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ORIGINAL PAPER

# EFFECTS OF HPS AND LED LIGHTING ON THE GROWTH AND THE CONTENT OF SELECTED NUTRIENTS IN THE FRUITS OF *CUCUMIS SATIVUS* L.*

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Abstract

A plant growing experiment was carried out in a three-aisle foil tunnel, built with the double, pumped foil technology. Cucumber plants were grown in a substrate (rock wool). The nutrients were provided as a nutrient solution through a fertilization system. The experiment consisted of 3 combinations and each combination comprised 4 replications. In the control, the plants had access only to natural sunlight and only as much as natural conditions allowed. In the second combination, the plants were lit with HPS lamps made of a single-body, inseparable Green ORX2-400 luminaire, adapted to power a 400W light source. In the third combination, plants were lit with Neonica Growy LED Plus 318 LED lamps. The main aim of the research was to test and compare the effect of LED lamps and sodium lamps (HPS) on the content of nutrients in *Cucumis sativus* L. fruits. Lighting *Cucumis sativus* L. with sodium and LED lamps results in higher fruit yields. Providing plants with artificial light (HPS and LED lamps) accelerates the harvest of *Cucumis sativus* L. The fruit of *Cucumis sativus* L., lit with HPS lamps is characterized by a higher content of nitrogen. The fruit of *Cucumis sativus* L. lit with LED diodes is characterized by a higher content of potassium, phosphorus, calcium and copper. Lighting *Cucumis sativus* L. with LED and HPS lamps, compared to plants with natural light, reduced the content of iron in cucumber fruits.

**Keywords:** Light Emitting Diode, High Pressure Sodium, cucumber, lighting plants.

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# INTRODUCTION

Modern-day technology is developing at an unprecedented pace, creating amazing opportunities for development in virtually every area of life. It is visible, among others, in horticulture or in the entire branch of agriculture through more and more advanced technologies used for growing vegetables. A dozen or so years ago, hardly anyone imagined that plants would not need organic substrates for proper growth, especially that it would be possible to grow plants practically all year round in heated facilities, in inorganic substrates with the use of artificial plant lighting and in addition with very good results. Today's horticulture is a continuous process of searching for new solutions that will result in the intensification of cultivation, i.e. increasing the yield and quality of product vegetables while maintaining economic profitability and at the same time not polluting the natural environment. One the main aspects that allow for very high intensification of cultivation under cover is the year-round cultivation of plants in heated foil tunnels or greenhouses. However, while the problem of heating can be easily solved, although not necessarily cheaply, in the conditions prevailing in northern Europe and the Scandinavian countries, autumn or winter crops were not produced because of the very low availability of solar radiation, which is one of the most important factors determining the proper plant growth and development. The solution to this problem turned out to be the development of technology and, consequently, the increasing availability of lamps suitable for artificial lighting of plants Morrow (2008). High-pressure sodium lamps, abbreviated as HPS lamps, turned out to be the most useful for the initial illumination of crops (Kumar et al. 2016). Despite the very good response of plants to lighting with these lamps, they were very expensive to operate, had low luminous efficiency, because much of the electricity consumed was transformed into heat, and had a relatively short service life compared to the most modern technological achievements. Today it is almost certain that HPS lamps will be replaced with the most modern LED lamps, which have many advantages and one generally key disadvantage in the form of very high costs of setting up such an installation. However, there are many advantages in favor of the use of LED technology in greenhouse crops, such as very high energy efficiency and high light efficiency, and thus a small percentage of energy is converted into heat. What is more, LED technology is the only one that allows the selection of an appropriate light spectrum to meet the plant's requirements, and even to match a particular phase of its growth, which is impossible in the case of all other light sources, whose structure does not allow for significant modifications in terms of obtaining the desired spectrum (Massa et al. 2008, Singh et al. 2015).

Plant lighting is a very important factor in the proper growth of plants, in addition to which, it is an extremely current direction in the development of modern horticultural farms. In modern horticultural farms, the main targets are to increase the yield and significantly improve the quality of produced vegetables.

The main objective of the research was to test and compare the effect of LED lamps and sodium lamps (HPS) on the content of nutrients in the fruit of *Cucumis sativus* L. Additionally, the paper presents the results of measurements of plant yield depending on the type of lighting, as well as differences in growth (biometric measurements) resulting from the different spectrum of light provided to plants during the research.

## MATERIAL AND METHODS

### Location and description of the research object

The experiment was carried out on a farm in the village of Dębe - Kolonia in Kalisz District. The research used a blocked, three-aisle foil tunnel, made with the use of double, pumped foil technology. The tunnel is 28.8 m x 50 m in width and length, and consists of 3 aisles size 9.6 m x 50 m. The facility is heated by a fine coal boiler WCO80 and a system of pipes and heating hoses. The pipes are located between the rows of plants, they are used for heating and as running tracks for nursing trolleys. There is a heating system between the plants, which consists of three heating hoses, located at a height of 50 cm, 80 cm, and 120 cm above the ground, and additionally one hose is located under the ground in order to maintain the right temperature in the root zone. Watering was carried out using a stick dripper system and emitters with pressure compensation and flow rate 2.2 l $h^{-1}$. A fertilization computer based on the principle of automatic selection of fertilizers and acid was used to supply the nutrient solution. It was coupled with the system of precise overflow and transpiration control. There was one air fan in every aisle, in its central part.

### Climatic conditions and nutrient solution

The day temp. was 19-20°C and the night temp. was 17-18°C. The temp. of the substrate was kept at 23-28°C. The humidity in the tunnel was 65% up to a max. of 85%. The moisture content of the mats after planting was gradually reduced to the level of 60%, while at the time of harvesting the first crops, the humidity was increased to about 80%. The composition of the nutrient solution in the tests during cultivation is presented in Tables 1 to 2.

