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ORIGINAL PAPER

Optimization of struvite application in stagnant hydroponic in tomato cultivation*

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Abstract

The aim of the study was to determine the effect of nutrient solution with different pH values on the yield and nutritional status of tomato plants cultivated in stagnant hydroponics using struvite. The plants were fertilized with a standard nutrient solution at different pH values: 4.5, 5.5 and 7.0 and control. The pH value of the nutrient solution and the type of phosphorus fertilizer applied significantly influenced the tomato yield of the Maskotka variety. The yield of was not dependent on the pH of the nutrient solution or the type of phosphorus fertilizer applied. However, the type of phosphorus fertilizer and the pH of the nutrient solution had a significant impact on the nutritional status of the plants. Despite the considerable variation in the average concentrations of mineral nutrients in the tomato leaves, the growth and development of the plants were normal, both in the roots and the fruits. The average content of available phosphorus in the fruits depended on the factors studied, such as pH, phosphorus fertilization, and the sampling time. In the second sampling period, the application of struvite resulted in a significant increase in its content under all tested pH values. The content of available phosphorus in the leaves was significantly highest at a pH of 5.5, while in the roots, the effect of this factor was not significant. The effect of struvite was particularly manifested with respect to the nutrient content. Its presence in the roots was strongly dependent on the type of phosphorus fertilizer used, with struvite causing a significant decrease compared to superphosphate (SUP). In contrast, struvite had a positive impact on the available magnesium content in the fruits. During the second sampling period, a statistically significant increase in magnesium was observed across all tested conditions when struvite was applied. This highlights the distinct influence of struvite on magnesium dynamics in different plant parts.

Keywords: nutrient solution, pH values, struvite, tomato yield

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INTRODUCTION

Phosphorus (P) fertilization plays a key role in sustaining the growing demand for agricultural production. It is also one of the most limiting nutrients for crop yields and quality. Phosphorus is needed in large quantities, as are nitrogen (N) and potassium (K – Nenova et al. 2019). The prospect of depleting phosphate deposits has prompted a search for alternative sources of this element (Antonkiewicz, Łabatowicz 2016).The use of struvite as a phosphate fertilizer is a promising method of recovering this valuable component from organic waste (Behjat et al. 2024). Struvite ($MgNH_4PO_46H_2O$) constitutes an alternative to conventional P fertilization and allows us to solve three problems: P deficiency, pollution of soil and surrounding environment. Struvite has a theoretical P content close to that of phosphate rock (12.6% dry weight (DW), and has been shown to be an effective P fertilizer also in hydroponics (Arcas-Pils et al. 2021, 2022). A defining characteristic of struvite is its low solubility in water. This property contributes to its classification as a slow-release fertilizer (Rahman et al. 2014).

Despite representing a relatively minor share of total global agricultural production, hydroponic cultivation holds considerable significance in the production of high-value vegetables and fruits, including lettuce, tomatoes, and herbs (Asao, 2012, Goh et al. 2023). In hydroponics, it is imperative that nutrients be supplied in precise proportions to ensure that plants are provided with all the necessary substances for optimal growth and development. Hydroponic cultivation allows obtaining good quality products more reliably than in conventional systems. Advantages of this system include high crop quality and yield, lower fertilizer expenses and more efficient use of water, as well as reduced environmental pollution and greater control and efficiency of the production process (Logendra et al. 2001).

In order for hydroponics to function properly, a rigorous approach to the composition of hydroponic nutrient solutions is required. Roots need to continuously develop in order to reach new soil sectors that are rich in phosphorus. Additionally, this process can be supported by proper control of the nutrient solution. It is vital that not only the nutrient composition, but also the solubility of individual nutrients must be considered. A review of the literature on struvite reveals that, under specific conditions, it can yield outcomes that are comparable to those of conventional fertilizers. However, the low solubility of struvite (0.23 g L^{-1} at 20°C) poses a significant challenge, as it limits the availability of phosphorus and magnesium to plants cultivated in hydroponics (Hofmann et al. 2024). Due to the scarcity of research on the solubility of struvite, which may be a promising source of phosphorus in hydroponics, it is important to focus on this challenge. The available research indicates that the focus should be on pH, as fluctuations in this parameter affect the solubility of struvite (Arcas-Pilz et al. 2022). Changes in pH influence not only the solubility of phosphorus. To guarantee optimal nutrient accessibility, it is essential to assess the solution's pH range and subsequently adjust it through the addition of a buffer. This approach allows us to maintain a balanced ionic environment conducive to optimal plant growth (Bergstrand et al. 2020, Malkawi et al. 2024).

Based on the research, greenhouse hydroponics is a technique that produces the largest quantities of tomatoes per unit area, resulting in higher productivity (Magaña-Lira et al. 2013). The environmental conditions under which tomatoes are grown vary and include field crops, greenhouse crops and small plantations in home gardens (Cela et al. 2024).

A review of the existing literature shows that there are insufficient data on how the pH of nutrient solutions affects plants grown in soilless culture systems, especially with struvite. An unresolved issue in hydroponic tomato cultivation is the use of struvite as a phosphorus source and its effects on the qualitative and quantitative traits of tomatoes. Specifically, the potential of struvite as a raw material in fertigation for the preparation of nutrient solutions remains unexplored. Given the limited research on the application of struvite in hydroponic systems, drawing definitive conclusions on its efficacy and impact is currently challenging (Carreras-Sempere et al. 2021).

The hypothesis of the study is that the use of struvite in hydroponic systems, while maintaining optimal pH, will be able to replace other phosphorus fertilizer and the yield will be comparable to conventional phosphorus fertilizers. The study evaluated the efficiency of struvite (Crystal Green) in tomato production compared to traditional phosphorus fertilizers, focusing on yield, fruit quality, biomass, and nutrient uptake (P and N).

MATERIALS AND METHODS

GREENHOUSE CONDITIONS

The experiment was conducted at the Research and Education Station in Psary, belonging to the Department of Horticulture at Wroclaw University of Environmental and Life Sciences., Wroclaw University of Life Sciences (51.19° N, 17.03° E). The experiment lasted from June to September 2023 and consisted of two series. The study was conducted during the summer months, starting with the preparation and sowing of tomato seeds and continuing through planting, hydroponic cultivation, and harvest. The microclimatic conditions in the greenhouse were controlled and maintained at: day temperature: 24 ± 1.0°C, night temperature: 16 ± 1.0°C, relative humidity: 40-50%, light daily.

The tomato (*Solanum lycopersicum* L.) variety used in the experiment was cv. Maskotka (an old variety, very popular for container and soilless cultivation, highly productive, with abundant tasty fruits), a determinate, dwarf variety that is characterized by its compact growth form and suitability for cultivation in containers. This cultivar is distinguished by its high yield potential, producing small to medium-sized fruits with a vibrant red coloration and a superior flavor profile. The cultivar's attributes, including its relatively brief growth cycle and its capacity to thrive in controlled environmental conditions, have promoted its frequent utilization in experimental settings involving greenhouse and hydroponic systems.

The examined factors in the experiment were: 1) pH of the solution – 4.5, 5.5 and 7.0; 2) different phosphorus fertilizers and doses – superphosphate and struvite (phosphorus fertilization, conventional phosphorus fertilizer, and struvite, marketed as Crystal Green), 3) three date sampling of plant material (leaves, roots and fruit): BBCH 79, BBCH 83 and BBCH 99. The total number of plants were 162. On the first two sampling dates, only fruits were collected for analysis, while on the final sampling date, fruits, leaves, and roots were collected. The chemical composition of nutrient solution was presented in Table 1.

The Ca to P ratio is 2.9:1, indicating almost three times more calcium than phosphorus. The Ca to Mg ratio is 2.06:1, with calcium being twice as abundant as magnesium. The K to Mg ratio is 6.21:1, showing potassium is over six times higher than magnesium. The K to Ca ratio is 3:1, meaning

Table 1

Chemical composition of the Hoagland nutrient solution according used in the experiment

Traits characterization	Unit	Content
pH	-	4.0 5.5 7.0
EC	mS cm^{-1}	1.70-1.80
N	Mmol dm^{-3}	12.49
NO_{-3}		2.98
P-		0.73
PO_4^{-3}		0.24
K^+		6.39
Ca^{+2}		2.12
Mg^{+2}		1.03
Na^+		0.67
Cl^-		0.76
SO_4^{-2}		0.77
Fe		0.02
Mn		0.01
Cu		0.001
Zn		0.005
B		0.03

potassium is three times more than calcium. The K to N ratio is 9.5:1, indicating potassium is nearly ten times higher than nitrogen. The K to (Ca + Mg) ratio is 2.03:1, showing potassium is twice as much as the combined calcium and magnesium. These ratios highlight the dominance of potassium and the greater abundance of calcium compared to phosphorus and magnesium in the nutrient solution.

