_{120}K_{200}$	B5. N_{200}

Note: in the table and text of the paper, the index P refers to the fertiliser rate in kg/ha P_2O_5, and K refers to K_2O
Source: compiled by the authors

The predecessor of chicory was winter wheat. Each year, soil preparation and research were identical. After harvesting the previous crop, stubble was ploughed with a disc harrow to a depth of 5-6 cm. A mixture of triple superphosphate (TPS, 46% P_2O_5) and potassium chloride (60% K_2O) was applied in advance before ploughing at a depth of 25-27 cm in September each year during the study period. Disking was carried out in spring when soil moisture reached 60% of field moisture capacity. In the second ten days of April, on the day of sowing, ammonium nitrate (34.4% nitrogen) was applied according to the experiment scheme to a depth of 4-6 cm in pre-sowing cultivation. Chicory was sown with drained seeds of the Tsesar variety to a depth of 2-3 cm with a row spacing of 45 cm and a seeding rate of 175 thousand germinating seeds/hectare. The area of each plot was 75.6 m^2 (5.4 m×14 m) of which 36 m^2 were accounting (3.6 m×10 m).

The selection of root crops for analysis was carried out in the first ten days of October each year. To this end, all plants were removed from an area measuring 3.96 m^2 (4 rows of 2.2 m). Root crops were separated from plants, cleaned from the soil, and the yield of root crops was determined. Biochemical parameters were set in air-dry biomass (drying mode – 48 hours at a temperature of 62°C and up to a stable weight). The total sugar content was determined by the procedure described by H. Gholami *et al.* (2018) on a UNICO 1205 Vis spectrophotometer (UNICO, Japan) using the phenol-sulphuric method (wavelength 480 nm) with the inulin standard. Reducing sugars were determined by the denitrosalicylic method with a wavelength of 530 nm and the D-fructose standard for constructing a calibration curve. The inulin content was calculated as the difference between total sugars and reducing sugars. The degree of polymerisation (DP) was determined by the equation of T. Paseephol *et al.* (2007):

$$DP = \text{Sugar content } (\%) \, / \, \text{Reducing sugar content } (\%). \quad (1)$$

Statistical analysis

Statistical analysis was performed in the R environment (version 4.4.2). PCA, cluster analysis, and correlation matrices (Pearson's pair correlation method) were developed in the package *ggplot2*. Analysis of variance (ANOVA) was performed for all parameters and considered the influence of weather conditions (years). The validity of the difference between the variants was established by Tukey's HSD post-hoc analysis at the significance level $p < 0.05$ for factors that were significant in the analysis of variance. Boxplot for inulin content and similarity indices were established by univariate analysis of variance for each year and for an average of 3 years within the phosphorus-potassium fertiliser block. The data is presented as averages with standard error ($n = 3$).

Results and Discussion

Environmental factors and the fertiliser system had different effects on individual biochemical parameters and chicory root yield (Table 2). In most cases, the effect of weather conditions on variation was dominant, in particular, on root yield, the content of reducing sugars, and the degree of inulin polymerisation. The effect of nitrogen on the total sugar content and inulin content was several times higher.

Table 2. *Analysis of variance of yield and biochemical parameters of chicory roots*

Effect	df	MS				
		Root yield	Sugar content	Inulin content	Reducing sugars content	Degree of polymerisation, n
N	4	777.2**	177**	175**	0.161**	32.5**
PK	4	827.9**	2 ns	2 ns	0.055**	5.6**
Year (Y)	2	4186.1**	35**	50**	1.626**	221.2**
N*PK	16	34.8**	1 ns	1ns	0.097**	9.5**
N*Y	8	9.67**	10**	9**	0.211**	18.3**
PK*Y	8	42.3**	16**	17**	0.105**	16.1**
Y*N*PK	32	6.5**	2**	2ns	0.109**	10.7**
Error		0.2	2	2	0.003	0.4

Note: ns – not significant impact, $p > 0.05$, * – $p < 0.05$, ** – $p < 0.001$

Source: developed by the authors based on research data

The yield variance under the influence of nitrogen and phosphorus-potassium fertilisers was similar, their interactions with each other and with weather conditions were significant (but the variance was ten times less). The highest yield of chicory roots on average for the study steps was 35.4 t/ha (Table 3) for combinations of N_{150} and $P_{90}K_{150}$, which is statistically different from all other options. Notably, these options are also the best among their factors.