Most of the experiment was performed when nutrient solution no 3 was being administered. Among other things, during the nutrition of plants with this nutrient solution, leaf and fruit samples were taken for laboratory analysis, the total fruit yield was collected and 3 out of 4 plant measurements were made.

Table 1

Fertilizer composition of the nutrient solution (g 1000 $dm^{-3}$)

| Fertilizer | Nutrient solution (g 1000 $dm^{-3}$) | | |
|---|---|---|---|
| | seedling production (nutrient solution no. 1) | planting plants (nutrient solution no. 2) | start of fruiting (nutrient solution no. 3) |
| Calcium nitrate | 640 | 690 | 545 |
| Potassium saltpeter | 525 | 705 | 655 |
| Ammonium sulphate | 18 | 15 | 23 |
| Magnesium sulfate | 340 | 230 | - |
| Magnesium nitrate | 70 | 235 | 350 |
| Monopotassium phosphate | 180 | 220 | 200 |
| Micro plus | 100 | 100 | 100 |

Table 2

The nutrient content of nutrient solution (mg $dm^{-3}$)

| Nutrient | Nutrient solution | | |
|---|---|---|---|
| | seedling production (nutrient solution no. 1) | planting plants (nutrient solution no. 2) | start of fruiting (nutrient solution no. 3) |
| $N\text{-}NH_4^-$ | 8.27 | 8.15 | 8.39 |
| $N\text{-}NO_3^-$ | 178.85 | 227.23 | 213.46 |
| P | 40.14 | 49.06 | 44.60 |
| K | 253.74 | 333.78 | 309.04 |
| Mg | 43.76 | 48.55 | 36.70 |
| Ca | 166.60 | 175.85 | 149.10 |
| $S\text{-}SO_4^-$ | 174.20 | 159.90 | 130.00 |
| B | 0.20 | 0.20 | 0.20 |
| Mo | 0.05 | 0.05 | 0.05 |
| Cu | 0.51 | 0.51 | 0.51 |
| Mn | 2.01 | 2.01 | 2.01 |
| Fe | 3.82 | 3.82 | 3.82 |
| Zn | 0.41 | 0.41 | 0.41 |

## Object of research and planting density

The object of research were plants of the *Cucumis sativus* L. CANTARA RZ F1 belonging to the family of cucurbits (*Cucurbitaceae*), the order of cucurbits (*Cucurbitales*), variety "Cantara". It is a parthenocarpic variety, intended for early planting in greenhouses or foil tunnels. It is characterized by a generative habit, balanced plant growth and fruit quality, which perfectly keeps the ratio of the length of the fruit to its thickness D / G = 3.1:1. Plants in the entire facility grew at a density of about 2.5 pieces $m^{-2}$ and no modification of the density was introduced in the experimental trials. The substrate for cultivation was Grodan Master mineral wool mats size 100 cm x 20 cm x 7.5 cm. The mineral wool boards were arranged in one row, on polystyrene pads wrapped with black and white garden foil. Four plants were planted on each mat.

The planting material was prepared in-house. Sowing took place on 20 December 2019, into a mineral wool substrate soaked in a nutrient solution, the composition of which is given in Tables 1-3. The seedling production

Table 3

Effect of the type of lamps on the fresh weight of cucumber fruit (kg) harvested on particular dates

| Date | Control (natural light) | HPS | LED |
|---|---|---|---|
| 20.02.2020 | – | 2.35 | 2.48 |
| 24.02.2020 | 1.90 | 2.82 | 2.82 |
| 27.02.2020 | 3.28 | 4.08 | 4.06 |
| 02.03.2020 | 3.88 | 7.68 | 7.44 |
| 05.03.2020 | 4.50 | 6.42 | 5.95 |
| 07.03.2020 | 3.24 | 3.85 | 3.40 |
| 11.03.2020 | 3.06 | 4.44 | 3.34 |
| 13.03.2020 | 7.78 | 6.60 | 7.16 |
| 15.03.2020 | 4.78 | 6.60 | 7.06 |
| 19.03.2020 | 5.26 | 7.48 | 7.34 |
| 22.03.2020 | 10.22 | 10.82 | 10.62 |

cycle took place in a heated room in a building where the plants were lit only with artificial light by HPS lamps. After 10 days, on 30 December 2019, the seedlings were transferred to the foil tunnel and planted into cubes of mineral wool. Throughout the production period, seedlings were lit only with HPS lamps. On 23 January 2020, the seedlings were transferred to the foil tunnel described previously, where the actual experiment began.

## The design of the experiment

The experiment consisted of 3 combinations, each comprising 4 replications. One replication consisted of 10 cucumber plants (40 plants in total in each combination):

– sample no. 1 (control, without plant lighting). In this test, the plants were not illuminated in any way. Plants had access only to natural solar radiation and only in such quantity as allowed by natural conditions. It was the control combination to compare the differences between plants with and without lighting. This test covered 16 $m^2$

with 2.5 plants $m^{-2}$, which meant 40 plants in a row length of 10 m, i.e. on 10 substrate mats;

- sample no. 2 (HPS lighting). Plant lighting with HPS lamps made of a single-body, inseparable Green ORX2-400 luminaire, adapted to power a 400W light source. Luminaire powered by alternating current with voltage of 230V. The size of the luminaire was 67.7 cm in length, 24.7 cm in width and 12.8 cm in height, while the weight was 10.20 kg. A 400W Philips Master SOT-T PIA Plus bulb was used as a light source. The rated luminous efficiency of the bulb used was 138.97 lm $W^{-1}$, the color temperature was 2000 K, and the luminous flux was around 56 700 lm. The spectrum of the radiation wavelengths had maxima between 560 nm and 600 nm. The bulbs were brand new. Four lamps were used, suspended 150 cm above the tops of the plants, and then gradually raised. The lamps were suspended in one row and covered 40 plants, which gives a length of 10 m, equal to 10 mats of substrate. The combination area was 16 $m^2$ and the plant density was 2.5 plants $m^{-2}$.
- sample no. 3 (LED lighting). Plant lighting with Neonica Growy LED PLUS 318 LED lamps, with power consumption of 120 W and emitted power of PPF 270 µmol $s^{-1}$. The spectrum of the radiation waves of the LEDs used had its maximum between 440 nm and 660 nm. The ratio of red to blue light was 4:1. The casing were 135 cm long, 10.6 cm high and 5.3 cm wide, and the weight was 3.74 kg. They were powered by alternating current with voltage of 230V. The lamps were brand new, not used before. Four lamps were used, suspended 80 cm above the tops of the plants. As the plants were growing, the lamps were gradually raised. The lamps were suspended in one row and covered 40 plants, which gives a length of 10 m, equal to 10 mats of substrate. The combination area was 16 $m^2$ and the plant density was 2.5 plants $m^{-2}$.