The hydroponic technique employed in the present experiment was that of a stagnant culture. This is a soilless cultivation method in which plants are grown in containers containing a static nutrient solution, which is not continuously circulated. The pots were filled with the nutrient solution (chemical composition above) The amount of fertilizers applied throughout the entire crop cycle was determined by weighing each fertilizer source used to prepare the nutrient solution (NS). During the growing period, the volume of nutrient solutions was maintained at a constant level by addition of deionized water. Each plant received the required nutrient solution, with a dose of 150-300 ml per plant. The amount of water added was 150-200 ml, and was replenished as needed due to water loss. Greater water losses were observed in the later developmental stages of the plants.

Tomato seeds were sown into plugs filled with mineral wool and micronutrients. The seedlings grew to the stage of several leaves and were then transplanted into containers with the nutrient solution. Afterwards, the seedlings were transplanted into the hydroponic system at the four-leaf stage (BBCH 14). The pots were covered with Styrofoam to hold in place plastic mini-pots with tomatoes and their loosely hanging root systems, which were submerged in the nutrient solution. The pH levels of the nutrient solution were regulated by the addition of diluted hydrochloric acid (HCl) or sodium hydroxide (NaOH) to establish target values. A control group consisted of plants irrigated with untreated water, where no pH modification was implemented. The experiment was conducted for 108 days (around 4 months). The experiment started at the beginning of April 2023 and ended at the beginning of July 2023. At the end of the experiments, the plant organs (leaves, roots, fruits) were harvested.

Biometric measurements

The roots, shoots, and fruits of the plants were harvested individually. Measurements were taken on six plants per treatment combination. Biometric measurements of the test plant were taken, including the biomass and the number of leaves of the test plant. The fresh biomass (g) was calculated as the average value from 6 plants. The dry biomass weight was measured by drying the samples (with a specific weight of 200–300 g of fresh mass) at 60°C for 48 h, followed by drying them at 105°C for 4 hours. Additionally, the number of leaves on each plant was counted and, at the end of the plant growing period, the fruit fresh yield weight was measured at each experimental site. For nutrient analysis, leaves, roots and fruit samples were dried in an oven at 60°C, while fruit samples were dried at 80°C for up to one week or until no further weight changes were detected. Dry matter (DM) determination was performed by drying plant organ materials in an oven at 105°C (OECD 2005). The plant tissues were then pulverized in an electric centrifugal mill with different sieve sizes, where leaves were ground using a 0.25 mm sieve and fruits – with a 0.5 mm sieve.

Chemical analysis of plant material

After the fresh biomass was determined, the leaves, root and fruits were chopped for analysis. The chemical analyses were conducted in a laboratory at the Horticulture Department of Wroclaw University of Environmental and Life Sciences. Available nutrient content in tomato was assessed after extraction with acetic acid (0.03 M). Phosphorus, magnesium, and nitrate nitrogen content in the plant material was determined colorimetrically: phosphorus was measured using ammonium vanadium molybdate, magnesium by the titanium yellow method, and nitrate nitrogen ($N\text{-}NO3^-$) was measured using an ion exchange nitrate electrode, while potassium and calcium were determined by flame photometry on a Carl Zeiss Jena, 1888325, 10/2603 apparatus (Komosa 2000). The total content of macroelements was determined in the Center for Environmental Quality Analysis, Wroclaw University of Environmental and Life Sciences. The plant material was subjected to dry mineralization. The resulting ash was dissolved in a mixture of nitric acid (HNO_3) and sulfuric acid (H_2SO_4), the solution was made up to 50 ml with distilled water, and subsequently filtered through hardened filter paper. As the samples had been prepared prior to analysis, certified reference materials (CRMs) in an aqueous solution were used to verify the accuracy of the instrument readings. These were Anitepo, Ontario-12, lot 0523 (for Mg, K and Ca) and ERA, catalogue no. 1349, lot 350922M (for P).

Statistical analysis

The chemical analysis data were processed using Statistica software (version 13.1, StatSoft, Poland) with a significance level set at α=0.05. To assess the impact of pH, phosphorus fertilizers and the dates of sampling on the chemical properties plant, one-way, two-way and three-way analyses of variance were performed. Since the data did not follow a normal distribution, nonparametric tests and correlation analyses were applied. To examine the relationships between the examined factors and elements, a decision tree was constructed using the C&RT method for recursive partitioning. This technique iteratively divides the dataset into two parts, aiming to minimize heterogeneity within each subset. The comprehensive C&RT method evaluates all potential splits among the available variables and divides the data based on one of the predictors, forming new sets with similar characteristics. The process continues until a stopping criterion is reached. In the decision tree diagrams, “Id” represents the node identification number, “N” stands for node abundance, “Ave” refers to the average value for the analyzed variable, and “Var” indicates the variance of the variable. The further subdivisions are shown visually below (Figure 1), with the splitting variable highlighted on the green horizontal line and its corresponding values displayed above the node block. Nonparametric tests were also used to calculate the average values of parameters and their associated p-values

RESULTS AND DISCUSSION

Tomato cultivation in a hydroponic system using struvite fertilizer was conducted in this study to examine and compare the yields fertilized with this type of fertilizer with traditional one as well as chemical composition of leaves, fruit and roots of tomato. The choice of roots as a study material was motivated by the fact that plants absorb and transport nutrients from the roots to the vascular system (the xylem and phloem) and are redistributed throughout the plant, with developing organs like leaves, flowers, and fruits having the highest nutrient demands. In hydroponic cultivation, where plants are grown in nutrient solution with added nutrients, precise control of pH is crucial to ensure proper plant growth. The pH of nutrient solution affects how well plants can absorb mineral elements that are essential for their healthy development.

*The effect of struvite on the **content of total elements** in the fruit in tomato hydroponics cultivation*

The factor that differentiated the **magnesium** content of the fruit is the date of sampling, with the highest content of this element achieved on the third date compared to the others. Mg content on the third date of sampling was differentiated by phosphorus fertilization. The double dose of struvite on the third application date resulted in the highest content of total magnesium in the fruit. In contrast, fertilization also varied the Mg content in fruit at the other dates. When fertilizing with superphosphate and struvite at the other dates, pH divided the samples. The lowest content of total Mg in the fruit was observed under pH 7.0 compared to the other combinations. With pH 4.0 and 5.5, this factor again led to higher Mg accumulation. The last-order factor was fertilization, where struvite proved to be the most beneficial (Figure 1).

The predominant factor affecting the total **potassium** content in tomato fruits was the pH of the solution. Higher potassium levels were found at a pH of 7 compared to the other pH levels. Within the pH of 7.0, the factor dividing the potassium content in the fruits was phosphorus fertilization. The most beneficial was phosphorus fertilization in the form of struvite

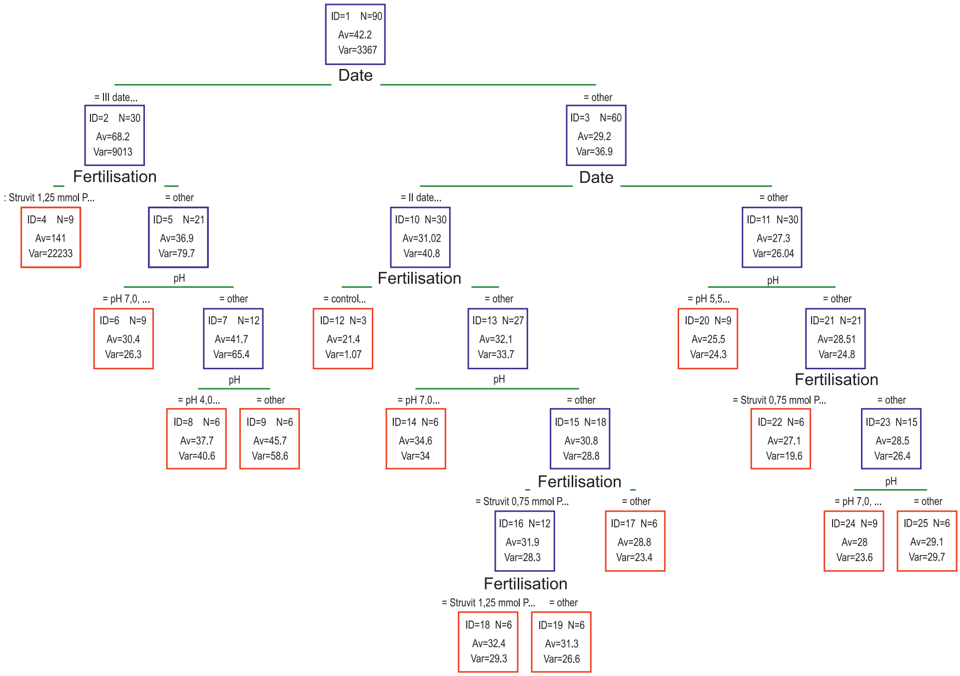


Fig. 1. The effect of struvite on the total content of Mg in tomato fruit in hydroponics cultivation

applied at a higher dose, compared to the smaller dose and superphosphate. For the smaller doses of struvite and superphosphate, the factor dividing the potassium content was the timing of fruit sampling for analysis. In the last sampling period, after the growing season ended, the total form content was lower compared to the other periods. The timing of the tomato fruit harvest was also a secondary factor. The second part of the diagram covers lower pH values, such as pH 7.0, which were influenced by the timing of fruit sampling. Higher potassium levels were observed in the first and third sampling periods compared to the last one. Within the sampling periods with a higher potassium content, the factor dividing the potassium content was the hydroponic system's pH, while in the last period (after the growing season), phosphorus fertilization played the dividing role. Within fertilization, the factor dividing the potassium content was again pH, which depended on phosphorus fertilization (Figure 2).

