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Optimization of nitrogen, phosphorus, and potassium fertilization for maximizing root yield and inulin yield in chicory (*Cichorium intybus* L.)

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Abstract. Root chicory (*Cichorium intybus* L.) is an important industrial crop for inulin production, but the optimization of mineral fertilization under fertile chernozem soils remains insufficiently defined. Under such conditions, additional fertilizer inputs may not proportionally increase root and inulin yield and may lead to higher residual nutrient levels after harvest. The aim of this study was to evaluate the effects of nitrogen and phosphorus-potassium fertilization on root biomass traits, crude inulin content, inulin yield, and post-harvest soil nutrient status of root chicory grown in the Right-Bank Forest-Steppe of Ukraine. A three-year field experiment (2021–2023) was conducted using a two-factor design with incremental PK and N rates. Cluster analysis and pairwise correlation coefficients were calculated between these parameters. The proposed approach to determining the optimal fertilizer rates for maximizing yield in individual years indicated values of $N_{130}P_{66}K_{110}$, $N_{150}P_{60}K_{100}$, and $N_{120}P_{72}K_{120}$, with an average of $N_{130}P_{66}K_{110}$. The highest inulin yield reached 5.80 t ha^{-1}, compared with 2.88 t ha^{-1} in the unfertilized control. Crude inulin concentration varied less than biomass-related traits, indicating that industrial raw material output depended primarily on root productivity rather than on large changes in inulin concentration alone. Post-harvest soil analysis showed that nitrogen fertilization increased residual hydrolysable nitrogen, whereas PK fertilization mainly increased mobile phosphorus at higher application rates. Thus, optimization of chicory fertilization under fertile chernozem conditions should be considered not only as a strategy for maximizing root and inulin yield, but a way to improve nutrient-use efficiency and avoid unnecessary nutrient surpluses.

Key words: agro-ecology, cluster, correlation, model, nutrient.

INTRODUCTION

Cultivated chicory (*Cichorium intybus* L.) is an important industrial crop because its roots accumulate high amounts of fructans, primarily long-chain inulin, which may account for up to 20% of root fresh weight and 60–80% of root dry matter (Gholami et al., 2018; Rambaud et al., 2025). Chicory-derived raw materials are used in food, dietary, medicinal, and processing industries, while chicory roots also contain several biologically active compounds, including chicoric acid, coumarins, flavonoids, and vitamins (Malik & Rehman, 2021). In addition to their role in food and health-related applications, chicory roots are also used for dried products, beverages, and other value-added industrial products. Therefore, stable production of high root biomass with high inulin concentration is essential for the efficient use of chicory as a technical raw material (Heimler et al., 2009). While recent studies have focused on the nutritional evaluation of chicory (Perović et al., 2021; Pouille et al., 2022) and its processed products, technological aspects of cultivation are still being refined (Zhang et al., 2023).

Variations in cultivation methods, sowing techniques, and seed treatments can limit the relevance and transferability of research findings across different growing regions (Bala et al., 2020; Tkach et al., 2024). The productivity and quality of root chicory are strongly influenced by environmental conditions and crop management. Root yield, inulin accumulation, and technological quality depend on weather conditions, soil nutrient supply, water regime, and growing season duration (Cranston et al., 2016; Bakhmat et al., 2023). Chicory forms a large leaf rosette and accumulates reserve carbohydrates in the root during the first year of vegetation, which results in a substantial demand for mineral nutrition, especially nitrogen and potassium (Mona et al., 2009; Tkach et al., 2022). However, the response of chicory to fertilization is not strictly linear. Excessive fertilizer rates may not proportionally increase root productivity and, under certain conditions, may even reduce yield because of osmotic effects, changes in assimilate partitioning, or altered root-to-shoot balance (Cranston et al., 2016; Honchar et al., 2020). This makes the optimization of fertilization regimes more important than the simple intensification of fertilizer inputs.

Although previous studies have demonstrated the importance of balanced NPK nutrition for chicory growth and biomass formation, the optimal fertilizer combination remains highly dependent on soil fertility, climatic background, and the production target (Khaghani et al., 2012; Zhang et al., 2023). This issue is especially relevant for highly fertile chernozem soils, where mineral fertilizers may play a corrective rather than a strongly yield-forming role. Under such conditions, identifying the rate at which additional nutrient input still provides agronomic benefit is necessary not only for maximizing root and inulin yield, but also for improving nutrient-use efficiency and reducing the risk of excessive residual nutrients after harvest. Thus, optimization of fertilization in chicory should be considered in both productive and environmental terms, particularly when the crop is intended for industrial processing and bio-based utilization.

Conducting exploratory studies to generate baseline data across a range of incremental fertilizer rates and developing fit models holds promise for determining optimal parameters for applying technological factors (Kalenska et al., 2024). While this approach optimizes resource use within a specific territory, its applicability diminishes with geographic distance, although the identified trends remain relevant for comparing individual elements of productivity. The biochemical parameters of chicory raw materials are essential for understanding the patterns of root yield formation and quality. Strong correlations between individual productivity elements enable the identification of critical parameters that can be improved by technological elements.

The present study evaluated the effects of nitrogen and phosphorus-potassium fertilization on root yield, root biomass traits, crude inulin content, inulin yield, and post-harvest soil nutrient status of root chicory grown on fertile chernozem soil in the Right-Bank Forest-Steppe of Ukraine. In addition, response-surface modelling and multivariate analyses were used to identify fertilizer combinations associated with maximum productivity. We hypothesized that root chicory productivity under these conditions is primarily determined by nitrogen supply because of its faster and more direct effect on plant growth, whereas the influence of phosphorus and potassium is expected to be less pronounced due to the high baseline nutrient status of the soil and the specific dynamics of nutrient transformation in chernozem.

MATERIALS AND METHODS

Field trial design

This research is part of a three-year field experiment (2021–2023) aimed at investigating the impact of fertilization systems on the biometric parameters of chicory, trends in metabolite accumulation in its leaves and roots, and the optimization of chicory cultivation technology for energy purposes. The study was conducted in collaboration with an associated farming enterprise on an experimental field under soil conditions typical of the Right-Bank Forest-Steppe zone (49°46' N, 30°44' E).

Table 1. Field trial scheme

Factor A Phosphorus-potassium fertilization	Factor B Nitrogen fertilization
A1. Without PK	B1. Without N
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 throughout the text, P refers to P_2O_5, and K refers to K_2O.