Table 3. *Yield of chicory roots depending on nitrogen and phosphorus-potassium fertiliser, t/ha*

Rate of phosphorus-potassium fertilisation	Rate of nitrogen fertilisers					Average
	N_0	N_{50}	N_{100}	N_{150}	N_{200}	
P_0K_0	16.4	20.0a	21.9	23.3c	26.3e	21.6
$P_{30}K_{50}$	18.0	20.6ab	26.6ef	31.0i	30.1h	25.3
$P_{60}K_{100}$	25.3d	29.4g	29.9gh	33.3	31.2ij	29.8

Table 3. *Continued*

Rate of phosphorus-potassium fertilisation	Rate of nitrogen fertilisers					Average
	N_0	N_{50}	N_{100}	N_{150}	N_{200}	
$P_{90}K_{150}$	25.6d	28.3	31.8j	35.4	31.6ij	30.5
$P_{120}K_{200}$	21.1b	23.4c	27.1f	27.0f	26.3e	25.0
Average	21.3	24.3	27.5	30.0	29.1	

Note: identical letters indicate that they belong to the same group for Tukey's HSD-test at confidence level 95%

Source: developed by the authors based on research data

The increase in yield under the influence of nitrogen fertilisers has a linear trend in the range from 0 kg/ha to 150 kg/ha, but with the introduction of N_{200} there is a decrease in yield for all PK variants, except for absolute control (without fertilisers). In the case of phosphorus-potassium fertilisers, the trend is described by a second-level polynomial with a peak in the variants with $P_{60}K_{100}$ and $P_{90}K_{150}$ (29.8 and 30.5 t/ha, respectively), but with an increase in the fertiliser rate to $P_{120}K_{200}$ there is a significant decrease to 25 t/ha, which is equivalent to a significantly lower rate of $P_{30}K_{50}$. The decrease in yield at the maximum rates of phosphorus-potassium fertilisers is more significant than nitrogen fertilisers, so their impact on biochemical parameters should be considered.

Phosphorus and potassium play an important role in the synthesis and transport of carbohydrates, but according to the results of ANOVA, their effect on the content of inulin in the roots was not significant, and on the content of reducing sugars and the degree of polymerisation is significantly lower than in nitrogen. Given these facts, it is advisable to focus on the effect of nitrogen fertilisers on biochemical parameters (Table 4).

Table 4. *Biochemical composition of chicory roots*

Nitrogen fertiliser option	Sugar content, %	Inulin content, %	Reducing sugars content, %	Degree of polymerisation, n
0	70.6 ± 0.2	67.9 ± 0.2	2.70 ± 0.02a	26.3 ± 0.3
50	73.1 ± 0.2	70.3 ± 0.2	2.83 ± 0.02	25.9 ± 0.2
100	74.3 ± 0.2a	71.6 ± 0.2a	2.72 ± 0.03ab	27.4 ± 0.3ab
150	75.0 ± 0.2	72.3 ± 0.2	2.74 ± 0.03b	27.6 ± 0.3b
200	74.3 ± 0.2a	71.6 ± 0.2a	2.74 ± 0.02b	27.2 ± 0.3a

Note: the values are presented with standard error (±SE). Identical letters in the column indicate that they belong to the same group for Tukey's HSD-test with 95% confidence level

Source: developed by the authors based on research data

The total sugar content of chicory roots on average ranged from 70.6-75.0% of the total dry matter. Without the use of nitrogen fertilisers, the sugar content was 70.6 ± 0.2%, with a gradual increase when nitrogen was applied at the rate 50-150 kg/ha of the active substance (a.s.), but when it was increased to 200 kg/ha, the sugar content decreased to 74.3%, which was at the rate of 100 kg/ha. The inulin content repeated the trend of total sugar content, since the remaining sugars (reducing sugars) in absolute values varied slightly (2.70-2.83%). The content of reducing sugars in dry matter changed in a different trend. Significantly more reducing sugars were formed when 50 kg/ha of nitrogen was applied, while at the rate of 100 kg/ha, their content was almost at the level of the control, and at the rate of 150 and 200 kg/ha it exceeded (a statistically significant increase). The ratio of total sugars and reducing sugars using the methods used helped to determine the average degree of polymerisation of inulin in samples (although in fact the products are a mixture of different fractions). It was found that the degree of polymerisation of samples in the control version was 26.3, and when 50 kg/ha was applied, it decreased to 25.9. A further increase in the fertilisation rate was accompanied by an improvement in the synthesis of longer inulin molecules and, as a result, an increase in the degree of polymerisation to 27.6 (at the rate of N_{150}).

