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Growth, Yield and Quality of Sweet Pepper Fruits Fertilized with Polyphosphates in Hydroponic Cultivation with LED Lighting

Anna Sobczak [1], Katarzyna Kowalczyk [1,*], Janina Gajc-Wolska [1], Waldemar Kowalczyk [2] and Monika Niedzińska [1]

1 Department of Vegetable and Medicinal Plants, Institute of Horticultural Sciences, Warsaw University of Life Sciences WULS—SGGW, Nowoursynowska 166, 02-787 Warszawa, Poland; anna_sobczak@sggw.edu.pl (A.S.); janina_gajc_wolska@sggw.edu.pl (J.G.-W.); monika_marcinkowska1@sggw.edu.pl (M.N.)

2 Laboratory of Chemical Analysis, Research Institute of Horticulture, Konstytucji 3 Maja 1/3, 96-100 Skierniewice, Poland; waldemar.kowalczyk@inhort.pl

* Correspondence: katarzyna_kowalczyk@sggw.edu.pl; Tel.: +48-22-59-32238

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Abstract: The aim of this study was to investigate the effect of phosphorus application in the form of polyphosphates on the yield and quality of sweet pepper fruits grown with LED (light-emitting diodes) assimilation lighting. Phosphorus is absorbed by the root system of plants mainly in the form of orthophosphates ions. The availability of phosphorus depends, among other things, on the pH of the substrate and the temperature. Two cultivars of sweet pepper with red fruits were tested in hydroponic cultivation on a mineral wool substrate. The plants were fertilized with one of three schedules, each of the same concentration of components, but differing only in the form of the applied phosphorus: polyphosphates (PP) and orthophosphates (OP). In the experiment, stem length extensions and number of leaves, chlorophyll concentration in leaves and fluorescence of the chlorophyll in a leaf were measured. The number and weight of fruits in total as well as marketable and non-commercial fruits with symptoms of dry rot (BER—blossom end rot) were studied. The concentration of dry matter and selected chemical components in fruits were examined and the sensory quality of fruits was evaluated using the QDA (Quantitative Description Analysis) method. The nutrient status of the pepper plants was also examined. Polyphosphates used in the medium increase the activity of photosynthetic apparatus of leaves and have a positive effect on the share of marketable yield of the total yield in the cultivar susceptible to BER. Fertigation in hydroponic cultivation with medium containing 30% phosphorus in the form of polyphosphates increased the uptake of calcium in pepper plants growing with LED lighting. The pepper cultivars tested differ in, among other things, the susceptibility to BER and the quality attributes of the fruit.

Keywords: SPAD; chlorophyll fluorescence; fruit quality; sensory quality

1. Introduction

Sweet pepper (*Capsicum annuum* L.) is a plant with a long growing period and requires good quality soil or substrate and adequate light, temperature and water [1,2]. The pepper fruit is highly valued for its taste and health-promoting qualities. Sweet pepper fruit provides vitamin C and vitamin A, flavonoids and antioxidants as well [3–5]. The demand for the fruit is high all year round. Growing plants in year-round greenhouses requires effective assimilation lighting.

Light is an important environmental factor with a significant role in plant life processes [6]. Plants use light as a source of energy for photosynthesis as well as for growth and development processes. There is a strong correlation between light availability and plant productivity. Insufficient light supplied to the plants can reduce the size and quality of the yield [7]. In practice, in the northern part of the globe, year-round greenhouse cultivation under natural light is only possible in latitudes below the 40th parallel. In moderate-climate countries, in latitudes above the 50th north parallel, in the autumn–winter period and early spring, due to the low solar radiation and shortage of natural sunlight, it is necessary to use assimilation lighting in plant production. At this time, HPS (High-Pressure Sodium) lamps are traditionally used most for supplementary lighting of plants, while solid-state light sources (LED) are being increasingly used [8]. LED technology allows to optimize the light spectrum to the requirements of individual plant species, provides a more energy-efficient way of lighting than HPS and improves yield and quality [9–11]. Environmental factors in pepper cultivation, such as light, temperature, humidity and fertilization, influence water and nutrient uptake, yield and fruit quality [12].

One of the most important macroelements in nucleic acids, high-energy compounds cell membranes, which participates in the process of photosynthesis and respiration, influences gene expression and activates or causes inhibition of enzymes by phosphorylation, is phosphorus [13,14].

The world's main source of phosphorus is phosphate rock. Global demand for phosphorus is expected to increase but it is a non-renewable resource [15]. The use of the traditional form of orthophosphates forces the application of higher doses of fertilizer than is normal for the plant, due to the tendency to make it unavailable to plants at both high- and low-substrate pH. Phosphorus application in the form of polyphosphates makes it more efficient and requires smaller doses of fertilizer, mainly in soil. This makes it possible to reduce phosphorus consumption in mineral form when fertilizing plants and thus slow down the exploitation of its resources. In addition, hydroponic crops provide the opportunity to control and optimize plant fertilization, contributing to the reduction of phosphorus fertilizer consumption.

The deficiency of phosphorus available to plants causes inhibition of shoot and root growth, reduction of leaf blade area and reduction of plant weight [16]. Plants absorb phosphorus in the form of $H_2\,PO_4^-$ and HPO_4^{2-} ions, the so-called orthophosphates [17]. However, a popular form is several combined water-soluble phosphorus molecules identified as polyphosphates (PP). Polyphosphates are an anionic linear polymer of orthophosphate residues joined by hydrogen phosphate bonds similar to those found in ATP. They can affect the transcription and translation of specific genes, modulate several stress responses, provide an alternative source of energy and act as a metabolic regulator [18,19]. The presence of polyphosphates in plant systems has been known for a long time but their role in cellular processes has only begun to be studied relatively recently [20,21].

