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**ORIGINAL PAPER**

# The effect of weed control method on the macronutrient content in tubers of two potato cultivars*

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**Abstract**

The aim of the study was to determine the effect of different types of sprayer nozzles on the content of selected macronutrients (phosphorus, potassium, calcium, and magnesium) in the tubers of two table potato cultivars (Jurek and Finezja). Field experiments were conducted in the years 2018-2020 at the Agricultural Experimental Station in Zawady, on slightly acidic soil belonging to the very good rye complex. The experiment was established in a split-plot design with three replications. The study included two factors: potato cultivar (Jurek, Finezja) and the method of herbicide application using four variants: (1) control object with mechanical weed control (four cultivations with harrowing before emergence, and one cultivation after emergence), (2) flat fan nozzles (AP12003), (3) hollow-cone nozzles (HCI8003) – the applications carried out with the same pressure and flow rate, and (4) 3D Hypro nozzles (3D100-03), also operated under identical parameters (4 bar; 1.39 L min$^{-1}$). The results showed that a weed control method had a significant effect on the content of phosphorus, potassium, magnesium, and calcium in potato tubers. The highest phosphorus and calcium contents were recorded after the use of 3D Hypro nozzles, whereas the highest potassium content was observed in the control object. Magnesium content differed significantly depending on the type of a sprayer nozzle used. A significant effect of cultivar on potassium content was also found. The results confirm that proper selection of sprayer nozzles can influence the quality of the raw plant material in terms of its nutritional value.

**Keywords:** *Solanum tuberosum L., sprayer nozzles, macronutrients*

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# INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the most important cultivated crops in the world, where it plays a key role in ensuring food security, particularly in developing countries (Almar et al. 2017, Hussain et al. 2021). In addition to its high energy value (Mystkowska et al. 2023), primarily due to its starch content, potato tubers are also a valuable source of mineral nutrients such as potassium, phosphorus, magnesium, and calcium (Leszczyński, 2012, Zarzecka et al. 2015). Adequate nutrient supply to plants can mitigate the negative effects of growth and developmental conditions, while also ensuring desirable tuber quality (Koch et al. 2020). Among the alternative approaches to provide crops with essential nutrients, foliar fertilization is of particular interest. This practice enables a rapid and efficient supplementation of both micro- and trace elements through the application of aqueous solutions of mineral salts or chelates directly onto the leaf surface (Jasim, Merhij 2018). As highlighted by Noaema (2018), foliar fertilization offers a means to improve insufficient plant nutrition and to compensate for deficiencies of specific bioelements. Potassium in particular – the content of which in tubers may range from 13.1 to 25.9 g $kg^{-1}$ dry matter (Zarzecka et al. 2015) – plays a crucial role in regulating water and ion balance in plants (Leszczyński, 2012). The mineral content of tubers depends on many factors, including the genetic traits of the cultivar (Sawicka et al. 2015, 2016), agrometeorological conditions, and the type and method of fertilization (Wierzbicka, Trawczyński 2011). Of particular interest is the effect of foliar fertilization on the content of macronutrients. The mineral content of potato tubers is considered by author Nassar et al. (2012) to be the main factor determining their suitability for direct consumption and food processing. These characteristics depend on the biology of the potato, which is strongly influenced by agrometeorological conditions during the growing season, agronomic practices, particularly fertilization and crop protection, and storage conditions (Ahmed et al. 2015, Goméz et al. 2017, Leonel et al. 2017, Wierzbowska et al. 2018, Głosek-Sobieraj et al. 2019, Rychcik et al. 2020). A study by Kozera and Barczak (2007) has shown that properly selected foliar formulations can increase the levels of nitrogen, phosphorus, and magnesium in potato tubers. On the other hand, some research suggests that intensive foliar fertilization may lead to a reduction in the potassium content in tubers. In recent years, increasing attention has been paid to improving the chemical composition of crop yield through foliar fertilization, which allows for the rapid delivery of nutrients to the plant, especially during periods of intensive growth or under conditions limiting root uptake (Coelho et al. 2021). The use of foliar fertilizers and biostimulants may positively affect plant physiology and the content of macronutrients in tubers (Burlingame et al. 2009). Gaj et al. (2020) demonstrated that foliar application of potassium fertilizers and micronutrients significantly increases potassium content in the yield, while Coelho et al. (2021) confirmed the effectiveness of calcium-based preparations ($CaCl_2$ and $Ca(NO_3)_2$) in increasing calcium and phosphorus content in tuber tissues. Moreover, Hadidi et al. (2017) demonstrated that foliar application of Ca and Mg directly increases the content of these elements in potato tubers, indicating that differences in spray deposition – controlled by a nozzle type – may lead to measurable differences in tuber mineral composition.