The field trial was arranged as a two-factor experiment (Table 1) using the root chicory cultivar Tsezar. Factor A consisted of phosphorus-potassium fertilization applied during primary autumn tillage at five levels: 0, $P_{30}K_{50}$, $P_{60}K_{100}$, $P_{90}K_{150}$, and $P_{120}K_{200}$. Factor B consisted of nitrogen fertilization applied before sowing at five levels: 0, N_{50}, N_{100}, N_{150}, and N_{200}. In Table 2 and throughout the manuscript, P refers to P_2O_5 and K refers to K_2O. The experiment had four replications and a systematic plot arrangement. Each plot measured 14 m × 5.4 m, and the net harvested area was 36 m² (3.6 m × 10 m).

The preceding crop was winter wheat. After its harvest, the field underwent disking using a Husker LDG-10 disk to a depth of 5–6 cm. Triple superphosphate (TPS, 46% P_2O_5) mixed with potassium chloride (60% K_2O) was applied and incorporated into the soil to a depth of 25–27 cm through ploughing in September. In spring, when field moisture capacity reached 60%, disking was performed to preserve soil moisture. In the second decade of April, on the day of sowing, nitrogen fertilizers (ammonium nitrate, 34.4% N) were applied according to the experimental scheme, followed by pre-sowing cultivation to a depth of 4–6 cm.

Phosphorus-potassium fertilizers were applied by broadcasting a pre-prepared mixture of triple superphosphate and potassium chloride. The fertilizer ratio in the mixture was 1:1.28. The base application rate was 65.2 kg ha^{-1} of superphosphate and 83.3 kg ha^{-1} of potassium chloride. These rates were proportionally increased in the respective treatment variants. The fertilizer mixture was broadcast using a fertilizer spreader with a spreading width of 14 meters. The uniformity of application was assessed within the designated accounting plot area. Nitrogen fertilizers were applied perpendicular to the phosphorus-potassium application based on the marked field layout.

The fertilizer spreading width was 6 meters, and the experimental plots were allocated at the center of the spreading strip. The base application rate was 150 kg ha^{-1} of ammonium nitrate, with the rate proportionally increased in the corresponding variants.

Pelleted chicory seeds were sown at a depth of 2–3 cm with a row spacing of 45 cm and a seeding rate of 175,000 viable seeds per hectare. Sowing was carried out using a 12-row seeder with a working width of 5.4 m. No chemical plant protection products were used during the growing season.

Soil and climate condition

The soil of research plots was classified as typical low-humus chernozem. Main agrochemical and agro-physical parameters are presented in Table 2. Bulk density ranged from 1.16 to 1.21 g cm^{-3}, porosity from 53.2 to 56.9%, humus content in the 0–20 cm layer from 4.36 to 4.58%, and soil pH (salt extract) from 7.2 to 7.6. The initial contents of hydrolysable nitrogen, mobile phosphorus, and exchangeable potassium in the 0–20 cm layer were consistently high across the experimental years, confirming the fertile status of the soil.

Table 2 Physical and agrochemical parameters of soil before fertilization

Parameter	2021	2022	2023
Bulk density, g cm^{-3}	1.21	1.18	1.16
Porosity, %	54.3	53.2	56.9
Humus content (Turin method) in 0–20 cm, %	4.53	4.36	4.58
Humus content in 20–40 cm, %	4.19	4.17	4.25
pH (salt extract)	7.30	7.6	7.2
Hydrolysed nitrogen (according to Kornfeld), mg kg^{-1} of soil	152	164	158
Mobile phosphorus (according to Kornfeld), mg kg^{-1} of soil	157	161	152
Exchangeable potassium (according to Chirikov), mg kg^{-1} of soil	148	150	157

The content of macronutrients was determined from samples taken from the 0–20 cm soil layer. Soil sampling for macronutrient analysis was carried out using composite samples collected before the application of mineral fertilizers (in the fall), while agro-physical parameters (bulk density, porosity) were measured immediately after pre-sowing cultivation (in the spring, before sowing). All these parameters were determined at the end of the growing season from soil samples taken from the same plots where plant samples for biochemical parameters were collected. Soil indicators after harvest are averaged across all plots.

The agroclimatic conditions during the years of the research differed significantly compared to typical for the Right-Bank Forest-Steppe zone, both in terms of long-term averages and deviations from them in individual years (Fig. 1).

During 2021–2023, air temperatures in most months exceeded long-term averages, with a gradual warming trend observed, particularly in spring and late summer. Annual precipitation showed pronounced interannual variability: total rainfall in 2023 exceeded the multi-annual mean, while 2021 and 2022 were generally drier. Rainfall distribution during the growing season was uneven, with sufficient moisture in May 2021 supporting early chicory growth, contrasted by below-average precipitation in subsequent summer months. In May 2022, reduced rainfall posed risks to early development despite moderate summer precipitation. In 2023, extremely dry conditions in May were followed by excessive rainfall in June and July, potentially disrupting balanced root formation due to alternating moisture deficit and surplus.

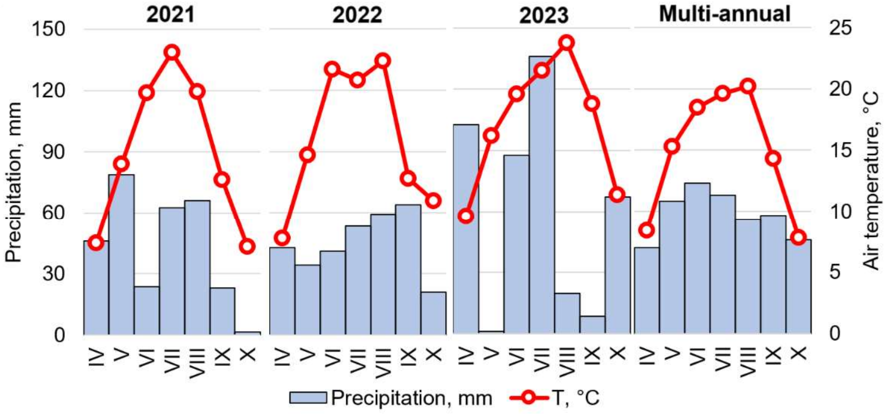


Figure 1. Air temperature and precipitation during experiment (2021–2023)

Sampling and laboratory analyses

Sample collection was conducted annually during the first decade of October (1st Oct 2021, 5th Oct 2022, 1st Oct 2023) by whole-plant sampling from an area of 3.96 m^2 (4 rows × 2.2 m). Roots were separated from the plants, cleaned of soil, and both the fresh weight of the roots and root yield were measured. Root yield is presented at the actual moisture content. Plant stand density was determined from the number of plants within the sampled area.