The use of polyphosphates in the nutrient solution has a significant effect on strong root system development, plant growth and earlier flowering [22]. The use of PP in plant production does not cause the formation of sludge in irrigation systems, which often results in irregular substrate moisture in hydroponic crops [23,24]. Reduced nutrient solution flow in the drip system, especially in the period of high temperature under covers, may be the cause of increased share of fruit with dry BER rot in such vegetables as tomato or pepper [25].

The aim of the study was to evaluate the effect of polyphosphates on the growth, yield and quality of pepper fruits in the cultivation with LED assimilation lighting.

2. Materials and Methods

The study was carried out in the greenhouse of the Department of Vegetable and Medicinal Plants at the Warsaw University of Life Sciences WULS—SGGW (longitude 21° E, latitude 51°15′ N) in the winter cycle of 2018. Two cultivars of sweet peppers with red fruits were taken into consideration: 'Aifos'—block type by Seminis (Bayer) and 'Palermo'—longer type by Rijk Zwaan. The transplants were produced in rockwool cubes, day/night temperature 22 °C/20 °C, air humidity RH (relative humidity) 60–70%, and average CO_2 concentration 800 ppm. Sweet pepper transplants were grown under 16 h a day photosynthetic photon flux density (PPFD) at 170 μmol m^{-2} s^{-1} provided by HPS lamps.

Sweet pepper was planted on mineral wool slabs type Grotop Master 100 × 20 × 10 cm (2 plants on each slab) on 6 December 2018 and the production was completed in July 2019. In the experimental chamber, with a useful area of about 40 m^2, the plants were grown on three beds. The plant density was about 2.5 per m^2 (the plants were pruned to have two main stems and staked individually in the shape of a "V."). Plants growing in each of the beds were fertilized with a nutrient solution differing in the form of applied phosphorus. Polyphosphates were applied using Antibloc Mineral (Yara). Fertilizer combinations: (1) P-15, where the nutrient solution contained 15% phosphorus in the form of polyphosphates and 85% phosphorus in the form of orthophosphates, (2) P-30, the nutrient solution containing 30% phosphorus in the form of polyphosphates and 70% phosphorus in the form of orthophosphates and (3) C, the nutrient solution in control containing 100% phosphorus in the form of orthophosphates. Nutrient concentration in the solution, EC (electro-conductivity) and pH were continuously controlled and kept at uniform levels for all experimental objects. The average pH and EC were respectively about 5.5–5.8 and 2.8–3.3 dS m^{-1} of drop solution. The concentration of nutrients (in mg.dm^{-3}) was in each combination as follows: $N - NO_3$—195, P—57, K—273, Mg—47, Ca—187, Fe—2, Mn—0.6, B—0.3, Cu—0.15, Zn—0.3, Mo—0.05. The experiment was established with the randomized blocks method in three replications, with 4 plants in each. In the experiment, top lighting with Green Power LED (Philips) top lighting units (DR/W–LB, 195 W) and inter-row 1-line of LEDs (module 2.5 m HO DR/B 100 W) (Philips) were applied. A daily light exposure equaled 16 h. The top lighting units switched off automatically when the solar radiation was higher than 250 W m^{-2}. Light conditions in terms of PAR (Photosynthetically Active Radiation) were closest to ~185 μmol·m^{-2} s^{-1} (PPFD). Light intensity was measured with a Li-Cor Light meter LI-250A, quantum sensor LI-190. Microclimate parameters were controlled by the Synopta Climate Computer and were as follows: temperature was 22–25 °C/18–20 °C during day/night respectively, CO_2 was supplied up to 800 ppm level and RH was approximately 75%. In each combination, weekly increments in stem length were measured by determining the total plant height and number of leaves. Twice during the vegetation period of the plants (8 and 16 weeks after planting: term 1 and term 2), in fully mature leaves, located on three levels of the plant: upper leaf, middle leaf and bottom leaf, a relative concentration of chlorophyll $a + b$ was measured with Minolta SPAD-502 apparatus. Relative SPAD meter values are proportional to the amount of chlorophyll present in the leaf [26]. The result was averaged from five unit measurements made on each examined leaf. Chlorophyll fluorescence was measured in the same leaves of pepper plants with the use of the FMS-2 Field Portable Pulse Modulated Chlorophyll Fluorescence Monitoring System (Hansatech Instruments Ltd., King's Lynn, Norfolk, England) and the following parameters were measured: Fs—steady-state fluorescence yield, Fm'—light-adapted fluorescence maximum and φPSII (Fv'/Fm')—quantum efficiency of photosystem II (PSII). The Pocket PEA fluorescence meter (Hansatech Instruments Ltd., King's Lynn, Norfolk, England) was used to measure direct fluorescence, obtaining a measurement of the maximum efficiency of the plant's photosynthetic camera after an earlier 30 min of adapting the leaves to darkness (using special clips). The following parameters were analyzed: maximum efficiency of PS II photosystem in the dark (Fv/Fm) and PI—PS II vitality index.

The nutrient status of the pepper plants fertilized with three kinds of medium, differing in the form of the applied phosphorus, was determined by leaf sample analysis. The samples were gathered in term 1 and term 2 where the analysis was performed for fully mature leaves, as above. The samples were dried at the temperature of 60 °C, in a forced-air oven, then ground in a Wiley stainless-steel mill. The samples were microwave digested in HNO_3, using closed Teflon vessels. The elements (P, K, Mg, Na, Ca, Fe, Mn, Cu, Zn, B) were determined by an inductively-coupled plasma spectrometer (ICP, Model OPTIMA 2000DV, PerkinElmer, Boston, USA). For total N determining, the plant material was mineralized after drying in concentrated sulfuric acid in the presence of copper-potassium catalyst. The N content was determined using the Kjeldahl apparatus (Vapodest, Königswinter, Germany). After distillation of nitrogen in the form of NH_3, the N content was determined by titration methods [27].