The effectiveness of foliar fertilization is also determined by the technical aspects of working fluid application, primarily the nozzle type, spray parameters, and droplet size (Hilz, Vermeer 2013). As shown by Hołownicki et al. (2021), an adequate size and proper distribution of droplets determine the degree of leaf surface coverage, the efficiency of active substance deposition, and the reduction of spray drift. Smaller droplets enable more uniform coverage and higher treatment efficacy, while larger ones reduce losses and minimize the risk of environmental contamination. Various nozzle types are used in practice, differing in their spray characteristics. Flat-fan nozzles, which produce a fan-shaped spray with a uniform distribution, are commonly used for applying herbicides, fungicides, and insecticides (Sikkema et al. 2008). Cone nozzles create a ring-shaped spray with high atomization, enabling better coverage of hard-to-reach surfaces. In contrast, modern Hypro 3D nozzles, thanks to their three-dimensional geometry, provide better coverage of asymmetrical plant parts, such as the underside of leaves (Smith et al. 2000). Sayinci and Bastaban (2011) documented that air-induction nozzles and double-fan nozzles provide the most uniform working fluid distribution and more effective coverage of the middle and lower parts of potato plants. The type of nozzle (e.g., flat-fan, hollow-cone, air-assisted) affects droplet size and deposition, which in turn determines the uptake of P, K, Mg, and even Ca by plants (Tunio et al. 2021). Analogous results regarding the effect of a nozzle type on yield and biomass production were obtained in aeroponic potato cultivation by Barros et al. (2019), further supporting the view that spray characteristics can influence nutrient acquisition efficiency. Despite the growing number of studies on working fluid application technology, the effect of a nozzle type on the mineral nutrient content in potato tubers remains poorly documented. Different types of sprayer nozzles influence the content of selected macronutrients in potato tubers, with the direction and intensity of these effects depending on the nozzle type and cultivar. Therefore, the aim of this study was to evaluate the impact of selected sprayer nozzle types (flat-fan, hollow-cone, and Hypro 3D) on the content of key macronutrients (P, K, Mg, Ca) in the tubers of two potato cultivars, Jurek and Finezja, grown under field conditions from 2018 to 2020.

## MATERIALS AND METHODS

Field experiments were carried out over a three-year period (2018–2020) at the Agricultural Experimental Station in Zawady, affiliated with the University of Siedlce. The trials were established using a split-plot design with three replicates, on slightly acidic soil classified as a very good rye complex. Soil parameters are shown in table 1. The experiment investigated two