The inulin content showed seasonal changes (MS = 50) and had interactions and weather conditions with phosphorus-potassium (MS = 17) and nitrogen fertiliser (MS = 9), although it was inferior to the influence of nitrogen fertiliser (MS = 175). A detailed review at the level of a single variant will allow assessing the influence of factors and identify the main patterns in inulin synthesis (Figs. 1A-1E).

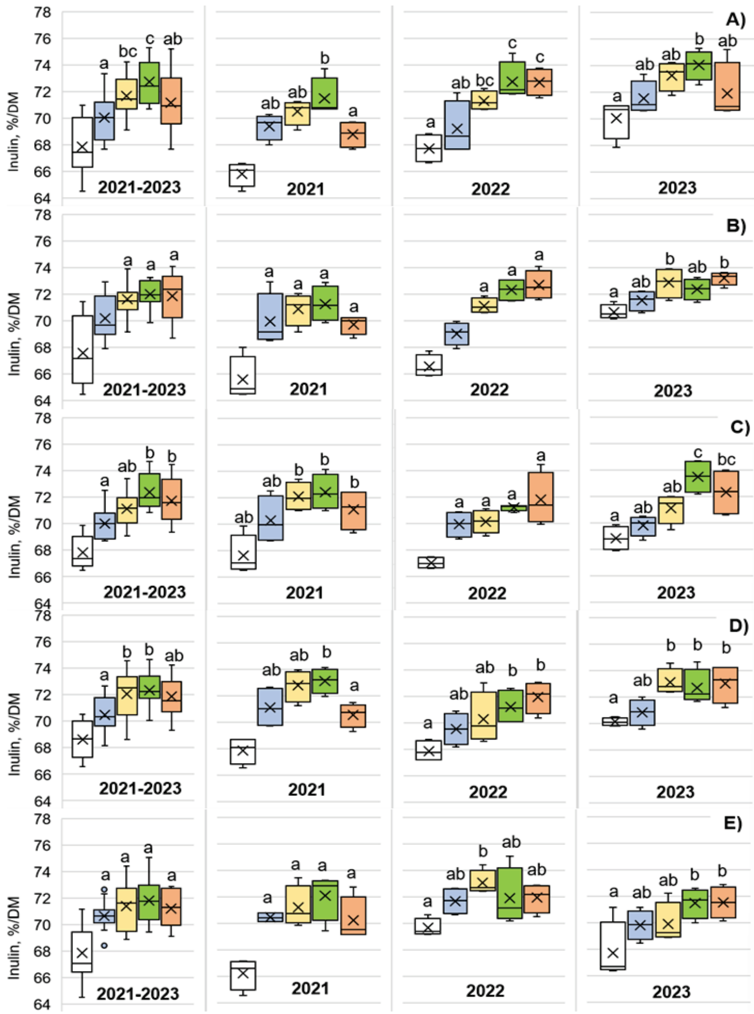

***Figure 1.** Effect of fertiliser on inulin content in chicory*

Note: A – P_0K_0; B – $P_{30}K_{50}$; C – $P_{60}K_{100}$; D – $P_{90}K_{150}$; E – $P_{90}K_{200}$; Box graph: cross – average value; line – median; box – 25%-75% percentile; bars – range of non-falling values. The same letters in the column indicate belonging to the same group according to Tukey's HSD-test with a 95% confidence level (a – group with the lowest value, the column without a value differs significantly from all groups)

Source: developed by the authors based on research data and statistical processing in the *ggplot2* package

The highest inulin content in the block without phosphorus-potassium fertiliser (annually and on average) was observed with N_{150} application, exceeding 72% (Fig. 1A). Options with N_{100}, N_{150}, and N_{200} showed no significant differences within the block with fertilisation rate of $P_{30}K_{50}$ (Fig. 1B). A similar trend was observed for $P_{60}K_{100}$ (Fig. 1C), although the rate of N_{200} significantly increased the spread of values. At the highest rate of phosphorus-potassium fertiliser ($P_{120}K_{200}$) with nitrogen application significantly increased the inulin content compared to the control without nitrogen. However, no significant differences were found between different nitrogen standards (Fig. 1E). The specific response of chicory to nitrogen application is probably associated with stimulation of inulin growth and synthesis, whereas cellulose, which is a component of cell walls, does not increase at the same rate.