## Measurement methods during cultivation

The cultivation experiment was carried out from 23 January 2020 to 23 March 2020, in the so-called high wire, i.e. the plants were systematically lowered with parallel tearing off the lower leaves. The plants were illuminated 12 h a day in two cycles: from 6:00 a.m. to 12:00 p.m. then from 4:00 p.m. to 10:00 p.m. The day was 16 h in total and the night lasted 8 hours. The method of watering for all three trials was the same, depending on the water requirements of the rest of the crop. The temperature was the same in each combination due to the use of air mixing fans. The removal of lower leaves was selected individually for each combination, according to the LAI coefficient.

**Fruit crops**

The fruit was always harvested in the morning, and all trials were carried out at the same time. The fruit was harvested when it reached the commercial premium quality, i.e. the fruit was about 8-11 cm long and not oversized in terms of thickness. The fruit was harvested 2-3 times a week, from all trials at the same time. The weight of the harvested crops was measured right after the harvest. Plant comparisons were made on average every 2 weeks, always at the same time.

**EC and pH measurements**

EC and pH measurements were always taken in the evening, at least one hour after the last watering cycle, with a meter built into the irrigation computer. The samples for the measurements were taken from all the base mats used in the experiment. About 20 ml of the nutrient solution in the substrate was taken from each block of mineral wool. All samples were taken in the same way, i.e. 2 cm from the bottom of the mat, from the center between the two middle plants, using a syringe and a needle approximately 4 cm long. Measurements were made from the entire volume of the taken nutrient solution, i.e. from about 200 ml of solution.

**Biometric measurements of plants**

The plants were measured every 2 weeks, at the same time in the afternoon. Handheld tools such as a tape meter and a ruler was used for biometric measurements. Results were obtained by averaging the measurements of 10 plants (in each replicate), 40 plants in combination. The internode length was measured from the upper central point of leaf development to the lower central point of leaf development. The size of the leaf blade was measured by juxtaposing the length and width of the blade. The length was measured along the main nerve from the end of the petiole, while the width was measured at the widest points of the leaf blade. The measurements were taken on mature, older leaves, i.e. the $12^{th}$ mature leaf from the top of the plant. All the buds in the node that the plant formed were counted, regardless of their size. The height of the plant was measured along the main shoot, from the ground to the top. 10 plants from each replication were always used for measurement. Only the number of main leaves was counted, without taking into account the number of leaves emerging on the side shoots, but taking into account broken leaves. The petiole length was measured on the same leaves on which the blade size was measured. Side shoots were all counted, without taking into account strictly generative shoots or vegetative shoots. Root system assessed in terms of color, number of hairs and its amount in the substrate. Ripe fruits that were harvested as a yield were assessed for their length.

### Collection of plant material for laboratory analysis

The plant material for analysis was collected on 15 March. Ripe fruit of commercial size were used. Immediately after harvesting from each replication, 10 pieces of fruit were randomly selected. The selected fruits showed no signs of mechanical damage, they were healthy, with no signs of disease and no signs of damage by pests. They were immediately cut into slices about 1-2 mm thick and placed on clean paper pads in a sunny place in the foil tunnel in order to dry as quickly as possible.

### Laboratory methods of fruit analysis

Slices of cucumber fruit dried in a hood dryer at 105°C, and then homogenized and subjected to chemical analysis. The content of macronutrients in the leaves was determined after wet mineralization with concentrated sulfuric acid using the Kiejdahl method, P – colorimetrically with ammonium vanadomolybdate, K, Ca and Na – photometrically, Mg – by the atomic absorption method (AAS).

The dried material was homogenized in a laboratory mill, and then wet mineralized in a mixture of concentrated $HNO_3$ and $HClO_4$ in the ratio 3 : 1 (Bosiacki, Roszyk 2010).

The contents of iron, copper, zinc and manganese were determined by atomic absorption on a AAS-5 spectrophotometer by Zeiss.

### Statistical methods

The results of the content of selected components and sodium were statistically assessed in the Stat Bat program. The statistical processing included one-way analysis of variance for the content of the tested elements in the dry matter of cucumber fruit under the influence of plant illumination. The differences between the means were determined using the Duncan's test, with the significance level $p<0.05$.

## RESULTS AND DISCUSSION

Light is an important aspect in cucumber cultivation. This plant requires high intensity of light, but light must be diffused. Direct, undistracted sunlight can cause leaf burns, which become white necrotic spots. The greatest growth and the highest yields of cucumbers occur when the day length is about 14 h (Ślusarski et al. 2013).

Light is one of the most important factors stimulating plant growth, next to the temperature, humidity and air composition as well as the abundance of nutrients in the substrate. It affects a number of very different physiological processes, including the efficiency of photosynthesis, and also plays a very important role in the regulation of growth and development processes known as photomorgenesis. On the other hand, the quality and quantity of light available to plants, in turn, affects the signaling pathway of specific photoreceptors, such as phytochromes, phototropins or cryptotochromes. The effect of light on individual plants is very diverse, therefore LEDs which allow easy selection of appropriate spectral characteristics create a possibility to optimize the spectral quality for individual plants and physiological processes, and to create an energy-saving and automated plant lighting system (Puternicki 2010, Lin et al. 2013, Olle, Viršile 2013, Singh et al. 2015).

