

Accumulation and yield formation in potato across controlled and field experiments: implications for nitrogen use efficiency research

I. Taškova^{1,2,*}, L. Rābante-Hāne^{1,2}, I. Alsiņa¹ and I. Skrabule²

¹Latvia University of Life Sciences and Technologies, Faculty of Agriculture and Food Technology, Institute of Soil and Plant Sciences, 2 Liela street, LV-3001 Jelgava, Latvia

²Institute of Agricultural Resources and Economics, Zinatnes street 2, LV-4126 Priekuli, Latvia

*Correspondence: inese.taskova@arei.lv

Received: February 1st, 2026; Accepted: May 19th, 2026; Published: May 27th, 2026

Abstract. Potato (*Solanum tuberosum* L.) productivity is strongly influenced by nitrogen (N), which regulates plant growth, biomass formation and tuber development. This study aimed to evaluate nitrogen accumulation and its relationship with biomass and yield, and to verify nitrogen use efficiency (NUE) assessment by comparing field trials with pot and *in vitro* experiments. Field experiments were conducted in Priekulī, Latvia, under organic (OF) and integrated (IF) farming systems and *in vitro* experiments under controlled conditions. Pot trials were carried out in Jelgava. Three varieties ('Monta', 'Prelma', 'Jogla') were tested. Nitrogen was applied at 60 kg N ha⁻¹ in IF field plots; pots received 60 and 120 kg N ha⁻¹, while *in vitro* treatments included 7.5, 20 and 60 mmol L⁻¹ N. Nitrogen content in tubers was significantly affected by growing year and variety in both field systems ($p < 0.05$), with a significant year × variety interaction in OF. 'Prelma' consistently showed the highest nitrogen content, whereas 'Jogla' had the lowest across systems. Yield varied substantially among years and cultivation systems. In IF, 'Jogla' produced the highest yield, while in OF 'Prelma' performed best; 'Monta' had the lowest yields in both systems. In pot experiments, the highest yield was obtained at 120 kg N ha⁻¹, particularly for 'Jogla'. Nitrogen use efficiency (NUE) decreased with increasing N rate. The relationship observed under field conditions that earlier-maturing varieties have lower NUE than later-maturing ones could not be confirmed in the *in vitro* and pot experiments. Overall, consistent varietal responses across systems indicate that controlled-environment methods can support NUE evaluation in potato research.

Key words: *in vitro*, integrated farming system, organic farming system, pot experiment, *Solanum tuberosum*.

INTRODUCTION

Potato is the third most important food crop in the world (FAO STAT, 2022). The potato plays an important role in global history and food security.

Nitrogen (N) is a major determinant of potato growth and productivity, as it plays a crucial role in core physiological and developmental processes mediated by nitrate uptake and signalling. Most of the N in the soil is partly available for plants (Barrow & Hartemink, 2023). Along with water, N is a primary resource for crops, and the two factors are closely interconnected and influence one another (Su et al., 2024). N is absorbed by plant roots in the form of nitrate and ammonium (Shafreen et al., 2021). Further N engages in N metabolism processes to the synthesis of stable functional compounds, such as chlorophyll synthesis and photosynthesis, as well as to the formation of inert structural components within plant tissues (Liu et al., 2025). N is unevenly distributed within the plant canopy, forming a vertical gradient, which may complicate N assessment using remote sensing techniques when only the upper canopy layers are detected (Zhang et al., 2024). Canopy photosynthesis depends on N content (Dreccer et al., 2000).

The potato requires abundant N (Haverkort, 2018). High N fertilization rates, combined with the shallow root system of potatoes, can promote nitrate leaching and subsequent groundwater contamination (Iwama, 2008; Cui et al., 2020). Excessive N application contributes to soil acidification, destabilizes soil structure, stimulates excessive vegetative growth and increases susceptibility to pests and diseases, ultimately reducing yield and quality (Zhang et al., 2022). Moreover, a substantial proportion of applied N fertilizers is lost to surface and groundwater rather than being taken up by plants, leading to eutrophication. This process causes a range of environmental impacts, and increased greenhouse gas emissions (Craswell, 2021).

In the early stages of potato development, nitrogen (N) is mainly supplied through the root system, whose growth is supported by assimilates transported from the lower leaves to the roots. During vegetative growth, nitrogen is remobilised from older leaves to younger, actively developing tissues (Lammerts van Bueren & Struik, 2017). Previous studies have demonstrated that nitrogen use efficiency (NUE) varies among potato varieties (Tiemens-Hulscher et al., 2014). Tuber yield, plant dry matter content and nitrogen accumulation at maturity are closely related to nitrogen availability and uptake. However, although higher nitrogen supply can increase overall nitrogen accumulation, the efficiency of its conversion into yield decreases at elevated N levels (Mustonen et al., 2010).

Understanding the relationship between NUE and plant physiology allows for better crop performance. High NUE is strongly correlated with tuber number per plant and the effective transfer of dry matter to tubers. Genotypes with higher NUE produce significantly better starch yields, even under variable N rates. While N supply promotes canopy development, excessive N can actually decrease starch content in tubers, making NUE knowledge vital for maintaining quality. Canopy and late-maturing cultivars generally exhibit higher NUE because they have a longer period to intercept light and accumulate total dry matter (Getahun et al., 2020, Skrabule et al., 2023, Zhang et al., 2024).

Field trials are crucial, pre-screening of genotypes under controlled environmental conditions can be helpful in the breeding and selection process (Schum & Jansen, 2014). In contrast, *in vitro* culture systems enable the study of large numbers of plants within a short time under strictly controlled conditions, while eliminating the influence of

pathogens (Schum & Jansen, 2014; Schum et al., 2017). Therefore, understanding NUE and its relationship with biomass and yield across different cultivation systems is critical for optimizing potato production.

The aim of this study was to evaluate differences in nitrogen (N) content in potato plants and tubers and to assess their relationships with biomass and yield under *in vitro*, pot and multi-year field conditions in organic and integrated farming systems.

We hypothesised that nitrogen availability significantly influences nitrogen accumulation, biomass and yield, and responses observed under controlled conditions are consistent with those in field conditions, enabling the use of controlled experiments for predicting nitrogen use efficiency (NUE).

