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„Áhrif LED topplýsingar á forræktun tómata, agúrku og papriku"

FINAL REPORT

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„Áhrif LED topplýsingar á forræktun tómata, agúrku og papriku“

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Abbreviations

DS	dry substance
E.C.	electrical conductivity
HPS	high-pressure vapour sodium lamps
kWh	kilo Watt hour
LED	light-emitting diodes
pH	potential of hydrogen
W	Watt

Other abbreviations are explained in the text.

1 SUMMARY

In Iceland, winter production of greenhouse crops is totally dependent on supplementary lighting and has the potential to extend seasonal limits and replace imports during the winter months. Adequate guidelines for lighting under LEDs are not yet in place for transplant production of tomatoes, sweet pepper and cucumbers and need to be developed. The objective of this study was to test if the light source is affecting growth and quality of seedlings and if light related costs can be decreased by the selection of the light source.

An experiment with ungrafted tomatoes (*Lycopersicon esculentum* Mill. cv Completo), sweet pepper (*Capsicum annuum* L. cv. Gialte) and cucumbers (*Cucumis sativus* L. cv. SEncere) was conducted during winter 2020 / 2021 in the experimental greenhouse of the Agricultural University of Iceland at Reykir. Seedlings were grown in rockwool plugs and cubes. Seedling production took six weeks for tomatoes, ten weeks for sweet pepper and five weeks for cucumbers. Two different light treatments as top lighting with 18 hours light were applied: 1. high-pressure vapour sodium lamps (HPS, 228 µmol/m^2/s) and 2. light emitting diodes (LED, 230 µmol/m^2/s). The day and night temperature was 20°C. The underheat was 35°C. No CO_2 was applied. Seedlings received standard nutrition as needed. The effect of the light source was tested and evaluated economically.

The germination rate was independent of the light source, but the further seedling development and their quality was influenced by the light source. Substrate temperature and leaf temperature was significantly higher under HPS lights. Young plants had a lower plant height and were more compact when grown under LEDs compared to HPS lights. In addition, transplants of tomatoes and sweet pepper had extra shoots coming out of the axils under LEDs.

Seedlings of cucumbers had a significantly higher stem diameter, fresh and dry biomass yield under HPS lights than under LEDs, whereas for seedlings of tomatoes and sweet pepper were no significant differences in these parameters between light sources found. This might be attributed to the stimulated biomass production of tomatoes and sweet pepper under LEDs and with that suppressing an otherwise possible advantage of HPS lights. The higher LAI of the biggest cucumber leaf under HPS lights might have attributed to the significantly higher biomass yield compared to seedlings grown under LEDs. The dry aboveground yield to height ratio was for all

seedlings higher under LEDs than under HPS lights. The number of leaves was for tomatoes and cucumbers independent of the light source. This effect was also observed for sweet pepper before the devision of the stem into two tops, but after that was the number of leaves significantly increased by LEDs, possibly because of their stimulation of additional growth.

Using LEDs was associated with about 15 % lower daily usage of kWh’s, resulting in 15 % lower expenses for the electricity but nearly three times higher investment costs compared to HPS lights. With that were the total light related costs higher for LED lighted seedlings than HPS lighted ones. The energy use efficiency was independent of the light source for seedlings of cucumbers, whereas for tomatoes and sweet pepper was light better transferred into yield under LEDs.

Results of the measurement parameters on seedlings have shown very clearly that different species may react different to the kind of supplemental light, indicating the necessarity of a species specific supplemental light selection. However, same families, as demonstrated with nightshades (*Solanceae*), might react more similar to the light source, whereas different plant families (*Solanceae* versus *Cucurbitaceae*) might show a different or contrary reaction. The used type of LED and their wavelength (ratio red:blue) in other experiments might explain possible controversial results within same plant families.

The tested high wire transplants were evaluated as too compact under LEDs and hampered therefore working after transplanting. In addition, the removal of additional shoots was adding to time-consuming. Therefore, seedling production of high wire crops only under LEDs cannot be recommended. At least hybrid lighting should be applied to seedlings that require later a high wire culture to ensure not too compact transplants. However, the quality of herbs, flowers and not high wire vegetables might be increased by LED lighting.

Possible recommendations for saving energy costs are discussed. From an economic viewpoint, it is not recommended to grow seedlings under LEDs in winter. Before LEDs can be adviced in practice, more scientific studies are needed: Further experiments must show which ratio of LED to HPS lights and which wavelength combinations are recommended for high wire transplants in order to get not too compact plants. Therefore, so far a replacement of the HPS lamps by LEDs is not recommended.

YFIRLIT

Vetrarræktun í gróðurhúsum á Íslandi er algjörlega háð aukalýsingu. Viðbótarlýsing getur lengt uppskerutímann og komið í stað innflutnings að vetri til. Fullnægjandi leiðbeiningar vegna forræktunar á tómötum, papriku og agúrkum undir LED ljósum eru ekki til staðar og þarfnast frekari þróunar. Markmiðið var að prófa hvort ljósgjafi (HPS eða LED) hefði áhrif á vöxt og gæði græðlinga og hvort hægt væri að minnka ljóstengdan kostnað með val á ljósgjafa.

Gerð var tilraun með óágrædda tómata (*Lycopersicon esculentum* Mill. cv. Completo), papriku (*Capsicum annuum* L. cv. Gialte) og agúrku (*Cucumis sativus* L. cv. SEncere) veturinn 2020 / 2021 í tilraunagróðurhúsi Landbúnaðarháskóla Íslands að Reykjum. Græðlingar voru ræktaðir í steinullarkubbum og forræktun af tómötum tók sex vikur, af papriku tíu vikur og af agúrkum fimm vikur. Prófaðar voru tvær mismunandi ljósmeðferðir sem topplýsing í 18 klst. ljósi: 1. háþrýsti-natríumlömpum (HPS, 228 µmol/m^2/s) og 2. ljósdíóðu (LED, 230 µmol/m^2/s). Dag- og næturhiti var 20°C. Undirhiti var 35°C. Ekkert CO_2 var gefið. Græðlingar fengu næringu eftir þörfum. Áhrif ljósgjafa voru prófuð og ávinningur þeirra metinn.

Spírunarhlutfall var óháð ljósgjafa, en frekari vöxtur græðlinga og gæði þeirra voru undir áhrifum af ljósgjafa. Hiti í ræktunarefni og laufhiti var marktækt hærri undir HPS ljósum. Græðlingar voru styttri og þéttvaxnari þegar þeir voru ræktaðar undir LED ljósum í samanburði við HPS ljós. Að auki voru tómata- og paprikugræðlingarnir með fleiri sprota sem komu út úr blaðöxlum.

Agúrkugræðlingarnir höfðu marktækt hærra þvermál stofns, blaut- og þurrvigt undir HPS ljósum en undir LEDs, en aftur á móti voru tómata- og paprikugræðlingarnir með engan marktækan mun á milli ljósgjafa í þessum breytum. Þetta gæti verið rakið til örvaðrar framleiðslu af lífmassa í uppskeru á tómötum og papriku undir LEDs og með því að bæla niður mögulegt forskot HPS ljósa. Hærra LAI stærsta gúrkublaðsins undir HPS ljósum gæti verið rakið til marktækt hærri lífmassa uppskeru miðað við græðlinga sem ræktaðir undir LEDs. Hlutfall þurrvigtar og hæðar var fyrir allar plöntur hærra undir LEDs en sem ræktaðir eru undir HPS ljósum. Fjöldi laufa fyrir tómata og agúrku var óháð ljósgjafa. Þessi áhrif komu einnig fram fyrir papriku áður en stofn skiptist í tvo toppa, en eftir það jókst marktækt fjöldi laufa með notkun LEDs, mögulega vegna örvunar þeirra á auknum vexti.

Með notkun LEDs var um 15 % minni dagleg notkun á kWh, sem leiddi til lægri útgjalda fyrir raforku, en næstum þrefalt hærri fjárfestingarkostnaðar miðað við HPS ljós. Þar með var heildar ljósatengdur kostnaður hærri fyrir græðlinga undir LEDs en fyrir græðlinga undir HPS ljósum. Skilvirkni orkunotkunar var óháð ljósgjafa fyrir agúrkugræðlingana, en fyrir tómata- og paprikugræðlinga var ljós betur tilfært í lífmassa uppskeru undir LEDs.