Table 1

Soil parameters in study years (2018-2020)

| Soil parametrs in study years (g $kg^{-1}$) | 2018 | 2019 | 2020 |
|---|---|---|---|
| P | 40.0 | 66.0 | 65.0 |
| K | 107.1 | 154.0 | 145.0 |
| Mg | 40.0 | 65.0 | 55.0 |
| N total | 9.0 | 13.6 | 12.0 |
| Organic matter | 21.0 | 24.0 | 22.0 |

factors: factor I – two table potato cultivars, Jurek and Finezja, both of which are medium-early varieties characterized by a leaf-stem growth habit; factor II – four herbicide application techniques using different nozzle types: chemical weed control using flat-fan nozzles (AP12003) – application at 4 bar pressure and 1.39 L $min^{-1}$ flow rate (1); hollow-cone nozzles (HCI8003) – application at the same pressure and flow rate (2) and Hypro 3D nozzles (3D100-03) – also operated under identical parameters (4 bar; 1.39 L $min^{-1}$) (3); Control – mechanical weed control (four cultivations with harrowing before emergence, and one cultivation after emergence) (4). The herbicide Avatar 293 ZC, a capsule suspension formulation for pre-emergence treatment, was applied at 1.5 $dm^3$ $ha^{-1}$ to control annual broadleaf weeds. Its active ingredients include clomazone (60 g $dm^{-3}$), which disrupts pigment biosynthesis, and metribuzin (233 g $dm^{-3}$ ), a photosynthesis inhibitor. Additionally, to control *Elymus repens* and other grasses, Fusilade Forte 150 EC (fluazifop-p-butyl, 150 g $dm^{-3}$) was applied post-emergence at a dose of 1.5 $dm^3$ $ha^{-1}$. This selective, systemic graminicide is absorbed through leaves and translocated to roots and rhizomes. Cereal was the preceding crop. Fertilization included organic manure at a dose of 25.0 t $ha^{-1}$ and mineral nutrients applied at: N – 90 kg $ha^{-1}$, P – 32.86 kg $ha^{-1}$ (0.44 × 90 $P_2O_5$), and K – 112.10 kg $ha^{-1}$ (0.83 × 135 $K_2O$). Potatoes were planted in April (23 April 2018, 18 April 2019, and 20 April 2020). All agronomic practices were carried out in accordance with the experimental guidelines. The concentrations of macroelements (P, K, Mg, Ca) in tubers were determined using inductively coupled plasma optical emission spectrometry (ICP-OES) with a Perkin Elmer Optima 8300 spectrometer. Analytical procedures included instrument calibration, performance verification, detection limit checks

(IDL, MDL), and quality control samples to confirm analytical reliability. The selected wavelengths and detection limits were as follows: P – 213.617 nm (0.090 mg $L^{-1}$), K – 766.490 nm (0.030 mg $L^{-1}$), Mg – 285.213 nm (0.002 mg $L^{-1}$), Ca – 317.933 nm (0.010 mg $L^{-1}$). Instrument settings included: RF power – 1500 W, plasma argon flow – 8 L $min^{-1}$, auxiliary flow – 0.2 L $min^{-1}$, nebulizer flow – 0.7 L $min^{-1}$, sample uptake – 1 mL $min^{-1}$, and an integration time of 10 s. An internal standard (Y – 371.029 nm) was used to eliminate matrix effects. All control tests confirmed the high precision and accuracy of the ICP-OES measurements. Statistical analysis of the data was performed using analysis of variance (ANOVA). The significance of main effects was verified using the Fisher-Snedecor $F$-test, while mean comparisons were made using the Tukey's HSD test at a significance level of $p$=0.05. Meteorological data recorded during the study period (Tables 2) revealed significant variability between years. The 2018 growing season (April–September) was

Table 2

Weather conditions in the growing season of potato according to the Zawady Meteorological Station

| Years | Month | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | April | May | June | July | Aug | Sept | |
| Temperature (°C) | | | | | | | |
| 2018 | 13.1 | 17.0 | 18.3 | 20.4 | 20.6 | 15.9 | 17.5 |
| 2019 | 9.8 | 13.3 | 17.9 | 18.5 | 19.9 | 14.2 | 15.6 |
| 2020 | 8.6 | 11.7 | 19.3 | 19.0 | 20.2 | 15.5 | 15.7 |
| 1980-2009 | 8.2 | 11.2 | 16.0 | 18.7 | 18.5 | 12.1 | 14.1 |
| Precipitation (mm) Total | | | | | | | |
| 2018 | 34.5 | 27.3 | 31.5 | 67.1 | 54.7 | 80.6 | 295.7 |
| 2019 | 5.9 | 59.8 | 35.9 | 25.7 | 43.9 | 17.4 | 188.6 |
| 2020 | 6.0 | 63.5 | 118.5 | 67.7 | 17.9 | 38.8 | 312.4 |
| 1980-2009 | 50.0 | 49.1 | 60.0 | 43.5 | 54.0 | 50.0 | 306.6 |