MATERIALS AND METHODS

Research material

Three Latvian potato varieties were used to evaluate the effect of nitrogen (N) on potato productivity under different growing systems in field, pot and *in vitro* experiments. The varieties were selected according to maturity group: ‘Monta’ (early), ‘Prelma’ (medium-early) and ‘Jogla’ (medium-late). Planting material for field and pot experiments was selected after evaluation, and the varieties were subjected to recovery using a combination of thermotherapy and meristem culture. In addition, micropropagated plant material was established for *in vitro* experiments.

Field trial

Field experiments were conducted at the Institute of Agricultural Resources and Economics, Priekule Research Centre, in 2020, 2021 and 2024. Potatoes were grown under organic (OF) and integrated farming (IF) systems. Soil agrochemical properties for the experimental years are presented in Table 1. In the IF system, mineral fertilisers were applied at rates of 60 kg ha⁻¹ N, 90 kg ha⁻¹ K₂O and 55 kg ha⁻¹ P₂O₅, whereas no additional nitrogen fertiliser was applied in the OF treatment. The organic trial was established in a certified organic field. The experiment was arranged in a randomised complete block design with four replications. Each potato genotype was grown in plots consisting of 16 plants per replication, arranged in a single row, with 0.3 m spacing between plants within the row and 0.7 m between rows. Tubers were harvested

Table 1. Agrochemical indicators of soil

Soil properties	2020		2021		2024	
	OF	IF	OF	IF	OF	IF
pH	5.7	5.5	5.6	5	5.5	5.3
Organic matter, %	2.3	2.3	2.7	2.1	2.5	2
K ₂ O mg kg ⁻¹	56	137	132	190	97	118
P ₂ O ₅ mg kg ⁻¹	101	179	164	175	144	193
Ca mg kg ⁻¹	736	663	939	1,214	692	587
Mg mg kg ⁻¹	143	539	127	121	99	97
Estimated plant-available soil N, kg ha ⁻¹	71	129	83	118	76	119

harvested from a plot area of 3.4 m². A more detailed description of the experimental design is provided by Skrabule et al. (2023). The experiment was arranged as a factorial design with two factors: farming system (factor I: OF and IF) and potato variety (factor II: ‘Monta’, ‘Prelma’ and ‘Jogla’).

Pot experiments were conducted in 2025 at the vegetation facility of the Faculty of Agriculture and Food Technology, Latvia University of Life Sciences and Technologies, under open-air conditions with supplementary irrigation. Potatoes were grown in 10 L pots filled with sandy loam soil. Soil agrochemical properties were determined at the Agrochemical Laboratory of the State Plant Protection Service of the Republic of Latvia: pH_{KCl} 7.5, organic matter 4.7%, P_2O_5 147 mg kg^{-1} , K_2O 127 mg kg^{-1} , Mg 795 mg kg^{-1} , Ca 2819 mg kg^{-1} , and $\text{SO}_4\text{-S}$ 2.6 mg kg^{-1} . Mineral fertiliser NPK (12–11–18) was applied at rates of 0, 3.5 and 7 g per pot, corresponding to N0, N60 and N120 treatments. The experiment was arranged in three replications in a completely randomised design. Plants were irrigated as required and grown until full senescence. The experiment was conducted as a two-factor completely randomised design, where nitrogen rate (factor I: N0, N60 and N120) and potato variety (factor II) were evaluated.

Leaf spectral reflectance was measured three times during the growing period using a spectroradiometer (RS-3500, Spectral Evolution). The Normalized Difference Vegetation Index (NDVI) (<https://www.indexdatabase.de>) was calculated. Four leaves per pot were analysed, and the mean of three spectral measurements was used for NDVI calculation.

In vitro

The *in vitro* experiment was conducted at the Institute of Agricultural Resources and Economics, Priekule Research Centre. Ten shoot tips per treatment were cultured on Murashige and Skoog (MS) basal medium. Three nitrogen levels were tested: standard (60 mmol L^{-1} , N60) and reduced levels (20 mmol L^{-1} , N20; 7.5 mmol L^{-1} , N7.5), adjusted using NH_4NO_3 , KNO_3 and KCl . Cultures were maintained at 22 ± 1 °C under a 16/8 h photoperiod and light intensity of 15.5 ± 2.5 W m^{-2} for 24 days, following Rābante-Hāne et al. (2025). The *in vitro* experiment was arranged as a two-factor design with nitrogen level as factor I (N60, N20, N7.5) and variety as factor II. The standard nitrogen level (N60) was used as the control treatment.

Sample preparation and dry matter determination

Ten healthy tubers of average size were collected separately from each replication of each treatment in both field and pot experiments. Tubers were washed, cut, dried, milled and homogenised. For dry matter determination, approximately 150 g of homogenised sample was frozen at -20 °C for 24 h and subsequently freeze-dried (Alpha 2-4 LDplus, Germany) under the following conditions: primary drying at -50 °C and 0.040 mbar for 48 h, followed by final drying for 8 h.

For *in vitro* experiments, ten plantlets (stems and leaves) per treatment were harvested, dried at 60 °C for 24 h and milled prior to nitrogen analysis.

Total nitrogen content and Nitrogen use efficiency determination

Nitrogen content in tubers and plant material was determined using a near-infrared (NIR) spectrometer (XDS, FOSS) in the wavelength range of 350–2500 nm. Calibration models were developed using reference values obtained by the Kjeldahl method.

Nitrogen use efficiency (NUE) was calculated as the ratio of tuber dry matter yield to total plant-available nitrogen (kg kg^{-1}) (Tiemens-Hulscher et al., 2014) according to Eq. 1:

$$NUE = \frac{\text{Dry matter yield}}{\text{total plant available N}} \quad (1)$$

Characteristics of meteorological conditions

Meteorological data were obtained from the Latvian Environment, Geology and Meteorology Centre station in Priekulī (2020, 2021 and 2024) and Jelgava local meteorological station.

Air temperature dynamics during the studied vegetation periods showed marked interannual variability (Fig. 1). For instance, the third decade of May was considerably warmer in 2024, when the average air temperature reached 20.1 °C, whereas in the other studied years it ranged only between 11.1 °C and 13.3 °C. In contrast, the average air temperatures in the first decade of June and in the first and second decades of August were relatively similar across all vegetation periods.