An important aspect is the duration of plant exposure, otherwise known as the photoperiod. It is based on the ratio of the length of the day to the length of the night. Changes in this ratio, i.e. extending the duration of the day or shortening it, have a significant impact on the plants. The photoperiod affects for example flowering, so by regulating the length of the day it is possible to induce or delay flowering (Rao 1999, Nisho 2000, Singh et al. 2015, Hall).

Currently, high-pressure sodium lamps (HPS) are most often used in horticulture. They are characterized by high luminous efficiency, ranging from 140 - 170 lm $W^{-1}$, relatively long service life and relatively low financial outlays for setting up an installation. High electricity prices strongly limit the introduction of HPS lamps into plant cultivation practice and for this reason they are mainly used for the production of vegetables and ornamental plant seedlings. Additionally, HPS lamps have low energy efficiency as they are able to convert only about 30% of the electricity consumed into utility light; at the same time they convert another 30% of energy into thermal energy. For this reason, they must be mounted quite high above the plants, which makes it impossible to illuminate between rows. The lifetime of today's gas discharge lamps is estimated at around 20,000 h, according to various manufacturers. After this time, the bulbs begin to lose their properties, which translates into poorer efficiency of lighting, and thus the production becomes less efficient (Singh et al. 2015).

Light-emitting diodes (LEDs) have many advantages and have great potential as the main or additional inter-row light source in various types of plant productions. They have definitely smaller, more compact sizes, and therefore also less weight. In addition, they are much more durable than traditional light sources, their operating time can be from about 30,000 to even 50,000 h, which, combined with high energy efficiency and increasingly efficient energy conversion, can translate into increasing production profitability despite the high costs of setting up an installation. The advantage of LEDs is also the fact that they do not heat up as much as HPS lamps, which means that they have a wider range of possible applications and allow the user to select and easily adjust the wavelength to match the spectrum to a particular plant (Massa et al. 2008, Singh et al. 2015).

Compared to high pressure sodium lamps, LED lamps heat up very little, so they can be used as additional inter-row lighting of plants, because they will not cause damage to plants.

The results regarding the yielding of plants indicate that additional lighting to the crop resulted in a significant increase in the yield, regardless whether LED or sodium lamps were used (Tables 3 and 4). In addition, in the control sample, the first harvest was delayed by 4 days compared to the other variants, which indicates that plant lighting not only increases the overall yield, but also accelerates the yielding of plants (Table 3). This is very important in early greenhouse plantings because it shortens the time before fruiting, and thus improves the profitability of a given crop.

Discussing the above results, it can be concluded that HPS and LED lighting caused an almost identical increase in the yield, to a small advantage of 1.47 kg for HPS lamps, but despite this increase in yield by about 2.3%, production with the use of LEDs turned out to be more profitable. LEDs consume 70% less electricity, which generated higher profits from cultivation owing to a significant reduction in costs (Table 4).

Table 4

Fruit yields

| Parameter | Control (natural light) | HPS | LED |
|---|---|---|---|
| The total weight of harvested fruit | 47.9 kg a | 63.14 kg b | 61.67 kg b |
| Number of harvested fruit | 10 | 11 | 11 |
| Average per harvest | 4.79 kg | 5.74 kg | 5.61 kg |

Cucumber cultivation was established on a mineral wool substrate. The parameters of the nutrient solution used before planting the plants were: EC (mS $cm^{-1}$) = 3 and the pH was in the range of 5.5 to 6.0.

In the control sample, the parameters remained within the acceptable limits. EC was slightly increased throughout the measurement period (Table 5). This was done intentionally to facilitate the plants' access to nutrients, which because of the early planting date and limited access to daily light took up little water and nutrients. The mean EC was 3.38. This is by 0.2 EC higher than in the sodium lamp test and similar to the sample lit with LEDs. The mean pH measured was 5.79. This is much lower than in the other two variants.

The lowest value of electric conductivity was recorded in variant 2, where HPS lamps were used. The reason was that the plants yielded the most abundant fruit and formed the largest green mass, which meant that these plants used the most nutrients, which caused a decline in EC in the substrate. The average EC was 3.2. This is by 0.2 EC lower than in the other samples. In the same test, the highest pH values were recorded, reaching even 7.22. The reason could be the reduced substrate humidity in relation to the other samples. As previously stated, the crop was irrigated according to the needs of plants growing without additional light, so the differences

Table 5

Influence of plant lighting on the EC and pH values on particular dates

| Date | Control (natural light) | | HPS | | LED | |
|---|---|---|---|---|---|---|
| | EC | pH | EC | pH | EC | pH |
| 29.01.2020 | 3.25 | 5.70 | 3.15 | 5.80 | 3.05 | 5.90 |
| 05.02.2020 | 3.20 | 5.80 | 3.10 | 5.90 | 3.35 | 5.90 |
| 10.02.2020 | 2.65 | 6.00 | 2.41 | 6.60 | 2.80 | 6.75 |
| 20.02.2020 | 3.00 | 5.80 | 2.40 | 6.20 | 2.64 | 6.30 |
| 26.02.2020 | 3.53 | 5.70 | 3.01 | 6.00 | 3.28 | 6.10 |
| 04.03.2020 | 3.95 | 6.80 | 3.66 | 7.20 | 3.83 | 7.40 |
| 10.03.2020 | 3.50 | 6.10 | 3.78 | 7.15 | 4.00 | 6.95 |
| 18.03.2020 | 3.73 | 6.71 | 3.66 | 7.22 | 3.86 | 7.00 |
| 23.03.2020 | 3.61 | 6.54 | 3.61 | 7.04 | 3.79 | 6.94 |
| Mean | 3.38 | 5.79 | 3.19 | 6.56 | 3.40 | 6.58 |

in the acidity of the substrate could be due to the different moisture content of the substrate. The proof may be the fact that in the pH in the samples lit with LED lamps was almost identical to that in the second variant.

