

## Soil nutrient contents in a long-term field experiment following the suspension of phosphorus and potassium fertilisation

GABRIELA MÜHLBACHOVÁ\*, HELENA KUSÁ, PAVEL RŮŽEK,  
MARTIN KÁŠ, RADEK VAVERA

Czech Agrofood Research Centre, Prague 6 – Ruzyně, Czech Republic

\*Corresponding author: [gabriela.muhlbachova@carc.cz](mailto:gabriela.muhlbachova@carc.cz)

**Citation:** Mühlbachová G., Kusá H., Růžek P., Káš M., Vavera R. (2025): Soil nutrient contents in a long-term field experiment following the suspension of phosphorus and potassium fertilisation. *Plant Soil Environ.*, 71: 770–781.

**Abstract:** The effect of mineral, organic (manure or straw + intercrop) and combined fertilisation on the development of soil nutrient contents over time and their mutual ratios was evaluated in a long-term field trial, IOSDV (established in 1984 at two sites), differing in the soil-climatic conditions. Three cropping cycles, from 2016 to 2018, 2019 to 2021, and 2022 to 2024, were studied in the following crop rotation: winter wheat-winter barley-root crop (sugar beet at Ivanovice na Hané and potatoes at Lukavec). Potassium and phosphorus in mineral fertilisers have not been applied since the year 2020 due to their high content found in soils after dry years with low yields. Consequently, their content decreased, most in the third rotation, both by the Mehlich 3 method and especially the exchange fraction extractable with  $\text{NH}_4$ -acetate (Ivanovice: P 5–14%, 32–40% and K up to 12%, 9–20% determined by Mehlich 3 and  $\text{NH}_4$ -acetate, respectively; Lukavec: Mehlich 3 – P increase: 5–16%, K decrease: 0–8%;  $\text{NH}_4$ -acetate decrease – P: 10–13%, K 8–23%). The mutual ratio of nutrients equivalents K:Mg:Ca was lower than required values 1:2–3:10–15 at both sites and all studied treatments, however a slight increase was observed during the studied period, above all in system with only mineral fertilisation (Ivanovice: K:Mg:Ca from 1:1.2:5.6 to 1:1.4:6.8, Lukavec: from 1:1.0:7.7 to 1:1.0:9.6). A correctly balanced ratio of nutrients in the soil is important for maintaining soil fertility. In this long-term field experiment, the increase in nutrient levels in soils over reasonable levels was observed, highlighting the necessity of regular nutrient testing in agricultural soils, especially when multiple types of fertilisers are used simultaneously.

**Keywords:** yields; uptake; nutrient ratio; soil tests

Routine applications of organic and mineral fertilisers are an essential component of soil management in arable crop production systems (Kautz et al. 2004) as they affect crop yields and quality. Long-term field experiments (LTEs) with different levels of fertilisation identify the most suitable fertilisation systems for sustainable soil fertility (Rasmussen et al. 1998). The international IOSDV (Der Internationale Organische Stickstoffdauerdüngungsversuch) experiments (Körschens et al. 2013), which were established more than 40 years ago across Europe, including the Czech Republic, are suitable for studying and demonstrating the effects of mineral (N, P, K) and

organic fertilisers on soil nutrient contents under different weather conditions.

Phosphorus is one of the most acquired and limited plant nutrients in soil, and its dynamics in soil depend on the physicochemical properties of the soil, the type of cropping system used, the type of fertilisation, climate variability, and the agro-climatic region (Asrade et al. 2024). Phosphates used for soil fertilisation with mineral fertilisers represent limited non-renewable sources. Therefore, other phosphorus sources, such as farmyard manure or postharvest residues, including straw, should be used preferentially.

Supported by the Ministry of Agriculture of the Czech Republic, Projects No. QL24020149, and No. MZE-RO0425.

© The authors. This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0).

<https://doi.org/10.17221/310/2025-PSE>

Potassium occurs in soil in water-soluble, exchangeable or available, fixed or non-exchangeable and mineral  $K^+$  forms, which are incorporated in the crystal lattice of minerals (Zebec et al. 2017). Potassium is present in soil as the monovalent cation  $K^+$ ; it remains in this form in soils and can limit the possibility of uptake of other nutrients ( $Mg^{2+}$  and  $Ca^{2+}$ ) by plants (Matula 2007).

The total content of magnesium in soils varies considerably; higher  $Mg^{2+}$  contents are typically found in clay and silty soils compared to sandy soils. In contrast to other cations, such as  $K^+$ ,  $Ca^{2+}$ , and  $NH_4^+$ , Mg is comparatively mobile in soils due to weaker bonds to soil charges (cation exchange capacity, CEC), resulting in higher  $Mg^{2+}$  concentrations in the soil solution. This has consequences for the magnesium mobility in the soil and implications for plant Mg nutrition (Gransee and Führes 2013). Magnesium availability is also affected by soil pH. In acidic soils, magnesium can be leached, leading to a deficiency; however, in neutral to slightly alkaline soils, magnesium becomes more readily available. Cation competition is a consequence of nutrient imbalances in soils. The uptake of  $Mg^{2+}$  is strongly influenced by the availability of other cations, such as  $NH_4^+$ ,  $Ca^{2+}$ , and  $K^+$  (Fageria 2001).

Calcium belongs among the most important macronutrients required by plants. Calcium is bound to clay minerals and organic matter in the soil by cation exchange. This means that  $Ca^{2+}$  can be exchanged with other cations ( $K^+$ ,  $Mg^{2+}$ ). The soil-exchangeable calcium content is positively correlated with the soil organic carbon (SOC) (Clough and Skjemstad 2000). Calcium availability is affected by soil pH in a manner similar to that of magnesium.

Soil health and quality depend on the correct ratio among cations, which in the soil sorption complex should range between 60% to 75% for calcium ( $Ca^{2+}$ ), 10% to 20% for magnesium ( $Mg^{2+}$ ), and 3% to 5% for potassium ( $K^+$ ) and 15% for other cations (Chaganti and Culman 2017, Chaganti et al. 2021, Culman et al. 2021, Soto et al. 2023). Soil metal cations, such as exchangeable calcium and magnesium, are also chemical drivers of aggregation, which can form cationic bridges with clay particles and organic carbon, protecting the organic matter from decomposition (Tian et al. 2023), improving soil structure and its ability to hold water and nutrients. Excessive fertilisation with potassium can, due to its antagonistic interaction with other cations ( $Mg^{2+}$ ,  $Ca^{2+}$ ) in the soil, result in their leaching into deeper parts of the

soil profile (Matula 2007). Potassium fertilisation in the absence of Mg fertilisers can therefore deplete magnesium reserves (Domagała-Świątkiewicz et al. 2019). This imbalance affects the soil structure, increases the risk of soil degradation and erosion and can become a significant limiting factor in intensive crop production systems, especially in soils fertilised only with N, P, and K. Additionally,  $Ca^{2+}$  and  $K^+$  concentrations in soils are also factors that affect the agronomic effectiveness of  $Mg^{2+}$  in crop yields (Çakmak and Yazici 2010). A deeper understanding of the intensity, kinetics, and capacity of nutrients, including potassium, in the soil is therefore necessary (Balík et al. 2022).

The unprecedented spring and summer droughts, noted since 2015, are expected to persist for the next 5 years in Central Europe, substantially affecting the productivity of natural and agricultural systems (Torbensohn et al. 2023). The long periods of drought also negatively affected crop yields in the long-term field experiment at Ivanovice, where extremely low crop yields were obtained (Káš et al. 2019). The combination of unexpectedly low crop yields and regular annual fertilisation led to unreasonably high phosphorus and potassium contents in soils, which greatly exceeded the P and K contents recommended by Decree 275/1998. In the Czech Republic, therefore, the application of mineral P and K has been suspended since 2020. The changes in nutrient contents following the fertilisation suspension are only rarely reported. However, for instance, Zhou et al. (2022) demonstrated a decrease in crop yields following the cessation of NPK mineral fertilisers, which was attributed to a lack of nitrogen.