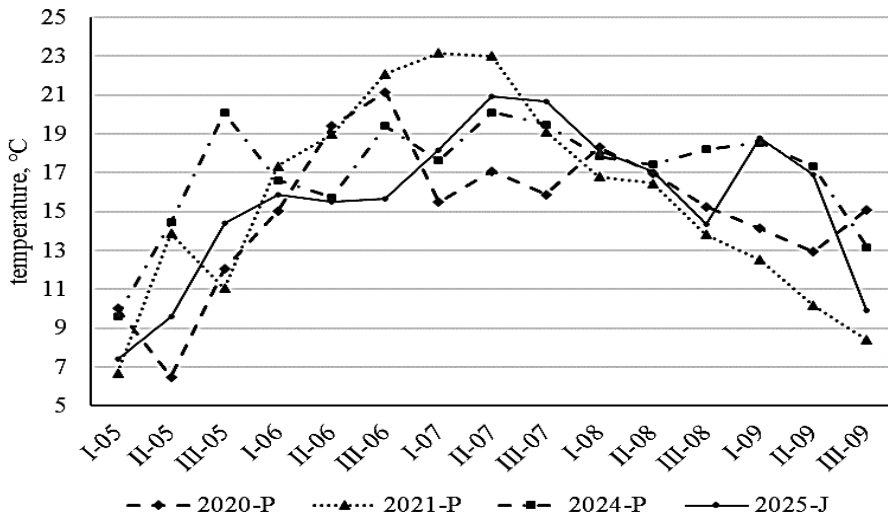


Figure 1. Average air temperature in Priekulī in 2020, 2021 and 2024, and in 2025 in Jelgava.

In all studied years, the average air temperature in the first or second decade of May remained below 10 °C, indicating relatively cool conditions at the beginning of the vegetation season. In June, mean air temperatures were comparable among vegetation periods, varying from 15.7 °C to 19.5 °C. Greater differences were observed in July, when 2020 was notably the coldest year with an average temperature of 16.2 °C, while 2021 was the warmest, reaching 21.8 °C.

August temperatures were highest in 2024 (17.8 °C), whereas in the remaining years they ranged from 15.7 °C to 16.8 °C. Substantial variability was also recorded in September: the lowest mean air temperature was observed in 2021 (10.4 °C), while the highest occurred in 2024 (16.3 °C). Overall, the results demonstrate pronounced

differences in thermal conditions among the studied vegetation periods, particularly in late spring, mid-summer, and early autumn.

The total amount of precipitation during the vegetation periods of the field trials differed among the studied years, amounting to 374 mm in 2020, 370 mm in 2021, and 333 mm in 2024. Although the overall seasonal totals were relatively similar in 2020 and 2021, pronounced monthly variability was observed within individual vegetation periods.

In 2021, substantial differences in precipitation distribution were recorded (Fig. 2). In May, precipitation reached 120 mm, whereas in the corresponding month of the other studied years it was considerably lower (13.6 mm and 33.6 mm). In contrast, July 2021 was comparatively dry, with only 44 mm of precipitation, while in the other years July totals were markedly higher, reaching 121 mm and 133 mm.

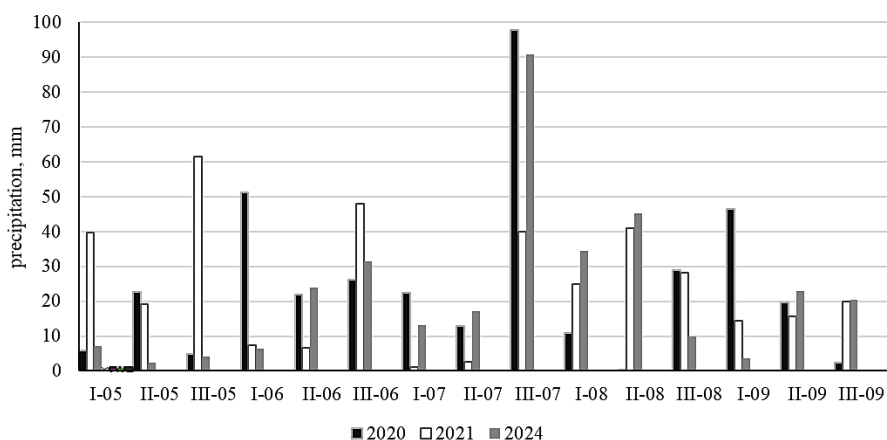


Figure 2. Precipitation amount in Priekuļi in 2020, 2021 and 2024.

For 2020, June was particularly notable, with a monthly precipitation total of 99 mm, compared with 62 mm in the other studied years. August 2020 was characterized by relatively low precipitation (40 mm), whereas in the remaining years August totals ranged between 90 mm and 94 mm. In addition, September 2020 recorded 68 mm of precipitation, exceeding the amounts observed in the other vegetation periods (47–50 mm).

Overall, the hydrothermal conditions most favourable for potato growth were observed in 2021, when warm temperatures during the main growth period and sufficient precipitation supported active plant development and tuber formation. In contrast, 2020 was characterised by cooler conditions during July, while 2024 showed higher temperature fluctuations and lower total precipitation during the vegetation period, which may have limited nitrogen uptake and yield formation.

Data processing

A two-factor analysis of variance (ANOVA) was used to evaluate the effects of genotype and nitrogen treatment. Differences between means were assessed using Tukey’s HSD test at a significance level of $p < 0.05$. Statistical analyses were performed using R software (version 4.5.1) and RStudio (version 2025.05.1).

RESULTS AND DISCUSSION

Nitrogen content in potato tubers and plants

Nitrogen content in potato tubers was significantly affected by farming system (factor I), variety (factor II), and their interaction (Fig. 3). In addition, hydrothermal conditions during the growing season significantly influenced nitrogen accumulation. The observed variability among years was primarily related to differences in temperature and precipitation, which influence soil nitrogen mineralisation and availability, particularly under organic farming conditions.