Previously, it was noted that some indicators may have polynomial dependences on the norms of phosphorus-potassium and nitrogen fertilisers, but the determination of correlation coefficients (Fig. 2) allows assuming that there are links between these parameters.

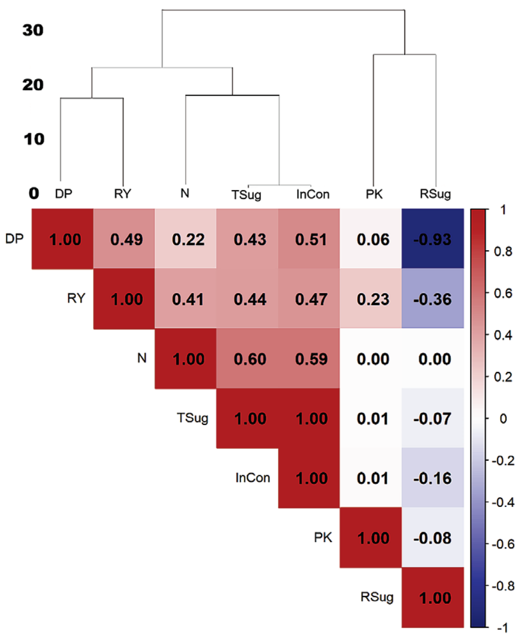

***Figure 2.** Correlation matrix between yield, fertiliser rates, and biochemical parameters of chicory roots*

Note: correlation coefficients within -0.21 ... 0.21 are unreliable (p>0.05); indices: DP – degree of polymerisation, RY – root yield, N – rate of nitrogen fertilisation, TSug –total sugar content, InCon – inulin content, PK – rate of phosphorus-potassium fertilisation, RSug – content of reducing sugars

Source: developed by the authors based on research data and statistical processing in the *ggplot2* package

It was found that the correlation between the rates of nitrogen fertilisation and a number of indicators was average positive (sugar content, inulin content, root yield) and weak with the degree of polymerisation. In the case of reducing sugars, there was no reliable linear relationship. In the case of phosphorus-potassium fertilisers, a significant correlation was recorded only with root yield, and the relationship itself was weak positive (r = 0.23). Among other interactions, root yield was distinguished, which has an average positive correlation with the degree of polymerisation (r = 0.49), total sugar content (r = 0.44), and inulin (r = 0.47), but a negative weak correlation with the content of reducing sugars (r = -0.36). The clustering performed indicates the presence of two clusters at a Euclidean distance of 30 (1 supercluster – phosphorus-potassium fertiliser and the content of reducing sugars; 2 supercluster – other indicators). At Euclidean distance of 20, 2 clusters were also distinguished within the second supercluster. The first includes indicators of yield and degree of polymerisation, and the second – the rate of nitrogen fertilisers, sugar content, and inulin content.

Clustering confirmed previously made observations, but did not allow finalising the conclusions, since some indicators change under the influence of unaccounted factors.

Principal component analysis (PCA) is used to take these factors into account. It was found that 87.83% of all data are described by two main components (PC1 – 59.34%, PC2 – 28.49 %) (Fig. 3). Notably, PC1 had a positive effect on the sugar content, inulin content, degree of polymerisation, and yield, but in the case of yield, its effect was less significant. This component had a negative effect on the content of reducing sugars. PC2, in turn, had almost no effect on yield, had a negative effect on the degree of polymerisation, but was positive for other biochemical parameters.