Niðurstöður af mælingarbreytum á græðlingum hafa sýnt mjög skýrt að mismunandi tegundir geta brugðist mismunandi við ljósgjafa, sem gefur til kynna nauðsyn að val á viðbótarlýsingu eigi að vera tegundasértækt. Hins vegar gætu sömu plöntufjölskyldur, eins og sýnt var fram með náttskugga (*Solanceae*), brugðist svipað við ljósgjafa, en mismunandi plöntufjölskyldur (*Solanceae* samanborið við *Cucurbitaceae*) gætu sýnt önnur eða andstæð viðbrögð. Tegundir LED sem voru notaðar og litróf þeirra (hlutfall rautt:blátt) í öðrum tilraunum gætu skýrt mögulegar umdeildar niðurstöður innan sömu plöntufjölskyldna.

Græðlingar voru metnir of þéttvaxnir undir LEDs og hindraði það umhirðu þeirra eftir að búið var að planta græðlingum. Að auki var tímafrekt að fjarlægja viðbótarsprotana. Þess vegna er ekki mælt með framleiðslu á græðlingum, sem þarfnast ræktunaraðferðar á vír, eingöngu undir LEDs. Að minnsta kosti ætti að nota hybrid lýsingu á forræktunarplöntur sem þurfa seinna ræktun á vír til að tryggja ekki of þéttvaxna græðlinga. Hins vegar gætu gæði jurta, blóma og grænmetis sem ekki er háð ræktunaraðferð á vír aukist við LED lýsingu.

Möguleikar til að minnka rafmagnskostnað eru taldir upp í umræðunum í þessari skýrslu. Frá hagkvæmnisjónarmiði er ekki mælt með því að rækta forræktunarplöntur með LEDs á veturna. Hins vegar vantar meiri reynslu á ræktun undir LED ljósum: Frekari tilraunir verða að sýna fram á hvaða hlutfall LED og HPS ljósa og hvaða litróf er mælt með fyrir græðlinga sem ræktaðir eru á vír til að fá ekki of þéttvaxnar plöntur. Þess vegna er ekki mælt með því að skipta HPS lömpum út fyrir LED að svo stöddu.

2 INTRODUCTION

The extremely low natural light level is the major limiting factor for winter greenhouse production in Iceland and other northern regions. Therefore, supplementary lighting is essential to maintain year-round vegetable production. This could replace imports from lower latitudes during the winter months and make domestic vegetables even more valuable for the consumer market.

The positive influence of artificial lighting on plant growth, yield and quality of tomatoes (*Demers* et al., 1998a), cucumbers (*Hao* & *Papadopoulos*, 1999) and sweet pepper (*Demers* et al., 1998b) has been well studied. It is often assumed that an increment in light intensity results in the same yield increase (*Marcelis* et al., 2006). Indeed, yield of sweet pepper in the experimental greenhouse of the Agricultural University of Iceland at Reykir increased with light intensity (*Stadler* et al., 2010). However, with tomatoes, a higher light intensity resulted in only a slightly higher yield (*Stadler*, 2013).

Supplemental lighting that is normally used in greenhouses has no or only a small amount of UV-B radiation. High pressure sodium (HPS) lamps are the most commonly used type of light source in greenhouse production due to their appropriate light spectrum for photosynthesis and their high efficiency. The spectral output of HPS lamps is primarily in the region between 550 nm and 650 nm and is deficient in the UV and blue region (*Krizek* et al., 1998). However, HPS lights suffer from restricted controllability and dimming range limitations (*Pinho* et al., 2013). In Iceland has it been common to use HPS lamps with electromagnetic ballast. However, HPS lamps with electronic ballast would safe about 8 % energy according to the company Gavita (*Nordby*, oral information). Therefore, it is appropriate to replace HPS lamps with an electromagnetic ballast. This is especially important as the energy costs having a big share in the total production costs of vegetables and the subsidy rate is decreasing.

Light-emitting diodes (LED) have been proposed as a possible light source for plant production systems and have attracted considerable interest in recent years with their advantages of reduced size and minimum heating plus a longer theoretical lifespan as compared to high intensity discharge light sources such as HPS lamps (*Bula* et al., 1991). These lamps are a radiation source with improved electrical efficiency (*Bula* et al., 1991), in addition to the possibility to control the light spectrum and the light intensity, which is a good option to increase the impact on growth and plant development. Several plant species (tomatoes, strawberries, sweet pepper, salad, radish) have been successfully cultured under LEDs (e.g. *Philips*, 2017; *Philips*, 2015; *Tamulaitis* et al., 2005; *Schuerger* et al., 1997; *Brown* et al., 1995; *Hoenecke* et al., 1992). However, with HPS was achieved a significantly higher fresh yield of salad in comparison to LEDs. But, two times more kWh was necessary with only HPS lights in comparision with only LEDs. The only use of HPS lights resulted in the highest yield, while the yield with only LEDs was about ¼ less (*Stadler,* 2015). In contrast, the light source did not affect the weight of marketable yield of winter grown strawberries. But, the development of flowers and berries and their harvest was delayed by two weeks under LED lights. This was possibly be related to a higher leaf temperature in the HPS treatment due to additional radiation heating. However, nearly 45 % lower daily usage of kWh's under LEDs were recorded (*Stadler*, 2018). These results are requesting scientific studies with different temperature settings to compensate the additional heating by the HPS lights and the delayed growth and harvest. When the air temperature was adapted was it possible to compensate the additional heating by the HPS lights and prevent a delayed growth and harvest of strawberries (*Stadler*, 2019) and tomatoes (*Stadler*, 2020).

So far, only the influence of LED lights on salad and on vegetables that were grown in order to harvest fruits, has been researched in Iceland: Seedlings were grown the first weeks under same light conditions and the experiment started, when seedlings were planted into different light treatments. However, the requirements to get a good harvest are among others dependent on the quality of the seedlings. Therefore, is it also important to test the influence of the light on seedlings. Seedlings of high quality fullfill the following characteristics: Good growing speed, leaf area index, rooting system and shoot root ratio. Such experiments with seedlings under either HPS or LED lights are also in limited quantity abroad. For example described *Hernández* & *Kubota* in the year 2015 that no studies are available regarding the comparision of HPS with LED supplemental lighting to produce transplants of greenhouse vegetables. On the other hand were many studies performed, where various wavelengths of LEDs have been tested on (vegetable) seedlings. Experiments, where seedlings under different light treatments (HPS or LED lights) were tested, are first and foremost found with seedlings of flowers: Seedlings of flowers were lower and with a higher diameter of the stem under LED lights with 15 % blue and 85 % red light compared to HPS light (*Randall* & *Lopez*, 2014). The authors concluded that most transplants that were grown under LEDs with both red and blue light were with a comparable or better quality than plants that were grown under HPS lights. LED light improved the quality of Japanese lady bell transplants by increasing stem diameter, biomass, leaf weight and root to shoot ratio compared to HPS light (*Liu* et al., 2019). In roses, stem elongation and leaf area were generally lower for plants grown under LED light while fresh and dry weight was unaffected by the lamp type (*Bergstrand* et al., 2016).

Light experiments with seedlings of vegetable plants under LED and HPS lights are very limited in recent years and results indicate that: Leaf thickness of tomato plants increased by 12 % when grown under LED lights with a ratio of 88:12 red:blue light compared to plants grown under HPS lights (*Dueck* et al., 2012b). Tomato seedlings that were grown undir LED lights were more compact, with a lower plant height, shorter stem and the leaf area was lower (*Bergstrand* et al., 2016). An experiment with grafted tomato seedlings showed that root length, biomass, leaf number, leaf chlorophyll (SPAD), scion dry weight to height ratio, specific leaf weight were the greatest for grafted seedlings grown under LEDs compared to HPS lights (*Wei* et al., 2018). But, before LEDs are put into practice on a larger scale, more knowledge must be acquired on effects of LED lighting on crops (*Dueck* et al., 2012b).

As tomatoes, cucumbers and sweet pepper are the vegetables that are most grown in greenhouses in Iceland, will the seedling production of these species be tested. It is important to test different plant species, as the may react differently to supplemental lighting and therefore, to improve the growth of in greenhouse cultivated seedlings should the selection of the kind of supplemental lighting be species specific. For example, *Hernández & Kubota* (2014) reported that the growth of tomato plants under 100 % red LEDs was comparable to that under HPS light, but the growth of cucumber plants was higher under HPS than 100 % red LED lighting. Also, *Treder* et al. (2016) reported that tomatoes respond differently than cucumbers to different light treatments. This indicates that it is important to test the cultivation of the main vegetable species in Iceland under different light treatments.