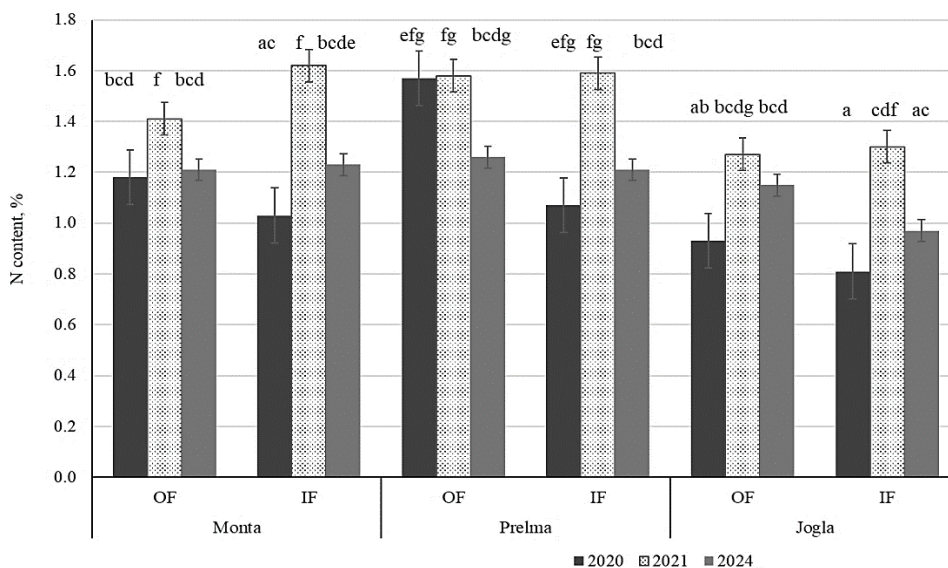


Figure 3. Nitrogen content (%) of potato varieties in field conditions.

Different letters indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$).

Earliness of the varieties also played an important role. The late-maturing variety 'Jogla' showed lower and more stable nitrogen content compared to earlier varieties, indicating a different nitrogen utilisation strategy. In contrast, early and medium-early varieties ('Monta' and 'Prelma') exhibited a stronger response to nitrogen availability.

Under favourable hydrothermal conditions, increased soil moisture and temperature likely enhanced nitrogen mineralisation, resulting in higher nitrogen uptake and accumulation in tubers. This explains the variability observed between years and supports previous findings that environmental conditions strongly regulate nitrogen accumulation in potato tubers (Ruža et al., 2013).

No consistent differences in tuber N content were observed between organic and integrated farming systems, indicating that nitrogen availability in organic systems may be sufficient under certain environmental conditions but less stable across years. The significant variety \times year interaction suggests that genotypes differ in their ability to utilise available nitrogen under changing environmental conditions.

In the pot experiment, nitrogen rate (factor I) and variety (factor II) both had a significant effect on tuber nitrogen content, with a significant interaction between the factors (Fig. 4). Increasing nitrogen supply resulted in higher nitrogen content; however, the response differed among varieties depending on their maturity group. The late-maturing variety ‘Jogla’ showed a limited response, whereas ‘Prelma’ responded strongly to increased nitrogen supply.

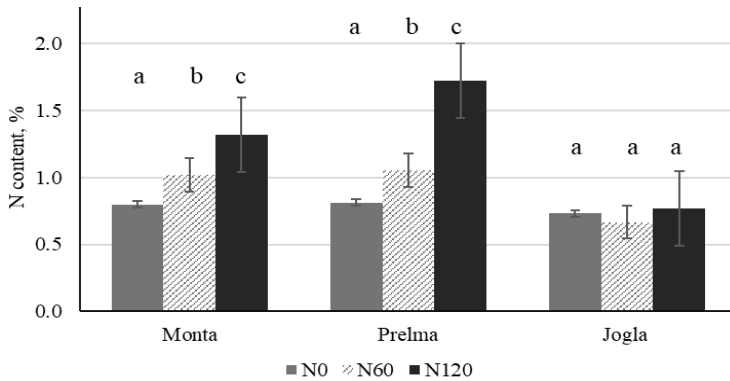


Figure 4. Nitrogen content (%) of potato varieties depending on different nitrogen levels in pot experiment. Different letters indicate significant differences between treatments according to Tukey’s HSD test ($p < 0.05$).

The variety ‘Prelma’ showed the strongest response to increased nitrogen supply, indicating a higher capacity for nitrogen uptake and assimilation. In contrast, ‘Jogla’ exhibited a limited response, suggesting a genotype-specific allocation strategy favouring starch accumulation over protein synthesis. This is consistent with previous studies showing that increased nitrogen availability may negatively affect starch accumulation in potato tubers (Bachmann-Pfabe & Dehmer, 2020).

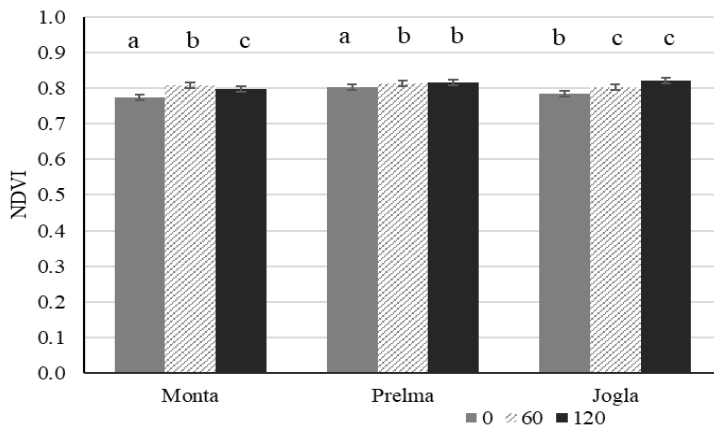


Figure 5. NDVI of potato varieties depending on different nitrogen levels in pot experiments. Different letters indicate significant differences between treatments according to Tukey’s HSD test ($p < 0.05$).

Spectral analysis (NDVI) confirmed the effect of nitrogen availability on plant development (Fig. 5). Higher nitrogen rates resulted in increased NDVI values, reflecting enhanced canopy development and chlorophyll content. However, varietal differences were significant, indicating that canopy structure and maturity influence spectral responses. These results suggest that NDVI can be used as a non-destructive indicator of nitrogen status, but its interpretation should consider genotype-specific traits. Experiments in Rumania showed that NDVI values of potato plants from fertilized variants were statistically differentiated according by variety, especially in the second part of the growing season (Bărăscu et al., 2016).