The fruit was harvested in the full color phase. The number and weight of fruit in the total, as well as marketable and non-marketable fruit with symptoms of dry rot (BER—blossom end rot), were determined. The quality of pepper fruit was tested twice (term 1 and term 2). For this purpose, fully colored fruit were randomly collected from each combination, in which, in one part, in three repetitions, the dry matter was determined by drying method at 105 °C, the concentration of ascorbic acid (AA) was determined using the Tillmans' method (Polish Standard PN-A-04019) [28] and total soluble solids (TSS) concentration (in °Brix) with digital refractometer (Atago CO.,LTD.) and total sugars (TS) were analyzed according to the Luff-Schoorl method (Polish Standard PN-90/A-75101/07) [29]. Nitrate (NO_3) concentration was determined spectrophotometrically, with the FIAstar device (Foss Tecator AB, Sweden), using the wavelength of 440 nm, and the concentration of P was determined with the colorimetric test. The concentration of K and Ca was determined with the flame method. Other parts of fruits served for sensory analysis. The sensory quality of fruits was evaluated using the QDA (Quantitative Description Analysis) method. This was achieved by a team of 20 trained panelists in two duplicates. The odor, texture and taste quality attributes were evaluated. Each panelist marked his evaluation of the investigated sample on a scale—a segment of a straight line with border marks. The marked notes were converted to numerical values in the stipulated units from 0 to 10. Also, overall sensory quality impression was taken into account as a separate descriptor. Overall quality is a general sensory quality impression and anchoring points from low quality to high quality (from 0 to 10). A semi-consumer test of pepper cultivars liking was also performed alongside the QDA procedure. For this evaluation, a non-structural scale was also used, with anchoring points: 'I do not like it'—'I like it very much'.

Statistical analysis was performed using two-way analysis of variance, ANOVA (Statistica, Version 13, Warsaw, Poland). Detailed comparison of means was performed by the Tukey's test at the significance level of $\alpha = 0.05$.

3. Results

The results of biometric measurements showed no effect of polyphosphates used in the nutrient solution for pepper fertigation in hydroponic cultivation with LED lighting on plant height, weekly shoot growth on the length and number of leaves in both studied pepper cultivars. Plant height depended on the cultivar. Plants of 'Palermo' were taller than 'Aifos', achieving an average height of 92.77 cm, and plants of 'Aifos'—64.45 cm (Table 1).

Table 1. Effect of fertilizer with polyphosphates in hydroponic cultivation on the height of pepper plant, number of leaves on the plant and weekly growth of stem depending on cultivar (average of two terms).

	Cultivar	Treatment		
		Control	**P-15**	**P-30**
Weekly growth of stem (cm)	'Aifos'	5.23 a	5.03 a	4.57 a
	'Palermo'	5.97 a	4.63 a	6.70 a
Plant height (cm)	'Aifos'	63.40 b *	66.07 b	63.87 b
	'Palermo'	89.10 a	90.70 a	98.50 a
Number of leaves (No.)	'Aifos'	24.90 a	29.47 a	25.97 a
	'Palermo'	28.87 a	29.90 a	33.03 a

* The mean values marked with the same letters do not differ significantly according to the Tukey HSD (honestly significant difference) test at $\alpha = 0.05$.

Pulse amplitude modulation (PAM) measurement of chlorophyll fluorescence allows to measure fluorescence under current light intensity conditions. One of the parameters measured by this technique is Fs, or stationary fluorescence. The influence of the use of polyphosphates in pepper hydroponic cultivation on Fs was observed. Fs value was the highest in peppers fed with P-15 medium in relation to control, regardless of the cultivar. For 'Aifos' cultivar, the fluorescence parameter such as Fs in P-30 combination was also higher than in the control (Table 2). Fm' maximum fluorescence of chlorophyll *a* in the leaves adapted to light, which is lower than the maximum fluorescence of chlorophyll achieved after adaptation to darkness (Fm), was also the highest in the P-15 combination (Table 2). However, no effect of polyphosphates' application on the current quantum yield of PSII, φPSII (Fv′/Fm′), was found in the examined pepper cultivars (Table 2). The maximum photochemical yield of PSII (Fv/Fm) determines the photochemical activity of the plant's photosynthetic apparatus. It is determined for plants adapted to darkness. The analysis of the obtained results showed lower maximum photochemical yield of PSII in 'Palermo' fed with P-15 medium, and lower vitality of PSII (PI inst.) in 'Palermo' than 'Aifos', whereas no positive effect of polyphosphates on the maximum yield of pepper photosynthetic apparatus was found (Table 2). The value of PI inst. was significantly lower in 'Palermo' than 'Aifos', although in the P-15 combination, PI inst. for cultivars did not differ significantly (Table 2). A significant dependence of the leaf chlorophyll index on the sweet pepper cultivar was found. The cultivar 'Aifos' had higher SPAD index in leaves than cultivar 'Palermo'. Whereas, no significant effect of polyphosphates application in the medium on chlorophyll concentration in pepper leaves was found (Figure 1).

Table 2. Effect of fertilizer with polyphosphates in hydroponic cultivation on the photosynthetic activity of pepper leaves depending on the cultivar (average of two terms).