Experience of seedling production of vegetable plants under LEDs (top lighting) in Iceland is not available and therefore, the effect of light on transplants over the high winter (with low levels of natural light) need to be tested under Icelandic conditons.

Incorporating lighting into a production strategy is an economic decision involving added costs versus potential returns. Therefore, the question arises whether these factors are leading after the young production stage to an appropriate yield, which will be part of a further experiment.

The objective of this study was to test if (1) HPS top lighting compared to LED top lighting is affecting growth and quality of seedlings of tomatoes, sweet pepper and cucumbers, if (2) it is possible to save energy costs without reducing development, and if (3) light related costs can be decreased by the choice of the light source. This study should enable to strengthen the knowledge on the best method of growing seedlings and give vegetable growers advice how to improve their production by modifying the efficiency of seedling production.

3 MATERIALS AND METHODS

3.1 Greenhouse experiment

An experiment with seedlings of tomatoes (*Lycopersicon esculentum* Mill. cv. Completo), sweet pepper (*Capsicum annuum* L. cv. Gialte) and cucumbers (*Cucumis sativus* L. cv. SEncere) and two different light sources was conducted in two chambers of the Agricultural University of Iceland at Reykir during winter 2020 / 2021:

1. HPS top lighting (**HPS**),
2. LED top lighting (**LED**).

Used were HPS lights with an electronic ballast and 600 W bulbs (Philips). LED top lights „Green power LED“ TL1.2 HO modules, deep red / white types (DR/W LB) from the company Signify were installed. The lamps were distributed in the way that seedlings got the most equal light distribution according to the light plan of Signify for the LED lights and of Agrolux for the HPS lights (Tab. 1). Lights were mounted horizontally in 2,8 m distance over the canopy, which corresponds to a height of 3,7 m from the floor.

Tab. 1: Number of lights and their distribution in the chambers.

Light treatment	Lights	Lights/chamber (no)	Distance between lights
HPS	HPS top lighting	12	3 C profiles with 4 HPS, 2,5 m for HPS distance centre centre and 2 m for HPS centre centre
LED	LED top lighting	36	9 C profiles with 4 modules, 1,1 m for HPS distance centre centre and 1,3 m for HPS centre centre

In average, the light level under HPS top lighting (228 µmol/m^2/s) was comparable with LED top lighting (230 µmol/m^2/s) (Tab. 2). The setup of the HPS lights was corresponding to 144 W/m^2. In addition, white plastic on all surrounding walls helped to get a higher light level at the edges of the growing area. Light was provided for 18 hours from 05.00-21.00.

Tab. 2: Light distribution of the HPS and LED chamber.

Middle bed in chamber (distance from glas)	HPS µmol/m^2/s	LED µmol/m^2/s
0,5 m	224	195
1,5 m	231	240
2,5 m	228	255
average	**228**	**230**

Completo from De Ruiter is a compact vigourous variety suitable for truss and loose harvest with a high yielding potential and uniform fruit weight of 90-95 g (*De Ruiter*, without year).

Gialte from Enza Zaden is a yellow block pepper with exceptional production and quality. The flexible nature of this variety makes it well suited to all cultivation systems (*Enza Zaden*, without year).

SEncere from Nunhems has a high virus resistance in combination with a high production. SEncere is a cucumber variety intended for traditional cultivation in summer and autumn (*Nunhems*, 2018).

On 02.11.2020 were seeds of tomatoes and sweet pepper sown in small rockwool plugs (plug size: 2 cm diameter x 2,7 cm high, Grodan® Plantop Plug). On 09.11.2020 were seeds of cucumbers sown in rockwool cubes (cube size: 10 cm long x 10 cm wide x 6,5 cm high, Grodan® Delta). Seeds were covered with plastic until germination and kept under 23°C. Tomato seedlings were transplanted in rockwool cubes (cube size: 10 cm long x 10 cm wide x 6,5 cm high, Grodan® Delta) one week after sowing and sweet pepper seedlings two weeks after sowing. As needed was the space between cubes increased in the row to one cube between cubes and one cube between rows. Later was the distance increased in the row to two cubes between cubes and one and a half cube between rows. Cubes were placed in the middle table of each chamber. Seedling production of tomatoes took six weeks (until 14.12.2020), of sweet pepper ten weeks (until 11.01.2021) and of cucumbers five weeks (until 14.12.2020). At the end of the seedling production had tomatoes developed one cluster, sweet pepper was dividing the stem into two tops and started to flower and cucumbers had developed six leaves.

The temperature was set on 20°C during day and 20°C during night. Ventilation started at 22°C. The underheat was set to 35°C. No carbon dioxide was provided. Installed was a misting system. Humidity was set to 70 %. To be able to decrease differences in the air temperature resulting of the high radiation heat under HPS lights, was the LED treatment set up next to a chamber that was characterized by high temperatures.

Seedlings were watered on a regular basis. Seedlings received standard nutrition consisting of calcium nitrate and “YaraTera™ Kristalon™ Scarlet” (N 7,5 %, P_2O_5 12 %, K_2O 36 %, MgO 4,5 %, SO_3 10 %, B 0,027 %, Cu 0,004 %, Fe 0,075 %, Mn 0,06 %, Mo 0,004 %, Zn 0,027 %) as needed.

3.2 Measurements, sampling and analyses

Substrate temperature was measured in 1-2 cm depth by a portable thermometer (TP1110-HD2307.0 Temperature meter, Nieuwkoop, Aalsmeer, The Netherlands) and leaf temperature by a portable infrared contact thermometer (BEAM infrared thermometer, TFA Dostmann GmbH & Co. KG, Wertheim-Reicholzheim, Germany) by hand.

In the beginning of the experiment were days until germination and germination rate counted. To be able to determine plant development, were randomly five seedlings of each light treatment measured weekly. The height (hypocotyl length + epicotyl length) of the plants, length and width of the biggest leaf was measured using a ruler. The number of leaves (a leaf was counted as a leaf when the length of the leaf was 2 cm or more) was counted. The diameter of the stem was measured immediately above the cotyledones using an electric digital caliper. The fresh yield of the leaves was measured and the fresh yield of the stem after cutting the stem at the substrate surface line. Samples were dried at 105°C for 24 h to determine dry matter yield of the leaves and dry matter yield of the stem. In addition, at the end of the seedling production was the dry matter yield of the roots (together with the rockwool cube) measured.

The leaf area of the biggest leaf was calculated as follows:

- For tomatoes: Length of the leaf x width of the leaf x 0,347 - 10,7 (*Blanco & Folegatti*, 2003),
- For sweet pepper: Length of the leaf x width of the leaf x 0,57 (*Rodríguez Padrón* et al., 2016),
- For cucumbers: Length of the leaf x width of the leaf x 0,347 + 2,7 (*Blanco & Folegatti*, 2003)

The ratio of dry aboveground biomass to height and the fresh and dry leaf weight to total biomass weight ratio was calculated.

Energy use efficiency (total cumulative biomass yield in weight per kWh) was calculated for economic evaluation.

3.3 Statistical analyses

SAS Version 9.4 was used for statistical evaluations. The results were subjected to one-way analyses of variance with the significance of the means tested with a Tukey/Kramer HSD-test at $p \leq 0,05$.

4 RESULTS

4.1 Environmental conditions for growing

4.1.1 Solar irradiation

Solar irradiation was allowed to come into the greenhouse. Therefore, incoming solar irradiation was affecting plant development and was regularly measured. The natural light level was low during the whole growing period. The value decreased from 2 kWh/m²/week after sowing continuously to less than 0,5 kWh/m²/week at the end of October and was staying at this value until the end of the experiment (Fig. 1).