Under *in vitro* conditions, tuber formation did not occur during the experimental period; therefore, nitrogen content was determined only in vegetative tissues (leaves and stems) (Fig. 6). Nitrogen concentration in leaves and stems was considerably higher than that observed in tubers from the field and pot experiments, reflecting intensive metabolic activity and nutrient uptake under controlled conditions.

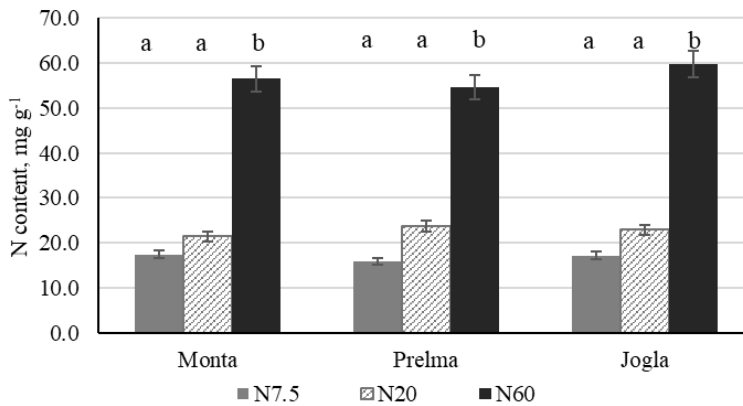


Figure 6. Nitrogen content mg g⁻¹ of potato varieties depending on different nitrogen levels under *in vitro* conditions. Different letters indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$).

Nitrogen content increased significantly with increasing nitrogen supply, but no differences were observed between the lowest nitrogen treatments. This indicates that under limited nutrient conditions, plants rapidly utilise available nitrogen, reaching a physiological threshold. Similar observations have been reported for *in vitro* systems, where nutrient availability and short growth periods strongly influence plant development (Wishart et al., 2013). Under *in vitro* growing conditions, time is a limited factor for nutrient management. Even if we managed to detect differences between variants, still in conditions where N levels are reduced, the potato microplant really fast reached the maximum available amount of nutrients.

These results indicate that nitrogen uptake and accumulation are controlled not only by nitrogen availability but also by genotype-specific traits and maturity group, as well as environmental conditions during the growing season.

Tuber yield response to nitrogen supply

Tuber yield under field conditions was significantly affected by hydrothermal conditions and, in the integrated system, also by variety (Fig. 7). The effect of nitrogen depended on variety, indicating a significant interaction between nitrogen rate and genotype. The lowest yields were observed under less favourable environmental conditions, while higher yields were associated with improved temperature and moisture regimes, highlighting the dominant role of environmental factors in yield formation. In the study conducted by Skrabule et al. (2012), it was found that under Latvian conditions, when using lower fertilizer rates, potatoes using N resources much more efficiently than in cases with higher N rates, where N fertiliser is not fully utilised.

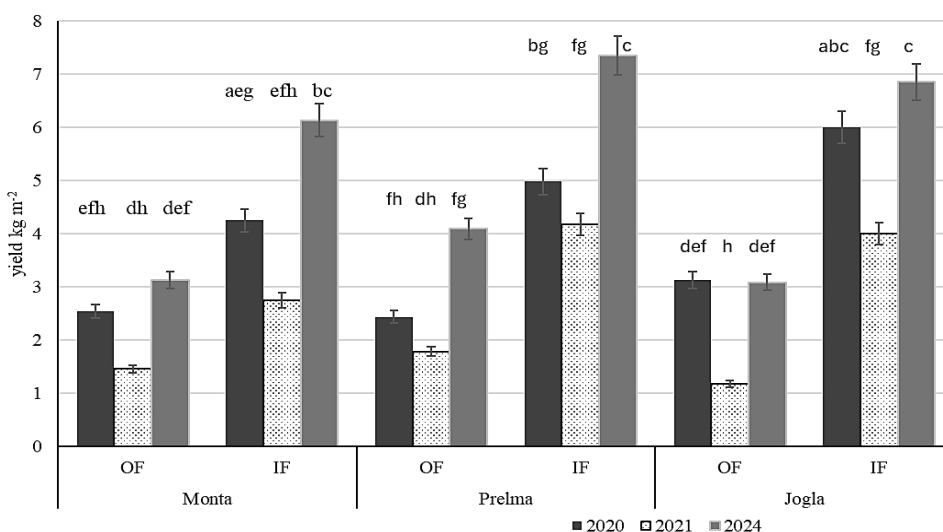


Figure 7. Average tuber yield of potato varieties in field conditions. Different letters indicate significant differences between treatments according to Tukey's HSD test ($p < 0.05$).

Average yields were higher in the integrated farming system compared to the organic system, reflecting the more stable nitrogen supply. However, the absence of significant varietal differences in the organic system suggests that environmental variability may override genotypic effects under limited nutrient availability. Later-maturing varieties tended to utilise nitrogen more efficiently under favourable conditions, resulting in higher yield compared to early varieties.

In the pot experiment, tuber yield increased with increasing nitrogen supply, although the response varied among varieties (Fig. 8). The greatest response was observed for 'Jogla', which showed a substantial increase in yield at higher nitrogen rates. This is in line with previous studies indicating that later-maturing genotypes often exhibit a stronger yield response to nitrogen fertilisation (Milroy et al., 2019).

In contrast, 'Prelma' showed no significant yield increase between moderate and high nitrogen levels, suggesting a saturation effect. Excessive nitrogen supply may inhibit tuber formation by promoting vegetative growth, as reported by Fontes et al.

(2010) and Zhang et al. (2022). These results highlight the importance of optimising nitrogen rates to avoid yield penalties associated with excessive nitrogen supply.