The dry matter content was determined in homogenized roots using the thermogravimetric method, with drying performed at 62 °C until a constant weight was achieved. Crude inulin was determined using the following equation:

$$\text{Crude inulin } (\%) = \text{Inulin content } (\%) \times \text{Dry matter content } (\%) \ / \ 100 \qquad (1)$$

Inulin yield was determined using the following equation:

$$\text{Inulin yield } (\text{t ha-1}) = \text{Root yield } (\text{t ha}^{-1}) \times \text{Crude inulin } (\%) \ /100 \qquad (2)$$

Fresh root mass was calculated as the average of 10 roots from each sample. Dry root mass was calculated by multiplying the fresh root mass by the dry matter content.

Biochemical parameters were determined in samples of roots that had been pre-dried and ground. The samples were dried for 48 hours at a temperature of 62 °C until a constant weight was achieved. The ground samples were placed in airtight containers and stored for analysis as needed.

Total sugar was determined using a spectrophotometer (UNICO 1205 Vis) by the phenol-sulfuric acid method (wavelength 480 nm), with inulin as the standard (Dubois et al., 1956). Reducing sugars were determined using the dinitrosalicylic acid method (Miller, 1959) on a spectrophotometer (wavelength 530 nm), with D-fructose as the standard. Both total sugars and reducing sugars were measured using calibration curves.

Inulin content was calculated as the difference between total sugars and reducing sugars.

Statistics

The data are presented as means ± standard error (SE). Statistical analyses were performed using STATISTICA (Tibco Inc., USA). An analysis of variance (ANOVA) was used for all measured characteristics, and treatment means were compared by *Tukey's* HSD test at $p < 0.05$. Identical letter indices indicate statistically homogeneous groups.

3D surface plots (Fit: Distance weighted LS) for root yield were generated using STATISTICA software for each year and cumulatively for the three years. Cluster analysis was performed for all parameters considered in the study, along with plant density (data not presented), using the tree-clustering method. Pairwise Pearson correlation coefficients were calculated for all parameters, and a correlation matrix was constructed.

Principal component analysis (PCA) was performed using the *ggplot2* statistical package in the R environment. Data from principal components 1 and 2 were used to construct the figures. Nitrogen and phosphorus-potassium application rate were used to construct the 'PCA plot of individual factors', while the variable indicators were used for the variables plot (excluding categorical factors, years, and replications).

RESULTS

Chicory root parameters

The primary raw material for chicory is the root with a high inulin content. The dry matter content, crude inulin, and root yield are determined by variety selection and growing conditions. A change in trophic conditions (in the context of the experiment are nitrogen and phosphorus-potassium fertilization) does not always have the same effect as improvements in weather conditions, moisture, and insolation. Therefore, it is important to analyse the impact of these factors on the variation and formation of root yield, fresh and dry root matter, inulin content, and inulin yield.

The analysis of variance revealed that the variance for all factors and their interactions was significant (Table 3). Root yield varied most significantly depending on weather conditions (year), with the impact being approximately five times greater than that of nitrogen (N) or phosphorus-potassium (PK) fertilization.

Table 3. ANOVA of chicory root parameters

Effect	*df*	Mean square (MS)				
		Root yield	Fresh RM	Dry RM	Crude inulin	Inulin yield
N	4	777.2**	44,319**	2,201.9**	6.4**	26.074**
PK	4	827.9**	48,503**	1,524.0**	31.93**	13.451**
Year (Y)	2	4,186.1**	333,058**	23,463.0**	76.20**	164.057**
N*PK	16	34.8**	2,218**	150.0**	1.79**	1.195**
N*Y	8	9.67**	859**	66.4**	2.27**	0.456**
PK*Y	8	42.3**	2,932**	166.7**	7.41**	1.613**
Y*N*PK	32	6.5**	382**	38.9**	1.48**	0.362**
Error	225	0.2	25	1.3	0.09	0.012

Note: ** – $p < 0.01$; Fresh RM – fresh root mass; Dry RM – dry root mass.

The fresh root mass followed the same trend as root yield, but the dry biomass showed significant differences. The effect of nitrogen fertilization ($s^2 = 2,201.9$) on the change in dry root mass was approximately 1.4 times greater than that of phosphorus-potassium fertilization ($s^2 = 1,524.0$). At the same time, the impact of weather conditions increased substantially, exceeding the effect of nitrogen fertilization by more than 10 times ($s^2 = 23,463.0$). Weather conditions also had the greatest impact on the crude inulin, while the effect of phosphorus-potassium fertilization was only half as large, and the impact of nitrogen fertilization was even smaller. Inulin yield depends on crude inulin and root yield, so the effects of the tested factors are combined. Since weather conditions had the greatest impact on both components, they subsequently influenced the target indicator. Regarding the effect of nitrogen and phosphorus-potassium fertilization, the variance for nitrogen was twice as large as that for phosphorus-potassium ($s^2 = 26.074$ and $s^2 = 13.451$). Therefore, nitrogen fertilization should be prioritized to achieve higher inulin yields.