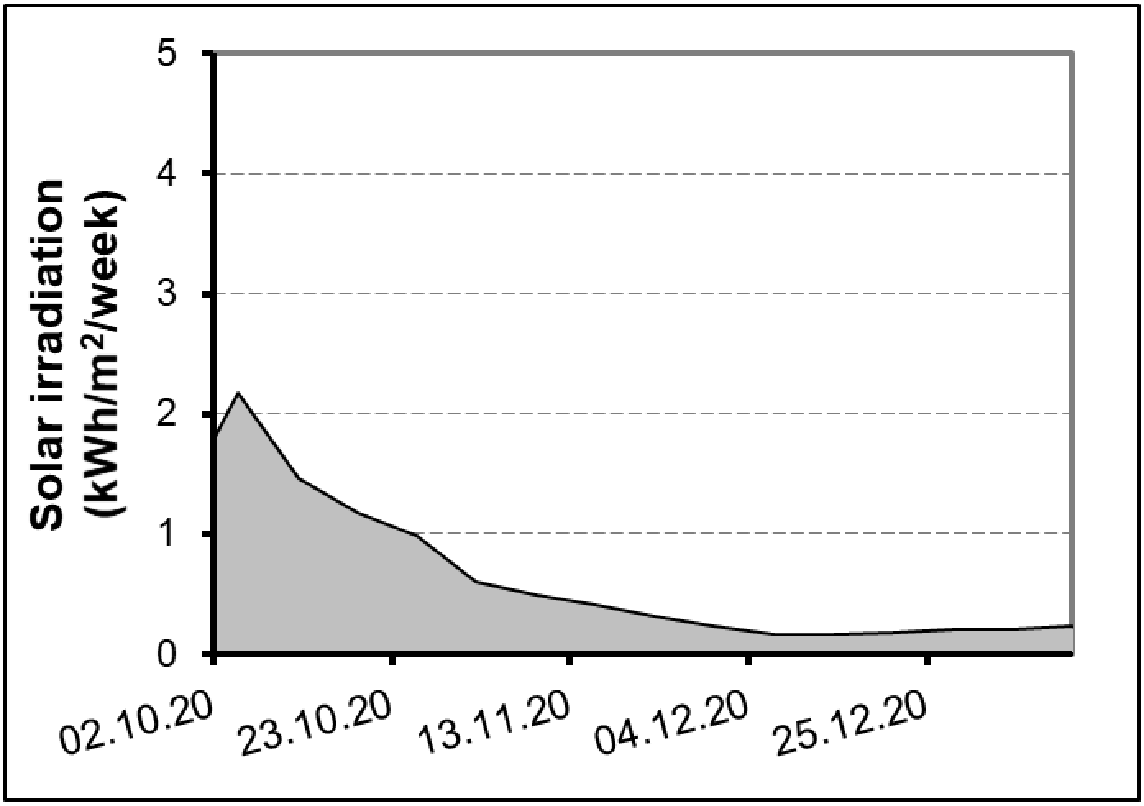

Fig. 1: Time course of solar irradiation.
Solar irradiation was measured every day and values for one week were cumulated.

4.1.2 Chamber settings

The settings in the chambers were regularly recorded. Table 3 shows the average of the air temperature (average, day, night), floor temperature (day, night) and windows opening.

The average air temperature amounted around 20-22°C and was in average about 0,8°C higher in the LED chamber as both the day as well as the night temperature was higher in the LED chamber compared to the HPS chamber as result of the higher temperature in the nighboring chamber next to the LED chamber. At the end of November was a problem with keeping heat in the greenhouse. The heat went down to 14°C. At the same time was a problem with the greenhouse computer, resulting that at this time were no data recorded.

The floor temperature during day and night was 33-40°C and was comparable between chambers. Windows were nearly the whole time during the experiment closed.

Tab. 3: Settings of the HPS and LED chamber according to greenhouse computer.

	Chamber	**Average**	**Min**	**Max**	**02.11-8.11**	**09.11-15.11**	**16.11-22.11**	**23.11-29.11**	**30.11-06.12**	**07.12-13.12**
Air (°C)	LED	**21,4**	14,3	23,8	21,7	22,7	20,9	Problem with the greenhouse computer, data was not recorded	21,0	20,3
	HPS	**20,6**	18,9	22,8	20,7	21,8	19,4		20,3	20,4
(°C) day	LED	**21,8**	14,4	24,5	22,0	23,3	21,5		21,1	20,7
	HPS	**21,1**	19,9	23,0	21,0	22,3	20,2		20,4	20,8
(°C) night	LED	**20,7**	14,1	23,0	20,9	21,9	19,9		20,6	19,9
	HPS	**20,1**	16,9	22,8	20,0	21,4	18,0		19,9	20,1
Floor (°C) day	LED	**34,5**	22,6	35,1	35,0	35,0	35,0		34,9	32,9
	HPS	**36,4**	34,0	38,8	37,2	37,2	36,8		35,9	35,3
Floor (°C) night	LED	**34,6**	22,8	38,1	35,0	35,0	35,0		35,5	33,1
	HPS	**37,5**	33,8	49,6	37,6	36,6	37,1		39,8	36,5
Windows opening 1 (%)	LED	**1,3**	0,0	13,7	4,4	0,7	0,0		1,0	0,0
	HPS	**0,2**	0,0	2,8	0,8	0,1	0,0		0,1	0,0
Windows opening 2 (%)	LED	**3,3**	0,0	22,0	7,1	2,9	0,6		0,9	3,8
	HPS	**0,5**	0,0	6,0	1,4	0,3	0,0		0,3	0,2

4.1.3 Germination

Seeds of tomatoes started to germinate six days after sowing, sweet pepper seven days and cucumbers three days after sowing (Fig. 2). It seems that tomatoes germinated earlier under LED lights, whereas this was not observed for sweet pepper and cucumbers. However, some days later were for all species no differences in the germination rate between light sources observed. A lower number at the end of germination compared to some days ahead was related to the fact that seeds germinated, but did not develop any further.

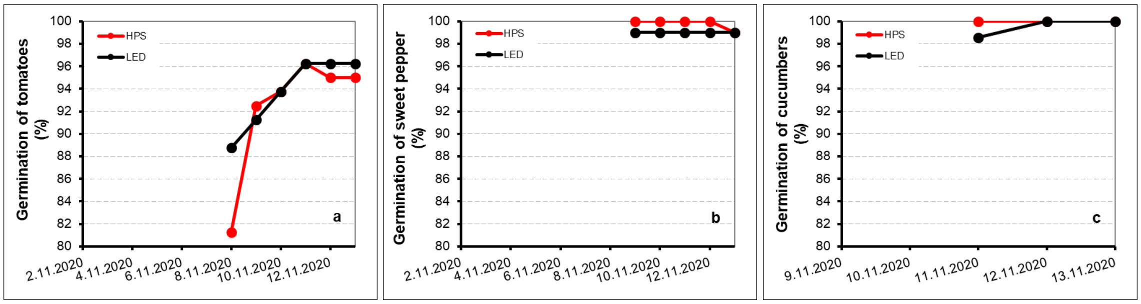

Fig. 2: Germination of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

4.1.4 Substrate temperature

Substrate temperature was measured weekly at low solar radiation in the morning at around 08.30 and fluctuated between 18-20°C (Fig. 3). Substrate temperature was in average significantly higher in the HPS treatment compared to the LED treatment. The difference amounted 0,3-1,0°C and was less pronounced with cucumbers.

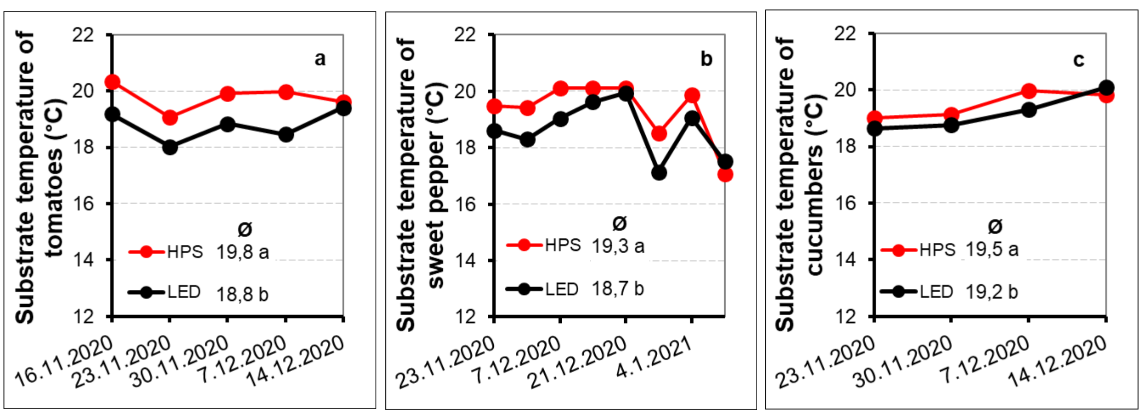

Fig. 3: Substrate temperature of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences (HSD, $p \leq 0,05$).

4.1.5 Leaf temperature

Leaf temperature was measured weekly at low solar radiation in the morning at around 08.30 and fluctuated between 14-20°C (Fig. 4). Leaf temperature was in average significantly higher in the HPS treatment compared to the LED treatment. The difference amounted 1,4-1,9°C.