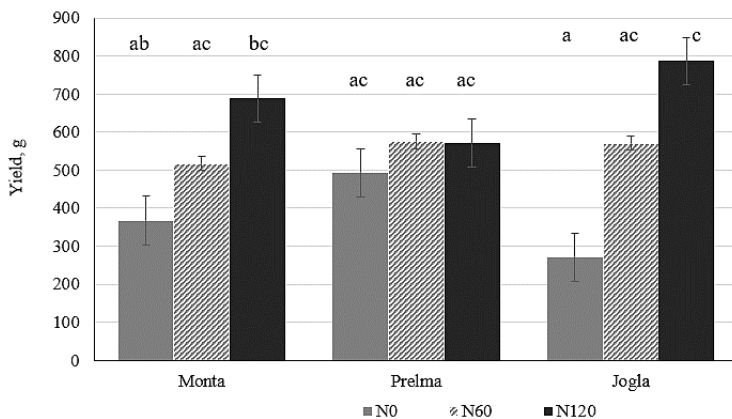


Figure 8. Tuber yield (g) of potato varieties depending on different nitrogen levels in pot experiment. Different letters indicate significant differences between treatments according to Tukey’s HSD test ($p < 0.05$).

Dry matter weight

Under *in vitro* conditions, dry matter accumulation was significantly affected by nitrogen supply (Fig. 9). The highest dry matter was observed at moderate nitrogen levels, while both low and high nitrogen levels resulted in reduced dry matter accumulation.

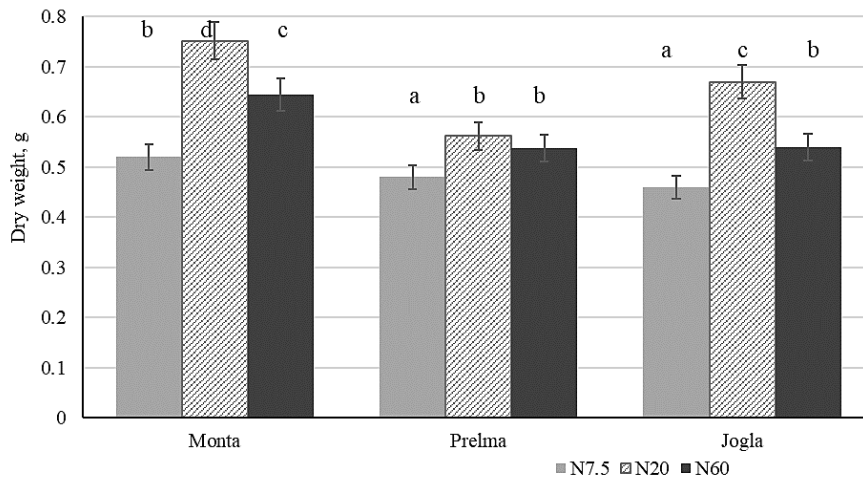


Figure 9. Dry matter weight (g) of potato varieties depending on different nitrogen levels under *in vitro* evaluation.

Different letters indicate significant differences between treatments according to Tukey’s HSD test ($p < 0.05$).

This pattern suggests that excessive nitrogen supply may negatively affect assimilate partitioning towards storage compounds, such as starch. Similar findings have been reported in previous studies, where high nitrogen availability reduced dry matter content in potato tubers (Alva, 2004; Zhang et al., 2022).

The absence of significant varietal effects indicates that nitrogen availability plays a more dominant role than genotype in determining dry matter accumulation under controlled conditions. Early and mid-early genotypes are characterised by lower dry matter content, still this characteristic is partly affected by the available N amount (Lisinska & Leszczynski, 1989).

In order to connect dry matter weight to pot experiments and field trials, it is necessary to understand N metabolism processes. The formation of dry matter in potatoes is associated with canopy development that leads to tuber initiation (Haverkort, 2018). However, to draw more accurate conclusions and uncover correlations, it is necessary to conduct further research in these areas.

The connection between nitrogen content and tuber yield in potato varieties under different growing conditions

The relationship between nitrogen content in plant tissues and tuber yield varied considerably depending on the growing conditions and experimental system.

In field experiments, a significant moderate negative correlation was observed between tuber nitrogen content and tuber yield in both farming systems. In the organic farming system, the correlation coefficient was $r = -0.50$ ($p < 0.01$), while a similar relationship was found in the integrated farming system ($r = -0.52$, $p < 0.01$). These results indicate that higher nitrogen accumulation in tubers was associated with lower yield under field conditions. This suggests that environmental constraints, together with genotype-specific responses, may lead to a trade-off between nitrogen concentration in tubers and yield formation. Under variable hydrothermal conditions, nitrogen accumulation in tubers may reflect altered biomass allocation patterns rather than improved productivity.

In the pot experiment, the relationship between tuber nitrogen content and yield was weak and not statistically significant ($r = 0.24$, $p > 0.05$), indicating that nitrogen content alone was not a reliable predictor of yield variation under controlled conditions. This suggests that other physiological or developmental factors played a more dominant role in determining yield formation in pot-grown plants.

In contrast, *in vitro* experiments showed a significant positive correlation between nitrogen content in vegetative tissues and plant dry weight ($r = 0.32$, $p < 0.001$). This indicates that under controlled conditions increased nitrogen accumulation was associated with enhanced biomass formation. However, this relationship reflects vegetative growth processes rather than tuber yield formation, as tubers were not developed in the *in vitro* system.

Overall, the results demonstrate that the relationship between nitrogen content and plant productivity is highly system-dependent. Under field conditions, higher nitrogen content in tubers was associated with reduced yield, whereas no clear relationship was observed in pot experiments and a positive association was found *in vitro* for vegetative biomass. These contrasting patterns highlight the strong influence of environmental conditions and genotype-specific responses on nitrogen uptake, allocation, and utilisation.

These results indicate that nitrogen content alone is not a sufficient predictor of yield and should be interpreted in relation to genotype and growing conditions. This is in agreement with previous studies, which have shown that optimal nitrogen supply is required to balance vegetative growth and tuber development (Ruža et al., 2013; Zhang et al., 2022).

NUE content in field, pot and *in vitro* trials

Nitrogen use efficiency (NUE) varied considerably among experimental systems, varieties and nitrogen levels (Table 2). In field conditions, NUE was strongly influenced by environmental factors, with higher values observed under favourable hydrothermal conditions.