marked by elevated temperatures and a rainfall deficit, especially in May and June. In 2019, air temperatures generally exceeded long-term averages, except in July (18.5°C). That year was also notably dry, with only May showing above-average rainfall. The 2020 season featured precipitation levels close to historical norms (312.4 mm) and slightly higher-than-average temperatures, making it the most favorable year in terms of hydrothermal conditions. To evaluate thermal and moisture conditions, the Selyaninov's hydrothermal coefficient (K) was calculated according to the classification by Skowera (2014) – Table 3.

Table 3

Selyaninov's hydrothermal coefficient (K) in the years of research (Zawady Meteorological Station in Poland)

| Months | Years | | |
|---|---|---|---|
| | 2018 | 2019 | 2020 |
| April | 0.88 | 0.20 | 0.23 |
| May | 0.52 | 1.44 | 1.74 |
| June | 0.57 | 0.67 | 2.05 |
| July | 1.06 | 0.51 | 1.15 |
| August | 0.86 | 0.71 | 0.29 |
| September | 1.69 | 0.41 | 0.83 |
| April-September | 0.93 | 0.66 | 1.05 |

K = 10 P/ Σt, Skowera et al. (2014), where: P – the sum of the monthly rainfalls in mm, Σt – monthly total air temp. > 0°C Ranges of values of this coefficient were classified as follows: up to 0.4 – extremely dry, 0.41-0.7 – very dry, 0.71-1.0 – dry, 1.01-1.3 – relatively dry, 1.31-1.6 – optimal, 1.61-2.0 – relatively humid, 2.01-2.5 – humid, 2.51-3.0 – very humid, above 3.0 – extremely humid.

## RESULTS AND DISCUSSION

The results of the study demonstrated a significant effect of the type of a nozzle used on the content of phosphorus in potato tubers (*Solanum tuberosum* L.). The highest values of phosphorus was recorded in plots where the Hypro 3D nozzle was applied, while the lowest were noted in variants with the hollow cone nozzle. The average phosphorus content in potato tubers ranged from 2.482 to 2.699 g kg$^{-1}$ DM (Table 4).

The highest concentration potassium was obtained in the control object, and the lowest one – in the flat fan nozzle variant. The analysis showed that among the types of nozzles used, the 3D Hypro nozzles had the greatest effect on the macronutrient content in potato tubers, with the highest potassium content recorded under their application. Differences between cultivars and the cultivar × year interaction were not statistically significant, whereas the effect of the research year proved to be significant, which may be associated with varying weather conditions during the respective growing seasons. The effectiveness of the Hypro 3D nozzle may be attributed to more uniform leaf surface coverage and higher spray deposition efficiency. As noted by Smith et al. (2000), spray efficacy depends both on droplet size and the characteristics of the treated surface. Smaller droplets generated by cone and 3D nozzles improve surface coverage, especially under favourable weather conditions, enhancing nutrient uptake after foliar application, as also reported by Hilz and Vermeer (2013). Potassium content in potato tubers varied between 24.235 and 28.856 g kg$^{-1}$ DM (Tab. 5).