The predominant factor affecting the **calcium** content in the fruits was the pH of the nutrient solution. Higher calcium levels were found at alkaline pH, where the next-order factor was phosphorus fertilization. When struvite was applied at a lower dose and superphosphate, the next-order factor was the timing of sample collection. In the first two sampling periods, the calcium content in the fruits was higher than in the last period. Within this part of the diagram, the secondary factor was the timing of the fruit sample

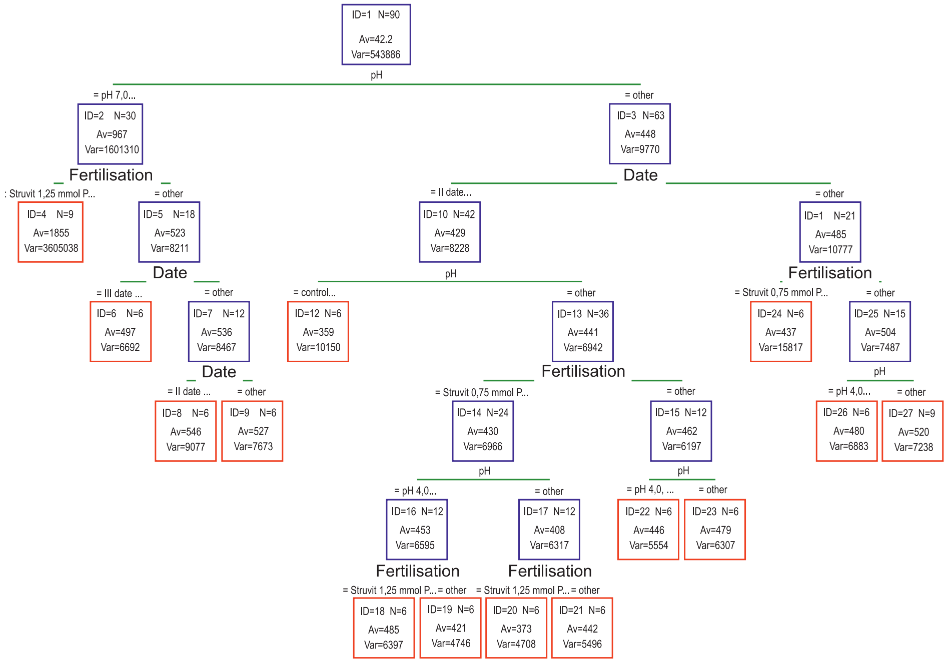


Fig. 2. The effect of struvite on the total content of potassium in tomato fruit in hydroponics cultivation

collection for chemical analysis. On the other side of the diagram, more calcium was found in the first and third sampling periods. In the second sampling period, the factor dividing the content was the pH of the solution, while in the other periods, phosphorus fertilization played the dividing role. More phosphorus was found when using struvite at a double dose and superphosphate, and within this factor, the last dividing factor was the pH of the solution. In the second sampling period, phosphorus fertilization contributed to a higher calcium content in tomato fruits compared to the control. The secondary factor was phosphorus fertilization, with its content depending on the pH of the solution (Figure 3).

A significant effect of the solution's pH on the total **phosphorus** content in tomato fruits was observed. The highest phosphorus content was found at a pH of 5.5, while the lowest was at a pH of 7.0. Phosphorus fertilization also had a significant impact on the phosphorus content in tomato fruits, with higher levels observed in the SUP fertilization (Figure 4). The total phosphorus content in the fruit decreased significantly as the growing season progressed (Figure 4).

The magnesium content in the fruits varied depending on the fertilization and pH level. A significant increase in the magnesium content in the fruits was observed with the use of superphosphate at a pH of 5.5, while a decrease was noted with struvite. Conversely, the opposite trend was observed at pH levels of 7.0 and 4.0 compared to control (Figure 5.)

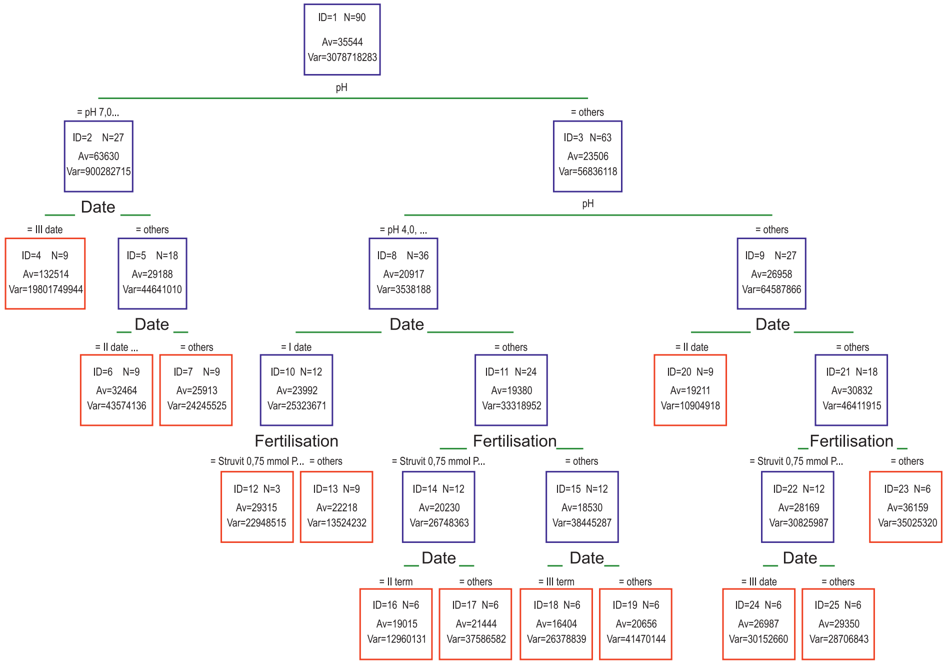


Fig. 3. The effect of struvite on the total content of calcium in tomato fruit in hydroponics cultivation

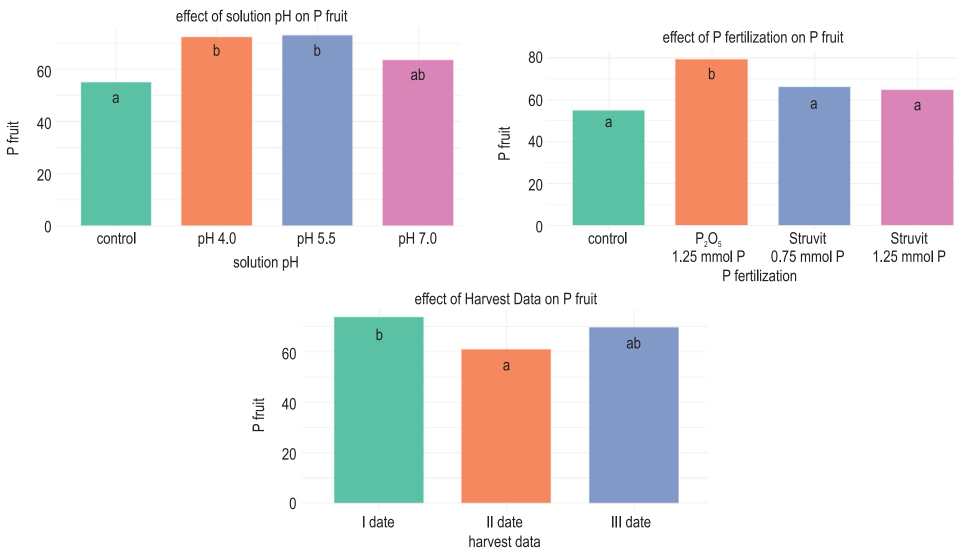


Fig. 4. Impact of nutrient solution's pH and phosphorus fertilization on total phosphorus content in tomato fruits throughout the growing season