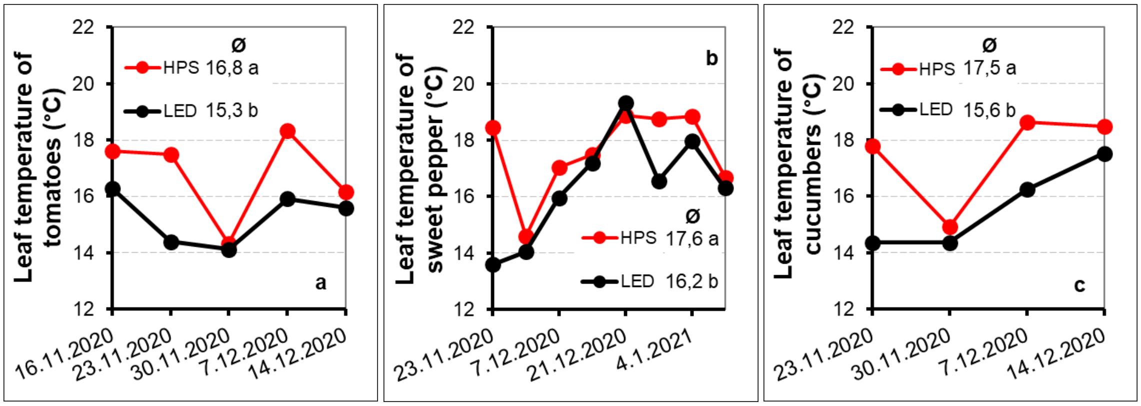

Fig. 4: Leaf temperature of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences (HSD, p ≤ 0,05).

4.2 Development of seedlings

4.2.1 Plant diseases and pests

Neither plant diseases nor pests were observed. However, at the beginning of the growth period were on some cucumber seedlings yellow spots on the cotyledons under LEDs (Fig. 5).

Fig. 5: Yellow spots on cotyledons on seedlings of cucumbers under LEDs.

4.2.2 Appearance of seedlings

Seedlings of tomatoes, sweet pepper and cucumbers were bigger under HPS lights and more compact under LED lights (Fig. 6). In addition, especially young plants of sweet pepper had a lot of additional growth under LEDs compared to HPS lights. Many extra shoots were coming out of the axil. This was also observed for seedlings of tomatoes under LEDs, but to a lesser extent than for sweet pepper. Seedlings of cucumbers had neither under LED lights nor under HPS lights additional growth. Plants that received HPS lights had a taller hypocothyl compared to plants that received LED light.

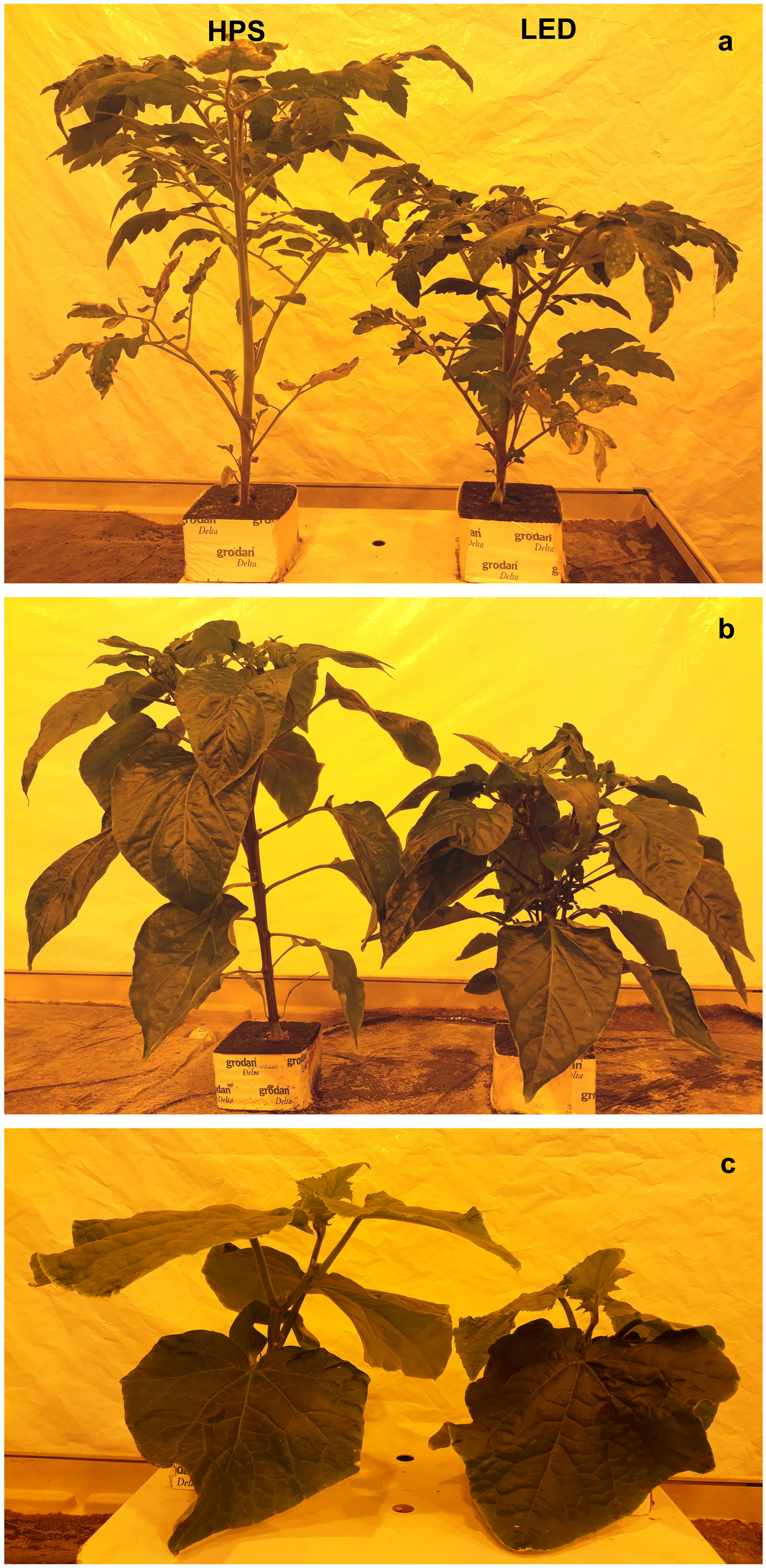

Fig. 6: **Seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under HPS and LED lights at the end of young plant production under different light sources.**

4.2.3 Height

Seedling of tomatoes, sweet pepper and cucumbers were significantly taller under HPS lights compared to LED lights (Fig. 7). Transplants under LED lights were about 10 cm smaller and with that more compact.

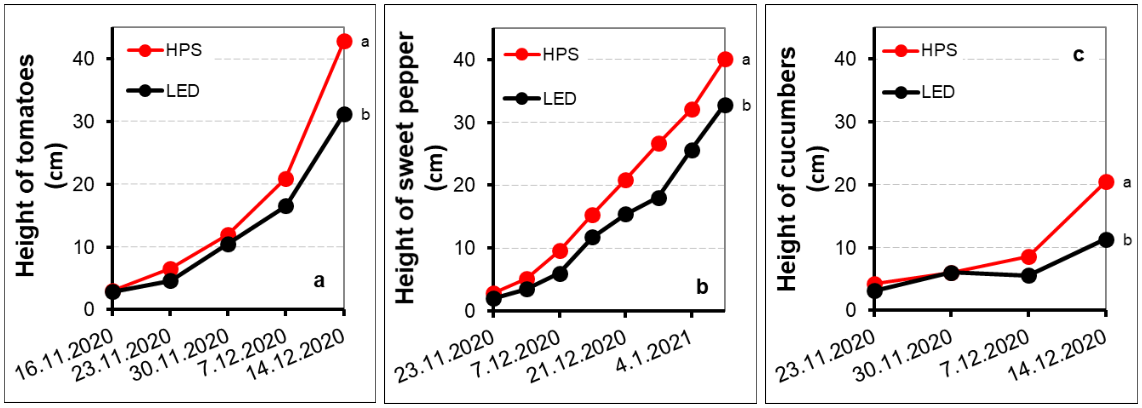

Fig. 7: Height of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.2.4 Diameter of the stem

The diameter of the stem increased during seedling production of tomatoes, sweet pepper and cucumbers. At the end of seedling production was the stem diameter independent of the light source for tomatoes and sweet pepper. However, for cucumbers was measured a significantly higher stem diameter under HPS lights compared to LEDs (Fig. 8).