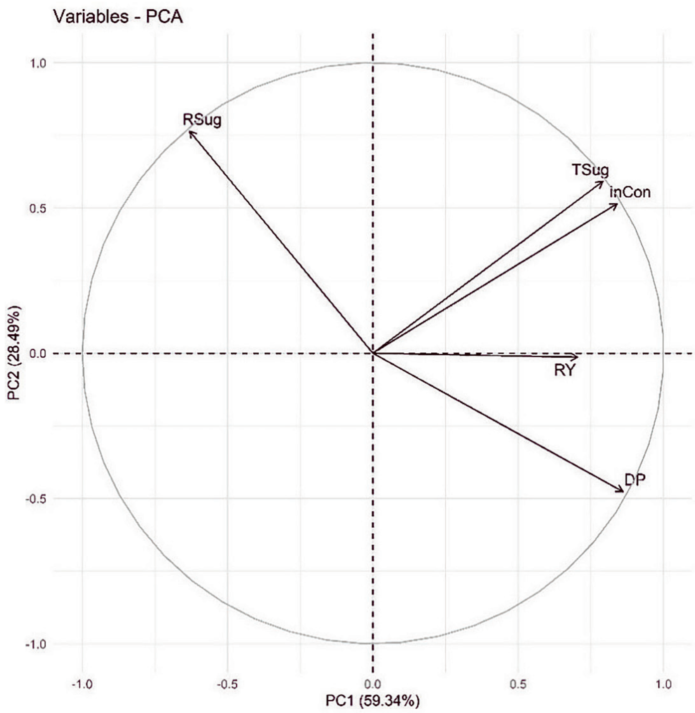

Figure 3. *Principal component analysis by main biochemical parameters and yield*

Note: RSug – reducing sugars, TSug – sugar content, InCon – inulin content, RY – root yield, DP – degree of polymerisation

Source: developed by the authors based on research data and statistical processing in the *ggplot2* package

Therefore, when further analysing the effect of the fertiliser system, it should be noted that PC1 mainly affected the yield, content, and quality of inulin, and PC2 only affected its content. This fact indicates that only coordinates along the PC1 axis can be considered for the estimate. The effect of nitrogen fertiliser was more significant in most cases, so grouping was based on this factor (Fig. 4).

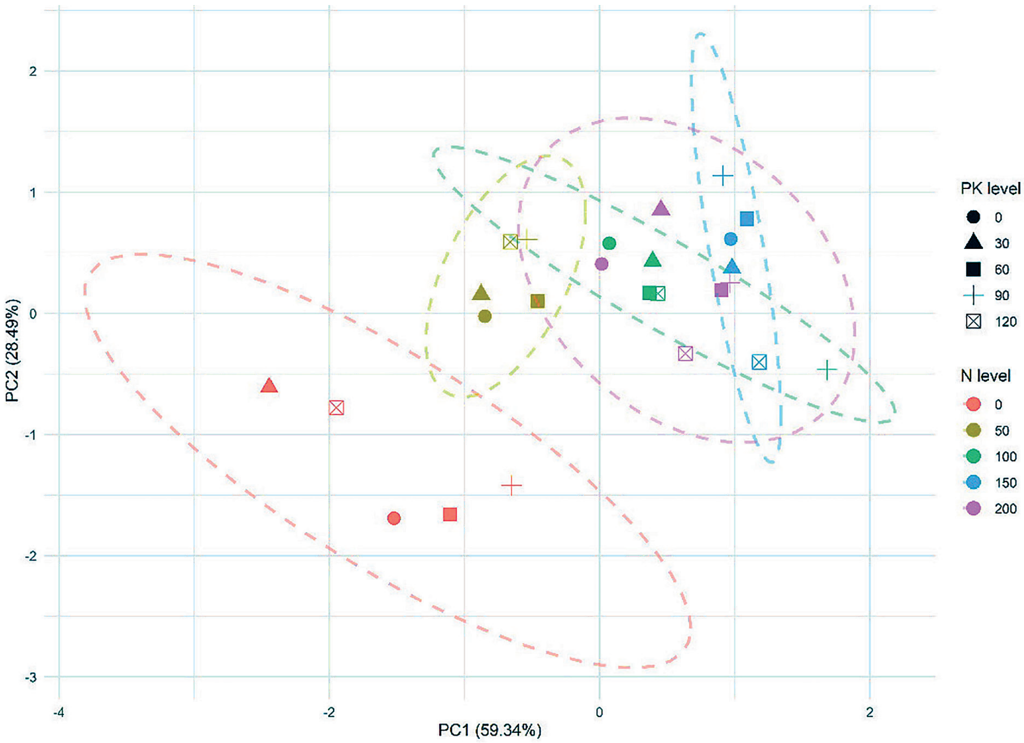

Figure 4. *Principal component analysis is grouped by variants*
Source: developed by the author based on research data and statistical processing in the *ggplot2* package