Table 4

Phosphorus (P) content in tubers of *Solanum tuberosum* (g kg$^{-1}$ D.M.)

| Variant | Year | | | Mean |
|---|---|---|---|---|
| | 2018 | 2019 | 2020 | |
| Jurek | | | | |
| Control object | 2.558 | 2.644 | 2.464 | 2.555 |
| Flat fan nozzle | 2.492 | 2.618 | 2.398 | 2.502 |
| Hollow cone nozzle | 2.364 | 2.685 | 2.270 | 2.439 |
| Hypro 3D nozzle | 2.702 | 2.584 | 2.608 | 2.631 |
| Mean | 2.529 | 2.632 | 2.435 | 2.532 |
| Finezja | | | | |
| Control object | 2.556 | 2.783 | 2.462 | 2.600 |
| Flat fan nozzle | 2.371 | 2.750 | 2.277 | 2.466 |
| Hollow cone nozzle | 2.338 | 2.674 | 2.244 | 2.418 |
| Hypro 3D nozzle | 2.624 | 2.860 | 2.530 | 2.671 |
| Mean | 2.472 | 2.766 | 2.378 | 2.538 |
| Mean for varieties | | | | |
| Control object | 2.557 | 2.713 | 2.463 | 2.575 |
| Flat fan nozzle | 2.431 | 2.684 | 2.337 | 2.484 |
| Hollow cone nozzle | 2.351 | 2.679 | 2.257 | 2.428 |
| Hypro 3D nozzle | 2.663 | 2.722 | 2.569 | 2.651 |
| Mean | 2.500 | 2.699 | 2.482 | 2.535 |
| $LSD_{0.05}$ for: * ns – cultivars, objects-0.13, years-0.168, interaction: cultivars x years-ns | | | | |

The highest average values were observed in 2019 and the lowest in 2018. The use of the Hypro 3D nozzle ensured the highest potassium content, while the cone nozzle produced the lowest results. The increased potassium content in the dry season of 2019 may be related to its role in osmoregulation and plant adaptation to drought stress, as emphasized by Wierzbicka and Trawczyński (2011), and Wierzbowska et al. (2015). The variability of this element under changing environmental conditions confirms its role in plant water management. Statistically significant differences between the cultivars were found only for potassium content, in agreement with Zarzecka et al. (2015) and Wierzbicka and Trawczyński (2011), who highlighted the importance of genotypic traits in nutrient uptake, especially for elements that are mobile or responsive to environmental fluctuations. The average magnesium content in tubers was 0.525 g kg$^{-1}$ DM – Table 6.

The highest levels were recorded in the Hypro 3D nozzle variant, and the lowest ones were in the control treatment. Differences between the cultivars were not significant, but both the year and the nozzle type had a statistically significant effect on the magnesium content. The highest values were

Table 5

Potassium (K) content in tubers of *Solanum tuberosum* (g kg$^{-1}$ DM)

| Variant | Year | | | Mean |
|---|---|---|---|---|
| | 2018 | 2019 | 2020 | |
| Jurek | | | | |
| Control object | 24.975 | 29.467 | 26.960 | 27.134 |
| Flat fan nozzle | 25.306 | 28.180 | 24.917 | 26.134 |
| Hollow cone nozzle | 23.622 | 29.473 | 27.003 | 26.699 |
| Hypro 3D nozzle | 25.695 | 30.283 | 27.020 | 27.666 |
| Mean | 24.899 | 29.350 | 26.475 | 26.908 |
| Finezja | | | | |
| Control object | 24.901 | 29.493 | 26.230 | 26.874 |
| Flat fan nozzle | 24.829 | 26.190 | 23.243 | 24.754 |
| Hollow cone nozzle | 22.383 | 29.113 | 24.797 | 25.411 |
| Hypro 3D nozzle | 22.176 | 28.660 | 25.697 | 25.511 |
| Mean | 23.572 | 28.364 | 24.991 | 25.637 |
| Mean for variaties | | | | |
| Control object | 24.938 | 29.475 | 26.590 | 27.001 |
| Flat fan nozzle | 25.067 | 27.185 | 24.080 | 25.444 |
| Hollow cone nozzle | 23.002 | 29.293 | 25.900 | 26.065 |
| Hypro 3D nozzle | 23.935 | 29.471 | 26.358 | 26.588 |
| Mean | 24.235 | 28.856 | 25.637 | 26.274 |
| $LSD_{0.05}$ for: cultivars – 1.03, objects – 0.93, years –1.07, interaction: objects x years – 1.61 | | | | |

noted in the 2019 season, suggesting more favourable conditions for magnesium uptake during that year and possibly an increased role of this element under environmental stress conditions, similarly to potassium.