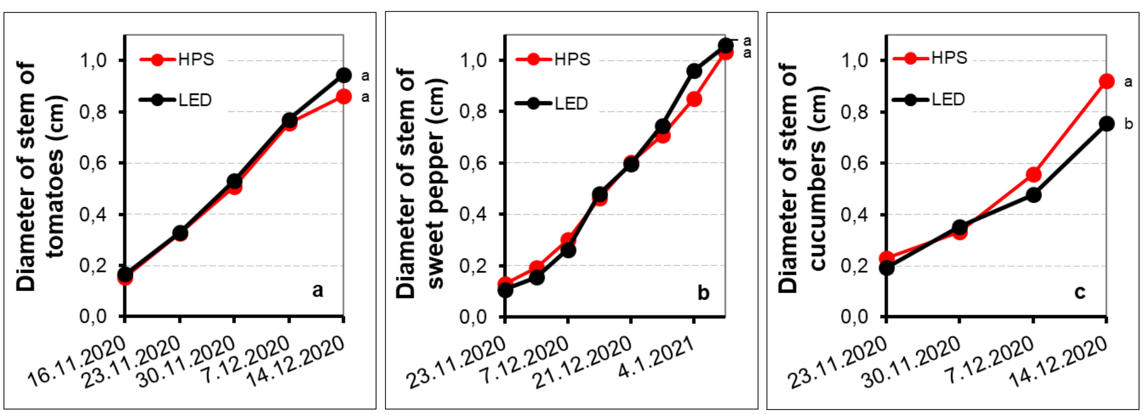

Fig. 8: Diameter of the stem of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.2.5 Number of leaves

During seedling production developed seedlings of tomatoes around ten leaves, sweet pepper around 60 leaves and cucumbers around six leaves. The number of leaves was independent of the light source for tomatoes and cucumbers. Also, sweet pepper had during the first weeks of seedling production the same amount of leaves under different light sources. However, at the two last sampling dates were statistic differences observed (data for the second last sampling date not shown), sweet pepper seedlings had significantly more leaves under LEDs compared to HPS lights (Fig. 9).

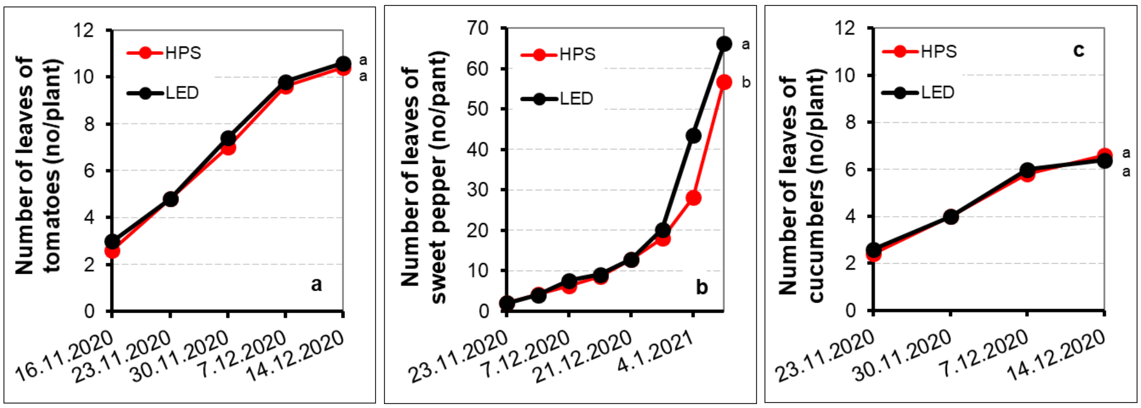

Fig. 9: Number of leaves on seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.2.6 Length of leaves

Length of the biggest leaf increased until the end of the experiment to about 35 cm for tomatoes, 25 cm for sweet pepper and 20-25 cm for cucumbers (Fig. 10). At the end of the seedling production was the length of the biggest leaf of tomatoes and cucumbers significantly taller for plants grown under HPS lights compared to LEDs. For sweet pepper was for all sampling dates (data not shown), except for the last sampling date, significant differences between light sources observed.

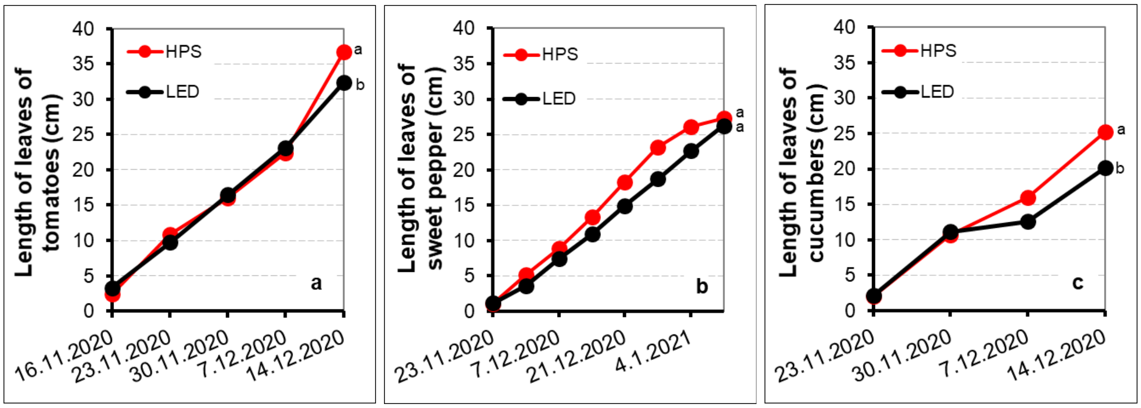

Fig. 10: Length of leaves on seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.2.7 Width of leaves

Width of the biggest leaf increased until the end of the experiment to about 35 cm for tomatoes, 10 cm for sweet pepper and 20 cm for cucumbers (Fig. 11). At the end of the seedling production was the length of the biggest cucumbers leaf significantly taller for plants grown under HPS lights compared to LEDs. However, for tomatoes and sweet pepper were at the end of the seedling production no significant differences between light sources observed.

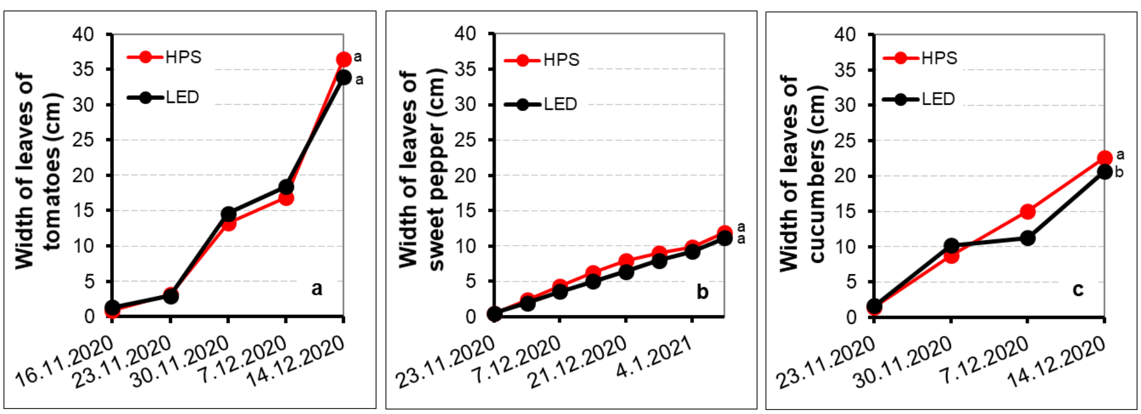

Fig. 11: Width of leaves on seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.2.8 Leaf area

The calculated leaf area of the biggest leaf increased during the seedling production of tomatoes, sweet pepper and cucumbers. Leaf area was significantly higher under HPS lights compared to LEDs for tomatoes and cucumbers (Fig. 12). For sweet pepper was the leaf area independent of the light source.