The red cluster is placed separately from the fertilised variants, which indicates the dominant effect of nitrogen fertilisers on yield and biochemical parameters. Fertilised options are placed differently on the plane. The cluster with a fertilisation rate of 50 kg/ha is in the negative range of values for PC1 and mainly in the positive range for PC2. The cluster with a rate of 100 kg/ha is scattered and is located mainly in the positive plane for PC1, but almost homogeneous for PC2 (in the range of -1 … +1). The cluster with N_{150} is located to the right on the PC1 axis, indicating the priority option for maximising yield and inulin content. Notably, the option $N_{100}P_{90}K_{150}$ located to the right of cluster N_{150}, although in terms of yield, it is inferior to $P_{150}P_{90}K_{150}$. On the one hand, this may indicate that the influence of other components can significantly affect the yield and thus exclude this variant from the PC1-PC2 system based on empirical observations.

The results of the current study confirmed that excessive application of nitrogen fertilisers negatively affects the yield of chicory roots. Similar conclusions are given in the paper by B. Cwalina-Ambroziak *et al.* (2022)**,** where the effect of different nitrogen doses on the productivity and mineral composition of chicory was studied. The researchers found that excessive doses of fertilisers reduced root yields and worsened plant health, in particular, due to increased sensitivity to pathogens. In addition, there was an imbalance of macronutrients in the tissues, which highlights the risk of excessive nitrogen nutrition. Thus, their results are consistent with the data of the current study, which also recorded a decrease in yield when exceeding the optimal level of N_{150}. In turn, S. Kalenska *et al.* (2024) using the example of coriander showed that increasing the doses of mineral fertilisers does not always lead to a proportional increase in yield.

In contrast, with excessive fertilisation, there was a sharp decrease in both seed productivity and the synthesis of secondary metabolites, including fatty and essential oils. These data are important for comparison, as they indicate the universality of the problem of excessive mineral load in different species. However, chicory is characterised by greater stability of inulin synthesis, which explains the more gradual decrease in yield in the current study. The study by S. Moscatello *et al.* (2023) provided additional evidence that excess nitrogen affects the distribution of metabolites in chicory. The researchers showed that most of the nitrogen accumulates in the leaves, rather than in the roots, which reduces the efficiency of its use in terms of root crop productivity. An adequate supply of nitrogen is crucial for maintaining an optimal ratio between roots and leaves, since this is what determines the ability of plants to accumulate fructans. These results support the conclusions of the current study, which found that optimal nitrogen doses contribute to the balanced development of plant organs.

Of particular interest are studies devoted to other vegetable crops. For example, J. Hong *et al.* (2022), using the example of lettuce, found that the combination of nitrogen, phosphorus, and potassium nutrition has a complex effect on product growth and quality. It was shown that excess nitrogen led to a decrease in plant weight, while optimal doses provided an increase in yield and improved leaf quality indicators. Similar patterns can be traced for chicory: when nitrogen doses were exceeded over N150, root productivity decreased. Similar results were obtained by M.M. Hoque *et al.* (2010)**,** who investigated the reaction of lettuce to different levels of mineral nutrition. The researchers showed that the yield and post-harvest quality of products increased only to a certain level of fertiliser, after which there was a deterioration in indicators. This was especially evident in the decrease in the marketable properties of products. Comparison of these results with the data of the current study shows a similarity in the reactions of different crops to excessive nitrogen loading: first, an increase in yield to the optimum, and then a decrease in productivity and quality.

An important role in the development of yield was played by weather conditions, which caused interannual differences. According to A.S. Mathieu *et al.* (2018), elevated temperatures did not always affect the inulin content, but led to a decrease in yield due to inhibition of sugar transport to the roots and slowing their growth. A.S. Mathieu *et al.* noted that under temperature stresses, the outflow of sucrose from the leaves to the roots was blocked, which directly reduced the biomass of root crops. However, the total fructan content remained relatively stable, which indicates a different sensitivity of physiological processes to temperature changes. Thus, the results of the current study confirmed the existence of a close relationship between the level of nitrogen fertiliser, biochemical parameters, and weather factors, which is consistent with the conclusions of previous studies.