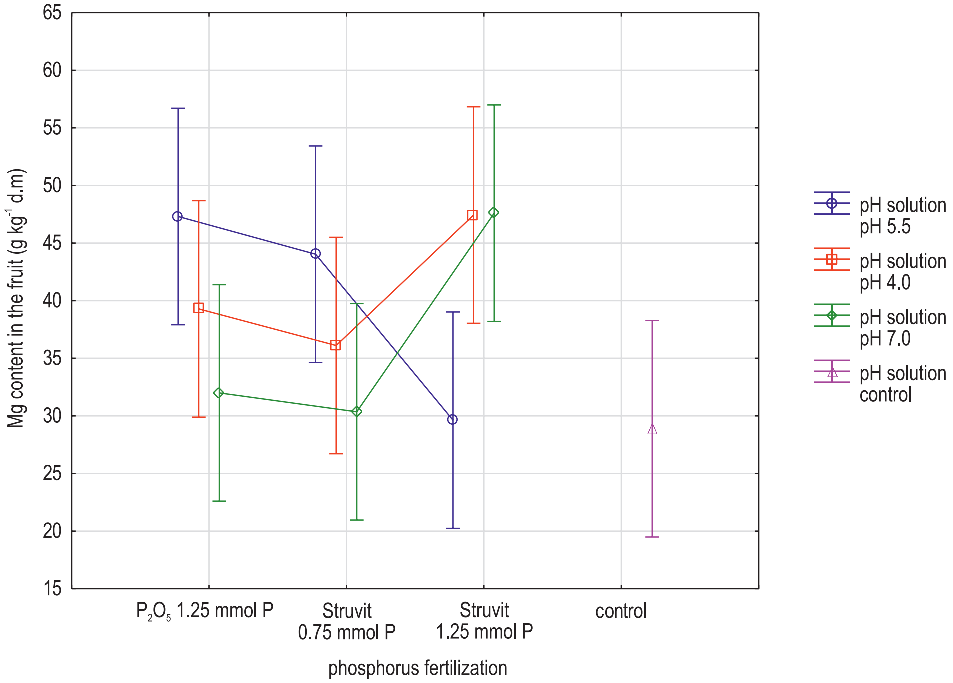


Fig. 5. The interaction of phosphorus fertilization and reaction on the content of the total magnesium in the fruit in hydroponics cultivation (p=0.00)

The potassium content in tomato fruits varied depending on the pH level and fertilization. The application of struvite at pH 5.5 resulted in a decrease in its content, while at pH 4.0 and 7.0, an increase was observed compared to the control and superphosphate (Figure 6).

Both phosphorus fertilization and the pH of the solution significantly affected the calcium content in tomato fruits. At a pH of 5.5, fertilization with struvite led to a significant decrease in its content, while the opposite trend was observed at the other tested pH levels (Figure 7).

The effect of struvite on the content of ***available elements in the fruit*** *in tomato hydroponics cultivation*

An important interaction between the studied factors was observed, considering the content of available magnesium in the fruits. It is clearly evident that the available magnesium content increased in the second sampling period at all tested pH levels with the application of struvite, both in smaller and larger doses. However, in the third sampling period, at pH levels 5.5 and 7.0, the use of a reduced struvite dose led to a decrease in the content of this element, while the higher dose resulted in an increase (Figure 8). Regarding potassium, it is clearly evident that the content of available potassium was highest at the highest pH level in both the second and third sampling peri-

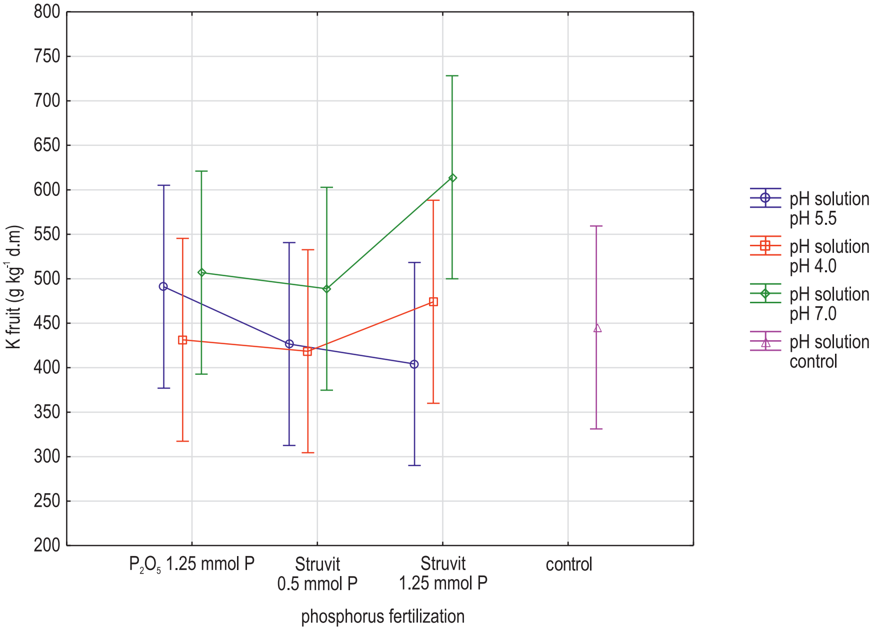


Fig. 6. The interaction of phosphorus fertilization and reaction on the content of the total potassium in the fruit in hydroponics cultivation (p=0.48)

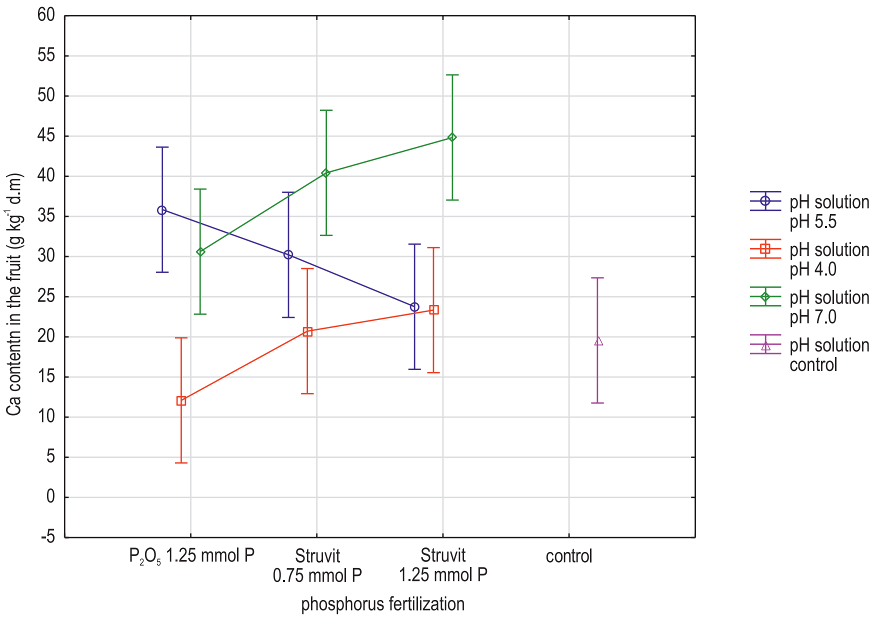


Fig. 7. The interaction of phosphorus fertilization and reaction on the content of the total calcium in the fruit in hydroponics cultivation (p=0.01)

ods. In the second period, at this pH level, the phosphorus content was higher under struvite fertilization compared to superphosphate fertilization and the control. In the first and third periods, fertilizing with a higher dose of struvite led to an increase in this element compared to the control. On the other hand, phosphorus content decreased under the influence of the studied factors in the subsequent sampling periods. In the second sampling period, the phosphorus content at the tested pH levels increased with the application of struvite, while decreasing in the third period.

The effect of struvite on the content of ***total elements in the leaves*** *in tomato hydroponics cultivation*

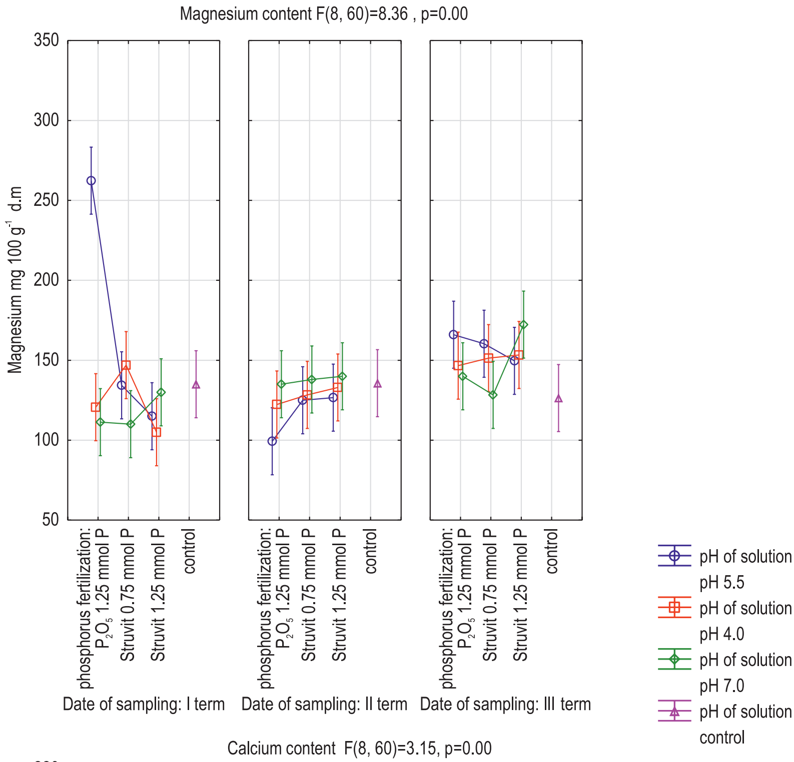
There were significant changes in the magnesium content taking into account pH of the solution as well as phosphorus fertilization. The highest content of magnesium was observed under pH of 5.5 and there was a decreasing tendency. Struvite in the lower doses contributed to a higher content of Mg in the leaves (Figure 9).