Chlorophyll Fluorescence Parameters	Cultivar	Control	P-15	P-30
Fs	'Aifos'	305 d *	385 ab	374 abc
	'Palermo'	312 cd	401 a	326 bcd
	Average	301 C	393 A	350 B
Fm′	'Aifos'	1289 b	1608 a	1468 ab
	'Palermo'	1276 b	1596 a	1289 b
	Average	1283 B	1602 A	1379 B
φPSII	'Aifos'	0.76 a	0.75 a	0.74 a
	'Palermo'	0.75 a	0.75 a	0.74 a
	Average	0.75 A	0.75 A	0.74 AB
Fv/Fm	'Aifos'	0.81 a	0.81 a	0.81 a
	'Palermo'	0.80 a	0.79 b	0.81 a
	Average	0.81 A	0.80 A	0.79 B
PI inst.	'Aifos'	11.72 a	10.86 ab	10.65 abc
	'Palermo'	8.81 cd	9.53 bcd	8.20 d
	Average	10.27 A	10.20 A	9.43 A

* The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$. The small letters indicate the differences in the interaction of cultivar x treatment, the capital letters indicate the differences in the treatment.

The highest total yield was obtained in combination P-15, on average from cultivars of 2.74 kg per one stem, that is 5.48 kg per one plant (pepper plants were cultivated with 2 stems), and in control and combination P-30, 2.37 kg and 2.26 kg per one stem, that is 4.74 kg and 4.52 kg per plant, respectively. A similar trend was found in the marketable yield for both pepper cultivars (Figure 2). The share of marketable yield in the total yield depended on the pepper cultivar and phosphorus source. 'Aifos' had from 13% to 16% lower marketable yield than total yield regardless of the phosphorus source used. On the other hand, the cultivar 'Palermo' which is more susceptible to BER had in the control combination as much as 42% lower marketable yield than the total one, mainly due to BER, but in combinations with polyphosphate use in concentrations P-15 and P-30, it had 28% and 29%, respectively. Differences in yielding were found between the examined pepper cultivars. 'Palermo' obtained a low share of marketable yield in the total yield, which was not observed in 'Aifos' (Figure 2). The reason was the higher susceptibility of 'Palermo' to BER (Figures 2 and 3). In this cultivar, the use of polyphosphates decreased the share of fruits with BER symptoms as compared to the control combination (Figure 3). In both investigated cultivars, the average weight of marketable fruit in combination with phosphorus in the form of polyphosphates was higher than in the control, although the differences were not statistically significant (Figure 4).

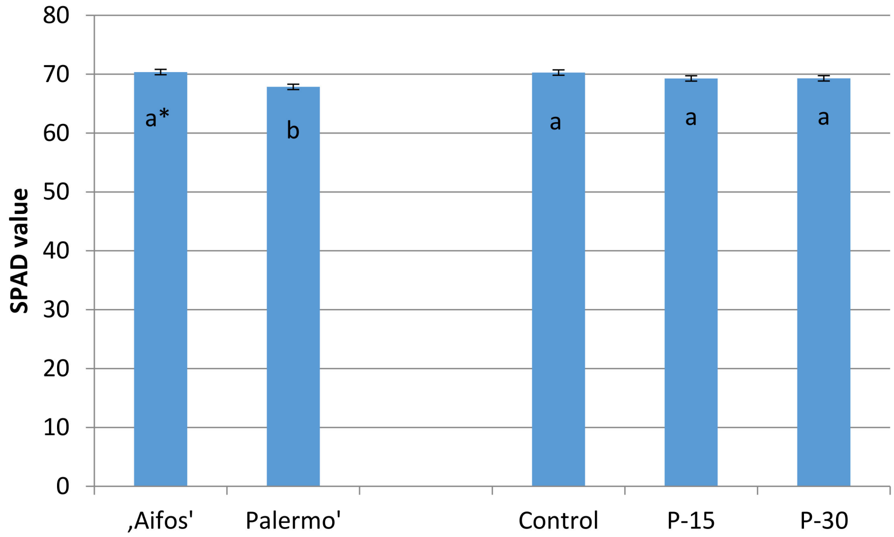

Figure 1. Effect of fertilizer with polyphosphates in hydroponic cultivation and cultivar of pepper on the chlorophyll index in pepper leaves (average of two terms). * The mean values marked with the same letters do not differ significantly according to the Tukey HSD test at α = 0.05.

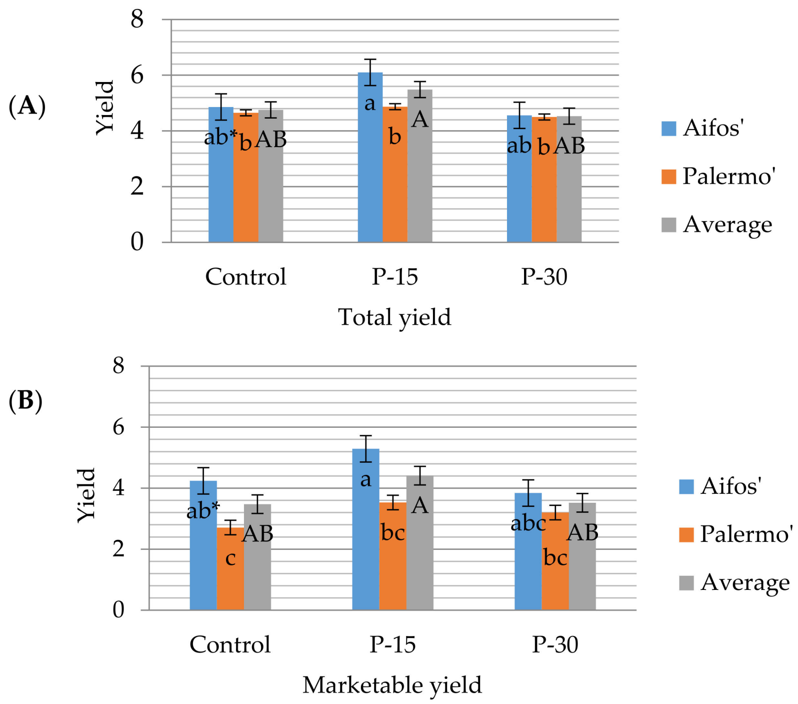

Figure 2. (**A**, **B**) Effect of fertilizer with polyphosphates in hydroponic cultivation on the total (**A**) and marketable (**B**) yield depending on the sweet pepper cultivar (kg plant^{-1}). * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at α = 0.05.