Table 4. Root weight and inulin yield parameters, average per 2021–2023

Application rate, kg ha^{-1}		Root mass, g plant^{-1}		Crude inulin,	Inulin yield,
PK	N	Fresh	Dry	%	t ha^{-1}
0	0	125.2 ± 8.3	32.2 ± 2.9 a	17.2 ± 0.5 ghi	2.88 ± 0.26 a
	50	154.9 ± 11.8 a	39.2 ± 3.8 bc	17.5 ± 0.5 hi	3.55 ± 0.32 bc
	100	166.8 ± 10.4 b	42.6 ± 3.7 d	18.0 ± 0.5 j	4.02 ± 0.34 e
	150	179.9 ± 11.6 c	44.0 ± 3.6 de	17.7 ± 0.4 ij	4.15 ± 0.31 ef
	200	198.9 ± 11.3 de	47.6 ± 3.0 gh	17.0 ± 0.4 g	4.47 ± 0.25 g
$P_{30}K_{50}$	0	135.7 ± 9.6	31.7 ± 2.4 a	15.7 ± 0.3 ab	2.86 ± 0.23 a
	50	158.7 ± 10.4 a	38.8 ± 3.1 b	17.0 ± 0.3 gh	3.53 ± 0.26 b
	100	207.2 ± 14.9 fg	47.5 ± 3.3 gh	16.5 ± 0.1 ef	4.39 ± 0.27 g
	150	234.3 ± 17.1 i	55.3 ± 4.8 l	16.8 ± 0.3 fg	5.27 ± 0.41 k
	200	232.4 ± 17.2 hi	55.1 ± 4.9 kl	16.9 ± 0.4 fg	5.13 ± 0.43 jk
$P_{60}K_{100}$	0	195.6 ± 13.3 d	45.6 ± 3.8 ef	15.7 ± 0.3 ab	4.01 ± 0.31 e
	50	226.1 ± 20.2 h	51.5 ± 5.3 i	15.8 ± 0.2 ab	4.68 ± 0.43 h
	100	225.8 ± 14.5 h	50.4 ± 3.3 i	15.9 ± 0.2 abc	4.75 ± 0.26 h
	150	255.7 ± 15.7	61.5 ± 5.0 m	17.2 ± 0.4 ghi	5.80 ± 0.44 l
	200	235.3 ± 13.3 i	53.6 ± 3.2 jk	16.3 ± 0.2 cde	5.10 ± 0.27 j
$P_{90}K_{150}$	0	197.1 ± 15.6 de	42.6 ± 3.7 d	14.7 ± 0.2	3.81 ± 0.32 d
	50	216.7 ± 19.3	48.5 ± 4.8 h	15.6 ± 0.2 ab	4.46 ± 0.40 g
	100	243.1 ± 22.2 j	53.9 ± 5.3 kl	15.9 ± 0.2 abc	5.09 ± 0.47 ij
	150	274.2 ± 18.7	61.1 ± 5.1 m	16.0 ± 0.3 bcd	5.71 ± 0.43 l
	200	239.1 ± 16.8 ij	52.0 ± 4.5 ij	15.5 ± 0.3 a	4.93 ± 0.39 i
$P_{120}K_{200}$	0	162.2 ± 11.3 ab	38.6 ± 3.2 b	16.0 ± 0.2 bcd	3.39 ± 0.24 b
	50	180.7 ± 15.7 c	40.7 ± 4.0 c	15.8 ± 0.2 ab	3.71 ± 0.32 cd
	100	204.1 ± 12.1 efg	46.8 ± 2.7 fgh	16.4 ± 0.2 def	4.42 ± 0.19 g
	150	208.5 ± 13.4 g	46.3 ± 2.7 fg	16.0 ± 0.2 bcd	4.32 ± 0.21 g
	200	200.1 ± 12.8 def	44.1 ± 2.8 de	15.7 ± 0.1 ab	4.14 ± 0.22 e

Note: Mean presented with standard error (±SE). Similar letters in column indicate homogeneous groups at *Tukey's* HSD-test at 95% confidence level. Means without letters significant differs from other.

In the context of the interaction between nitrogen and phosphorus-potassium fertilization, the most effective combinations for each parameter can be identified (Table 4). The highest fresh root mass was observed with the application of $P_{90}K_{150}$, and this indicator in each nitrogen application rate was at or above the levels recorded for other phosphorus-potassium variants. The highest average fresh root mass was found in the $N_{150}P_{90}K_{150}$ treatment (274.2 ± 18.7 g). It should be noted that increasing the nitrogen rate to N_{200} led to a reduction in root mass, but in the variant without phosphorus-potassium fertilization, the effect was the opposite, while the difference was insignificant in the $P_{30}K_{50}$. The highest dry root mass was observed in the $N_{150}P_{60}K_{100}$ variant (61.5 ± 5.0 g), which was comparable to the best variant for fresh root mass – $N_{150}P_{90}K_{150}$ (61.1 ± 5.1 g).

Crude inulin content varied more significantly depending on the phosphorus-potassium fertilization rate, which may be related to the potassium uptake, as potassium plays a key role in the translocation of inulin. The highest crude inulin was recorded in the variant without phosphorus-potassium fertilization (17.0–18.0%), and its content gradually decreased with increasing fertilization rates. This phenomenon may be attributed to a reduction in the proportion of dry matter in the root, as its mass increased.

Inulin yield is an important technological parameter and an indicator of the effectiveness of chicory cultivation. In the absolute control variant (without fertilizers), the average inulin yield was 2.88 t ha^{-1}, while the highest yield was 5.80 t ha^{-1} ($N_{150}P_{60}K_{100}$), which is almost twice as much. It should be noted that the nitrogen rate of N_{150} was the best across all blocks where phosphorus-potassium fertilizers were applied, and increasing the fertilizer rate led to a reduction in inulin yield. An exception was the control variant for phosphorus-potassium fertilization, where inulin yield continued to increase.

Optimization of root yield by response-surface modelling

Since the variant $N_{150}P_{90}K_{150}$ stands out for a combination of valuable traits, it is worth considering it average yield over the study period. The average values for the factors show that root yield has a certain peak when a specific factor value is reached, and then decreases, indicating a nonlinear relationship. The highest average yield for the phosphorus-potassium fertilization factor (30.5 t ha^{-1}) was observed in the $P_{90}K_{150}$ variant, while the highest yield for nitrogen fertilization was in the N_{150} application rate – 30.0 t ha^{-1}.

Since both factors have a nonlinear impact on root yield, it is necessary to identify the points at which root yield is maximized. The 3D plot was constructed using the cumulative data for three years, as well as for each year separately, where yield is represented on the *z*-axis, nitrogen fertilization on the *x*-axis, and phosphorus-potassium fertilization on the *y*-axis, The surface plot is created by 'Distance Weighted LS' fit, on which the peak corresponding to the highest yield can be identified geometrically (Fig. 2, blue line). The coordinates on the *x* and *y* axes will represent the theoretical values for nitrogen and phosphorus-potassium fertilization rates, respectively.

The maximum on the 3D plot occurred at the point corresponding to $N_{130}P_{66}K_{110}$ across the three-year period (Fig. 2. a). Considering the spread on the plateau (areas with similar results), this point is close to the actual results, but with a shift toward $P_{60}K_{100}$. There is some variation in both the yield range, its amplitude, and the maximum point in individual years. The peak yield in 2021 and 2023 and the corresponding *x* and *y* coordinates were similar to the average for the three years. However, there was a shift toward N_{150} and $P_{60}K_{100}$ in 2022, indicating a shift in optimal conditions under specific weather patterns.