The electrical conductivity of the nutrient solution in the substrate from variant 3 remained higher than in the control or the HPS samples. It can be concluded that the nutrient solution with which the crop was watered did not fully meet the requirements of plants lit with LED lamps, therefore, despite a higher yield and increased use of nutrients than in the control, the salinity of the substrate was maintained at an increased level, similarly to that of the control nutrient solution.

It can also be noticed that the electrical conductivity in the third variant tended to increase at the end of the experiment, in contrast to the control, where it remained stable throughout the cultivation period, or to the second one, where it was decreasing.

The highest increase in the monitored parameters appeared in early March in all tested samples. This was due to a temporary large increase in solar radiation. However, after a few days, the amount of sunshine subsided and the parameters returned to normal.

## The first biometric measurement of plants

Plants lit with LEDs had the shortest internodes, their average length was 11.5 cm, while the longest were in the second variant, where HPS lamps were used, and were the average internode was 13.4 cm long (Table 6). In the control sample (without additional lighting), despite the evident shortage of solar radiation in relation to the current needs of plants, the internodes were not the longest, as they measured 12.6 cm on average.

Table 6

Influence of lighting of cucumber plants according to biometric measurements

| Biometric measurement | Combination | Internodes length (cm) | Leaf blade size (cm) | Fruit buds in a node (pieces) | Plant height (cm) | Number of leaves (pieces) | The length of the petioles (cm) | The length of the fruit (cm) |
|---|---|---|---|---|---|---|---|---|
| I measurement (05.02.2020) | control (natural light) | 12.6 | 21x20 | 2 | 88 | - | - | - |
| | HPS | 13.4 | 22x24 | 2 | 100 | - | - | - |
| | LED | 11.5 | 20x25 | 2 | 95 | - | - | - |
| II measurement (20.02.2020) | control (natural light) | 10.3 | 21x27 | 2 | 162 | 13 | 17.7 | - |
| | HPS | 10.8 | 25x33 | 1-2 | 185 | 15 | 18.8 | - |
| | LED | 9.4 | 24x30 | 2-3 | 173 | 15 | 13.4 | - |
| III measurement (05.03.2020) | control (natural light) | 11.5 | 21x26 | 2 | 260 | 15 + 6 collected | 16.9 | 8.8 |
| | HPS | 14.8 | 22x28 | 1-2 | 320 | 18 + 9 collected | 22.0 | 10.5 |
| | LED | 10.0 | 24x25 | 2 | 275 | 17 + 9 collected | 21.3 | 9.3 |
| IV measurement (23.03.2020) | control (natural light) | 10.6 | 24x29 | 2 | 365 | 15 + 15 collected | 17.9 | 8.5 |
| | HPS | 13.5 | 23x26 | 1-2 | 420 | 19 + 18 collected | 22.0 | 10.9 |
| | LED | 10.8 | 23x24 | 2-3 | 375 | 17 + 18 collected | 20.6 | 10.7 |

The observed differences in the length of internodes also influenced the height of the plants themselves. The longest internodes in plants lit with HPS resulted in the tallest plants, on average 100 cm. The lowest plants grew in the trial without additional lighting, where the average height was 88 cm. Although the plants did not have the shortest internodes, they were the lowest. The reason for this was fewer leaves and fewer internodes. In the third variant, the average height of plants lit with LED diodes was 95 cm, which was slightly less than in the second variant, taking into account the differences in the length of internodes.

The length of leaves differed between the combination, but the differences were not significant. The research revealed significant differences in the width of leaf blades. The blades from plants lit with artificial light were much wider than in the control plants. The difference in the width of the lamellae compared to the control was 4 cm for plants under HPS lamps and 5 cm for plants under LED lamps.

The leaves of the control clearly showed symptoms of insufficient sunlight. Leaf blades were the smallest, parallel to the ground, quite thin, very delicate. In the test with HPS lamps, leaf blades were much larger, more elongated and drooping, but they were still quite thin and without characteristic folds. Leaf blades of plants lit with LED lamps looked the best because they were very fleshy, rough, wavy and thick.

Despite the differences in the overall structure of the plant, the plants produced two buds per node during the time of measurement in each of the combinations tested.

At this point, accurate measurements and descriptions of side shoots were not carried out, because some of them had been removed during planting and the measurements would not be reliable. However, there were differences in the shoots. In the third variant, where plants were lit with LED lamps, they were very generative, distinctly shortened, had many buds, and they grew on each node.

In the second variant, in which the plants were lit with HPS lamps, the shoots grew much stronger, they were more vegetative, had fewer buds and did not grow on each node. In plants that did not use additional illumination, side shoots were very weak and the plants produced few buds, which did not grow on each node.

**Second biometric measurement of plants**

The lengths of the internodes of plants without additional illumination and those lit with HPS lamps practically the same, as the difference was exactly 0.5 cm (Table 6). The study showed a change compared to the previous round of measurement, where plants growing under HPS lamps had the longest nodes. The shortest nodes were grown by plants lit with LED lamps.

In the second series of measurement, the size of the leaf blade visibly differed. The control plants had the smallest leaves, which remained delicate, not very elaborate and undulating. Additionally, there were small, light green discolorations at the veins of the leaves. In the second measurement, plants lit with HPS lamps had the largest leaf blades measuring 25 x 33 cm, which indicates that these plants had enough light to develop properly. The leaf blades were large, very drooping, rough, but no characteristic undulations were visible. In plants lit with LED lamps, leaf blades were smaller than those of plants illuminated with HPS lamps, but the plants tended to develop strongly folded, fleshy and rough-surface leaves. At the same time, the length of the petioles began to vary. For control plants, it was on average 17.7 cm. The longest petioles (18.8 cm on average) were found in plants lit with HPS lamps. The biggest surprise was the length of the petioles of plants growing under LED lamps, because they were by far the shortest at only 13.4 cm.