The aim of the research was (i) to evaluate the changes in nutrient contents in soils during period 2016–2024 comprising three complete crop rotations (before, during and after the change of fertilisation); (ii) study the impact of changing P and K fertilisation on crops yield and plant nutrient uptake, and (iii) the mutual nutrient ratios in soils are only rarely studied, but their calculation and comparison with desirable ones can help to understand possible imbalance in soil nutrition. The decrease of excessive phosphorus and potassium contents in soils over three crop rotations also improves nutrient ratios and soil health. On the other hand, it could negatively affect nutrient availability for crops and limit yields in an extreme case. This evaluation, therefore, helps to assess the necessity of fertilisation interventions in future.

## MATERIAL AND METHODS

**Field trial.** The long-term field experiment IOSDV (Internationaler Organischer Stickstoffdüngungs-dauerversuche) was established in 1984, and its design in the Czech Republic was already described by Káš et al. (2019). There are two different sites – Lukavec [49.5562469N; 14.9773867E, potato production area, altitude 620 m a.s.l., Cambisol, loamy-sandy soil, average precipitation and temperature – 715 mm; 8.2 °C,  $\text{pH}_{\text{CaCl}_2}$  5.9, CEC – 127  $\text{mmol}_+/[\text{kg}]$  and Ivanovice na Hané (briefly Ivanovice) [49.3110883N; 17.09551692E, beet production area, altitude 225 m a.s.l., degraded Chernozem, loamy soil, average precipitation and temperature – 558 mm; 9.3 °C,  $\text{pH}_{\text{CaCl}_2}$  6.3, CEC – 201  $\text{mmol}_+/[\text{kg}]$ . The crop rotation is as follows: root crops (potatoes at Lukavec, sugar beet at Ivanovice)-winter wheat-winter barley with an intercrop.

Three basic fertilisation systems were adopted: (i) only mineral fertilisation; (ii) 30 t/ha of farmyard manure (FYM) applied once in 3 years to root crop; (iii) straw remaining in the field after the cereals harvest plus 50 kg of N for postharvest residues decomposition plus intercrop grown once in 3 years – after winter barley. Straw is removed from the mineral and manure systems. The annual mineral fertilisation, based on the international concept of the IOSDV experiments, was 35 kg P/ha and 83 kg K/ha, applied in the autumn. Phosphorus was applied as triple superphosphate, and potassium was applied as potassium chloride. Nitrogen was applied as ammonium nitrate with limestone in the following doses: 0-40-80-120-160 kg N/ha in relevant treatments for cereals and 0-50-100-150-200 kg N/ha for root crops. The P and K annual mineral fertilisation has been suspended since 2020 due to the high nutrient content in the soil. Farmyard manure applied to the FYM system itself contained a considerable amount of nutrients – on average 5.5 g P/kg, 8.4 g K/kg, 1.6 g Mg/kg and 8.2 g Ca/kg in the fresh matter. The mean nutrient content in straw returned in the straw-intercrop system was 1.5 g P/kg, 21.6 g K/kg, 0.9 g Mg/kg and 3.3 g Ca/kg. Three replicates for each crop, fertilisation system and N dose are used in the trial. Tillage is conventional, with mouldboard ploughing to a depth of 25 cm.

Soil samples for nutrient determinations were taken annually before winter wheat harvest from the 0–30 cm soil layer. Mean values of five levels of mineral N fertilisation per one crop rotation in the

three systems of organic fertilisation (no organic, manure, straw + intercrop) were evaluated. Three crop rotations were compared: (i) 2016–18 with P, K mineral fertilisation according to the original IOSDV methodology; (ii) the transitional rotation 2019–21, where only 2021 was affected by the suspension of potassium and phosphorus application and a significant effect could not occur; (iii) 2022–24, where the decrease in nutrient content after the suspension in fertilisation should already be noticeable.

**Nutrient determination.** Nutrient contents were determined using two extraction methods: the Mehlich 3 method (Mehlich 1984) and extraction *via* an  $\text{NH}_4$  acetate solution at pH 7 (Matula 2007, Mühlbachová et al. 2024). Each method extracts different nutrient fractions from soils. The Mehlich 3 method is used for soil surveys by national authorities and extracts less available nutrient fractions. The  $\text{NH}_4$  acetate solution extracts the more readily available exchangeable nutrient fractions.

**Mehlich 3 method:** 100 mL of Mehlich 3 extractant (0.2 mol/L  $\text{CH}_3\text{COOH}$ , 0.015 mol/L  $\text{NH}_4\text{F}$ , 0.013 mol/L  $\text{HNO}_3$ , and 0.25 mol/L  $\text{NH}_4\text{NO}_3$ , 0.001 mol/L EDTA) was mixed with 10 g of air-dried soil and shaken at 200 rpm in a 250 mL plastic flask for 10 min.

**$\text{NH}_4$  acetate:** 5 g of air-dried soil was mixed by hand with a stick for 30 s in a 100 mL solution of 0.05 mol/L  $\text{NH}_4$  acetate and 0.005 mol/L  $\text{NH}_4$  fluoride, adjusted to pH 7. After that, the suspension rested for 16 h at laboratory temperature (20–22 °C) and subsequently was mixed by hand 4 times for 30 s at 5 min intervals.

The suspensions were filtered, and their nutrient contents were analysed using the Thermo Fisher Scientific 7400 iCAP ICP-OES analyser (Carlsbad, USA).

**Ratios of cation equivalents.** Ratio of the cation equivalents was calculated as follows: the exchangeable nutrient contents (expressed in mg/kg of soil) were divided by the atomic weight of nutrients and their valency ( $\text{K} - 39.098$ ,  $\text{Mg} - 24.305/2 = 12.15$ ,  $\text{Ca} - 40.078/2 = 20.039$ ). The final Mg and Ca ratios were calculated as mutual equivalent proportions with potassium.

**Statistical analysis.** The results from the three complete crop rotations (2016–2018, 2019–2021, 2022–2024) were statistically analysed using Statistica 14.0 software (TIBCO Software, Santa Clara, USA). A two-way factorial ANOVA, considering crop rotation cycles (2016–18, 2019–21, 2022–24), fertilisation system (mineral, farmyard manure, straw + intercrop), and the given parameter, was used to evaluate the

<https://doi.org/10.17221/310/2025-PSE>

effects on the content of soil nutrients. All N fertilisation levels were taken into account. The same letters in the figures indicate statistically identical values, as determined by Tukey's test ( $P \leq 0.05$ ).

## RESULTS AND DISCUSSION

Unified fertilisation with phosphorus and potassium was introduced in the IOSDV experiment in the 1980s at all experimental sites throughout Europe, regarding the needs of root crops included in crop rotations (Varga et al. 2022). The accumulation of nutrients in the soil occurred gradually as a result of constant fertilisation and low crop yields and nutrient uptake achieved in dry years (above all in 2017, 2018, and earlier, e.g., 2012, 2007, 2003).

In particular, an increase in the content of phosphorus and potassium was detected. Higher nutrient contents were determined in Chernozem in the drier region (Ivanovice na Hané) than in the Cambisol in the wetter site (Lukavec), because the drought period had a more significant impact on reducing yields and nutrient uptake at the Ivanovice site.

**Weather conditions.** The three-year average temperatures and precipitation levels at Ivanovice and Lukavec are shown in Figure 1. The drought noted in the spring periods of 2017, 2018, and 2019, together with higher temperatures, as reported by Torbenson et al. (2023), notably affected the growth of crops at Ivanovice, mainly winter wheat and sugar beet. This weather pattern was less pronounced in the last crop rotation (2022–24), when more precipitation was noted since April and temperatures were lower. On the other hand, the lower precipitation noted at both sites, mainly in July 2022–24, could

negatively affect the growth and, consequently, the yield of root crops.