Calcium content remained relatively stable across the years, with a mean value of 0.387 g kg$^{-1}$ DM (Table 7).

The highest content was observed with the use of the Hypro 3D nozzle, and the lowest one was in the control plots. Although differences between the cultivars were minimal, statistically significant interactions were found between the spray application technology and the year of study. The relative stability of the calcium content may indicate lower sensitivity of this element to variable weather conditions compared to potassium and magnesium. The application of the Hypro 3D nozzle resulted in the highest increase in the concentration of all analysed macronutrients. The finer droplet size and more uniform spray deposition support more effective foliar nutrient uptake, as reported by Hilz and Vermeer (2013). Although the use of flat-fan nozzles also positively affected mineral composition in tubers compared to the control (mechanical cultivation), their efficiency was lower than that of the Hypro 3D nozzle. Similar observations were made by Mona et al. (2012),

Table 6

Magnesium (Mg) content in tubers of *Solanum tuberosum* (g kg$^{-1}$ DM)

| Variant | Year | | | Mean |
|---|---|---|---|---|
| | 2018 | 2019 | 2020 | |
| Jurek | | | | |
| Control object | 0.461 | 0.614 | 0.393 | 0.489 |
| Flat fan nozzle | 0.481 | 0.711 | 0.383 | 0.525 |
| Hollow cone nozzle | 0.465 | 0.734 | 0.376 | 0.525 |
| Hypro 3D nozzle | 0.535 | 0.729 | 0.429 | 0.564 |
| Mean | 0.485 | 0.697 | 0.395 | 0.525 |
| Finezja | | | | |
| Control object | 0.444 | 0.711 | 0.368 | 0.507 |
| Flat fan nozzle | 0.473 | 0.715 | 0.375 | 0.521 |
| Hollow cone nozzle | 0.458 | 0.693 | 0.360 | 0.503 |
| Hypro 3D nozzle | 0.552 | 0.741 | 0.435 | 0.572 |
| Mean | 0.480 | 0.715 | 0.384 | 0.525 |
| Mean for varieties | | | | |
| Control object | 0.452 | 0.662 | 0.380 | 0.498 |
| Flat fan nozzle | 0.477 | 0.713 | 0.379 | 0.523 |
| Hollow cone nozzle | 0.461 | 0.713 | 0.368 | 0.514 |
| Hypro 3D nozzle | 0.543 | 0.735 | 0.432 | 0.570 |
| Mean | 0.483 | 0.705 | 0.389 | 0.525 |
| $LSD_{0.05}$ for: * ns – cultivars, objects – 0.02, years – 0.02 | | | | |

who found that foliar fertilization with urea increased the nitrogen, phosphorus, and potassium content in potato tubers. Karlsson et al. (2006) confirmed that fertilizers containing calcium significantly enhance its accumulation in tubers. Additionally, Sayinci and Bastaban (2011) reported that dual-spray and injector nozzles showed the lowest coefficient of variation and the most effective coverage of the middle part of potato plants, while cone nozzles were the least effective in delivering spray to the lower leaf surface, potentially reducing their efficiency. Another important issue is the impact of a herbicide application technology on mineral nutrient uptake. Gugała et al. (2015) found that plant protection treatments could increase the total nitrogen content but reduce potassium and phosphorus levels. In the present study, higher concentrations of these macronutrients were recorded in treatments involving more technologically advanced nozzles, suggesting that a precise spray technology may act as an alternative or supplement e.g. to biostimulants. Our results clearly indicate that advanced nozzles significantly influence macronutrient content in potato tubers. This effect is likely also linked to more effective weed control, as weeds compete with the crop for available mineral nutrients.