The narrow range of fluctuations in the content of inulin in dry matter between years can be explained by the specific physiological response of chicory to water stress. As shown by B. Vandoorne *et al.* (2012), cell hydration is of key importance because the inulin content of fresh roots varies significantly depending on growing conditions. The researchers have shown that water deficiency dramatically reduces root growth and inulin yield, and this effect occurs regardless of the level of photosynthetic activity. This indicates that it is the violation of the water regime, and not a decrease in the production of photosynthesis, that limits the accumulation of reserve carbohydrates. In plants growing under arid conditions, the degree of polymerisation of inulin molecules may increase over time, while under favourable conditions, equilibrium is achieved much faster. The water stress did not significantly affect the degree of polymerisation, but it had a stronger effect on the overall yield, which confirms the dependence on the complex effect of solar radiation and temperature.

The findings by J. van Arkel *et al.* (2012) showed that in temperate regions, the average degree of inulin polymerisation increases until mid-September, after which it gradually decreased due to increased glucose levels, while inulin yield stabilises. J. van Arkel *et al.* traced the dynamics of changes in enzymatic activity in the process of "filling storage facilities" of roots: at first, there was an intense accumulation of long-chain fructans, but with the progression of the season, the activity of invertases increased, which caused an increase in glucose concentration and, accordingly, a decrease in the average DP. This confirms that the timing of harvesting is a critical factor for maintaining a stable carbohydrate composition. Similar patterns can be traced in the paper by R.G. Wilson *et al.* (2004)**,** where it was found that an increase in the proportion of short-chain fructans (DP 3-10) occurs at late harvesting, especially in conditions of high temperatures of the growing season. Their experiments have shown that with delayed harvesting, the yield of root crops increased, but the quality of products decreased due to an increase in the content of easily soluble sugars. In temperate regions, these processes were less pronounced, which indicates a significant influence of thermal growing conditions. Data by J. Wierzbowska *et al.* (2023) supplemented these results by demonstrating that late harvesting can reduce both the content of inulin and the degree of its polymerisation, even in conditions of an overall increase in root crop yield. The researchers stressed that an increase in root yield is not always accompanied by an increase in quality indicators, and with excessive postponement of harvesting, inulin fractions degrade to short-chain compounds. This confirms that optimising harvesting time is just as important as fertiliser levels or weather conditions.

The results of the current study confirm the importance of optimising the levels of nitrogen and phosphorus-potassium nutrition to increase the yield and quality of chicory. It has been found that excessive doses of fertilisers, especially nitrogen fertilisers, can reduce productivity and worsen biochemical characteristics, while moderate standards provide the best balance between quantity and quality of products. Weather conditions, in particular, fluctuations in temperature and water conditions, have a significant impact on the results, which causes interannual differences and confirms the need for adaptive fertiliser systems. The obtained data indicate the complex nature of the interaction of nutrition and climatic factors, which should be taken into consideration when forming practical recommendations for growing chicory. Data by M. Voitovyk *et al.* (2023) from typical chernozem show that organo-mineral fertiliser provides an increase in humic acid levels and an increase in soil buffer capacity, which is consistent with our results on improving the stability of soil organic matter with moderate doses of fertilisers.

The results obtained confirmed the complex nature of the interaction of mineral nutrition and weather factors in the development of yield and quality of chicory roots. Nitrogen fertiliser turned out to be the key factor that most affected inulin synthesis, total sugar content and degree of polymerisation, while the effect of phosphorus-potassium fertilisers was more moderate and mainly affected yield. Moreover, weather and water conditions significantly modified the effect of fertilisers, which emphasises the need for an adaptive approach to crop nutrition. Data summarisation provides an opportunity to determine the optimal ranges for fertiliser application to achieve high and stable productivity and raw material quality indicators.