**Yields and P and K uptake by crops.** The average yields considering all treatments (0–160 kg N/ha) of winter wheat at Ivanovice ranged between 4.71 and 5.52 t/ha, 4.55 and 5.08 t/ha and 6.13 and 7.06 t/ha in 2016–18, 2019–21 and 2022–24 rotations (Table 1). The yields at Ivanovice were affected by drought, most pronounced in the spring, when the lowest yields in the highest N-fertilised treatments reached only 2 t/ha in 2017 (Káš et al. 2019) and about 4 t/ha in 2018. The extreme weather event (hail) in 2021 resulted in very low yields, with the highest yield obtained at 120 N/ha, achieving only 2.8 t/ha. The last crop rotation was characterised by more regular precipitation, resulting in higher yields of winter wheat. Similarly, lower average yields were obtained for sugar beet in 2016–18 and 2019–21. The lowest yields, at around 40 t/ha, were observed in the years 2017, 2018, and 2019 (Káš et al. 2022). Low yields were caused not only by low precipitation during the given periods, but also by their irregular distribution, which resulted in lower plant growth and the creation of fewer bulbs (Káš et al. 2022). Winter barley was less affected by weather conditions, giving yields 6.03–6.67 t/ha, 6.67–6.99 t/ha and 5.98–7.49 t/ha in the rotations 2016–18, 2019–21 and 2022–24. The highest barley yield in each rotation was achieved in the straw + intercrop system. The effect of the fertilisation system was not clear-cut for the other crops. The highest barley yield was achieved in the second, transitional rotation, and for wheat and beet, even in the third one. The omission of P and K mineral fertilisation has not yet had a negative impact on crop yield; the influence of weather conditions

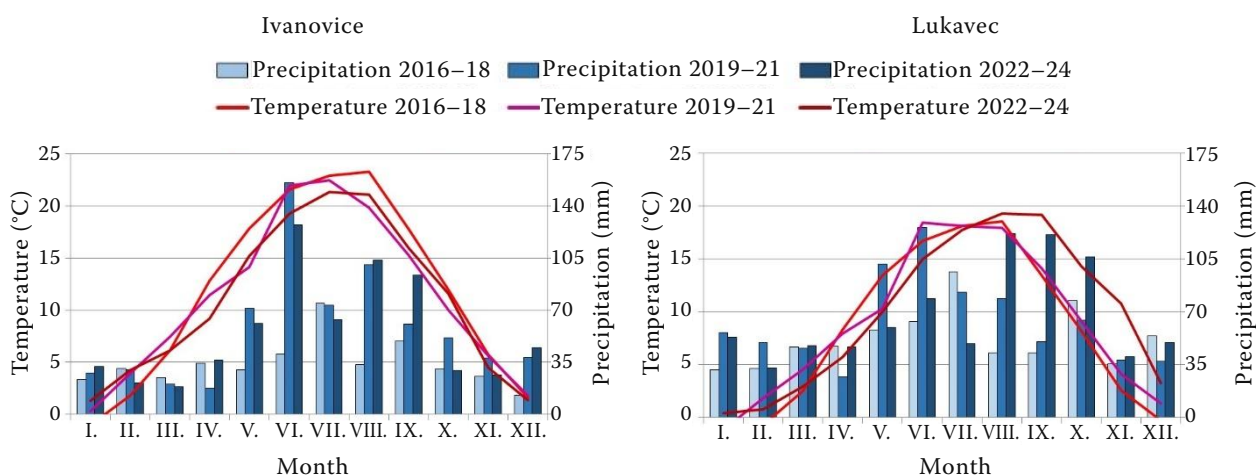


Figure 1. (A) Temperature and (B) precipitation averages in the years 2016–18, 2019–21, and 2022–24

<https://doi.org/10.17221/310/2025-PSE>

Table 1. Average crop yields grown under different mineral and organic fertilisation in the years 2016–18, 2019–21, and 2022–24

| Period  | Fertilisation system | Ivanovice          |                      |                   | Lukavec           |                      |                   |
|---------|----------------------|--------------------|----------------------|-------------------|-------------------|----------------------|-------------------|
|         |                      | winter wheat       | sugar beet           | winter barley     | winter wheat      | potatoes             | winter barley     |
|         |                      | (t/ha)             |                      |                   |                   |                      |                   |
| 2016–18 | mineral              | 5.52 <sup>ab</sup> | 42.93 <sup>a</sup>   | 6.03 <sup>a</sup> | 5.36 <sup>a</sup> | 37.70 <sup>abc</sup> | 4.39 <sup>a</sup> |
|         | farmyard manure      | 5.29 <sup>ab</sup> | 47.79 <sup>ab</sup>  | 6.48 <sup>a</sup> | 6.32 <sup>a</sup> | 46.00 <sup>a</sup>   | 5.02 <sup>a</sup> |
|         | straw + intercrop    | 4.71 <sup>a</sup>  | 50.80 <sup>abc</sup> | 6.67 <sup>a</sup> | 5.92 <sup>a</sup> | 43.82 <sup>abc</sup> | 4.97 <sup>a</sup> |
| 2019–21 | mineral              | 4.55 <sup>a</sup>  | 42.47 <sup>a</sup>   | 6.71 <sup>a</sup> | 4.76 <sup>a</sup> | 39.80 <sup>abc</sup> | 4.58 <sup>a</sup> |
|         | farmyard manure      | 5.08 <sup>ab</sup> | 47.17 <sup>ab</sup>  | 6.99 <sup>a</sup> | 5.63 <sup>a</sup> | 45.27 <sup>a</sup>   | 5.18 <sup>a</sup> |
|         | straw + intercrop    | 5.00 <sup>ab</sup> | 46.79 <sup>ab</sup>  | 7.48 <sup>a</sup> | 5.18 <sup>a</sup> | 44.62 <sup>abc</sup> | 5.35 <sup>a</sup> |
| 2022–24 | mineral              | 6.15 <sup>ab</sup> | 52.81 <sup>abc</sup> | 5.98 <sup>a</sup> | 4.83 <sup>a</sup> | 24.20 <sup>a</sup>   | 4.54 <sup>a</sup> |
|         | farmyard manure      | 7.07 <sup>b</sup>  | 57.21 <sup>bc</sup>  | 7.13 <sup>a</sup> | 5.64 <sup>a</sup> | 32.08 <sup>abc</sup> | 5.03 <sup>a</sup> |
|         | straw + intercrop    | 6.57 <sup>ab</sup> | 62.95 <sup>c</sup>   | 7.49 <sup>a</sup> | 5.27 <sup>a</sup> | 29.14 <sup>ab</sup>  | 5.01 <sup>a</sup> |

The same letters indicate statistically identical values, as determined by Tukey's test ( $P \leq 0.05$ )

was more significant than the changes in fertilisation. The cessation of mineral fertilisers, NPK, was studied, for instance, by Zhou et al. (2022). In his study, all mineral fertilisers, including nitrogen, were suspended, and nitrogen was the main reason why lower yields were observed.

In contrast to Ivanovice, crop yields at Lukavec were less affected by weather conditions and responded better to the N doses and fertilisation system. Yields of all crops, except barley in the 2019–21 rotation, were consistently highest in the farmyard manure treatment. The average yields of all treatments in the rotation for each crop differed by no more than 12%. Only the potato yield in the 2022–24 rotation was significantly lower due to the lack of precipitation in July, when tubers are formed (Table 1).

The average annual phosphorus uptake by crops from a field at Ivanovice was similar during the first two rotations (21.1 and 21.4 kg P/ha/year), including dry years with low crop yields, and 16% higher (24.7 kg P/ha/year) in the 2022–24 rotation (Table 2). The lowest P uptake was noted in 2017, during a drought in the spring months, which negatively affected the yields of winter wheat and sugar beet. Their plots consumed only 12 and 15 kg P/ha on average across all fertilisation systems. Differences in phosphorus uptake by crops among the fertilisation systems reached units of kg P/ha and were significant only between mineral fertilisation in 2016–18 and 2019–21, and FYM and straw + intercrop systems in 2022–24 (Table 2).