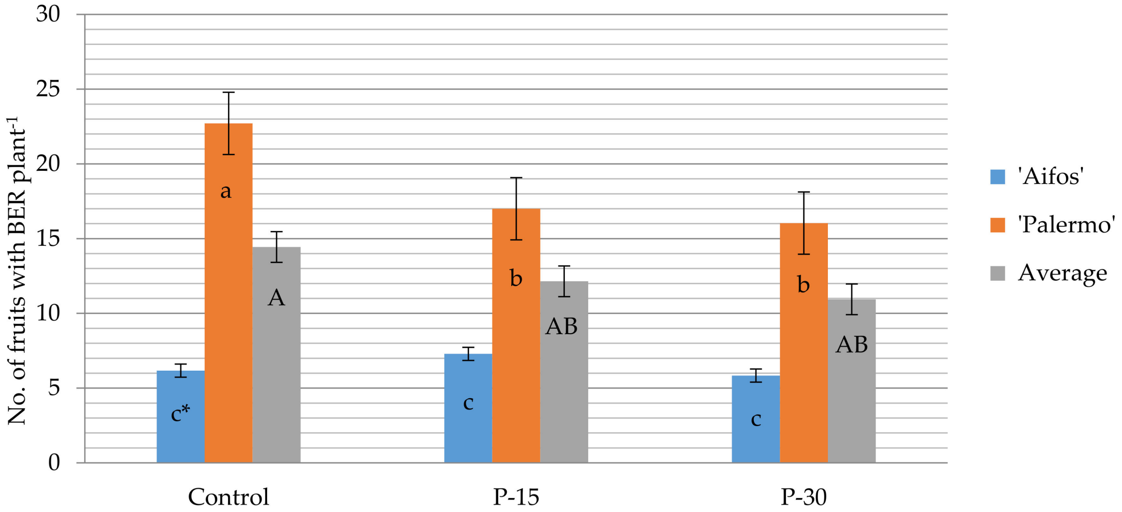

Figure 3. Effect of fertilizer with polyphosphates in hydroponic cultivation on the number of BER (blossom end rot) fruit depending on the sweet pepper cultivar. * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at α = 0.05.

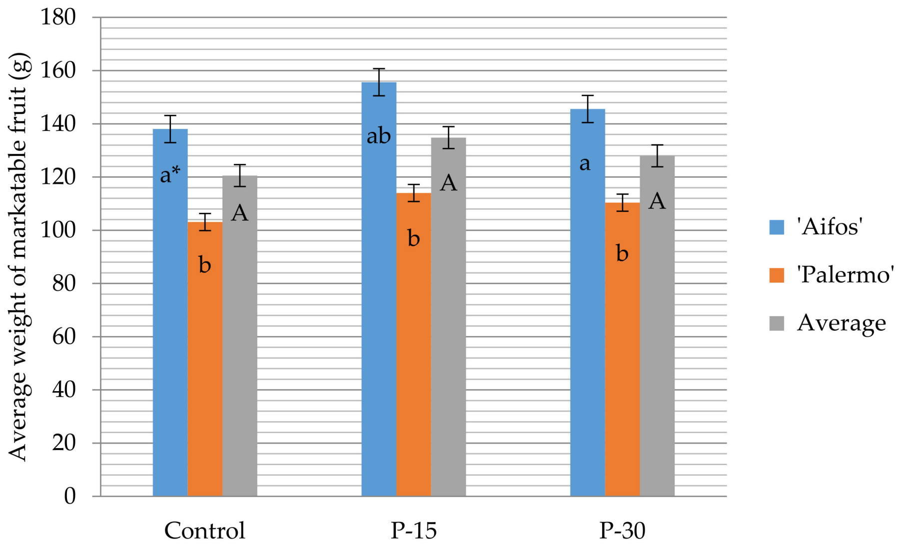

Figure 4. Effect of fertilizer with polyphosphates in hydroponic cultivation on the average weight of marketable fruit depending on the sweet pepper cultivar. * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at α = 0.05.

Calcium concentration in the drip nutrient solution for plant fertigation, on average for the growing period of pepper, was about 187 mg dm^{-3} for each combination (See Section 2). In the case of pepper fertilization with PP medium in the substrate, a lower accumulation of Ca was found in P-30 than in the P-15 combination and in the control (Figure 5). Probably in the combination P-30, the pepper plants taken up more calcium than when fertilized with medium at P-15 and with the nutrient solution containing 100% phosphorus in the form of orthophosphates.

The concentration of mineral components in pepper leaves, on average of the two measurement dates and combinations, was the following for macronutrients in % of dry matter: N—4.80, P—0.24, K—6.60, Ca—3.42, Mg—0.62, S—0.57, and for micronutrients in mg kg^{-1} of dry matter: Fe—171.0, Mn—194.9, Cu—4.6, Zn—151.1, B—43.0. There were no significant differences between the cultivars in the mineral content of leaves. In comparison to the control, the content of especially P as well as K, Zn, S and Ca in pepper leaves, was higher when PP was applied in nutrient solution at a concentration of

15%, and when PP was applied at a concentration of 30%, the content of Ca and Mg in leaves was higher than in the control plants (Figure 6).