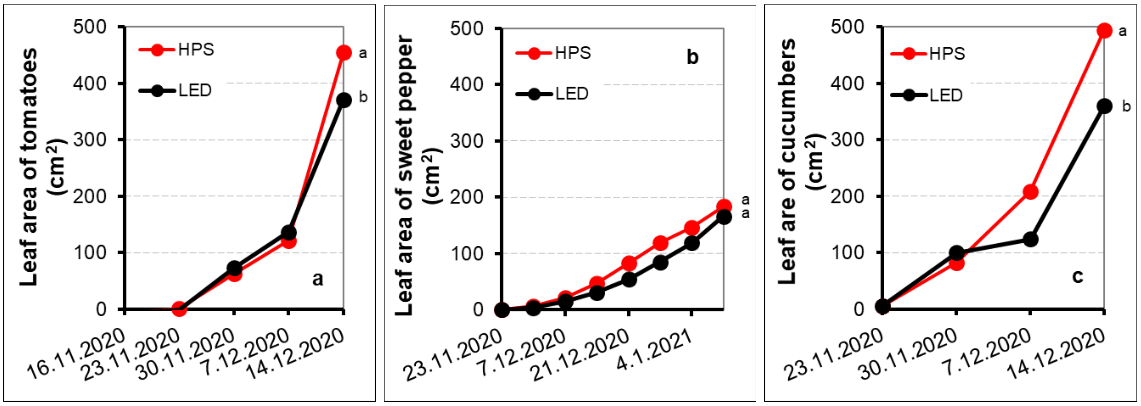

Fig. 12: Leaf area of the biggest leaf of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.3 Yield

4.3.1 Fresh biomass yield

4.3.1.1 Fresh yield of leaves

The fresh yield of leaves of seedlings of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 13). For tomatoes and sweet pepper was the fresh yield of leaves not statistically different between light sources. However, tendentially was the fresh yield of leaves higher under LEDs. This difference amounted about 20 %. At the second last sampling date was the fresh yield of leaves of tomatoes and sweet pepper significantly higher under LEDs (data not shown). In contrast, for cucumbers, was the fresh yield of leaves significantly higher under HPS lights.

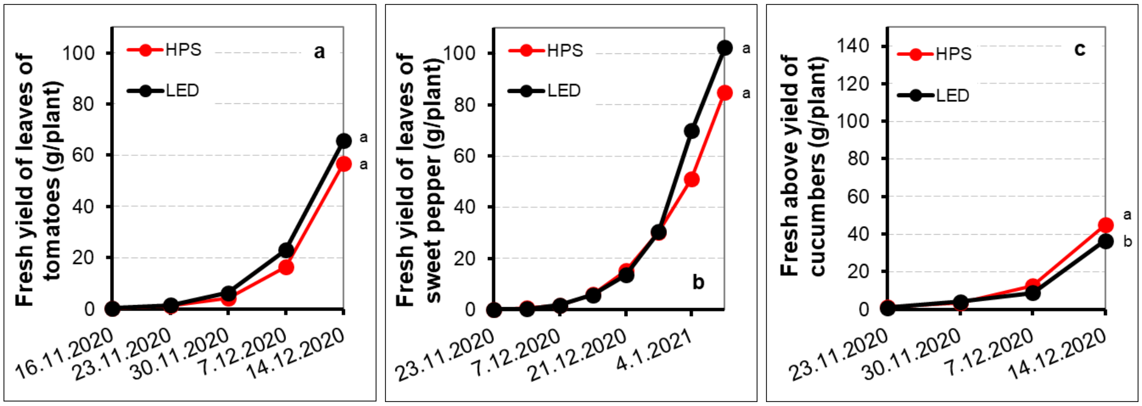

Fig. 13: Fresh yield of leaves of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.1.2 Fresh yield of the stem

The fresh yield of the stem of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 14). The fresh yield of the stem was at the end of the young plant production higher under HPS lights compared to LEDs. For tomatoes and cucumbers was this difference statistically different, but for sweet pepper was only a tendentially difference observed. However, at most of the before sampling dates for sweet pepper was also here a significantly higher fresh yield of the stem under HPS lights measured (date not shown).

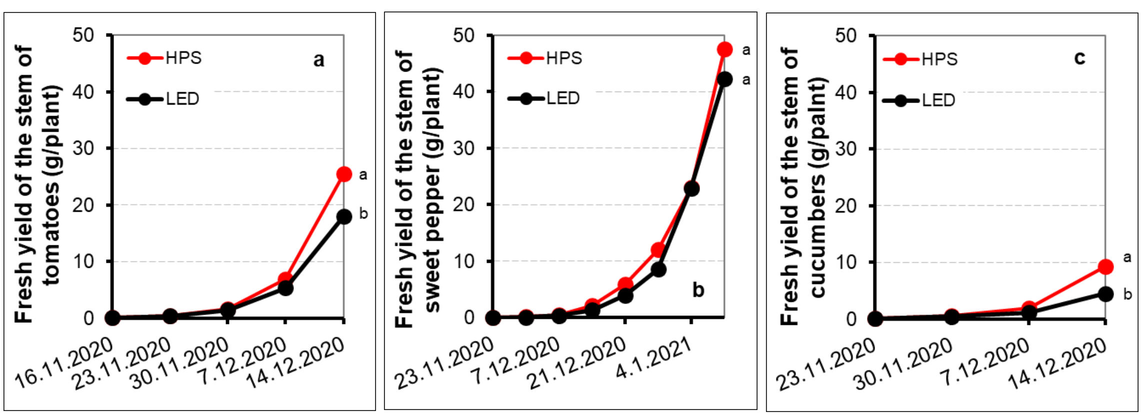

Fig. 14: Fresh yield of the stem of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.1.3 Fresh aboveground yield

The fresh aboveground yield of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 15). The fresh aboveground yield was for tomatoes and sweet pepper independent of the light source, while for cucumbers was a significantly higher aboveground fresh yield under HPS lights observed.

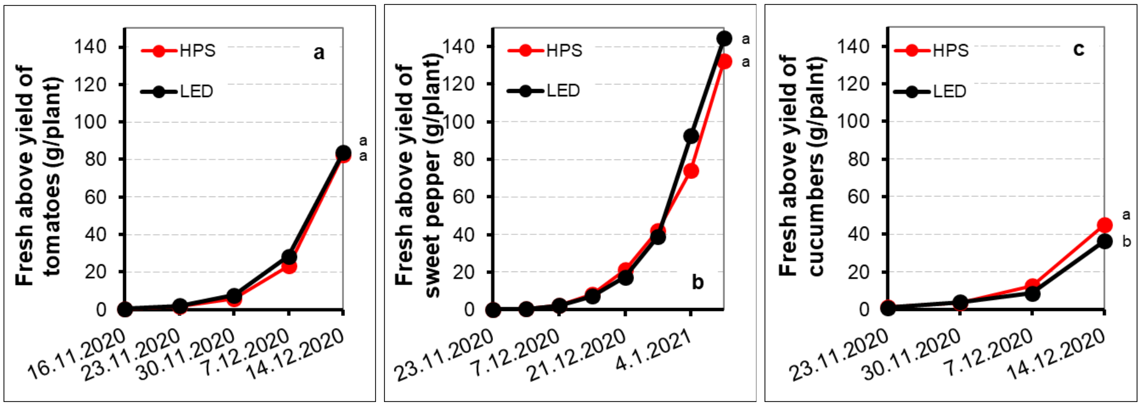

Fig. 15: Fresh aboveground yield of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.3.1.4 Fresh leaf weight to aboveground weight ratio

The fresh leaf weight to aboveground weight ratio stayed more or less the same during the seedling production for tomatoes and cucumbers, but decreased for sweet pepper (Fig. 16). The fresh leaf weight to aboveground weight ratio was significantly higher under LEDs compared to HPS lights.