Significant changes in the phosphorus content were observed depending on the pH of the solution and phosphorus fertilization. The highest phosphorus content was recorded at a pH of 5.5 and 4.0, with a decreasing trend at the other pH level. Struvite applied in two doses contributed to a lower phosphorus content in the leaves compared to superphosphate (Figure 10).

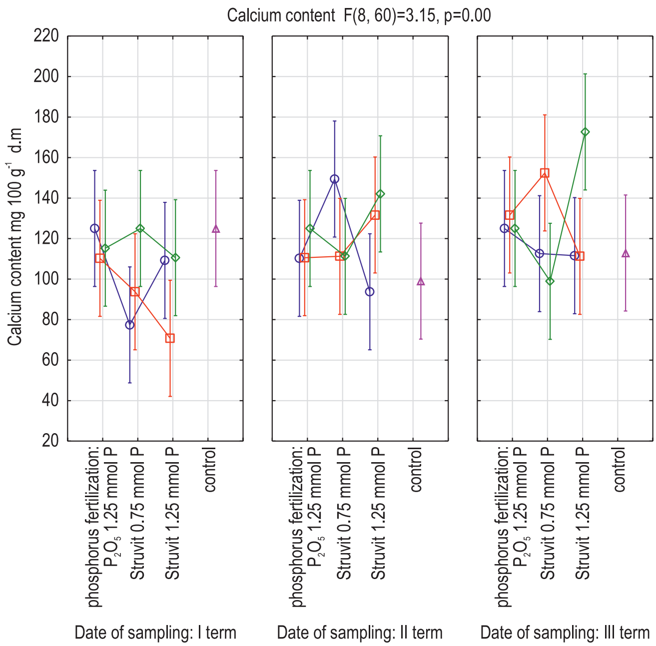
Only pH of solution differed the total potassium content in the leaves of tomato. The highest total potassium content in the leaves of tomato was found in the solution with the highest pH 7.0 (Figure 11).

The calcium content in the leaves of tomato depended significantly on phosphorus fertilization. Phosphorus fertilization caused a decrease in the content of this element in the leaves of tomato (Figure 12.)

In the present study, the **main nutrients,** both total and available elements, were significantly altered by the pH of the solution and fertilization treatments. The levels of Ca, P, K and Mg in the leaves were adequate with all fertilization treatments. On the one hand, the Mg levels were higher with phosphorus fertilization (struvite), probably because this fertilizer was richer in this element. Nurzyński et al. (1995) reported that a high pH in the root zone negatively impacted the phosphorus nutritional status of plants. As the pH of the nutrient solution increased, the phosphorus content in tomato plants decreased, with no significant difference observed between the pH levels of 5.5 and 6.0. This was also confirmed by Kowalczyk and Kaniszewski (2005). In the study of Alexopoulos et al. (2021), the leaf phosphorus (P) concentration decreased when the pH of the nutrient solution was raised to 7.0, which aligns with findings by Assimakopoulou (2006), who observed similar effects in spinach plants grown in high pH conditions. In our study, pH had no impact on P in the roots.



Magnesium content F(8, 60)=8.36 , p=0.00
Magnesium mg 100 g-1 d.m
350
300
250
200
150
100
50
phosphorus fertilization: P2O5 1.25 mmol P
Struvit 0.75 mmol P
Struvit 1.25 mmol P
control
Date of sampling: I term
Date of sampling: II term
Date of sampling: III term
pH of solution pH 5.5
pH of solution pH 4.0
pH of solution pH 7.0
pH of solution control



Calcium content F(8, 60)=3.15, p=0.00
Calcium content mg 100 g-1 d.m
220
200
180
160
140
120
100
80
60
40
20
phosphorus fertilization: P2O5 1.25 mmol P
Struvit 0.75 mmol P
Struvit 1.25 mmol P
control
Date of sampling: I term
Date of sampling: II term
Date of sampling: III term

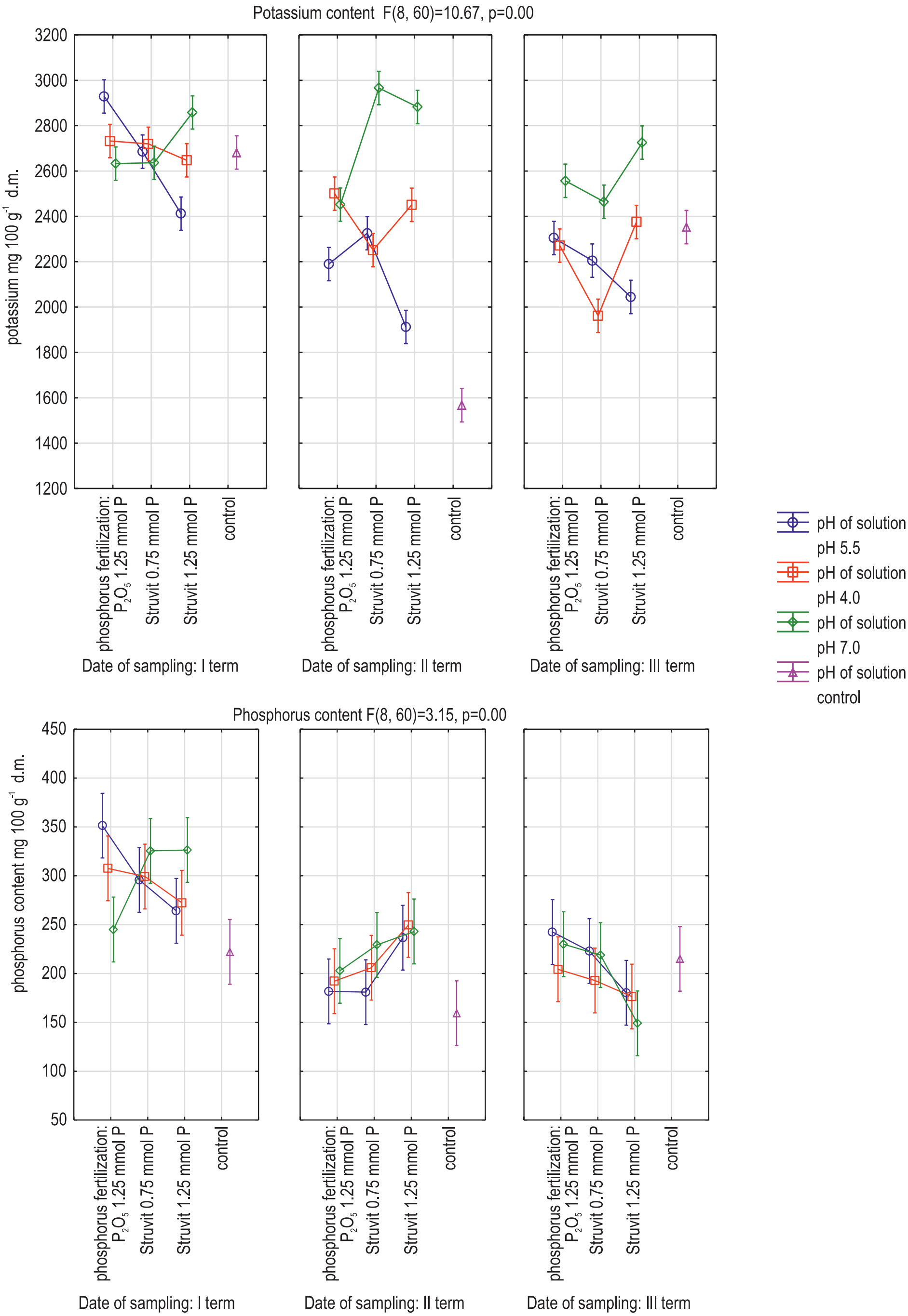


Fig. 8. The effect of struvite on the available content of selected elements in tomato fruit in hydroponics cultivation