In the pot experiment, NUE decreased with increasing nitrogen supply for most varieties, indicating reduced efficiency of nitrogen utilisation at higher application rates. This trend is consistent with previous studies (Zebarth et al., 2004; Hirel & Lemaire, 2006; Ospina et al., 2014; Tiemens-Hulscher et al., 2014; Ospina, 2016; Getahun, et al., 2020), which demonstrate that excessive nitrogen reduces NUE due to diminishing returns in yield response.

Table 2. NUE, (kg kg⁻¹) in field trials, *in vitro* and pot experiment

	Fields						Pots			<i>In vitro</i>		
	2020		2021		2024		0	N60	N120	N7.5	N20	N60
	IF	OF	IF	OF	IF	OF						
Monta	80	74	49	52	121	104	85	82	78	99	54	15
Prelma	75	68	67	44	124	110	96	69	48	92	40	13
Jogla	126	129	77	35	163	122	71	106	112	88	48	13

Varietal differences in nitrogen use efficiency (NUE) were evident, with later-maturing varieties generally showing higher efficiency compared with early-maturing varieties. The results presented in Table 2 indicate genotype-specific differences in NUE among the studied potato varieties. In field conditions, later-maturing varieties tended to exhibit higher NUE values; however, this trend was not consistent across all experimental conditions, suggesting a strong influence of environmental factors. These findings indicate that nitrogen use efficiency is determined by both genotype and growing environment. The observed differences among varieties in their ability to convert available nitrogen into yield support the concept that NUE-related traits should be considered in breeding strategies (Zebarth et al., 2004; Skrabule et al., 2023). Furthermore, the results suggest that optimal nitrogen supply is essential to balance vegetative growth and tuber formation, which is consistent with previous studies (Fontes et al., 2010; Zhang et al., 2022).

Overall, the results indicate that both environmental conditions and genotype play a key role in determining nitrogen use efficiency, and that controlled experiments can provide valuable insights into nitrogen dynamics, although their predictive capacity for field conditions remains genotype-dependent.

CONCLUSIONS

Nitrogen content in potato tubers and nitrogen use efficiency were significantly affected by nitrogen availability, genotype and growing conditions. Field experiments demonstrated that hydrothermal conditions during the growing season were the main factors influencing nitrogen uptake, accumulation and yield formation. Genotype-specific responses were observed, particularly in relation to maturity group and nitrogen supply. Later-maturing varieties generally exhibited higher nitrogen use efficiency under field conditions, whereas controlled experiments revealed variable genotype responses.

The results showed that increasing nitrogen supply reduced nitrogen use efficiency, indicating lower efficiency of nitrogen utilisation under excessive nitrogen application. Controlled pot and *in vitro* experiments were useful for evaluating specific aspects of nitrogen uptake and plant response; however, their ability to predict field performance was limited due to environmental variability and genotype-specific traits.

Overall, the study demonstrates that reliable assessment of nitrogen use efficiency in potatoes requires an integrated approach combining field, pot and *in vitro* experiments. Future research should focus on improving the linkage between controlled experimental systems and field performance under varying environmental conditions, as well as identifying genotype traits associated with stable and efficient nitrogen utilisation.

ACKNOWLEDGEMENTS. This research benefits from the Project on Fundamental and Applied Studies (FLPP) ‘Breeding for low input and organic farming systems: nitrogen use efficiency and quality aspects of potato protein’ and project ‘Strengthening the Institutional Capacity of LBTU for Excellence in Studies and Research’, funded by The Recovery and Resilience Facility and Breeding material development program.

REFERENCES

- Alva, L. 2004. Potato nitrogen management. *Journal of vegetable crop production* **10**(1), 97–132. doi: 10.1300/J068v10n01_10
- Bachmann-Pfabe, S. & Dehmer, K.J. 2020. Evaluation of Wild Potato Germplasm for Tuber Starch Content and Nitrogen Utilization Efficiency. *Plants* **9**(7), 833, 1–19. doi: 10.3390/plants9070833
- Bărăscu, N., Duda, M. & Olteanu, G. 2016. Study of dynamics SPAD and NDVI values of potato plants according to the differentiated fertilization. *Agriculture* **73**(1), 5–14. doi: 10.15835/buasvmcn-agr:12003
- Barrow, N.J. & hartemink, A.E. 2023. The effects of pH on nutrient availability depend on both soils and plants. *Plant and Soil* **487**(1), 21–37. doi: 10.1007/s11104-023-05960-5
- Bijay-Singh & Craswell, E. 2021. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. *SN Applied Sciences* **3**, 518. doi: 10.1007/s42452-021-04521-8
- Cui, S., Qin, Y., Yu, J., Shi, X., Jia, L. & Fan, M. 2020. Improving tuber yield and phosphorus use efficiency using split phosphorus application to potatoes in Inner Mongolia. *American Journal of Potato Research* **97**(3), 318–324. doi: 10.1007/s12230-020-09783-3
- Dreccer, M.F., Van Oijen, M., Schapendonk, A.H.C.M., Pot, C.S. & Rabbinge, R. 2000. Dynamics of vertical leaf nitrogen distribution in a vegetative wheat canopy. Impact on canopy photosynthesis. *Annals of Botany* **86**(4), 821–831. doi.org/10.1006/anbo.2000.1244