Table 7

Calcium (Ca) content in tubers of *Solanum tuberosum* (g kg$^{-1}$ DM)

| Variant | Year | | | Mean |
|---|---|---|---|---|
| | 2018 | 2019 | 2020 | |
| Jurek | | | | |
| Control object | 0.379 | 0.425 | 0.389 | 0.397 |
| Flat fan nozzle | 0.380 | 0.316 | 0.348 | 0.348 |
| Hollow cone nozzle | 0.377 | 0.391 | 0.351 | 0.373 |
| Hypro 3D nozzle | 0.437 | 0.462 | 0.402 | 0.433 |
| Mean | 0.393 | 0.398 | 0.372 | 0.387 |
| Finezja | | | | |
| Control object | 0.346 | 0.376 | 0.366 | 0.362 |
| Flat fan nozzle | 0.375 | 0.365 | 0.374 | 0.371 |
| Hollow cone nozzle | 0.382 | 0.388 | 0.355 | 0.375 |
| Hypro 3D nozzle | 0.454 | 0.450 | 0.425 | 0.443 |
| Mean | 0.389 | 0.394 | 0.380 | 0.387 |
| Mean for varieties | | | | |
| Control object | 0.362 | 0.400 | 0.377 | 0.379 |
| Flat fan nozzle | 0.377 | 0.340 | 0.361 | 0.359 |
| Hollow cone nozzle | 0.379 | 0.389 | 0.353 | 0.373 |
| Hypro 3D nozzle | 0.445 | 0.455 | 0.419 | 0.439 |
| Mean | 0.390 | 0.396 | 0.377 | 0.387 |
| LSD $_{0.05}$ for: cultivars – ns, objects – 0.01 years – 0.2, interaction: cultivars x objects – 0.03, objects x years – 0.03 | | | | |

In conclusion, the results clearly indicate that a nozzle type plays a crucial role in the effectiveness of foliar treatments and in shaping the mineral composition of potato tubers. The application of the Hypro 3D nozzle proved particularly beneficial, supporting its use as a technology that enhances crop quality by improving the uptake efficiency of macronutrients. These findings are consistent with report by Shanwaz et al. (2018), who emphasized that effective foliar fertilization improves nutrient availability by increasing photosynthetic activity and enhancing soil nutrient uptake.

## CONCLUSIONS

The type of a sprayer nozzle significantly influenced the content of phosphorus calcium and magnesium in potato tubers, with the highest efficiency achieved using the Hypro 3D nozzle. Potato tubers sprayed with Hypro 3D nozzles exhibited the highest levels of phosphorus, calcium, and magnesium, indicating a beneficial effect of the spatial distribution of the working fluid on the treatment efficacy. Treatments employing flat-fan nozzles also contributed to increased magnesium content compared to the control (mechanical weeding), although they were less effective than Hypro 3D nozzles. Variability in meteorological conditions during the study years had a significant impact on the macroelement content in tubers, particularly potassium and magnesium, highlighting the importance of environmental factors in mineral nutrient accumulation. Potato cultivar significantly affected only the potassium content in tubers, confirming the role of genotypic traits in the plant's mineral management. The results indicate that appropriate selection of the working fluid application technology, including the type of nozzle, can enhance the nutritional value of potatoes by increasing the content of essential macroelements.

### Author contributions

M.G. – conceptualization, M.G. K.Z. P.F. – methodology, E.Rz. M.G. – formal analysis, E.Rz. – writing-original draft preparation, visualization, Ł.D – editing. All authors have read and agreed to the published version of the manuscript.

### Conflicts of interest

The authors declare no conflict of interest.

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