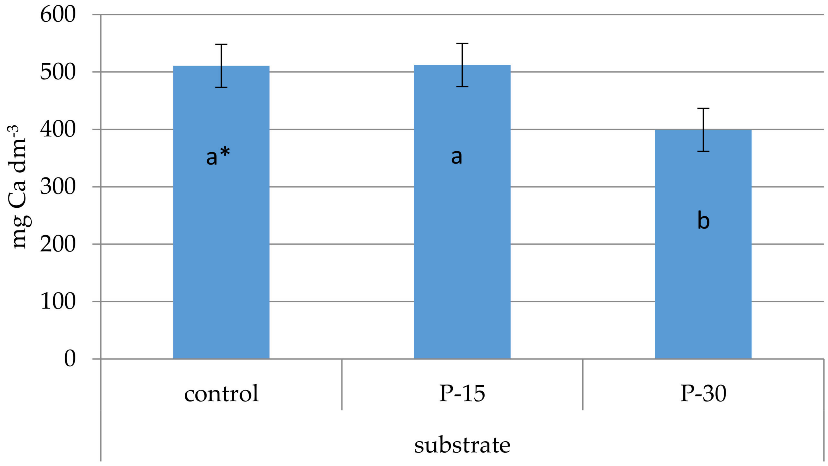

Figure 5. Calcium concentration in the substrate depending on the level of PP (polyphosphates) applied in the drip nutrient solution, on average for the growing period of pepper. * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

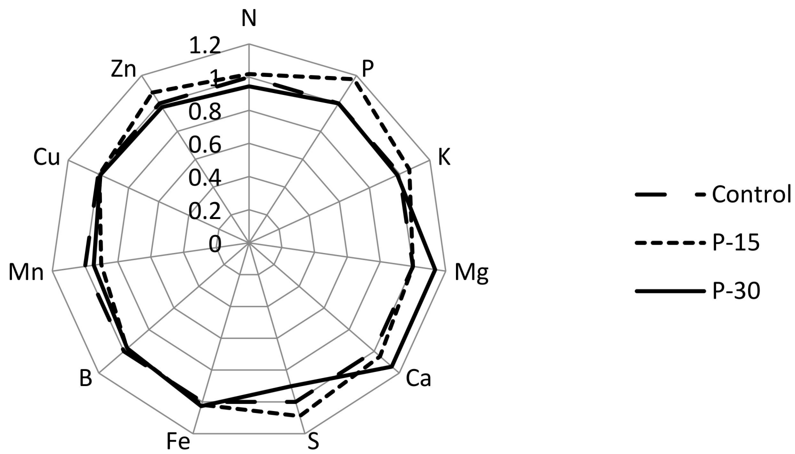

Figure 6. The concentration of mineral components in pepper leaves normalized to the values in control content as radar plots under different PP combinations (average of two terms).

The analysis of chosen quality features of pepper fruits did not show any influence of polyphosphates on the concentration of such components in pepper fruits as dry matter, TSS (total soluble solids), ascorbic acid, TS, P, NO_3, K and Ca (Table 3). The concentration of these components in the fruit depended mainly on the cultivar. The 'Palermo' fruit contained more dry matter, TSS and total sugars (TS). The fruits of the 'Palermo' had a higher TSS content in combination P-15 and a higher TS content in combination P-30 than in the control. Nitrates contained the most fruits fertilized with PP in the P-15 combination and potassium contained the most fruits from the P-30 combination. In the control combination, without applied polyphosphates in the nutrient solution, there was less calcium in 'Palermo' than in 'Aifos' (Table 3). In this combination, 'Palermo' was found to yield the most fruit with BER (Figure 3). Sensory analysis of pepper fruits did not show the influence of polyphosphates on attributes concerning odor, texture and flavor of pepper fruits (Table 4). On the other hand, the fruits between the cultivars differed significantly in terms of, among others, sweet taste, which correlates with sugar concentration. 'Palermo' fruits were assessed significantly higher in terms of sweet taste and 'Aifos' fruits were found to have higher flesh texture, crispier flesh and tougher skin than the other one (Figure 7). The overall sensory quality for pepper fruits did not depend on the PP applied in fertilization. The cultivar 'Palermo' obtained a higher score than the 'Aifos' (Figure 8).

Table 3. Effects of fertilizer with polyphosphates in hydroponic cultivation on the concentration of dry weight and chosen chemical components in pepper fruit depending on the cultivar (average of two terms).

Component	Cultivar	Control	P-15	P-30
Dry weight (%)	'Aifos'	8.01 b *	8.08 b	8.05 b
	'Palermo'	10.14 a	10.60 a	10.34 a
	Average	9.07 A	9.19 A	9.34 A
TSS (°Brix)	'Aifos'	7.57 c	7.42 c	7.27 c
	'Palermo'	9.45 b	10.15 a	9.47 b
	Average	8.50 A	8.78 A	8.37 A
Ascorbic Acid (mg.100 g^{-1} FW)	'Aifos'	26.54 a	22.33 b	22.07 b
	'Palermo'	19.56 b	21.00 b	21.73 b
	Average	23.04 A	21.66 A	21.89 A
TS (g.100 g^{-1} FW)	'Aifos'	4.56 c	3.75 d	3.94 d
	'Palermo'	6.01 b	6.30 ab	6.45 a
	Average	5.28 A	5.03 A	5.20 A
P (mg.kg^{-1} FW)	'Aifos'	249.95 a	249.00 a	248.35 a
	'Palermo'	247.65 a	272.5 a	250.15 a
	Average	248.8 A	260.75 A	249.25 A
NO_3^- (mg.kg^{-1} FW)	'Aifos'	56.27 ab	58.04 a	56.04 abc
	'Palermo'	50.95 c	56.48 ab	52.06 bc
	Average	53.61 B	57.26 A	54.05 B
K (mg.kg^{-1} FW)	'Aifos'	2335.85 abc	2325.4 bc	2148.45 c
	'Palermo'	2384.63 ab	2523.2 a	2335.85 abc
	Average	2360.24 A	2424.3 A	2242.2 B
Ca (mg.kg^{-1} FW)	'Aifos'	26.5 a	22.65 a	20.00 a
	'Palermo'	19.9 a	22.00 a	22.65 a
	Average	23.2 A	22.33 A	21.33 A

* See Table 2.