- Fao stat 2022. Available at <https://www.fao.org/faostat/en/#data/QCL>
- Fontes, P.C., Braun, H., Busato, C. & Cecon, P.R. 2010. Economic optimum nitrogen fertilization rates and nitrogen fertilization rate effects on tuber characteristics of potato cultivars. *Potato Research* **53**(3), 167–179. doi: 10.1007/s11540-010-9160-3
- Getahun, B.B., Kassie, M.M., Visser, R.G.F. & van der Linden, C.G. 2020. Genetic Diversity of Potato Cultivars for Nitrogen Use Efficiency Under Contrasting Nitrogen Regimes. *Potato Res.* **63**, 267–290 doi: 10.1007/s11540-019-09439-8
- Haverkort A.J. 2018. *Potato handbook. Crop of the future*. Wageningen, The Netherlands: Aardappelwereld BV, 592 pp.
- Hirel, B. & Lemaire, G. 2006. From agronomy and ecophysiology to molecular genetics for improving nitrogen use efficiency in crops. *Journal of Crop Improvement* **15**(2), 213–257. doi: 10.1300/J411v15n02_07
- Iwama, K. 2008. Physiology of the potato: new insights into root system and repercussions for crop management. *Potato Research* **51**(3), 333–353. doi: 10.1007/s11540-008-9120-3
- Lammerts van Bueren, E.T. & Struik, P.C. 2017. Diverse concepts of breeding for nitrogen use efficiency. A review. *Agronomy for Sustainable Development* **37**(50). doi: 10.1007/s13593-017-0457-3
- Lisinska, G. & Leszczynski, W. 1989. *Potato science and technology*. Springer Science & Business Media, 391 pp.
- Liu, Hui, Xiuhua Gao, Weishu Fan, & Xiangdong Fu. (2025) "Optimizing carbon and nitrogen metabolism in plants: From fundamental principles to practical applications. *Journal of Integrative Plant Biology* **67**(6), 1447–1446. doi: 10.1111/jipb.13919
- Milroy, S.P., Wang, P. & Sadras, V.O. 2019. Defining upper limits of nitrogen uptake and nitrogen use efficiency of potato in response to crop N supply. *Field Crops Research* **239**, 38–46. doi: 10.1016/j.fcr.2019.05.011
- Mustonen, L., Wallius, E. & Hurme, T. 2010. Nitrogen fertilization and yield formation of potato during a short growing period. *Agricultural and Food Science* **19**, 173–183. <https://doi.org/10.2137/145960610791542334>
- Ospina, C.A., Lammerts van Bueren, E.T., Allefs, J.J.H.M., Engel, B., van der Putten, P. E.L., van der Linden, C.G. & Struik, P.C. 2014. Diversity of crop development traits and nitrogen use efficiency among potato cultivars grown under contrasting nitrogen regimes. *Euphytica* **199**, 13–29. doi: 10.1007/s10681-014-1203-4
- Ospina, C.A. 2016. *Nitrogen use efficiency in potato: an integrated agronomic, physiological and genetic approach*. PhD thesis: Wageningen, Wageningen University. 187 pp.
- Răbante-Hăne, L., Dimante, I. & Skrabule, I. 2025. Evaluation of biomass production in different potato genotypes under various nitrogen levels in vitro. *Research for Rural Development* **40**, 53. doi: 10.22616/RRD.31.2025.006
- Ruža, A., Skrabule, I. & Vaivode, A. 2013. Influence of nitrogen on potato productivity and nutrient use efficiency. In *Proceedings of the Latvian Academy of Sciences. Section B. Natural, Exact, and Applied Sciences* **67**, 247–253. doi: 10.2478/prolas-2013-0043
- Schum, A. & Jansen, G. 2014. In vitro method for early evaluation of nitrogen use efficiency associated traits in potato. *Journal of Applied Botany and Food Quality* **87**, 256–264. doi: 10.5073/JABFQ.2014.087.036
- Schum, A., Meise, P., Jansen, G., Seddig, S. & Ordon, F. 2017. Evaluation of nitrogen efficiency associated traits of starch potato cultivars under in vitro conditions. *Plant Cell, Tissue and Organ Culture (PCTOC)* **130**(3), 651–665. doi: 10.1007/s11240-017-1254-z
- Shafreen, M., Vishwakarma, K., Shrivastava, N. & Kumar, N. 2021. Physiology and distribution of nitrogen in soils. In *Soil nitrogen ecology*. Cham: Springer International Publishing, pp. 3–31.

- Skrabule, I., Rābante-Hāne, L., Dimante, I., Taškova, I. & Sviatchenko, S. 2023. The effect of nitrogen use efficiency on significant traits of potato starch production. *Zemdirbyste-Agriculture* **110**(4). doi: 10.13080/z-a.2023.110.037
- Skrabule, I., Vaivode, A. & Ruža, A. 2012 The effect of nitrogen fertilizer rates on nutrient utilization rates in potatoes. In: *Proceedings of the International Practical Conference Science for the Future of Latvian Agriculture: Food, Forage, Fiber and Energy* (p. 90) (in Latvian).
- Su, D., Zhang, H., Teng, A., Zhang, C., Lei, L., Ba, Y., Zhou, C., Li, F., Chen, X. & Wang, Z. 2024. Potato growth, nitrogen balance, quality, and productivity response to water-nitrogen regulation in a cold and arid environment. *Frontiers in Plant Science* **15**, 1451350. <https://doi.org/10.3389/fpls.2024.1451350>
- Tiemens-Hulscher, M., Lammerts van Bueren, E.T. & Struik, P.C. 2014. Identifying nitrogen-efficient potato cultivars for organic farming. *Euphytica* **199**, 137–154. doi: 10.1007/s10681-014-1143-z
- Wishart, J., George, T.S., Brown, L.K., Ramsay, G., Bradshaw, J.E., White, P.J. & Gregory, P. J. 2013. Measuring variation in potato roots in both field and glasshouse: the search for useful yield predictors and a simple screen for root traits. *Plant and Soil* **368**, 231–249. <https://doi.org/10.1007/s11104-012-1483-1>
- Zebarth, B. J., Tai, G., Tarn, R.D., De Jong, H. & Milburn, P.H. 2004. Nitrogen use efficiency characteristics of commercial potato cultivars. *Canadian Journal of Plant Science* **84**(2), 589–598. <https://doi.org/10.4141/P03-050>
- Zhang, C., Yi, Y., Zhang, S. & Li, P. 2024. Quantitative Analysis of Vertical and Temporal Variations in the Chlorophyll Content of Winter Wheat Leaves via Proximal Multispectral Remote Sensing and Deep Transfer Learning. *Agriculture* **14**(10), 1685. <https://doi.org/10.3390/agriculture14101685>
- Zhang, Y., Ye, C., Su, Y., Peng, W., Lu, R., Liu, Y., Huang, H., He, X., Yang, M. & Zhu, S. 2022. Soil Acidification caused by excessive application of nitrogen fertilizer aggravates soil-borne diseases: Evidence from literature review and field trials. *Agriculture, ecosystems & environment* **340**, 108176. <https://doi.org/10.1016/j.agee.2022.108176>