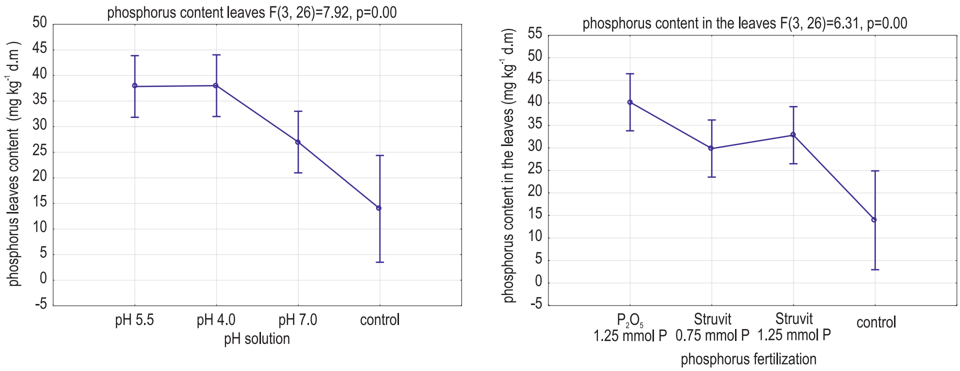


Fig. 9. The content of total magnesium in tomato leaves under struvite fertilization and different pH of the nutrient solution

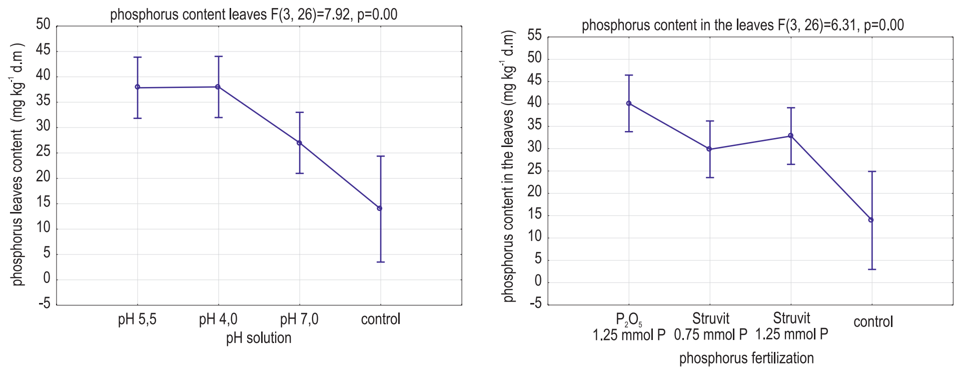


Fig. 10. The content of total phosphorus in tomato leaves under struvite fertilization and different pH of the nutrient solution

The effect of struvite on the content of ***total elements in the roots*** *in tomato hydroponics cultivation*

The magnesium content depended statistically on the pH of the solution, with the greatest content under pH 7.0, while phosphorus fertilization did not changes its content in the roots (Figure 13)

The phosphorus content was not depended on the pH of the nutrient solution, but relied on phosphorus fertilization. We observed the highest content of phosphorus in the solution with SUP, and a decreasing trend under struvite fertilization compared to SUP was noted (Figure 14).

The content of potassium depended significantly on the pH of the nutrient solution, while it did not depend on phosphorus fertilization (Figure 15).

Calcium content depended significantly on both tested factors. The content of calcium decreased under a higher pH, while struvite applied in the lower dose turned out to be the most conducive to calcium accumulation (Figure 16).

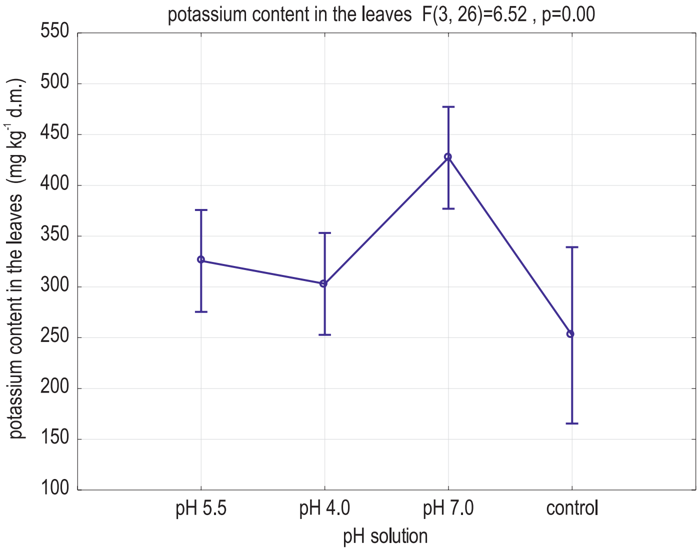


Fig. 11. The content of total potassium in tomato leaves under different pH of the nutrient solution

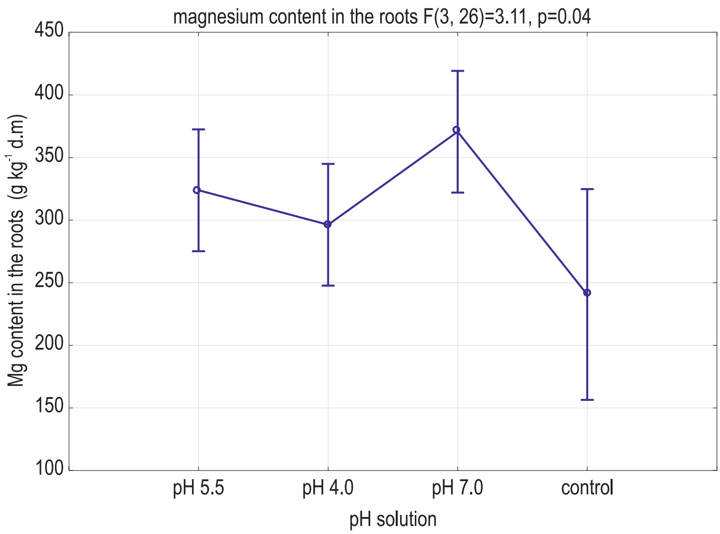


Fig. 12. The content of total calcium in tomato leaves under struvite fertilization

The highest calcium content in tomato leaves was observed in plants fertilized with a nutrient solution at pH 6.0, while significantly lower levels were found at pH values of 4.5, 5.0, and 6.5, and - in our study – with the solution's pH of 5.5. In the study of Dyśko et al. (2009), the variation in pH of the nutrient solution did not affect the magnesium nutritional status of the plants, contradictory to our results, where the highest content of Ca was determined at pH 7.0. Dyśko et al. (2008) demonstrated that organic sub-

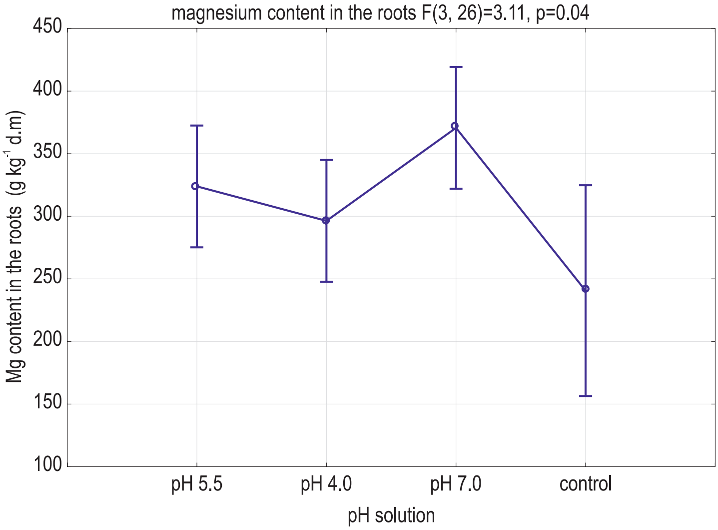


Fig. 13. Total magnesium content in the roots under different pH of solution and phosphorus fertilization

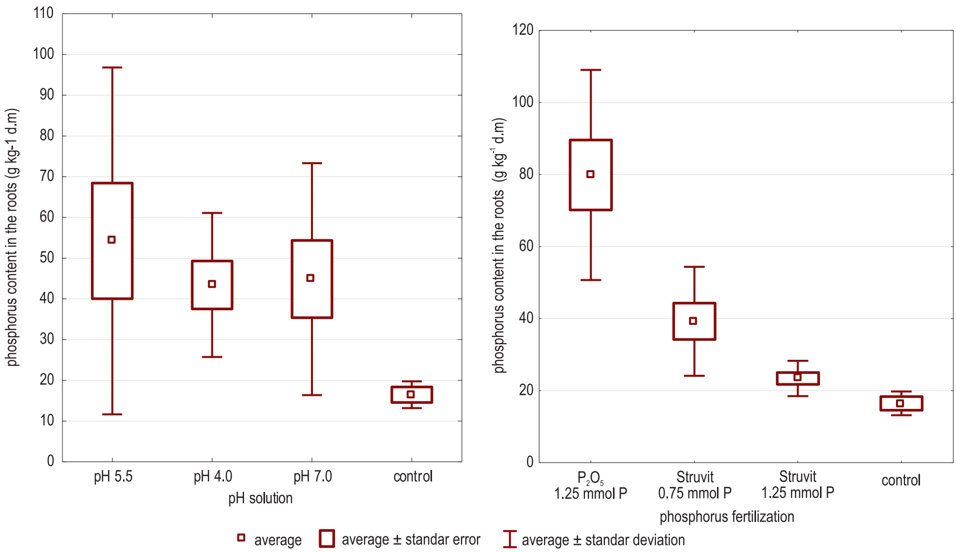


Fig. 14. The content of total phosphorus in the leaves under struvite fertilization and different pH of the nutrient solution (p=0.24, p=0.00)

strates with high buffer capacity, when using a nutrient solution's pH of 4.5, maintained a pH range of 6.4-7.1 in the root zone (Dyśko et al. 2008). The reduction in leaf and root potassium (K) concentrations observed at the low pH level (pH 4.0) in *T. officinale* and *R. picroides* (only at H1) is consistent with findings in other species, such as *Trifolium repens* L. and *Lolium perenne* L. (Rosas et al. 2007).