Table 4. The results of sensory analysis concerning odor, texture and taste for pepper fruits as affected by cultivar and PP treatment, scale 0–10 (average of two terms).

Attributes of Odor, Texture and Taste	Cultivar	Control	P-15	P-30
Odor of fresh pepper	'Aifos'	5.77 a *	6.02 a	5.25 a
	'Palermo'	5.33 a	5.16 a	5.36 a
	Average	5.53 A	5.60 A	5.31 A
Skin hardness	'Aifos'	5.39 ab	5.72 a	5.38 ab
	'Palermo'	4.27 b	4.72 ab	4.54 ab
	Average	4.81 A	5.24 A	4.94 A
Flesh fibrousness	'Aifos'	6.27 ab	6.48 ab	6.98 a
	'Palermo'	5.88 ab	5.47 b	6.10 ab
	Average	6.07 A	5.99 A	6.52 A

Table 4. *Cont.*

Attributes of Odor, Texture and Taste	Cultivar	Control	P-15	P-30
Flesh juiciness	'Aifos'	5.77 a	6.04 a	5.81 a
	'Palermo'	5.98 a	5.37 a	5.86 a
	Average	5.88 A	5.72 A	5.83 A
Flesh firmness	'Aifos'	6.81 a	7.04 a	6.50 a
	'Palermo'	4.31 a	3.77 b	4.58 a
	Average	5.51 A	5.48 A	5.51 A
Typical pepper taste	'Aifos'	5.99 ab	6.01 ab	5.41 b
	'Palermo'	6.51 ab	6.29 ab	6.98 a
	Average	6.27 A	6.15 A	6.23 A
Sour taste	'Aifos'	1.82 a	1.59 a	1.74 a
	'Palermo'	1.70 a	1.74 a	1.78 a
	Average	1.75 A	1.66 A	1.76 A
Sweet taste	'Aifos'	3.16 c	3.74 bc	3.07 c
	'Palermo'	5.13 ab	5.32 a	5.69 a
	Average	4.19 A	4.49 A	4.43 A
Bitter taste	'Aifos'	1.69 a	0.78 ab	1.24 ab
	'Palermo'	0.62 b	0.76 ab	0.64 b
	Average	1.13 A	0.77 A	0.93 A
Pungent flavor	'Aifos'	0.93 a	0.70 a	0.98 a
	'Palermo'	0.76 a	0.99 a	0.85 a
	Average	0.84 A	0.84 A	0.91 A
Off-flavor	'Aifos'	0.28 a	0.21 a	0.23 a
	'Palermo'	0.28 a	0.26 a	0.28 a
	Average	0.15 A	0.11 A	0.11 A
Overall quality	'Aifos'	6.38 a	6.69 a	6.58 a
	'Palermo'	7.07 a	6.74 a	7.15 a
	Average	6.73 A	6.86 A	6.87 A

* See Table 2.

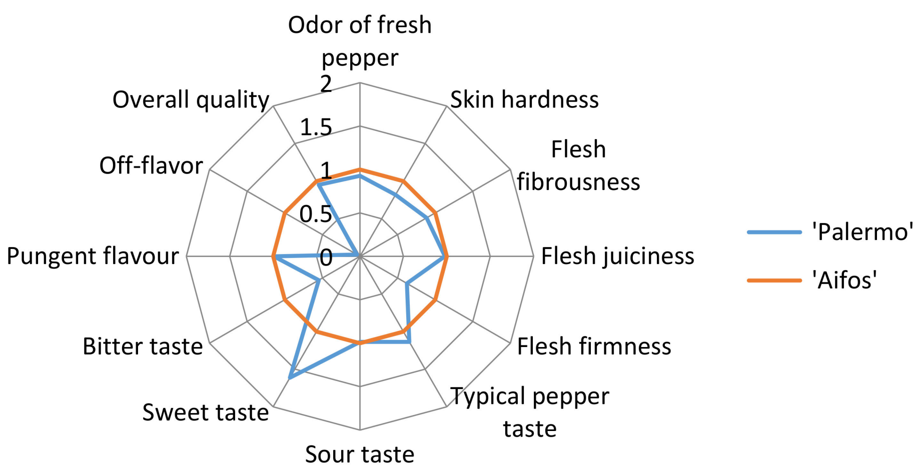

Figure 7. The results of sensory analysis concerning odor, texture and taste and overall quality for pepper fruits normalized to the values of 'Aifos' cultivar as radar plots compared to the 'Palermo' cultivar (average of two terms).

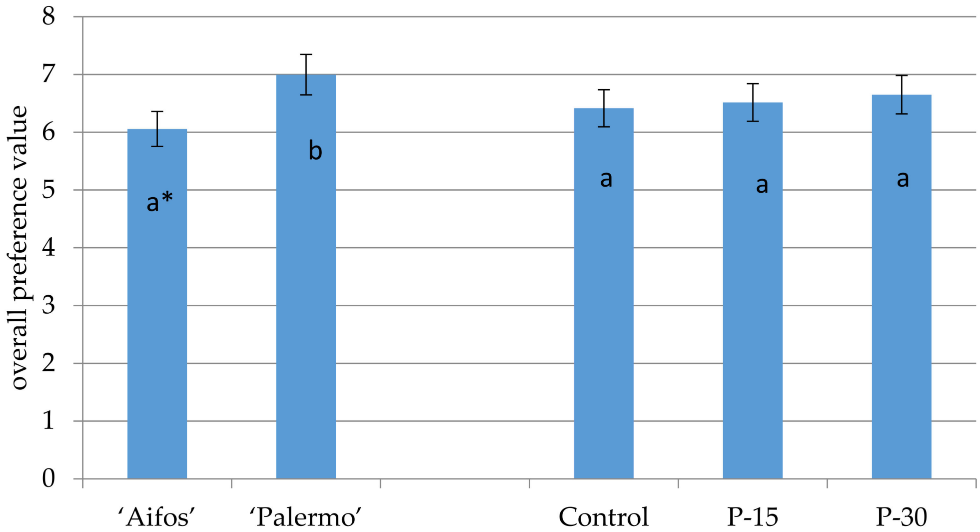

Figure 8. Overall sensory preference for pepper fruits as affected by cultivar and fertilized with polyphosphates in hydroponic cultivation (average of two terms). * The bars marked with the same letters do not differ significantly according to the Tukey HSD test at $\alpha = 0.05$.