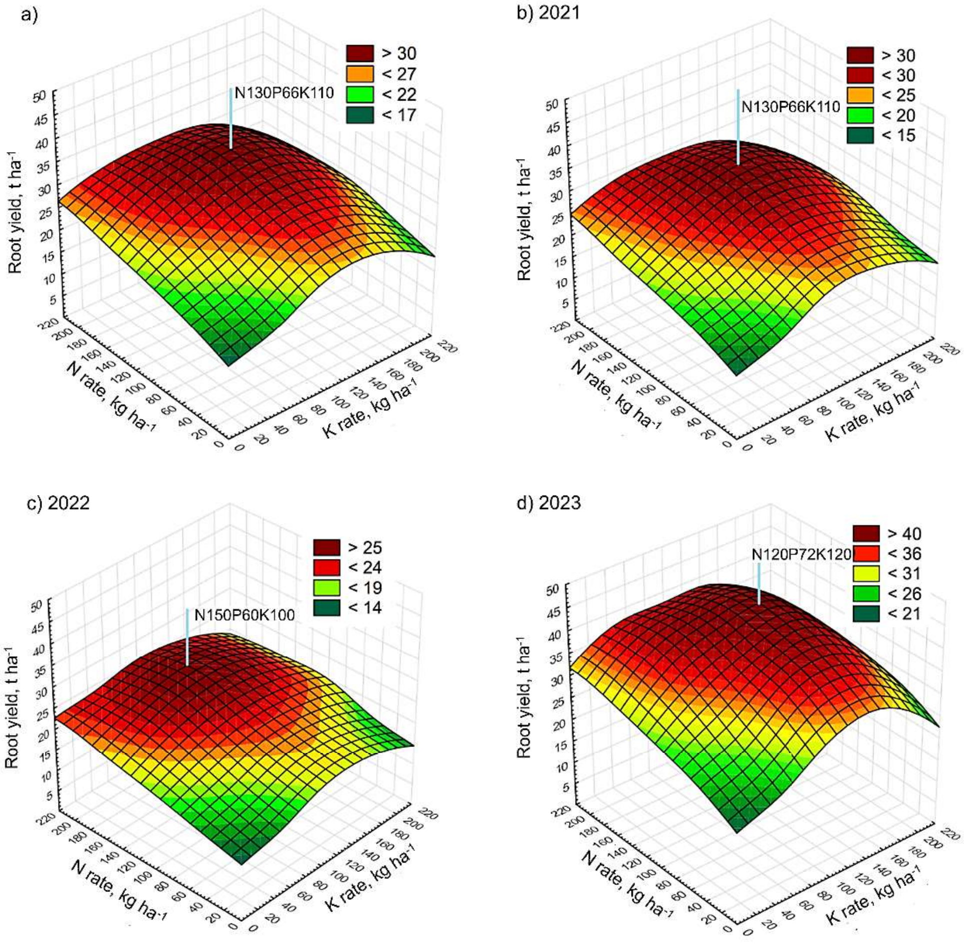


Figure 2. 3D plot of dependence of root yield from nitrogen and phosphorus-potassium fertilization (Fit: Distance weighted LS). Periods: a) 2021–2023; b) 2021; b) 2022; c) 2023. Axis *y* related to PK rate (P/K ratio 0.6)

Post-harvest soil nutrient status under different fertilization treatments

Chicory cultivation combined with mineral fertilization altered the post-harvest availability of nitrogen, phosphorus, and potassium in the 0–20 cm soil layer (Table 5). Easily hydrolysable nitrogen declined after harvest relative to the initial soil status in all treatments, indicating substantial crop uptake during the growing season. Nevertheless, treatments that received nitrogen fertilizer retained higher residual nitrogen than the unfertilized control, while increasing PK rates tended to slightly reduce residual hydrolysable nitrogen, likely reflecting improved nutrient uptake efficiency under more balanced nutrition.

The level of mobile phosphorus after harvest was also significantly lower compared to the initial values. However, the effect of chicory cultivation under different fertilizer rates was manifested differently than in the case of nitrogen. Nitrogen fertilization rates did not influence soil phosphorus levels, whereas the application of PK fertilizers led to an increase in available phosphorus, especially at rates of 90 kg ha^{-1} and above.

Potassium content, in turn, was not affected by the applied PK fertilizer rate, but it did vary slightly depending on the nitrogen fertilization level.

Table 5. The content of available forms of nitrogen, phosphorus, and potassium in the 0–20 cm soil layer after chicory harvest, average for 2021–2023

PK rate	N rate					Average by PK rate
	0	50	100	150	200	
Easily hydrolysed nitrogen						
0	136.7 ± 2.9	144.3 ± 3.3	145 ± 1.5	146.3 ± 2.9	144.3 ± 1.5	143.3 ± 1.3**B**
30	132 ± 2.5	137.7 ± 2.0	139 ± 1.5	140 ± 1.0	140.3 ± 1.2	137.8 ± 1.0**A**
60	133 ± 3.5	140.3 ± 2.2	143.7 ± 3.7	140.7 ± 2.0	138.7 ± 1.8	139.3 ± 1.4**AB**
90	132.3 ± 5.6	135.3 ± 0.9	140.7 ± 3,5	134.7 ± 3.5	137.7 ± 3.0	136.1 ± 1.6**A**
120	130±3.1	138.7 ± 1.7	136.7 ± 0.7	139.3 ± 3.7	138.3 ± 1.9	136.6 ± 1.3**A**
Av. by N	132.8 ± 1.5	139.3 ± 1.1**a**	141 ± 1.2**a**	140.2 ± 1.5**a**	139.9 ± 1.0**a**	
Mobile phosphorus						
0	131.0 ± 3.5	135.3 ± 4.1	131.0 ± 5.7	131.3 ± 4.7	133.3 ± 5.4	132.4 ± 1.8**A**
30	133.3 ± 3.0	136.3 ± 0.9	136.0 ± 1.5	137.3 ± 0.7	134.3 ± 2.0	135.5 ± 0.8**A**
60	141.7 ± 5.2	141.7 ± 2.0	137.7 ± 2.3	141.7 ± 2.7	144.3 ± 2.0	141.4 ± 1.3**B**
90	143.7 ± 2.2	142.3 ± 2.0	140.7 ± 1.3	141.3 ± 1.9	141.0 ± 0.6	141.8 ± 0.7**B**
120	148.0 ± 3.5	143.7 ± 3.0	141.7 ± 2.7	140.3 ± 1.2	143.7 ± 3.0	143.5 ± 1.3**B**
Av. by N	139.5 ± 2.2**a**	139.9 ± 1.3**a**	137.4 ± 1.6**a**	138.4 ± 1.4**a**	139.3 ± 1.7**a**	
Exchangeable potassium						
0	139.3 ± 1.2	147.0 ± 4.0	144.3 ± 1.9	144.7 ± 1.2	143.0 ± 3.2	143.7 ± 1.2**A**
30	148.7 ± 1.5	147.0 ± 4.5	146.0 ± 2.0	147.0 ± 2.6	141.0 ± 1.0	145.9 ± 1.2**A**
60	149.0 ± 1.0	146.3 ± 2.6	144.3 ± 2.7	140.7 ± 1.5	144.3 ± 2.0	144.9 ± 1.1**A**
90	146.7 ± 5.5	146.3 ± 0.9	149.7 ± 1.3	148.7 ± 1.5	141.3 ± 0.3	146.5 ± 1.3**A**
120	141.0 ± 3.0	147.3 ± 1.9	149.3 ± 1.3	140.3 ± 1.2	142.3 ± 2.8	144.1 ± 1.3**A**
Av. by N	144.9 ± 1.5**ab**	146.8±1.2**b**	146.7 ± 1.0**ab**	144.3 ± 1.1**ab**	142.4 ± 0.9**a**	