Table 2. Average phosphorus and potassium uptake by crops grown under different mineral and organic fertilisation in the years 2016–18, 2019–21 and 2022–24 (three-year averages)

| Period  | Fertilisation system | Ivanovice na Hané  |                     | Lukavec           |                   |
|---------|----------------------|--------------------|---------------------|-------------------|-------------------|
|         |                      | phosphorus         | potassium           | phosphorus        | potassium         |
|         |                      | (kg/ha/year)       |                     |                   |                   |
| 2016–18 | mineral              | 20.4 <sup>a</sup>  | 80.5 <sup>a</sup>   | 17.3 <sup>a</sup> | 68.6 <sup>a</sup> |
|         | farmyard manure      | 21.4 <sup>ab</sup> | 84.9 <sup>ab</sup>  | 20.3 <sup>a</sup> | 80.9 <sup>a</sup> |
|         | straw + intercrop    | 21.4 <sup>ab</sup> | 85.5 <sup>ab</sup>  | 19.5 <sup>a</sup> | 77.5 <sup>a</sup> |
| 2019–21 | mineral              | 20.2 <sup>a</sup>  | 79.4 <sup>a</sup>   | 17.1 <sup>a</sup> | 68.3 <sup>a</sup> |
|         | farmyard manure      | 21.8 <sup>ab</sup> | 86.1 <sup>abc</sup> | 19.6 <sup>a</sup> | 78.4 <sup>a</sup> |
|         | straw + intercrop    | 22.3 <sup>ab</sup> | 87.9 <sup>abc</sup> | 19.3 <sup>a</sup> | 76.9 <sup>a</sup> |
| 2022–24 | mineral              | 22.3 <sup>ab</sup> | 89.4 <sup>abc</sup> | 15.0 <sup>a</sup> | 58.0 <sup>a</sup> |
|         | farmyard manure      | 25.6 <sup>b</sup>  | 101.7 <sup>bc</sup> | 17.7 <sup>a</sup> | 68.9 <sup>a</sup> |
|         | straw + intercrop    | 26.3 <sup>b</sup>  | 105.2 <sup>c</sup>  | 16.8 <sup>a</sup> | 65.3 <sup>a</sup> |

The same letters indicate statistically identical values, as determined by Tukey's test ( $P \leq 0.05$ )

<https://doi.org/10.17221/310/2025-PSE>

The potassium uptake at Ivanovice, depending on the fertilisation system, was 80–85 kg K/ha/year, 79–86 kg K/ha/year, and 89–105 kg K/ha/year in the 2016–18, 2019–21, and 2022–24 crop rotations, respectively. K uptake was attributed to the drought and extreme weather conditions in 2017 and 2018, resulting in an average K uptake of 35 kg K/ha for winter wheat and 75 kg K/ha for sugar beet across all fertilisation systems. The year 2021 was exceptional, as wheat was damaged by hail, and low grain yields also resulted in low nutrient uptake (7 kg P/ha/year, 23 kg K/ha/year).

Differences in potassium uptake by crops among the fertilisation systems were units of kg K/ha, and, similar to phosphorus, were significantly lower under the mineral fertilisation system in 2016–18 and 2019–21, whereas the highest and significant K uptake was observed for straw + intercrop in the 2022–24 period. The highest uptake of both phosphorus and potassium by crops was found in the system straw + intercrop, followed by the farmyard manure system, and the least nutrients were consumed in the mineral fertilisation system. Although the highest contents of the monitored nutrients were found in the soil under the farmyard manure system (see below), this did not cause the highest nutrient uptake due to the lower yields.

The availability of major nutrients, phosphorus and potassium utilisation, is related to soil characteristics, such as clay content and cation exchange capacity, as well as climate conditions (Blake et al. 2000a, b); therefore, different trends were found in the colder and wetter site at Lukavec.

The P uptake was between 17–20 kg P/ha/year in 2016–18 and 2019–21, and 15–18 kg P/ha/year in 2022–24, across all fertilisation systems, on average. Greater variations were found in the potassium uptake reaching 69–81 kg K/ha/year, 68–78 kg K/ha/year and 58–69 kg K/ha/year in 2016–18, 2019–21 and 2022–24 rotations. The highest nutrient uptake by crop was detected in the farmyard manure system, closely followed by straw + intercrop and then mineral fertilisation, corresponding to the achieved crop yields (except barley in the second rotation, Table 1). In contrast to Ivanovice, at Lukavec, the differences in phosphorus and potassium uptake by crops among the fertilisation systems were not significant in any period or fertilisation system.

The amount of nutrients corresponding to 135 kg P/ha and 252 kg K/ha was applied in farmyard manure to relevant treatments every three years. Similarly,

P and K were returned to the soil in a straw + intercrop system in doses corresponding to 8.7 kg P/ha and 121.5 kg K/ha at Ivanovice. 6.6 kg P/ha, 94.8 kg K/ha at Lukavec per one crop rotation. Only the system with mineral fertilisation alone has remained without an additional source of phosphorus and potassium since 2020, which has not yet negatively affected crop growth – the highest crop yields and nutrient removals in this system were achieved in the 2022–24 rotation at Ivanovice. At Lukavec, an insignificant decrease in P and K uptake by plants was found in the 2022–24 rotation compared to the previous ones, mainly due to the exceptionally low yield and nutrient uptake by potatoes caused by the lack of precipitation during tuber formation.

### Nutrients in soil

**Phosphorus.** At Ivanovice, the P-Mehlich 3 content averaged 131–237 mg P/kg across various fertilisation systems for the 2016–18 rotation, while a content of 51–115 mg/kg is considered appropriate (Decree No. 275/1998 coll.). The highest phosphorus values (132–242 mg P/kg) were obtained during the second studied rotation, 2019–2021, in which only the last year was not fertilised with P (Figure 2A). After that, an expected decrease (125–210 mg P/kg) was noted in the 2022–2024 rotation. Generally, higher nutrient contents were determined in the FYM system, followed by the mineral and straw + intercrop systems. Farmyard manure itself contains a considerable amount of nutrients. It therefore represents an important source of additional nutrient supply, resulting in the highest P-Mehlich 3 contents under FYM treatments (210–242 mg P/kg) throughout the entire monitoring period. Similarly to Ivanovice, at Lukavec, the highest P-Mehlich 3 contents were found in soils fertilised with FYM (201–231 mg P/kg), followed by straw + intercrops and mineral systems. P contents gradually increased during all rotations studied under all fertilisation systems (Figure 3A).

Phosphorus release or sorption is influenced by a range of soil properties, including clay content,  $\text{CaCO}_3$ , organic matter, Al and Fe content, CEC, as well as the P sources applied to the soil (Rashmi and Biswas 2018). The maximum P availability near pH 6.5, as described by Lindsay (1979), remains true today (Penn and Camberato 2019). However, shifts in various P sorption mechanisms occur as a result of soil pH, positive or negatively charged soil surfaces, the formation of multiple bonds, and the presence of