Plants that were not exposed to light were again the lowest on the second date of biometric measurements, and their average height was exactly 162 cm, which, with the longest internodes, translated into a smaller number of grown leaves (13 leaves per plant on average). In the test with high-pressure sodium lamps, cucumber plants were again the highest. Their average height was 185 cm, that is 23 cm more than the control. The number of leaves grown on the plant was 15 on average, exactly the same as found on plants lit with LED lamps, which measured an average of 173 cm.

The number of fruit buds was approximately 2 pieces per node in underexposed plants, from 1 to 2 pieces in plants lit with HPS lamps, and from 2 to 3 pieces for plants lit with LED lamps. Thus, the LEDs stimulated the generative growth of cucumber plants the most.

Side shoots in underexposed plants were characteristic of the variety used, as they grew out of each node. Some varieties grew quite vigorously and vegetatively, having a small number of shoots, and the ones they grew were very short and generative with a large number of fruit buds. Plants growing under sodium lamps were characterized by mainly generative shoots or their complete absence. Vegetative shoots did not emerge at all. In plants lit with LED lamps, all shoots were generative, but they grew on each node.

The root system of cucumber plants that were not exposed to illumination was properly developed, white and with a lot of hairs. However, the plant roots had not completely penetrated the substrate, so the main clusters of the root system were still in the upper or middle part of the mineral wool mat, where the plant was planted. Cucumber plants lit with HPS lamps had a significantly different root system compared to the control sample. It was very strong, strongly developed and grew through the entire substrate. The main roots constituted the vast majority of the roots, while the development of hair roots was very poor. The root system of plants lit with LED lamps was also characteristic. It had a structure similar to the roots from the control sample, i.e. properly developed, white, grown mainly under the plants in the upper and middle part of the substrate. However, the difference was in the preponderance of hair roots dominated, they were the most numerous among all the combinations.

Until 20 February, no ripe fruit was obtained from plants that were not artificially illuminated, hence no data on their parameters. The fruits obtained from plants lit with HPS lamps were the longest and measured on average 10 cm and had a distinct, thick nodule. The color of the skin was adequate, vivid and intensive, but without the characteristic shine. The fruits of plants lit with LED lamps were 1 cm shorter than in the previous sample. They also had a vivid and intensive color, with a distinct shine.

## The third biometric measurement of plants

In the next series measurements, the shortest internodes (10 cm on average) were grown by plants lit with LED lamps (Table 6). Slightly longer internodes, with an average length of 11.5 cm, were found in plants growing without additional lighting. Large differences were found in plants lit with HPS lamps, in which the average length was 14.8 cm, that is 4.8 cm more than in plants lit with LED lamps.

Plant height differed significantly in each trial, which was caused by a different length of internodes and this time also a significant difference in the number of developed leaves. In the first combination, the plant height was 260 cm on average. Of all the trials, these were the lowest plants; they had quite short internodes and fewer leaves (15 leaves grown per plant and 6 removed). Cucumber plants lit with HPS lamps turned out to be the highest again. Their total height was on average 320 cm, and the average number of leaves per plant was 18 pieces and 9 leaves were removed. The plants from the last combination were similar in this respect, as they had an average of 17 leaves per plant and 9 leaves removed; the difference was that the whole plants were 40 cm to 50 cm lower than in the previous sample, and their average height was 275 cm. They also achieved the most uniform height in the combination.

Leaf blades in the control sample did not change much in relation to the previous measurement. Their length was 21 cm and the width was 26, i.e. slightly different from the previous ones. The length of the petioles, compared to previous measurements, was only 0.8 cm bigger. The leaves and petioles in plants lit with HPS and LED showed a significant difference. In both samples, the size of the laminae was significantly reduced with the simultaneous elongation of the internodes and petioles. In the second variant (lighting with HPS lamps), the petioles were extended by an average of 3.2 cm, and in the third one (lighting with LED lamps) – by as much as 7.9 cm.

Internode buds remained similar in each trial. In the control plants and plants lit with LED light, there were 2 buds per node on average, and the only difference from the previous measurements was the fewer buds per node in plants lit with LED lamps. Also, plants lit with HPS lamps had from 1 to 2 buds per node on average.

In the control combination, the presence of side shoots, both vegetative and generative, emerging from each node (characteristic for the cultivar under study) was found. The root system was properly developed. The presence of both main and hair roots was found, growing through the entire mineral wool mat. The progress of root development in the substrate lower layer was noticed.

In combination with HPS lamps, side shoots still tended to be either absent or to grow very poorly while the plants developed a very strong root system, mainly composed of main roots without particularly noticeable hair roots. The root system had already penetrated the entire substrate during the previous test and this tendency continued.

The growth is also stimulated in plants illuminated with LED lamps. Plants formed generative shoots on each node but vigorously growing shoots did not emerge yet. Many buds were formed on these shoots, which the plant was unable to maintain, thus some were shed. The root system was well developed, built of strong main roots with numerous, very well-developed hair roots, and it had penetrated the entire volume of the mat.

The fruit from plant left without artificial lighting was the shortest at 8.8 cm, and did not achieve the length-to-thickness ratio characteristic for this variety. Despite the proper growth of the whole plant and lack of any major problems with the parameters in the substrate, slight discoloration of leaf blades in the vicinity of the nerves appeared again. In the other experimental combination, lit with HPS lamps, the fruits were again the longest at 10.5 cm, but the ratio of length to thickness was also distorted. Plants appeared very large, vigorously growing and expanding in terms of habit, despite the lack of side shoots. The best fruit was from the third combination, where the plants were lit with LED lamps. They were the closest to the right proportions for this variety, but had the least gloss. Overall, the whole plants looked very good.