Note: Mean presented with standard error (±SE). Similar uppercase letters in column indicate homogeneous groups at *Tukey's* HSD-test at 95% confidence level. Similar lowercase letters in rows indicate homogeneous groups at *Tukey's* HSD-test at 95% confidence level. Initial soil nutrient baseline values provided in table 2.

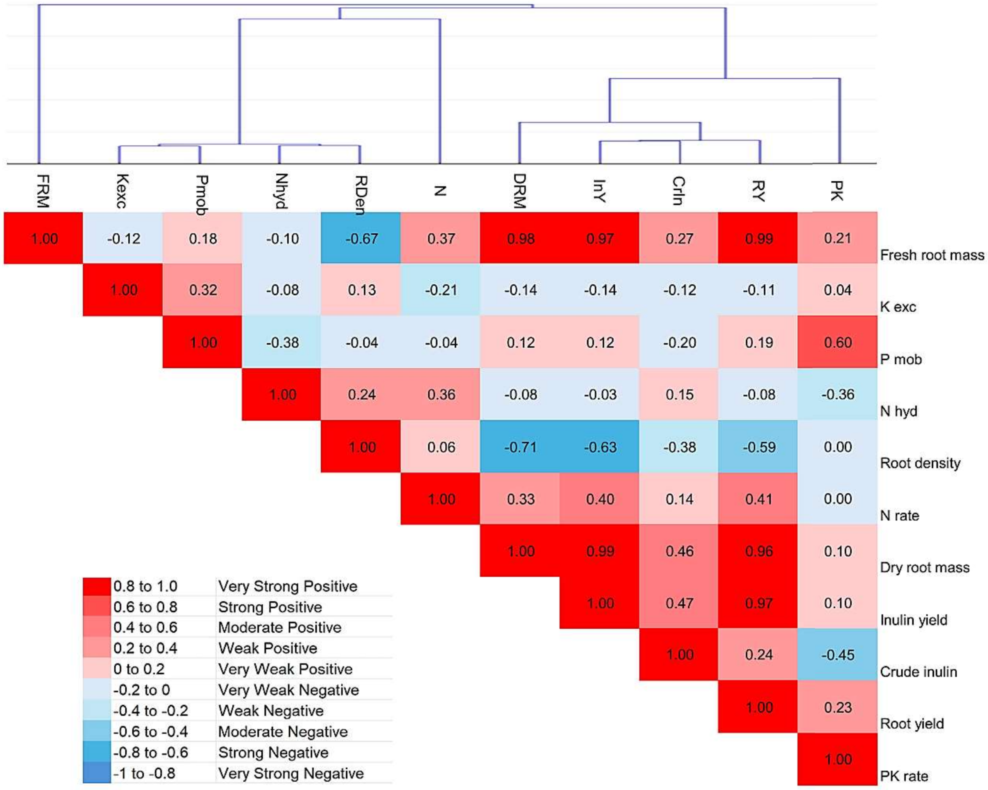
It is worth noting that under the optimal fertilizer rate, the content of easily hydrolysable nitrogen remains at a level comparable to the unfertilized variant, indicating its efficient uptake and, consequently, a reduced potential for volatilization or leaching into groundwater. Meanwhile, the levels of mobile phosphorus and exchangeable potassium remain close to their baseline values (prior to plowing and fertilization).

Multivariate relationships among productivity and soil traits

Cluster analysis revealed several key clusters of characteristics that may be interdependent (Fig. 3). It is important to note that the primary characteristics for industrial use of root chicory are those related to inulin yield, which, in turn, depend on root yield and raw inulin content.

At a relative distance of 0.4, two main clusters can be distinguished: (I) soil parameters (available mobile nutrients) and plant density; (II) productivity indicators, including root yield, inulin yield, and individual plant traits.

The nitrogen application rate is most strongly associated with the first cluster, whereas the phosphorus-potassium fertilization rate is primarily associated with the second cluster. Notably, these relationships are also reflected in the correlation matrix.



	FRM	Kexc	Pmob	Nhyd	RDen	N	DRM	InY	CrIn	RY	PK
Fresh root mass	1.00	-0.12	0.18	-0.10	-0.67	0.37	0.98	0.97	0.27	0.99	0.21
K exc		1.00	0.32	-0.08	0.13	-0.21	-0.14	-0.14	-0.12	-0.11	0.04
P mob			1.00	-0.38	-0.04	-0.04	0.12	0.12	-0.20	0.19	0.60
N hyd				1.00	0.24	0.36	-0.08	-0.03	0.15	-0.08	-0.36
Root density					1.00	0.06	-0.71	-0.63	-0.38	-0.59	0.00
N rate						1.00	0.33	0.40	0.14	0.41	0.00
Dry root mass							1.00	0.99	0.46	0.96	0.10
Inulin yield								1.00	0.47	0.97	0.10
Crude inulin									1.00	0.24	-0.45
Root yield										1.00	0.23
PK rate											1.00

0.8 to 1.0	Very Strong Positive
0.6 to 0.8	Strong Positive
0.4 to 0.6	Moderate Positive
0.2 to 0.4	Weak Positive
0 to 0.2	Very Weak Positive
-0.2 to 0	Very Weak Negative
-0.4 to -0.2	Weak Negative
-0.6 to -0.4	Moderate Negative
-0.8 to -0.6	Strong Negative
-1 to -0.8	Very Strong Negative

Figure 3. Cluster analyse and correlation between root parameters of chicory (|r| > 0.27 is significant at 95 % confidence level).