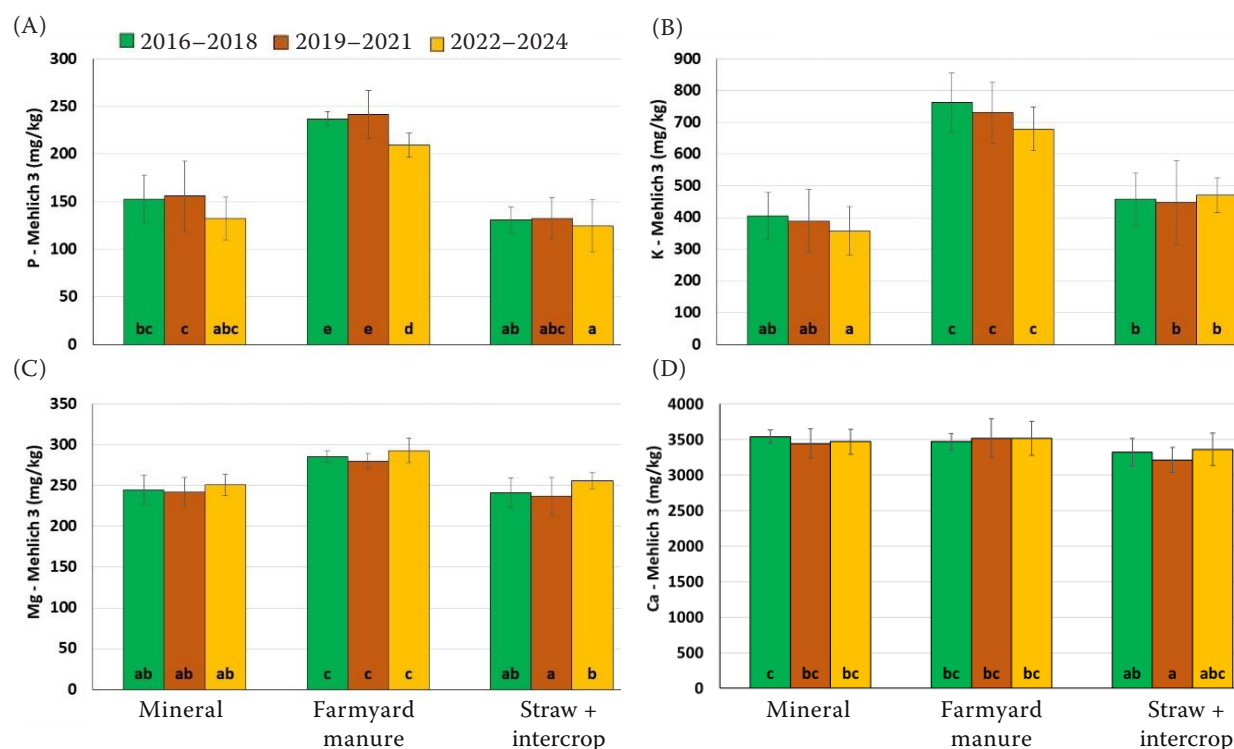


Figure 2. Mehlich 3 nutrient contents at Ivanovice in Chernozem under different mineral and organic fertilisation in the years 2016–18, 2019–21, and 2022–24. (A) Phosphorus; (B) potassium; (C) magnesium, and (D) calcium. The same letters in the figures indicate statistically identical values according to Tukey's test ( $P \leq 0.05$ ), and the bars represent standard deviation

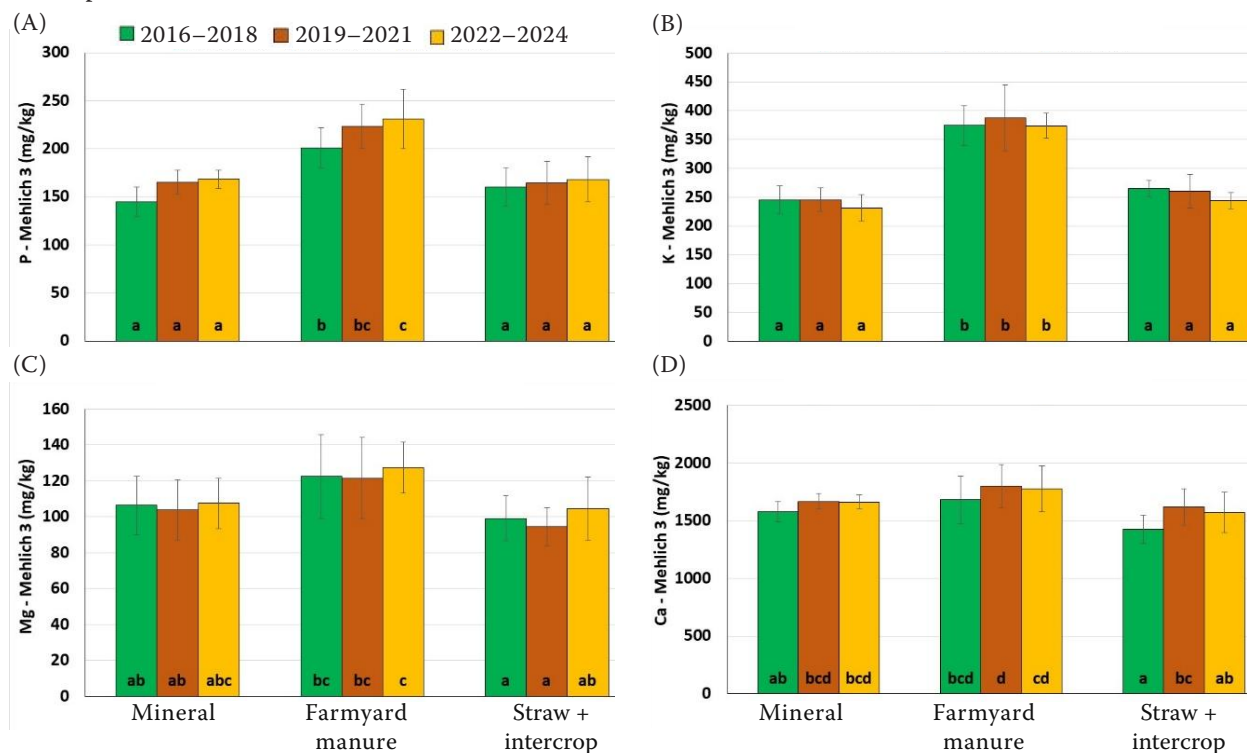


Figure 3. Mehlich 3 nutrient contents at Lukavec in Cambisol under different mineral and organic fertilisation in the years 2016–18, 2019–21, and 2022–24. (A) Phosphorus; (B) potassium; (C) magnesium, and (D) calcium. The same letters in the figures indicate statistically identical values according to Tukey's test ( $P \leq 0.05$ ), and the bars represent standard deviation

<https://doi.org/10.17221/310/2025-PSE>

Ca-rich minerals (Penn and Camberato 2019). This can partly explain the increase in the P-Mehlich 3 contents at Lukavec during the study period despite the suspension of phosphorus fertilisation. In contrast to Ivanovice, soils at Lukavec have lower Ca contents, so the eventual formation of bonds with carbonates, which are agents capable of fixing and retaining P (Carreira et al. 2005), is limited.

The phosphorus content in soil extracted by  $\text{NH}_4$  acetate was only 12% (Ivanovice) and 19% (Lukavec), compared to Mehlich 3, and was related to the higher and lower calcium content found in Chernozem and Cambisol, respectively. Compared to other major nutrients, phosphorus is firmly bound in soils due to the precipitation of P with calcium ions in calcareous soils (Carreira et al. 2005, Khan et al. 2018). The same trend of P- $\text{NH}_4$  acetate contents was observed at both sites across all fertilisation systems: insignificant differences between the first two rotations and a significant decrease (by 32% to 40% in Chernozem and 20–29% in Cambisol) in 2022–24 after fertilisation was suspended. The largest response was found in the FYM system, where the highest yields and nutrient removals are achieved in the long term (Figures 4A, 5A).

**Potassium.** The annual dose of 83 kg K/ha, mainly in combination with FYM, increased the K-Mehlich 3 contents in soil to a very high level, reaching up to 900 mg K/kg at Ivanovice in some years. The highest values were determined in the first studied rotation at Ivanovice, with an average of 762 mg K/kg in the FYM system (Figure 2B), followed by the straw + intercrop (458 mg K/kg) and mineral (405 mg K/kg) systems. A similar trend, but with significantly different values of K content, was found at Lukavec, where the soil is lighter and has a lower CEC value. During the first two rotations, the K-Mehlich 3 contents in the soil were balanced and decreased in the order of fertilisation systems as follows: FYM (374 mg K/kg), straw + intercrop (265 mg K/kg) and mineral (245 mg K/kg) (Figure 3B). Farmyard and organic fertilisers are significant sources of potassium. Balík et al. (2022) also found a positive potassium balance with regular manure application (every 3 years) in different locations. The absence of mineral potassium fertilisation since 2020 was reflected in the K-Mehlich 3 content, with a decrease of 3–11% in the last rotation (most pronounced in the FYM system in Ivanovice). Still, the differences between the studied rotations were not statistically significant (Figures 2B, 3B).