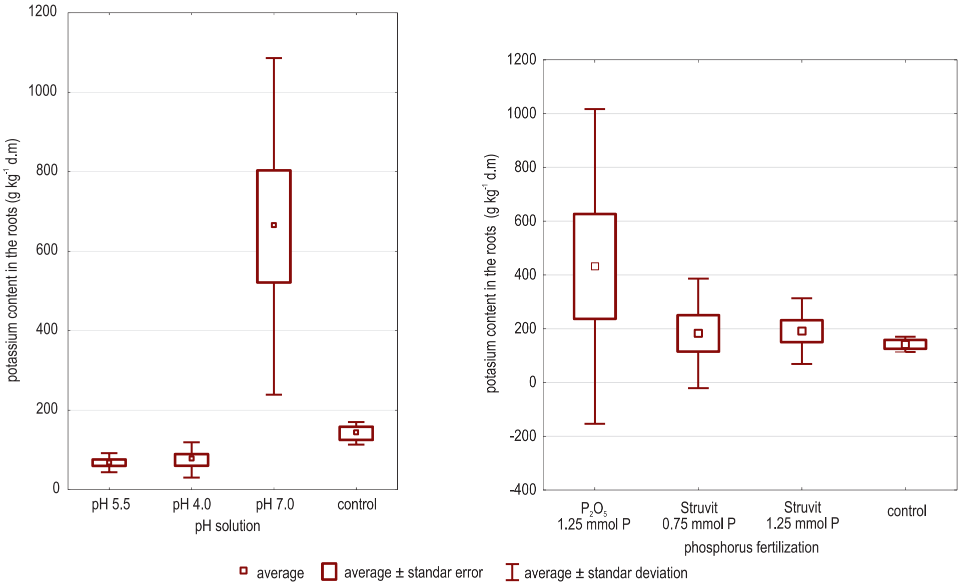


Fig. 15. The content of total potassium in the roots under struvite fertilization and different pH of the nutrient solution (p=0.02, p=0.16)

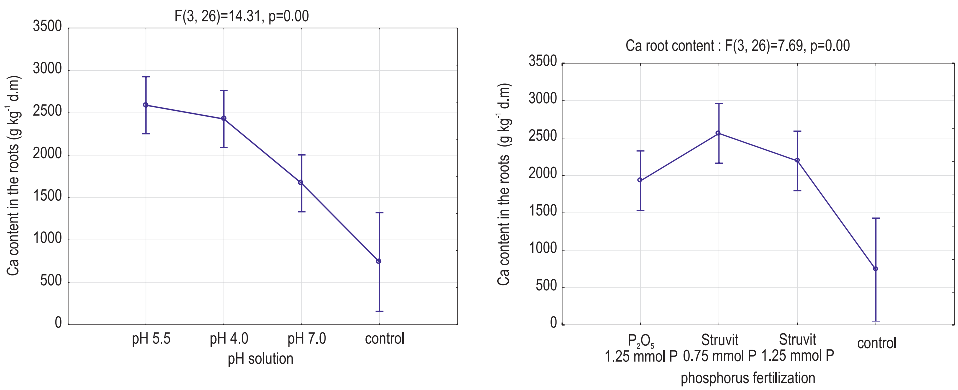


Fig. 16. The content of total calcium in the roots under struvite fertilization and different pH of the nutrient solution (p=0.02, p=0.16)

The content of selected elements in the tomato parts

There are statistically significant differences in the total content of elements in different parts of tomato. The higher content of magnesium was observed in the roots, while phosphorus and potassium were more abundant in the fruits (Figure 17).

In a study by Bautista et al. (2020), **there were no statistically significant differences observed between plant organs** in terms of the accumulation of P, Mg, and Fe. In certain instances, higher levels of macronutrients were observed in the roots and stems than in other parts of the

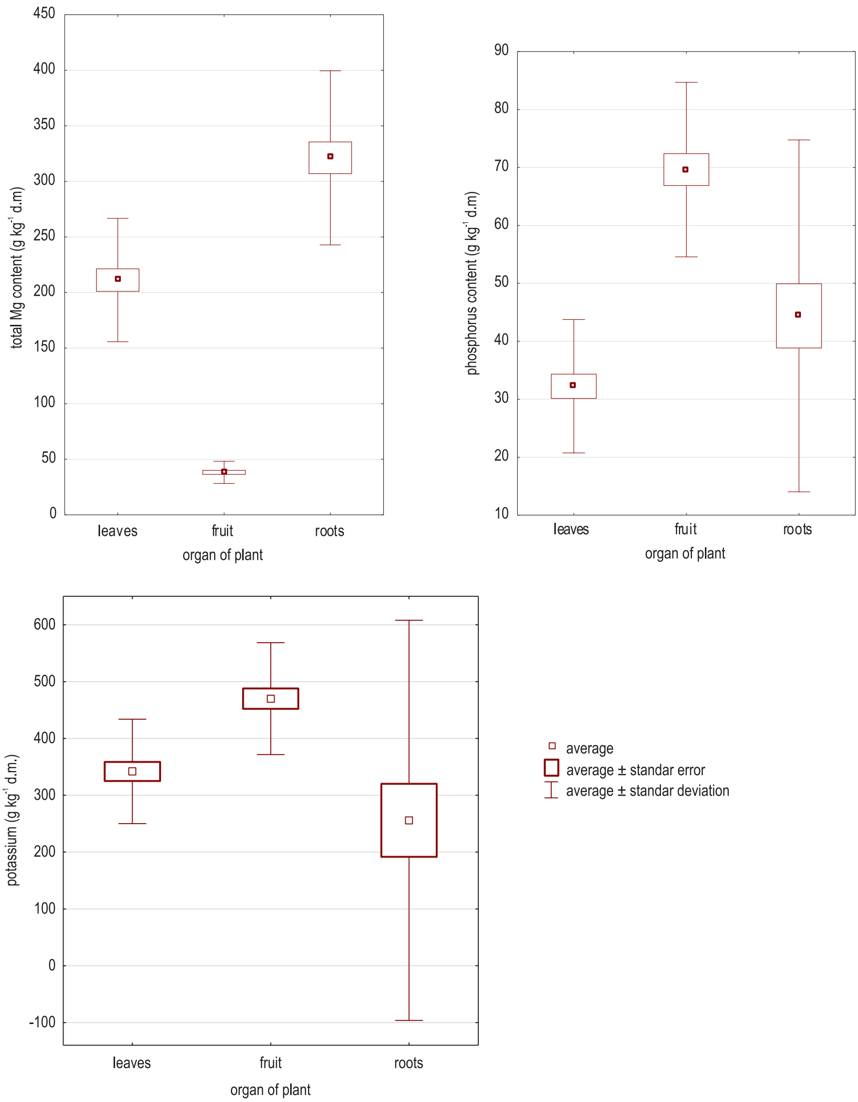


Fig. 17. The content of selected elements in the tomato organs

plant. Youssef and Eissa (2017) observed that when rabbit manure, rock phosphate, feldspar, and biofertilizer inoculation were combined, the concentrations of N, P, and K in tomato leaves increased by 34%, 35%, and 50%, respectively, compared to the control. Tonfack et al. (2009) observed that the application of organic fertilizers, mineral fertilizers, or a combination of both significantly improved the content of P, K, Ca, and Na in the fruit. In our study, a higher content of total content of magnesium was found in the roots, while potassium and phosphorus were more abundant in the fruits.