Fresh chicory root mass shows the strongest correlations with dry root mass, root yield, and inulin yield (r = 0.97 … 0.98), whereas the effects of nitrogen fertilization are weakly positive (r = 0.37). Regarding nitrogen application, its relationship with productivity traits is generally weakly positive, while its correlations with mobile phosphorus and exchangeable potassium are negative, although not statistically significant (r = –0.21 … –0.04).

Phosphorus-potassium fertilization exhibits a significant linear relationship only with crude inulin, hydrolysable nitrogen, and mobile phosphorus. In essence, this supports the hypothesis that increasing the rate of these fertilizers enhances the content of mobile phosphorus even after harvest (r = 0.6) and, through improved trophic conditions, promotes nitrogen uptake (r = –0.36), resulting in a reduction of residual nitrogen reserves.

The most effective combinations of nitrogen and phosphorus-potassium fertilization were identified based on the joint interpretation of PC1 and PC2 (Fig. 4). The first two components explain 71.93% of the total variance, with PC1 (46.27%) representing the main productivity gradient and PC2 (25.66%) reflecting soil-related and structural characteristics of the crop-soil system. Fertilization variants with higher nitrogen rates (particularly N_{150}) are positioned further to the right along the PC1 axis compared with variants receiving the same phosphorus-potassium rates but lower nitrogen input, confirming the dominant role of nitrogen in driving productivity-related variation.

Variants with low nitrogen input (N_0 and N_{50}) are mainly located in the left or lower-central part of the PCA-plot (Fig. 4, left), corresponding to reduced values of yield-related parameters. Increasing nitrogen supply (N_{100}–N_{150}) results in a progressive shift of treatments toward the positive PC1 region, whereas the highest nitrogen rate (N_{200}) is associated with greater dispersion, indicating increased variability and reduced stability of system responses under excessive nitrogen input. The clustering of treatments in the upper-right quadrant (I) therefore reflects a combination of high productivity and sufficient nutrient availability rather than a purely nitrogen-driven effect.

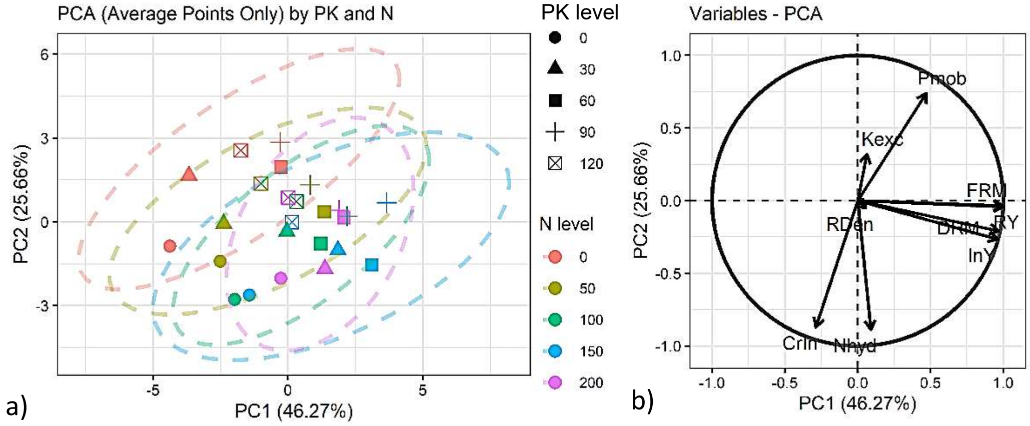


Figure 4. PCA of individual factor (left) and variables (right) plot for components 1 and 2.

The interpretation of variable loadings (Fig. 4, right) shows that PC1 is strongly influenced by fresh root mass (FRM), dry root mass (DRM), root yield (RY), and inulin yield per hectare (InY), all of which exhibit high positive loadings and near-collinear orientation along the PC1 axis. This confirms that PC1 can be interpreted as an integrated productivity index reflecting biomass accumulation and inulin output at the field scale.

PC2 is not dominated by yield or quality traits alone, but instead reflects variation related to residual soil nutrient status. Positive loadings on PC2 are associated with mobile phosphorus (Pmob) and exchangeable potassium (Kexch), whereas hydrolyzable soil nitrogen (Nhyd) and crude inulin content (CrIn) show negative loadings. This pattern indicates a differentiation between intensive biomass production and the accumulation or redistribution of residual soil nutrients. The opposing orientation of CrIn relative to FRM, DRM, and InY indicates that increases in total inulin yield are primarily driven by biomass accumulation rather than by higher inulin concentration in individual roots.

Overall, the PCA-plot demonstrates that PC1 is primarily driven by yield-related parameters, while PC2 reflects soil nutrient balance and structural trade-offs within the agroecosystem, rather than purely chemical quality indicators. These results highlight that optimal fertilization strategies should be based on achieving high productivity along

PC1 while avoiding excessive shifts along PC2 associated with residual nutrient accumulation and reduced system stability.

DISCUSSION

Effect of NPK fertilization on chicory growth, root yield, and inulin yield

The present study showed that, under fertile chernozem conditions, weather variability remained the dominant driver of chicory productivity, but among the fertilizer factors nitrogen had the strongest influence on root biomass accumulation and final inulin yield. This agrees with previous reports showing that nitrogen supply substantially affects root chicory growth, dry matter accumulation, and harvestable biomass, whereas the specific form of nitrogen is usually less important than the overall rate applied (Mohammad Sokri et al., 2015; Cwalina-Ambroziak et al., 2022; Wierzbowska et al., 2023). The stronger contribution of nitrogen relative to PK in our experiment is also consistent with the physiological role of N in supporting rapid canopy development and assimilate production, especially during the long vegetative period of root chicory. At the same time, the large effect of year observed in the ANOVA confirms that fertilizer efficiency in this crop is strongly modulated by hydrothermal conditions, which determine both biomass formation and the partitioning of assimilates into the root.

Phosphorus and potassium fertilization also play crucial roles, and balanced NPK application enhances both root and shoot biomass in chicory (Khaghani et al., 2012). These high nutrient requirements are primarily linked to the synthesis of aboveground biomass (Litvinova et al., 2023), so a significant portion of NPK accumulates in the leaves (Tkach et al., 2022). Fructans (including inulin) have osmoprotective properties (Valluru & van den Ende, 2008), which enable chicory to tolerate high salt concentrations resulting from elevated fertilizer doses. The reduction in root yield after the ‘peak point’ on 3D plots may be due to unaccounted factors, such as water deficiency inducing osmotic stress, or modifications in plant physiology that altered the root-to-leaf ratio (Moosavi, 2012). Gardner et al. (2024) reported that chicory cultivation promotes nitrogen mineralization in the soil, both during vegetation and after harvest. This explains the small amplitude of yield fluctuations along the ‘N fertilization’ axis at average levels of phosphorus-potassium fertilization across all years of the study.