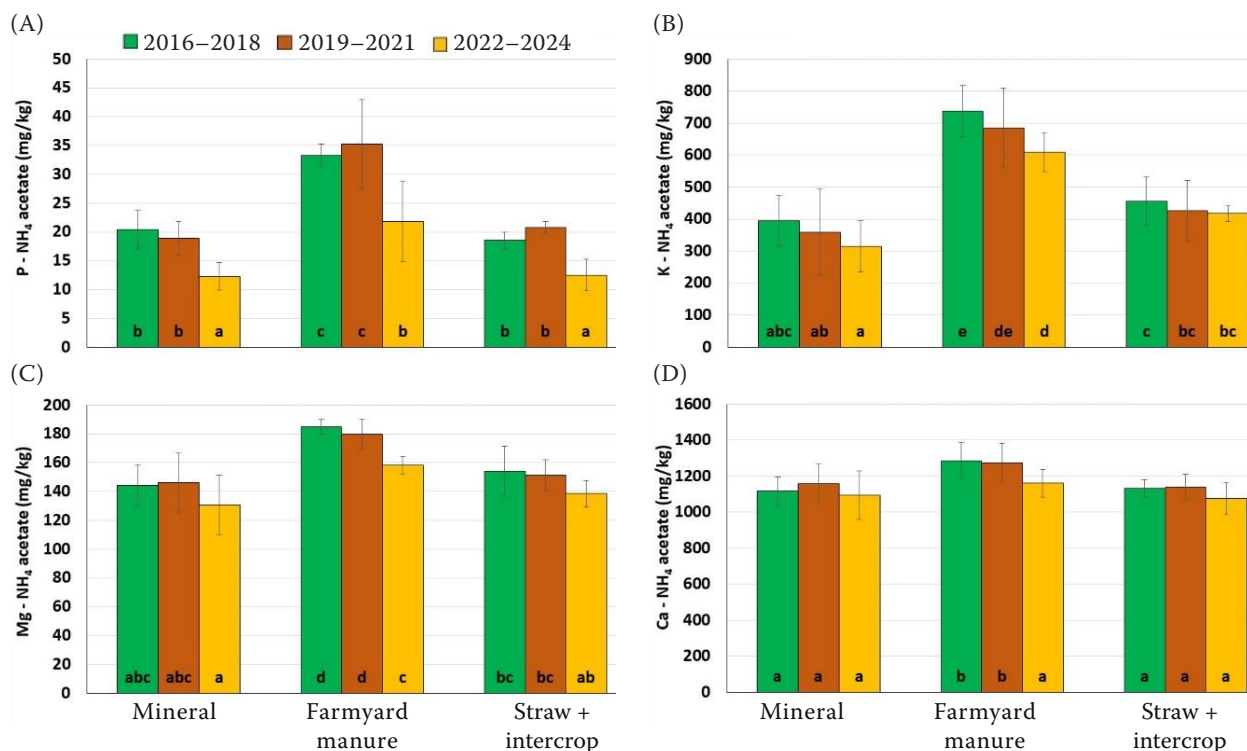


Figure 4.  $\text{NH}_4$  acetate nutrient contents at Ivanovice in Chernozem under different mineral and organic fertilisation in the years 2016–18, 2019–21, and 2022–24. (A) Phosphorus; (B) potassium; (C) magnesium, and (D) calcium. The same letters in the figures indicate statistically identical values according to Tukey's test ( $P \leq 0.05$ ), and the bars represent standard deviation

Slight differences in the content of potassium extractable by Mehlich 3 and  $\text{NH}_4$ -acetate were found.  $\text{NH}_4$ -acetate extractable K was at the level of 89–104%, as determined by Mehlich 3, depending on the site, crop rotation, and fertilisation system. A slight decrease (often significant) in the content of exchangeable K in the soil was observed during the studied rotations at both sites in all fertilisation systems, with the largest decrease (up to 23%) occurring in mineral systems (Figures 4B, 5B).

The potassium contents determined in the soils at Lukavec and Ivanovice can be classified as high or very high, according to Decree No. 275/1998 Coll. about the agrochemical soil testing in the Czech Republic. In fact, climate change is becoming increasingly apparent, particularly in relation to periods of drought (Meitner et al. 2023, Torbenson et al. 2023). Additionally, fluctuations in yields have also been noted in the IOSDV field experiment (Káš et al. 2019). This resulted in lower potassium crop uptake and was one of the reasons for the increase in K content in soils under regular annual K fertilisation. When soils are fertilised with monovalent cations (e.g.  $\text{K}^+$ ) in amounts that, due to uncertainty of yields, should not be taken up by plants, their increased concentration in soils can facilitate the leaching of bivalent cations ( $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$ ) into deeper soil layers (Mühlbachová et al. 2024). In this case, the imbalance of single- and double-bonded cations occurs in the topsoil, adversely affecting the stability of soil aggregates. Jaša et al. (2019) found an increase in the proportion of fine soil elements and a deterioration in the soil structural coefficient after repeated application of organic or livestock fertilisers with a high potassium content. Csitári et al. (2021) also confirmed lower aggregate stability when manure was applied than after straw incorporation. One of the consequences of soil structure deterioration is also limited water infiltration into the soil, the availability of which is one of the main factors limiting crop yields. The importance of water availability is expected to increase in the context of ongoing climate change, characterised by irregularly distributed precipitation, rising temperatures, and more frequent periods of drought. Similarly, Hliseníkovský et al. (2021) attributed 95% of the effect of year conditions and only 5% of the effect of nutrition to the size of crop yields in fertile soils. Additionally, in our IOSDV experiments, the effect of the year is predominant; however, a decrease in yields after a change in fertilisation has not yet been observed.

**Magnesium and calcium.** The Mg content did not differ significantly among the different fertilisation systems at individual sites. Higher Mg contents (up to 293 mg Mg/kg and 128 mg Mg/kg at Ivanovice and Lukavec, respectively) were obtained in the systems with farmyard manure, which also contained magnesium. In difference to potassium, Mg-Mehlich 3 contents showed a slight increase during the study period at both sites, about 1–6% at both sites (Figures 2C, 3C), which may be a favourable consequence of the decrease in K-Mehlich 3 content due to known antagonism between K and Mg (Matula 2007). On difference from Mehlich 3, the decrease of exchangeable Mg of about 8–14% at Ivanovice and 10–21% at Lukavec) was observed during the studied rotations (Figures 4C, 5C).

Average calcium contents determined by the Mehlich 3 method at Ivanovice (up to 3 518 mg Ca/kg) did not show any clear tendency to increase or decrease during three crop rotations (Figure 2D). The calcium content at Lukavec, determined by the Mehlich 3 method, increased by 5–13% from 2019 to 2021 (Figure 3D) compared to the years 2016–2018. A slight decrease (up to 10%) in Ca content in the soil of both experimental sites was observed during three crop rotations, as determined by  $\text{NH}_4$  acetate (Figures 4D, 5D), indicating possible uptake of more readily available Ca fractions by crops. The exchangeable fraction of calcium represented 31–37% and 55–66% of the Ca content determined by Mehlich 3 at Ivanovice and Lukavec, respectively. This document describes the different types of calcium bonds in the soils of individual locations. The lower proportion of exchangeable Ca in Ivanovice reflects a higher proportion of carbonates than in Lukavec, which is confirmed by the higher pH value.