4. Discussion

Phosphorus (P) is an essential macronutrient for plant growth and development [30]. P affects the light use efficiency of PSII and deficiency of phosphorus could cause detectable fluctuations of the kinetic parameters of photosynthetic fluorescence [31–35].

According to Kalaji [36], a decrease in chlorophyll fluorescence parameters may result from macro- and micro-elements' deficiency. The results obtained from our experiment suggest better nutrient availability in PP compared to control. Significant effects of P-15 and P-30 on Fs and of P-15 on Fm' could be due to the differences in phosphorus availability during cultivation.

Torres-Dorante et al. [22] reported that the P availability was dependent on the source of P and soil properties. Efficiency of fertilization was significantly higher for PP treatments in the silty-loam soil where the plants have produced longer roots. However, no differences were observed in the sandy soil, between OP and PP treatments [34]. Although, according to Dicklowa [35], the effectiveness of a unit amount of P taken up by ryegrass and corn plants in increasing the dry matter yield was similar among the polyphosphates and the conventional P fertilizer, orthophosphate. However, these studies concern traditional crops in different soils.

According to Flexas et al. [33], measurements of Fs—steady-state fluorescence yield is a promising tool for remote water shortage diagnosis. Effectively, it shows the effect of many reactions resulting from consequences that follow stomatal closure in response to water stress. The relationship between Fs and g (stomatal conductance) provides a new method for detection of water stress, which can cause BER in pepper fruits. Our results showed that higher values of pepper leaves' chlorophyll a fluorescence parameters in plants fertilized with polyphosphates indicate an increased yield of pepper photosynthetic apparatus in the case of pepper cultivar more susceptible to BER. In hydroponic crops, the problem of water and nutrient uptake and partitioning, and transport to particular plant parts, is more frequent than their availability in the substrate. Li and Erel [34] report that PP can function as a chelate for micronutrients and Ca. Moreover, in hydroponic crops, PP can improve the nutrient solution flow in the drip system by reducing the accumulation of insoluble salts.

Fm' maximum fluorescence of chlorophyll a in the leaves adapted to light was also the highest in the P-30 combination, with the acceptors of photosystem II (PSII) partially reduced in this case [37]. According to Borawska-Jarmułowicz et al. [38], it is temperature stress that is the key factor in any Fm' decrease. The Fv/Fm index presents the maximum quantum yield of photosystem II [39]. Graham and McDonald [40] observed a decrease in the Fv/Fm due to high temperature, a decrease in this parameter may indicate active sun protection of the plant [41]. Baker and Rosenqvist [26] concluded in their studies that a decrease in Fv/Fm may inhibit the rate of photosynthesis and also affect plant growth and development. The PI PSII vitality index, on the other hand, shows the ability of plants to adapt to stress conditions [42].

The use of polyphosphates to fertilize pepper grown in rockwool influenced the activity of the photosynthetic apparatus. A large share of BER fruits in the control is a reaction to environmental stress conditions during the growing period. Possible reasons are a short-term increase in temperature or substrate EC (electrical conductivity), a decrease in substrate moisture or the increase in fruit load on the plant.

Differences in yield, fruit quality and susceptibility to BER were found between pepper cultivars. Plants fertilized with phosphorus in the form of polyphosphates were less susceptible to common disorders that have been associated with fruit calcium deficiency (BER), especially the cultivar which was more susceptible to BER. Many authors report [43,44] that proper nutrition of plants with calcium has a significant impact on reducing the occurrence of BER. According to Michałojć and Horodko [45], the share of fruits with BER symptoms in the total yield is lower when plants are properly supplied with calcium.

According to Selahle et al. [46], the taste of sweet peppers is determined by the sugar and organic acid concentrations. Pepper flavor is a complex trait, influenced by environmental factors during growth [47,48]. However, polyphosphates used in the nutrient solution for fertigation in hydroponic cultivation of pepper with LED lighting do not significantly change the sensory quality of pepper fruits.

5. Conclusions

The following conclusions can be drawn from the study.

The use of polyphosphates for fertigation in hydroponic cultivation increase the activity of photosynthetic apparatus of pepper leaves and has a positive effect on the share of marketable yield of the total yield in the cultivar susceptible to BER.

Pepper plants fertilized with polyphosphates are characterized by increased values of such fluorescence of chlorophyll parameters as Fs—steady-state fluorescence yield, and Fm′—maximum fluorescence of chlorophyll *a*.

Fertigation in hydroponic cultivation with medium containing 30% phosphorus in the form of polyphosphates increased the uptake of calcium in pepper plants growing with LED lighting.

The polyphosphates used in the nutrient solution do not significantly change the quality of pepper fruits.

The pepper cultivars tested differ in the yield and the susceptibility to BER and such features as the height of the plants, the dry matter and sugar concentration of the fruit, and the sensory quality characteristics of the fruit, such as sweet taste, consistency of the flesh, crispness of the flesh and hardness of skin.

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