**The fourth biometric measurement of plants**

At this stage, the differences between the combinations began to blur. This can be seen in data on the internode length. An almost identical length was found in the first and third combinations: 10.6 cm for the control and 10.8 cm for plants lit with LED diodes (Table 6). Only in the combination lit with HPS lamps, the tendency for growing longer internodes continued, but even here the difference diminished to less than 3 cm compared to the other combinations. Also, the size of leaf blades began to equalize. The average length for all combinations ranged around 23 cm and it was 1 cm longer in the control sample than the other combinations, which indicates that the effect of additional lighting on plant growth was diminishing. Slightly larger differences appeared in the case of the width of the leaf blades, but here too the largest leaves (29 cm) were grown by plants without additional lighting. The smallest leaves (24 cm) were on plants illuminated with LED lamps. Slightly larger leaves (26 cm) were measured on plants lit with HPS lamps, but they were only 2 cm larger than the leaves of plants lit with LED lamps.

The number of shoots was similar to the previous measurements. Here, the differences were negligible throughout the experiment. In the combination without plant lighting, there were 2 buds per node, in plants lit with HPS lamps, the tendency to grow from 1 to 2 buds continued. In plants lit with LED lamps, a small increase in fruit setting was noticed, i.e. from 2 to 3 pieces per node.

Plants without additional lighting and plants lit with LED lamps began to grow to the same height. The plants from the control combination had an average height of 365 cm, while those lit with LED lamps were 375 cm tall. Once the amount of sunshine started to increase, the control plants began to catch up with the plants grown under LED lamps. However, in the combination lit with HPS lamps, the plants were still much taller, reaching an average height of 420 cm. In this combination, the number of grown leaves was also the highest, averaging 19 pieces per plant and 18 pieces removed. 2 fewer leaves per plant were found in the combination lit with LED lamps, which gives 17 leaves per plant and also 18 torn off. In the control combination, the plants had 15 grown leaves and 15 ones removed.

The length of the petioles in the first combination slightly changed throughout the experiment, reaching 17.9 cm on the day of the last measurements, slightly shorter (by 2.7 cm) than the petioles of plants from the combination lit with LED diodes. Plants lit with HPS lamps had the longest petioles: 22 cm.

The key difference was the significant weakening of side shoots in all combinations. For the first time, the side shoots did not grow from all the nodes in the control plants, and the ones that appeared were very weak and had trouble fruit setting. A similar tendency was found in the experimental combination, where shoots grew only in about 50% of cases and some of them died out. In plants lit with LED lamps, generative shoots were formed and produced many fruit, but they did not grow in each node either.

The root system in all three combinations was weakened. In the control combination, it penetrated the entire volume of the substrate mat, but it lost vitality as evidenced by a small number of young growths and the loss of a nice white color of hairs. In the HPS combination, the root was mostly composed of main roots but it was possible to notice many more hair roots compared to all previous measurements,. However, despite the appearance of hairs, the root system had the fewest new growths compared to the other variants. In the combination lit with LED lamps, the root growth was weakened, but many young growths were visible, which indicates that the root system in this combination began to regenerate the fastest compared to the root systems of plants growing in the control combination or lit with HPS lamps. However, the number of hair roots had decreased significantly.

The fruit of the plants growing in the control and with HPS lamps did not change their dimensions significantly enough to affect the final measurement results. On the other hand, in the combination lit with LED lamps, the fruit was significantly elongated, measuring on average 10.7 cm, which is 1.4 cm more than in the previous measurement.

### Effects of LED and HPS lighting on the content of selected nutrients and sodium in the dry matter of leaves and cucumbers *Cucumis sativus* L.

Lighting with HPS and LED lamps did not significantly influence the nitrogen content in leaves (Table 7). Lighting with HPS lamps resulted in a higher content of K, Ca, Mg and Na in leaves than the control and plants lit with LED. The cucumber leaves of plants lit with LED lamps had the lowest content of all tested nutrients. Compared to the control and HPS lamp variants, significantly less potassium, calcium, iron, copper and zinc were determined.

Among the tested experimental combinations, the significantly highest nitrogen content in cucumber fruits was found in plants lit with HPS lamps (Table 8). Nitrogen content in cucumber lit by LED diodes did not differ significantly from that found in plant fruits without additional lighting. The highest, statistically significant content of phosphorus, potassium, cal-

Table 7

Effects of HPS and LED lighting on the content of selected nutrients and sodium in the dry matter of *Cucumis sativus* L. leaves

| Chemical element | Type of plant lighting | | |
|---|---|---|---|
| | control (natural light) | HPS | LED |
| N (%) | 4.99 *a* | 4.80 *a* | 4.66 *a* |
| P (%) | 0.70 *b* | 0.63 *a* | 0.63 *a* |
| K (%) | 3.40 *b* | 3.66 *c* | 3.15 *a* |
| Ca (%) | 2.67 *b* | 2.92 *c* | 2.25 *a* |
| Mg (%) | 0.98 *a* | 1.28 *b* | 0.95 *a* |
| Na (%) | 0.049 *a* | 0.052 *b* | 0.048 *a* |
| Fe (mg $kg^{-1}$) | 168.52 *b* | 178.63 *b* | 130.56 *a* |
| Mn (mg $kg^{-1}$) | 241.88 *b* | 173.56 *a* | 188.06 *a* |
| Cu (mg $kg^{-1}$) | 11.10 *c* | 9.99 *b* | 9.00 *a* |
| Zn (mg $kg^{-1}$) | 90.11 *c* | 76.48 *b* | 55.09 *a* |

Table 8

Effects of HPS and LED lighting on the content of selected nutrients and sodium in the dry matter of cucumbers *Cucumis sativus* L.