**Ratios of cation equivalents.** The Mehlich 3 extractant, due to its composition and low pH, extracts proportionally more cations than ammonium acetate, with which exchangeable cations are typically determined (Culman et al. 2021). For the determination of ratios, the exchangeable nutrient contents were taken into consideration. The nutrient K:Mg:Ca ratio in soils should be 1:2–3:10–15 to ensure proper soil functions (Loide 2004, Matula 2007, Mühlbachová et al. 2024). Long-term annual application of mineral K fertilisers and absence of Mg and Ca inputs in mineral fertilisers lead to remarkably high K contents in soils and to a discrepancy in K:Mg:Ca ratios both at Ivanovice and Lukavec (Table 3). The system with mineral fertilisation alone showed the best

<https://doi.org/10.17221/310/2025-PSE>

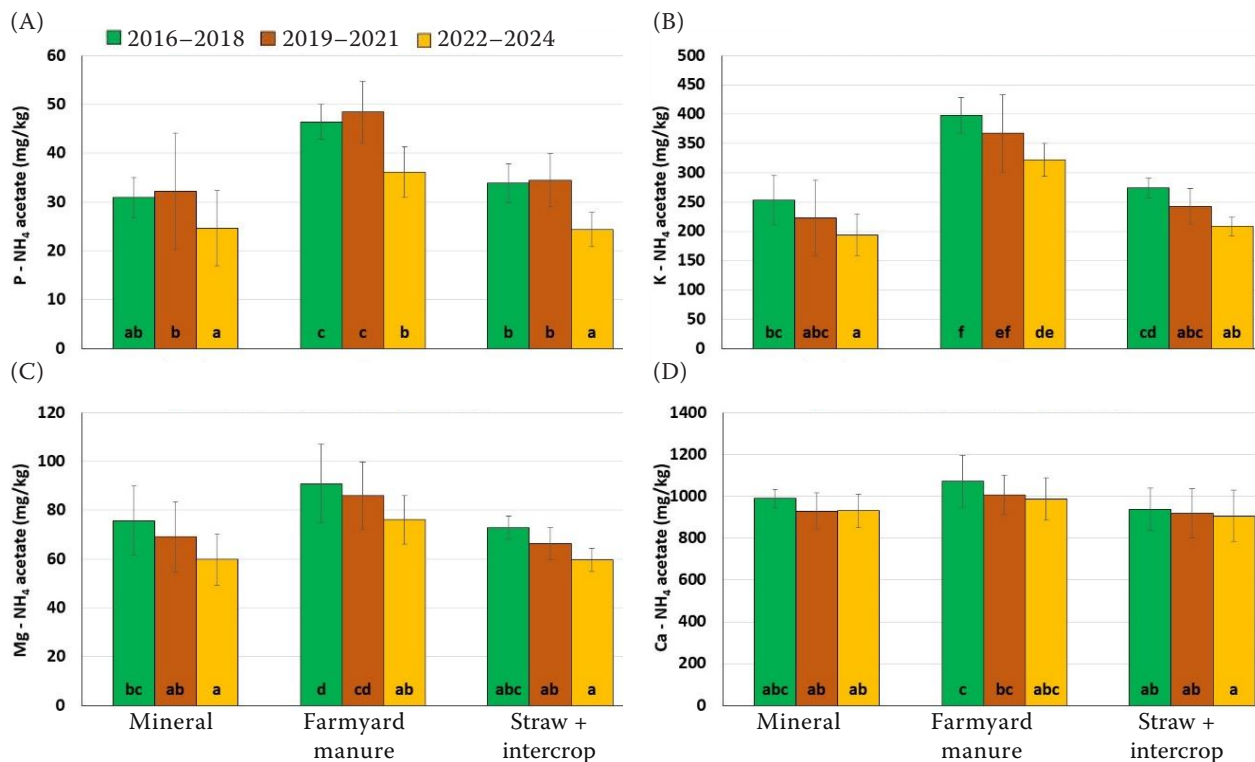


Figure 5.  $\text{NH}_4$  acetate nutrient contents at Lukavec in Cambisol under different mineral and organic fertilisation in the years 2016–18, 2019–21, and 2022–24. (A) Phosphorus; (B) potassium; (C) magnesium, and (D) calcium. The same letters in the figures indicate statistically identical values according to Tukey's test ( $P \leq 0.05$ ), and the bars represent standard deviation

soil nutrient ratios and improved gradually during studied rotations with decreasing potassium content in soil (Ivanovice: K:Mg:Ca from 1:1.2:5.6 to 1:1.4:6.8, Lukavec: from 1:1.0:7.7 to 1:1.0:9.6). In other fertilisation systems, potassium was additionally supplied in post-harvest residues or manure and its predominance over divalent cations ( $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ) was even more pronounced.

An inappropriate K:Mg:Ca ratio in the surface layer can cause deterioration in soil structure and water infiltration, and consequently, possibly decrease crop yields. High  $\text{K}^+$  contents in soils can cause competition among cations and inhibit or leach divalent cations, such as  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  (Matula 2007, Li et al. 2018). Additionally, the different surface reactions of metal ions with variably charged soil particles can significantly influence particle interactions and their aggregation, sedimentation, dispersion, and transportation (Tian et al. 2013).

The suspension of mineral fertilisation with K in the long-term IOSDV experiment led not only to a decrease in unacceptable high potassium contents, but also to the stabilisation of Mg and Ca contents in the topsoil, noted mainly when the Mehlich 3

extractant was used. However, nutrient extraction in  $\text{NH}_4$  acetate showed a decrease in Mg and Ca exchangeable fractions, which are more readily available for plants. Soils regularly fertilised with farmyard manure, therefore, for the moment do not need additional mineral phosphorus and potassium fertilisers. However, relying solely on organic amendments can lead to plant nutrient deficiency due to decreased or imbalanced levels of readily available nutrients in the soil (Chen et al. 2018). In case of phosphorus applied to soils with a higher calcium content and pH value, the potentially releasable phosphorus, which may occur in bonds with Ca, should be taken into account.

High P and K contents in soils were found due to long-term annual mineral fertilisation, and low crop yields and nutrient uptake caused by drought. A further increase in the content, especially potassium, was caused by the regular application of organic fertilisers (mostly manure, with less straw and intercrop) that contained a high portion of potassium. Unreasonably high doses of potassium without adequate supplementation of magnesium and calcium led to an unbalanced ratio of cations, which had a negative impact on soil

fertility. The suspension of the application of mineral P and K fertilisers (since 2020) in all fertilisation systems has led to a gradual decrease in the content of these nutrients. The mutual ratios of nutrient equivalents K:Mg:Ca in the topsoil were improved during the studied period despite a slight decrease in Mg and Ca contents due to their uptake by plants and the absence of fertilisation. The best soil condition was in the system with only mineral fertilisation, where the greatest changes were found (Ivanovice: K:Mg:Ca from 1:1.2:5.6 to 1:1.4:6.8, Lukavec: from 1:1.0:7.7 to 1:1.0:9.6). The critical soil condition, from this point of view, remains in the system with farmyard manure, especially on Chernozem soils with a higher potassium content and higher sorption capacity. The knowledge gained from the long-term experiment highlights the need to consider the nutrients applied in organic fertilisers and post-harvest residues. It is also necessary to respond to fluctuations in yields and nutrient uptake by plants due to adverse weather conditions. The importance of a balanced ratio of ions in the soil and a stable structure necessary for water infiltration is gaining significance with the ongoing climate change, as well as the lack of and irregularity of precipitation.