The role of phosphorus in chicory root formation is secondary to that of nitrogen and potassium; however, in terms of its concentration in dry matter, it surpasses that of nitrogen. High phosphorus levels increase its accumulation in the roots, although its deficiency does not significantly reduce yield compared to nitrogen deficiency, as shown in alfalfa (Fan et al., 2016). Since phosphorus was applied together with potassium in our study, it is difficult to isolate its individual effect. Considering that the total nutrient amount in each phosphorus-potassium treatment increased by 80 kg ha^{-1} of active ingredient ($P_{30}K_{50}$), while the nitrogen application increment was 50 kg ha^{-1} and given that the yield increase was similar (or even dominated by nitrogen), this confirms the primary role of nitrogen in determining yield formation. Sugars serve not only as storage and signalling molecules but also contribute to enhanced resistance to excess heavy metals (Honchar et al., 2021), whether present in the soil or taken up by the plant. Phosphorus deficiency may stimulate additional sucrose synthesis (Hammond & White, 2008) as a compensatory mechanism to mitigate stress effects.

The high potassium requirement is associated with dry matter synthesis, carbohydrate transport within the plant, and inulin biosynthesis. In some studies (Poursakhi et al., 2020), year-to-year variance in accumulated nitrogen was nearly twice as high as variance between cultivars, whereas for potassium, variability was comparable to the cultivar factor. This suggests the importance of ensuring adequate potassium supply, particularly for potassium-demanding cultivars, to avoid potential deficiency. Potassium deficiency can lead to reduced turgor, impaired chlorophyll and carotenoid synthesis, and the development of plants with fewer leaves, smaller leaf area, and reduced root diameter (Alves et al., 2024). Since field crops in our study did not exhibit critical potassium deficiency symptoms, no extreme variations were observed across treatments, even with potassium application rates ranging from 0 to 200 kg ha^{-1}.

Conversely, balanced NPK fertilization has been found to increase both fresh and dry root weights, highlighting the importance of adequate nutrient management (Umami et al., 2019). Excessive fertilizer application may lead to soil salinization and osmotic stress. Typical indicators of osmotic stress include reduced root size and weight, along with decreased inulin content (Mohammadi et al., 2024). The decline in crude inulin concentration with increasing PK supply, despite higher fresh and dry root mass, is therefore more likely to reflect a dilution effect associated with biomass accumulation than a reduction in the plant's capacity to synthesize reserve carbohydrates. The contrast between crude inulin concentration and inulin yield per hectare is especially relevant for industrial interpretation of the results. The highest crude inulin values were observed in treatments without PK fertilization, but these treatments did not maximize inulin yield because root biomass remained lower. In contrast, the best-performing treatments in terms of inulin yield combined substantial root biomass with still acceptable inulin concentration, resulting in the highest output of technical raw material per unit area. This confirms that, for agronomic optimization, inulin yield is a more informative target trait than concentration alone.

Effect of NPK fertilization on soil fertility after growing chicory

Mineral fertilizers, owing to their high content of soluble nutrients, were efficiently absorbed by plants throughout the growing season, also contributing to the replenishment of soil reserves. Notably, higher nitrogen application rates led to an increase in the residual nutrient pool, even with increased chicory yields. However, the highest rate (200 kg ha^{-1} of nitrogen) resulted in lower yields and poorer soil nutrient levels, potentially posing a risk of soil contamination and indicating inefficient resource use. These findings are consistent with previous research by Rezaienia et al. (2017), which reported improved soil microbial activity and root development under balanced NPK fertilization, contributing to the rebalancing of soil nutrient profiles.

Phosphorus and potassium exhibited different dynamics. The content of mobile phosphorus remained significantly higher in plots receiving PK fertilizers at rates ≥90 kg ha^{-1}, which also aligns with the findings of Godoi et al. (2021) in eucalyptus seedlings. In contrast, potassium levels appeared more stable, likely due to the chemical nature of K and its strong sorption by soil particles.

Taken together, the post-harvest soil results strengthen the practical interpretation of the yield data. The treatment region associated with the highest root and inulin productivity was also characterized by limited residual nitrogen accumulation and by phosphorus and potassium levels remaining close to the baseline range. This suggests that fertilizer optimization in root chicory should be understood not only as a strategy for maximizing industrial raw material yield, but also as a way to improve nutrient-use efficiency and reduce the environmental burden associated with over-fertilization. Under fertile chernozem conditions, where baseline nutrient supply is already high, the agronomic task is therefore not to maximize input intensity, but to identify the fertilizer range in which additional nutrients still produce a measurable productive effect without creating unnecessary nutrient surpluses in the soil.

CONCLUSIONS

Under fertile chernozem conditions of the Right-Bank Forest-Steppe of Ukraine, weather variability was the dominant factor affecting root chicory productivity, but among the fertilizer factors nitrogen had a stronger effect than phosphorus-potassium fertilization on root biomass formation and final inulin yield. The response of chicory to mineral fertilization was nonlinear, indicating that productivity was maximized within a moderate-to-high fertilizer range rather than at the highest tested rates.

Root yield exhibited a clear nonlinear response to increasing fertilizer rates, confirming the existence of an optimal fertilization range. Surface modelling and multivariate analyses identified a theoretical optimum close to $N_{130}P_{66}K_{110}$, with moderate year-to-year shifts reflecting climatic variability. Higher nitrogen rates beyond this range did not improve productivity and were associated with increased variability and reduced system stability.

Post-harvest soil analysis showed that nitrogen fertilization increased residual hydrolysable nitrogen, whereas PK fertilization mainly increased mobile phosphorus at higher application rates, while exchangeable potassium remained comparatively stable. Therefore, fertilization optimization in root chicory should be interpreted not only as a strategy for maximizing yield and inulin output, but also as a way to improve nutrient-use efficiency and avoid unnecessary nutrient surpluses under conditions of initially high soil fertility. Overall, the study demonstrates that nitrogen-focused optimization of fertilization regimes can enhance chicory productivity while minimizing fertilizer inputs and environmental risks, providing a basis for sustainable and resource-efficient chicory cultivation.

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