| Chemical element | Type of plant lighting | | |
|---|---|---|---|
| | control (natural light) | HPS | LED |
| N (%) | 4.04 *a* | 4.39 *b* | 4.02 *a* |
| P (%) | 0.94 *a* | 1.05 *b* | 1.13 *c* |
| K (%) | 6.07 *b* | 5.91 *a* | 6.25 *c* |
| Ca (%) | 0.51 *a* | 0.47 *a* | 0.71 *b* |
| Mg (%) | 0.59 *b* | 0.53 *a* | 0.58 *b* |
| Na (%) | 0.08 *a* | 0.08 *a* | 0.10 *a* |
| Fe (mg $kg^{-1}$) | 176.16 *b* | 155.53 *a* | 157.85 *a* |
| Mn (mg $kg^{-1}$) | 52.71 *a* | 66.52 *b* | 74.99 *b* |
| Cu (mg $kg^{-1}$) | 8.38 *a* | 9.34 *b* | 9.70 *c* |
| Zn (mg $kg^{-1}$) | 56.76 *a* | 60.13 *b* | 63.28 *b* |

cium and copper in cucumber fruits was obtained in plants lit with LED diodes, compared to other methods of plant lighting. As a result of lighting plants with HPS and LED lamps, cucumber fruits had a higher content of manganese and zinc, compared to cucumber fruits with natural light. Lighting of plants with LED and HPS lamps, compared to control fruits, reduced the content of iron in cucumber fruits. No statistically significant differences were found in the sodium content of cucumber fruits as a result of plant lighting.

KUMAR et al. (2016) conducted an experiment on cucumbers grown in mini-greenhouses, in which overhead lighting in the form of HPS lamps and inter-row lighting with the use of one and two strips of LED lamps were used. There was a significant increase in the amount of chlorophyll in the lower leaves, the quality of the fruit also improved and the overall yield increased by 22.3% with a single LED lighting strip and by 30.8% with two-strip lighting compared to lighting only upper.

An experiment carried out by KOWALCZYK et al. (2020) showed that the leaves of cucumber plants lit with high-pressure sodium lamps placed above the tops of the plants caused faster leaf aging compared to lighting using LED technology. This is confirmed by the higher ion concentration Ca, Mg, S, Mn and B with a simultaneous lower concentration of K ions in the lower leaves of plants.

Research on the influence of various radiation wavelengths on the growth and development of plants was also carried out by HOGEWONING et al. (2012). An experiment by HOGEWONING et al. (2012) involved lighting cucumber and tomato plants with various setups of artificial light. These were, among others, HPS lamps and two types of LEDs. The first combination (LED RB) consisted of a 15% blue / 85% red spectrum, while the second (LED RB - FR) was a 15% blue / 85% red spectrum with a far red combination. The results show that the length of the stem in both tomato and cucumber was greatest in the case of LEDs with an additional far red spectrum and the shortest in the case of LEDs with only red and blue light. The results were similar regarding the length of petioles. In the cucumber, the length of petioles was the longest under the RB-FR LEDs and averaged 14.2 cm. This was over 60% more than the length of petioles under the illumination of HPS, where an average length of 8.6 cm was measured. Significant differences also appeared in the dry matter content. The highest values were recorded in the combination of RB - FR LEDs in both tested species: 4.5 g for cucumber and 6.0 g for tomato. For comparison, the dry weight of the combinations with HPS lamps and RB LEDs was similar for both species without significant differences. Furthermore, the diameter of the stem, the number of leaves and the average area of the leaves were similar in both tomato and cucumber. The differences in measurements were negligible and it was impossible to assess the effect of different light sources on the growth and development of plants from those results.

An experiment carried out by Novičkovas et al. (2012) indicates that light in the form of wavelengths 470 nm, 505 nm and 530 nm significantly improved cucumber growth, while 455 nm LEDs had a negative effect on plants because the cucumbers were shorter, had smaller leaves and inhibited growth. In a study carried out by Trouwborst et al. (2010), the inter-row lighting of cucumber in winter cultivation using LED lamps with a spectrum of only red to blue light in the 80% to 20% ratio affected the course and efficiency of plant photosynthesis in its lower leaves, causing an increase in leaf mass per area and dry matter allocation to leaves. At the same time, additional lighting in the rows of plants did not increase the total plant biomass and did not increase the cucumber yield compared to the top illumination.

Lighting cucumbers with different light sources also causes differences in the nutrient content of dry matter in different parts of the plant. A study by Kowalczyk et al. (2020) showed the differences in the content of markers and micronutrients in leaf blades and petioles, for example under the influence of ovearhead lighting with sodium lamps and overhead and inter-row lighting with LED diodes. Fully developed leaves, taken from two different heights, were used for the tests. Thhey were 3-5 and 10-12 leaves counting from the top. In our experiment, we found out that – regardless of the method of illumination and the type of light source – leaf blades were characterized by a higher content of macronutrients, such as N, Mg, Ca, S, and micronutrients, such as Fe, Cu, Mn, Zn, than determined in leaf petioles. On the other hand, the content of K in petioles was more than five as high as in leaf blades. The samples collected from the younger leaves showed a higher content of K ions with a lower concentration of Ca, Mg, S, Zn, Mn and B ions compared to older leaves growing lower. Based on our results, it can be concluded that the biggest differences in the concentration of nutrients depending on the light source and the method of illumination appeared in the combination with LEDs for upper and inter-row lighting, because the plants in this variant had the highest content of P ions Ca, Mg, S, Cu, Zn, and B in petioles. Plants grown only with upper lighting using HPS lamps were characterized by the highest amount of Ca and Mg ions in leaf blades, especially in older leaves.

## CONCLUSIONS

1. Lighting *Cucumis sativus* L. with sodium and LED lamps results in higher fruit yields.

2. Providing plants with artificial light (HPS and LED lamps) accelerates the harvest of *Cucumis sativus* L.

3. The fruit of *Cucumis sativus* L., lit with HPS lamps is characterized by a higher content of nitrogen.

4. The fruit of *Cucumis sativus* L. lit with LED diodes is characterized by a higher content of potassium, phosphorus, calcium and copper.

5. Lighting of *Cucumis sativus* L. with LED and HPS lamps, compared to plants with natural light, reduced the content of iron in cucumber fruits.

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