Conclusions

The results of three years of field studies have confirmed that the effectiveness of growing common chicory is largely determined by the balance of mineral nutrition, while nitrogen fertilisers play a leading role. The application of nitrogen in doses up to 150 kg/ha significantly increased the yield of roots (up to 35.4 t/ha), and the content of total sugars and inulin increased by 4-5%

compared to the control, excessive use (200 kg/ha) caused a decrease in productivity, which was manifested in a decrease in root yield up to 20% compared to the best variant. The effect of phosphorus-potassium fertiliser on yield was characterised by a parabolic trend: the maximum indicators were formed at the rate $P_{60}K_{100}$-$P_{90}K_{150}$, however, a further increase in the dose ($P_{120}K_{200}$) led to a decrease in yield. Biochemical analysis showed that nitrogen fertiliser stimulated the synthesis of inulin and an increase in the degree of its polymerisation, while the effect of phosphorus and potassium was weaker and mainly associated with the processes of carbohydrate transport. Principal component analysis showed that more than 87% of the variations were conditioned by two main components, of which the first was mainly related to yield and inulin content. Positive correlations were established between the yield and the degree of polymerisation (r = 0.49), the total sugar content (r = 0.44) and inulin (r = 0.47). Simultaneously, a negative association with reducing sugars was observed (r = -0.36), which indicates a predominant synthesis of fructans under favourable conditions.

The optimal fertiliser regime for common chicory in the conditions of the Right-Bank Forest-Steppe of Ukraine should be considered the application of nitrogen in the range of 100-150 kg/ha in combination with phosphorus-potassium fertilisers at the rate $P_{60}K_{100}$ or $P_{90}K_{150}$. This strategy ensures the development of high yields, high inulin content, and rational use of resources, which makes the technology of growing chicory economically feasible and environmentally sustainable. Further research should focus on integrated fertiliser systems involving organic soil improvers, studying the carbon and ecological footprint of chicory production, and evaluating the effectiveness of technologies in the context of resource-saving agriculture.

Acknowledgements

This work was carried out within the framework of the research "Optimisation of the Technology for Growing Inulin-Containing Crops for Raw Material Production for Alternative Energy Needs" (No. 0121U111237), which is part of the thematic plan of the National University of Life and Environmental Sciences of Ukraine.

Funding

None.

Conflict of Interest

None.

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Вплив азотного та фосфорно-калійного удобрення на урожайність та біохімічний склад цикорію коренеплідного (*Cichorium intybus* L.)

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Анотація. Цикорій коренеплідний (*Cichorium intybus* L.) є важливою технічною культурою, цінною завдяки високому вмісту інуліну та функціональних біоактивних сполук. Оптимізація мінерального удобрення залишається ключовим фактором для максимізації врожайності та поліпшення біохімічного складу в умовах змін клімату. Метою даного дослідження було оцінити вплив азотного та фосфорно-калійного удобрення на урожайність та біохімічні показники цикорію. Польові дослідження проводилися у 2021-2023 рр. у Правобережному Лісостепу України на чорноземі слабогумусному за двофакторною схемою, що включала 5 варіантів азотного удобреннння (0-200 кг/га) та п'ять варіантів фосфорно-калійного удобрення (0-120 кг P_2O_5 та 0-200 кг K_2O). Урожайність коренеплодів, загальний вміст цукрів, вміст інуліну, редукуючих цукрів та ступінь полімеризації визначали за стандартизованими біохімічними та статистичними методами (дисперсійний аналіз, post-hoc тест Tukey's HSD, Principal Component Analysis (PCA), кластерний аналіз). Результати досліджень показали, що азотне удобрення впливало на всі біохімічні показники та урожайність, але найбільше на вміст інуліну (до 75 % від сухої речовини) та ступінь полімеризації, тоді як фосфорно-калійні добрива лише на урожайність та ступінь полімеризації. Максимальна середня врожайність у роки досліджень (35,4 т/га) була досягнута при внесенні $N_{150}P_{90}K_{150}$, тоді як надмірне внесення азотних та фосфорно-калійних добрив (200 кг/га) знижувало продуктивність посівів та урожайність. Загальний вміст цукрів та інуліну зростав при внесенні азоту до 150 кг/га, після чого спостерігалося зниження. PCA підтвердив домінуючу роль азоту у формуванні як урожайності, так і біохімічних показників. Оптимальні норми азоту (100-150 кг/га) у поєднанні з помірними рівнями фосфорно-калійного удобрення забезпечували стабільну врожайність коренеплодів та високий вміст інуліну, що є важливим як для промислової переробки, так і для сталого агровиробництва

Ключові слова: кореляція; інулін; цукри; Principal Component Analysis; полімеризація