Table 2

The yield of tomato in a hydroponic experiment with struvite

Examined factors	Yield (g/plant)				Average mass of fruit (g)
	early	total	commer-cial	non-com-meracial	
Average for pH					
5.5	82.7	298.1	266.6	31.6	12.1
4.5	105.4	357.2	325.2	32.0	11.1
7	79.4	153.6	140.5	13.1	10.2
NIR	6.5	16.8	15.6	**2.1**	**0.4**
Average for P fertilization					
P_2O5 1.25 mmol P	66.2	250.3	226.1	24.2	10.9
Struvite 0.75 mmol P	81.3	251.6	225.4	26.2	11.4
Struvite 1.25 mmol P	120.0	306.9	280.8	26.2	11.1
LSD for P	**15.2**	**12.4**	**1.2**	**ns**	**ns**
LSD for interaction pH x P	**3.8**	**16.5**	**14.1**	**1.8**	**0.4**

A statistically significant influence of pH was observed, with the highest total yield recorded at pH 4.5 (357.2 g/plant), which differed significantly from the yield at pH 7.0 (153.6 g/plant), as determined by the least significant difference ($p<0.05$ Table 2). Likewise, early yield was maximized at pH 4.5 (105.4 g/plant), showing a statistically significant increase compared to values observed at pH 5.5 and 7.0 (Figure 18)

The highest total yield was obtained with the application of struvite at a concentration of 1.25 mmol P (306.9 g/plant), which was significantly greater than the yield achieved with P_2O_5 at the same phosphorus concentration (250.3 g/plant), as indicated by the least significant difference ($p<0.05$). A similar trend was observed for early yield, with struvite at 1.25 mmol P

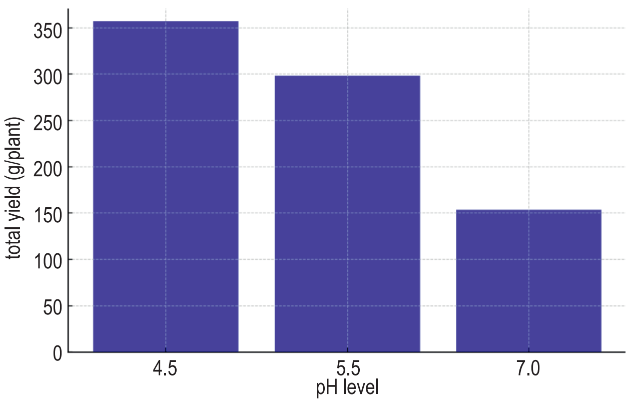


Fig. 18. Effect of pH on tomato yield

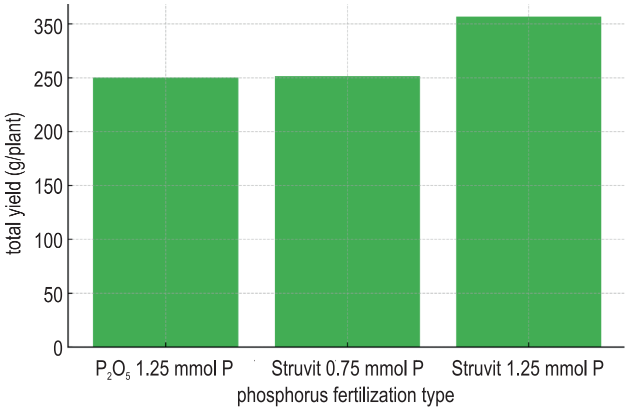


Fig. 19. Effect of phosphorus fertilization on tomato yield

(120.0 g/plant) exhibiting the most favorable outcome. However, no statistically significant differences were detected in non-commercial yield or average fruit mass (Figure 19)

The highest least significant difference (LSD) values were recorded for total yield in both the pH factor (16.8 g/plant) and the pH × phosphorus (P) interaction (16.5 g/plant), indicating that these factors substantially contribute to yield variability. Early yield also exhibited significant differences, particularly in response to phosphorus fertilization (LSD = 15.2 g/plant). In contrast, no statistically significant differences (ns) were observed for non-commercial yield or average fruit mass under phosphorus fertilization, suggesting that P fertilization exerts a minimal effect on these parameters. (Figure 20)

Chohura et al. (2004) and Kowalczyk (2003) suggest that the pH of the nutrient solution did not affect early yield; however, a pH higher than the

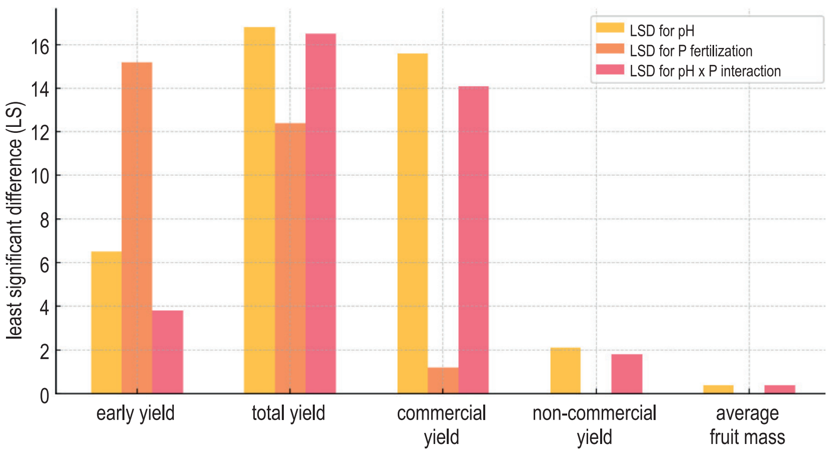


Fig. 20. Least significant difference (LSD) values for different factors affecting tomato yield

recommended 5.5 led to a decrease in tomato fruit yield. In Willumsen's (1980) tomato aquaculture experiments, varying pH levels (4.5-6.5) in the nutrient solutions did not affect marketable yield. However, a nutrient solution with a pH of 4.5 was found to reduce the size of the fruit. The same results were obtained by Anugoolprasert, et al. (2012) where pH 4.0 did not influence the number of leaves per plant in *Metaxylon sagu* or *Paeonia lactifolia* (Zghao et al. 2013). However, it did reduce the plant height and total leaf area in *Paeonia lactifolia* (Zhao et al. 2013) indicating a potential impact of low pH on plant morphology. Our findings are contradictory, as mass of tomato increased at pH 4.0 in terms of early, commercial and non-commercial yield. A higher dose of struvite was more efficient considering the yield.

In the study by Alexopoulos et al. (2021), the dry matter content (DMC, %) of both leaf and root tissues in the species remained unchanged by pH, suggesting that water absorption and accumulation in the plants were not influenced by the pH levels tested. This also indicates that the root function was not disrupted by potential damage caused by non-optimal pH values in the nutrient solution. In our study, dry mass accumulation was also consistent across the different pH treatments, supporting the observation by Alexopoulos et al. (2021) that nutrient solution pH within the tested range does not significantly impair root function or water uptake efficiency. This stability in dry matter content further suggests that the plants maintained adequate physiological performance, likely due to an effective buffering capacity against pH-induced stress at the root level.

CONCLUSIONS

The optimum dose of struvite for maximizing tomato yield was 1.25 mmol P. The availability of elements varied; however, it was generally more favorable for struvite. The appropriate dosage of struvite, along with pH adjustment, is crucial for ensuring optimal nutrient availability and maintaining a balanced hydroponic environment. Proper management of these two factors helps prevent nutrient imbalances, promotes healthy plant growth, and enhances the overall efficiency of the hydroponic system. The application of struvite as a phosphorus fertilizer enhances phosphorus and magnesium content in tomato fruits, with the effects varying depending on pH levels and plant parts as well as its yield. The results indicate that the highest concentration of Ca in the roots was observed at a pH of 5.5, and potassium at a pH of 7.0 in both the roots and leaves. For phosphorus in the leaves, the optimal pH is 5.5, while for magnesium in the roots and leaves, the pH is 7.0 and 5.5, respectively, are optimal. In the case of fruits, the pH for phosphorus is 5.5 and 4.0, while for magnesium, it is 5.5 in the leaves. Struvite contributed to the highest level of calcium in the roots at pH 4 and 7, as well as to an increased magnesium content in the leaves and a higher total calcium concentration in the roots. Future studies should include the use of nutrient solutions containing struvite in subsequent cultivation cycles to assess its long-term effectiveness and sustainability. By incorporating struvite into repeated cycles of hydroponic cultivation, researchers can better evaluate its impact on plant growth, nutrient availability, and yield consistency over time. This approach would also help identify any potential build-up or negative effects from continuous use, as well as its efficiency in comparison to other fertilizers.

Supplementary materials

Not applicable.

Author contributions

Conceptualization – R.R., M.C. and A.J.R., methodology – B.G, R.R., software – R.R., validation – R.R., formal analysis – A.J.R., investigation – R.R. and B.G., resources – M.C., data curation – R.R., writing – original draft preparation, R.R., B.G, A.J.R, writing – review and editing – A.J.R, R.R, visualization – R.R., supervision – A.J.R. and B.G., project administration – R.R., A.J.R. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest. The authors ensure that they have neither professional nor financial connections related to the manuscript submitted to the Editorial Board.

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