## REFERENCES

- Asrade D.A., Kulhánek M., Balík J., Černý J., Sedlář O., Suran P. (2024): Phosphorus availability and balance with long-term sewage sludge and nitrogen fertilisation in Chernozem soil under maize monoculture. *Plants*, 13: 2037.
- Balík J., Vaněk V., Suran P., Pavlíková D. (2022): Soil Nutrient Pools – Focused on the Topic of Potassium. In: *Proceedings of 28<sup>th</sup> International Conference on Reasonable Use of Fertilizers*, 1.12. 2022. Prague, Czech University of Life Sciences, 17–26. (In Czech)
- Blake L., Mercik S., Koerschens M., Goulding K.W.T., Stempen S., Weigel A., Poulton P.R., Powlson D.S. (2000a): Potassium content in soil, uptake in plants and the potassium balance in three European long-term field experiments. *Plant and Soil*, 216: 1–14.
- Blake L., Mercik S., Koerschens M., Moskal S., Poulton P.R., Goulding K.W.T., Weigel A., Powlson D.S. (2000b): Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments. *Nutrient Cycling in Agrosystems*, 56: 263–275.
- Çakmak I., Yazici A.M. (2010): Magnesium: a forgotten element in crop production. *Better Crops*, 94: 23–25.
- Carreira J.A., Viñegla B., Lajtha K. (2005): Secondary  $\text{CaCO}_3$  and precipitation of P-Ca compounds control the retention of soil P in arid ecosystems. *Journal of Arid Environment*, 64: 460–473.
- Chaganti V.N., Culman S.W., Herms C., Sprunger C.D., Brock C., Soto A.L., Doohan D. (2021): Base cation saturation ratios, soil health, and yield in organic field crops. *Agronomy Journal*, 113: 4190–4200.
- Chaganti V.N., Culman S.W. (2017): Historical perspective of soil balancing theory and identifying knowledge gaps: a review. *Crop, Forage and Turfgrass Management*, 3: 1–7.
- Chen Y., Camps-Arbestain M., Shen Q., Singh B., Cayuela M.L. (2018): The long-term role of organic amendments in building soil nutrient fertility: a meta-analysis and review. *Nutrient Cycling in Agroecosystems*, 111: 103–125.
- Clough A., Skjemstad J.O. (2000): Physical and chemical protection of soil organic carbon in three agricultural soils with different contents of calcium carbonate. *Australian Journal of Soil Research*, 38: 1005–1016.
- Csitári G., Tóth Z., Kökény M. (2021): Effects of organic amendments on soil aggregate stability and microbial biomass in a long-term fertilization experiment (IOSDV). *Sustainability*, 13: 9769.
- Culman S.W., Brock C., Doohan D., Jackson-Smith D., Herms C., Chaganti V.N., Kleinhenz M., Sprunger C.D., Spargo J. (2021): Base cation saturation ratios vs. sufficiency level of nutrients: a false dichotomy in practice. *Agronomy Journal*, 113: 5623–5634.
- Domagała-Świątkiewicz I., Gąstoł M., Kiszka A. (2019): Effect of nitrogen and potassium fertilization on the magnesium content in vineyard soil, and in the leaves and berries of Bianca and Sibera grapevine cultivars. *Journal of Elementology*, 24: 755–769.
- Fageria V.D. (2001): Nutrient interactions in crop plants. *Journal of Plant Nutrition*, 24: 1269–1290.
- Gransee A., Führs H. (2013): Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant and Soil*, 368: 5–21.
- Hliseníkovský L., Menšík L., Křížová K., Kunzová E. (2021): The effect of farmyard manure and mineral fertilizers on sugar beet beetroot and top yield and soil chemical parameters. *Agronomy*, 11: 133.
- Jaša S., Badalíková B., Červinka J. (2019): Influence of digestate on physical properties of soil in ZD Budišov. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 67: 75–83.
- Káš M., Mühlbachová G., Kusá H. (2019): Winter wheat yields under different soil-climatic conditions in a long-term field trial. *Plant, Soil and Environment*, 65: 27–34.
- Káš M., Mühlbachová G., Kusá H. (2022): Pre-crop value of sugar beet under conditions of climate change. *Listy Cukrovarnické a Řepářské*, 138: 60–62.
- Khan A., Lu G., Ayaz M., Zhang H., Wang R., Lv F., Yang X., Sun B., Zhang S. (2018): Phosphorus efficiency, soil phosphorus dynamics and critical phosphorus level under long-term fertilization for single and double cropping systems. *Agriculture, Ecosystems and Environment*, 256: 1–11.

<https://doi.org/10.17221/310/2025-PSE>

- Körschens M., Albert E., Armbruster M., Barkusky D., Baumecker M., Behle-Schalk L., Bischoff R., Čergan Z., Ellmer F., Herbst F., Hoffmann S., Hofmann B., Kismányoky T., Kubat J., Kunzova E., Lopez-Fando C., Merbach I., Merbach W., Pardor M.T., Rogasik J., Rühlmann J., Spiegel H., Schulz E., Tajnsek A., Toth Z., Wegener H., Zorn W. (2013): Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. *Archives of Agronomy and Soil Science*, 59: 1017–1040.
- Li H.X., Chen Z.J., Zhou T., Liu Y., Zhou J.B. (2018): High potassium to magnesium ratio affected the growth and magnesium uptake of three tomato (*Solanum lycopersicum* L.) cultivars. *Journal of Integrative Agriculture*, 17: 2813–2821.
- Lindsay W.L. (1979): *Chemical Equilibria in Soils*. Hoboken, John Wiley and Sons Ltd, 449. ISBN: 0471027049
- Loide V. (2004): About the effect of the contents and ratios of soil's available calcium, potassium and magnesium in liming of acid soils. *Agronomy Research*, 2: 71–82.
- Kautz T., Wirth S., Ellmer F. (2004): Microbial activity in a sandy arable soil is governed by the fertilization regime. *European Journal of Soil Biology*, 40: 87–94.
- Matula J. (2007): *Optimization of Nutrient Status of Soils by KVK-UF Soil Test. Methodology for Praxis*. Prague, Crop Research Institute, 48. ISBN: 978-80-87011-16-4 (In Czech)
- Mehlich A. (1984): Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, 15: 1409–1416.
- Meitner J., Balek J., Bláhová M., Semerádová D., Hlavinka P., Lukas V., Jurečka F., Žalud Z., Klem K., Trnka M. (2023): Estimating drought-induced crop yield losses at the cadastral area level in the Czech Republic. *Agronomy*, 13: 1669.
- Mühlbachová G., Růžek P., Kusá H., Vavera R., Káš M. (2024): Nutrient distribution in the soil profile under different tillage practices during a long-term field trial. *Agronomy*, 14: 3017.
- Penn C.J., Camberato J.J. (2019): A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture-Basel*, 9: 120.
- Rashmi I., Biswas A.K. (2018): Phosphorus sorption characteristics of soils for managing the fertilizer phosphorus in three dominant soil types of India. *Chemical Science Review and Letters*, 7: 725–731.
- Rasmussen P.E., Douglas C.L. jr., Collins H.P., Albrecht S.L. (1998): Long-term cropping system effects on mineralizable nitrogen in soil. *Soil Biology and Biochemistry*, 30: 1829–1837.
- Soto A.L., Culman S.W., Herms C., Sprunger C., Doohan D. (2023): Managing soil acidity vs. soil Ca:Mg ratio: what is more important for crop productivity? *Crop Forage Turfgrass Management*, 9: e20210.
- Tian R., Li H., Zhu H., Liu X., Gao X. (2013):  $\text{Ca}^{2+}$  and  $\text{Cu}^{2+}$  induced aggregation of variably charged soil particles: a comparative study. *Soil Science Society of America Journal*, 77: 774–781.
- Torbenson M.C.A., Buentgen U., Esper J., Urban O., Balek J., Reinig E., Krusic P.J., del Castillo E.M., Brázdil R., Semerádová D., Štěpánek P., Pernicová N., Kolář T., Rybníček M., Koňasová E., Arbelaez J., Trnka M. (2023): Central European agroclimate over the past 2000 years. *Journal of Climate*, 36: 4429–4441.
- Varga I., Jović J., Rastija M., Markulj Kulundžić A., Zebec V., Lončarić Z., Iljkić D., Antunović M. (2022): Efficiency and management of nitrogen fertilization in sugar beet as spring crop: a review. *Nitrogen*, 2022: 170–185.
- Zebec V., Rastija D., Lončarić Z., Bensa A., Popović B., Ivezić V. (2017): Comparison of chemical extraction methods for determination of soil potassium in different soil types. *Eurasian Soil Science*, 50: 1420–1427.
- Zhou W.M., Ata-Ul-Karim S.T., Moritsuka N., Kato Y. (2022): Exploring the association between inherent soil nutrient availability and crop responses following long-term cessation of fertilizer inputs in a wheat-maize cropping system. *Journal of Plant Nutrition and Soil Science*, 22: 4683–4692.

Received: July 16, 2025

Accepted: November 3, 2025

Published online: November 19, 2025