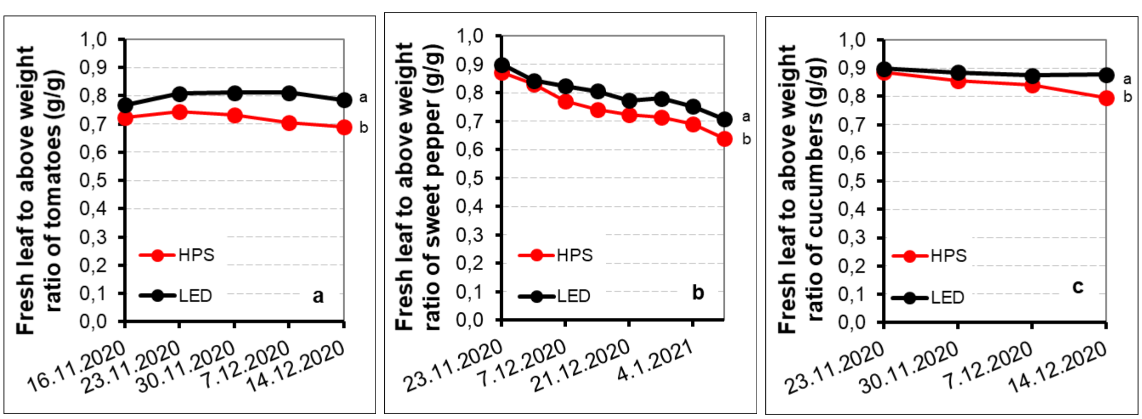

Fig. 16: Fresh leaf weight to aboveground weight ratio of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.3.2 Dry biomass yield

4.3.2.1 Dry yield of leaves

The dry yield of leaves of seedlings of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 17). For tomatoes and cucumbers was the dry yield of leaves independent of the light source. However, for sweet pepper was the dry yield of leaves significantly higher under LEDs.

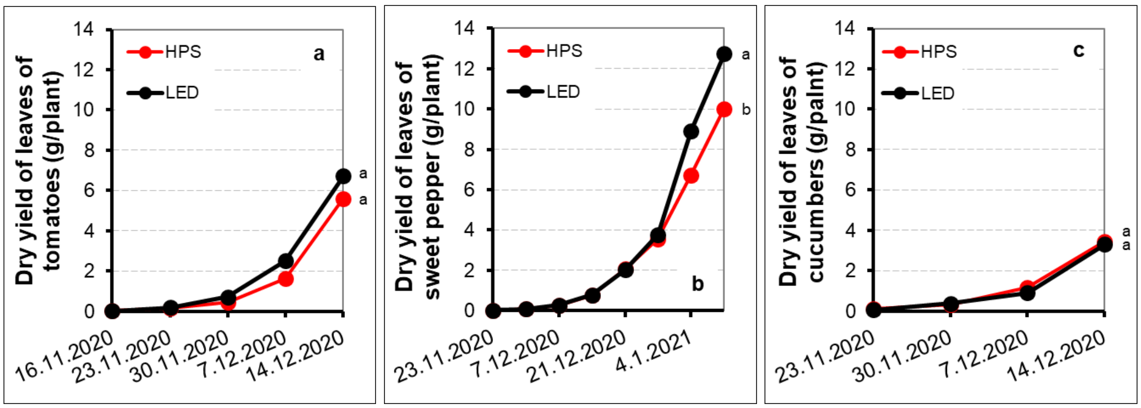

Fig. 17: Dry yield of leaves of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.2.2 Dry yield of the stem

The dry yield of the stem of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 18) and was at the end of the young plant production significantly higher under HPS lights than under LEDs for tomatoes and cucumbers, but for sweet pepper independent of the light source.

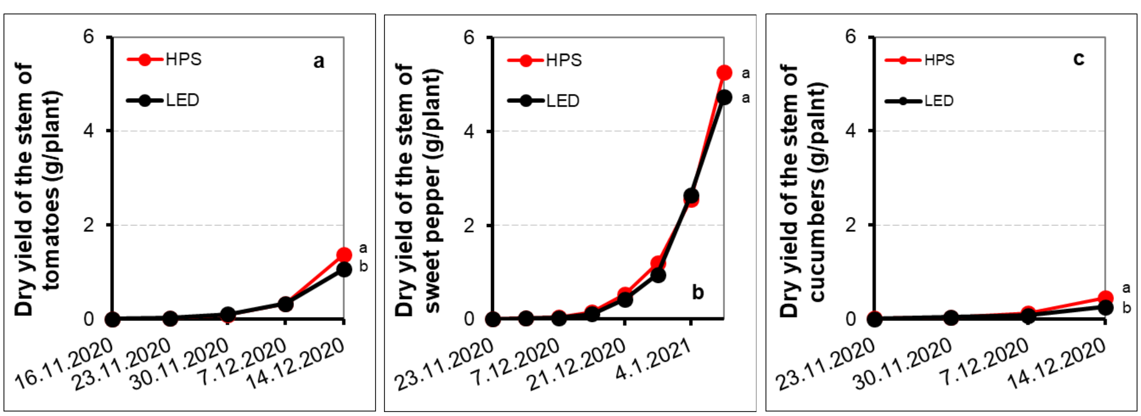

Fig. 18: Dry yield of the stem of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.2.3 Dry aboveground yield

The dry aboveground yield of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 19). The dry aboveground yield was for tomatoes and sweet pepper independent of the light source, while for cucumbers was a significantly higher dry aboveground yield under HPS lights measured.

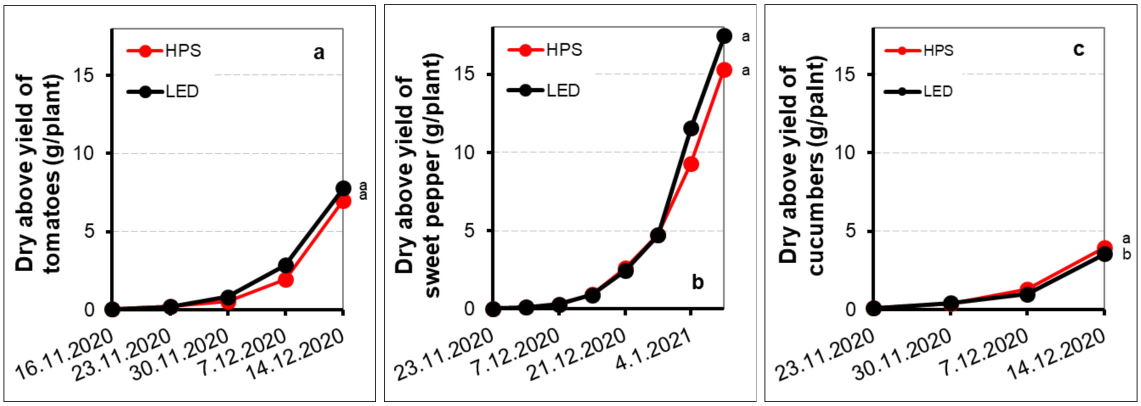

Fig. 19: Dry aboveground yield of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.3.2.4 Dry leaf weight to aboveground weight ratio

The dry leaf weight to aboveground weight ratio stayed more or less the same for seedlings of tomatoes and cucumbers during the seedling production, but decreased for sweet pepper (Fig. 20). The dry leaf weight to aboveground weight ratio was significantly higher under LEDs compared to HPS lights for seedlings of tomatoes, sweet pepper and cucumbers.

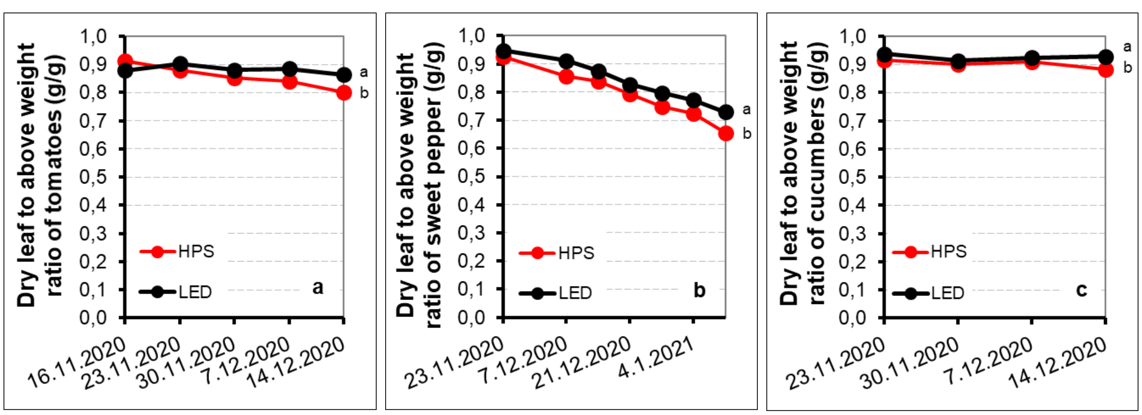

Fig. 20: Dry leaf weight to above weight ratio of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.3.2.5 Dry aboveground yield to height ratio

The dry aboveground yield to height ratio of seedlings of tomatoes, sweet pepper and cucumbers increased during the young plant production (Fig. 21). The dry aboveground yield to height ratio was for seedlings of tomatoes, sweet pepper and cucumber significantly higher under LEDs than under HPS lights.

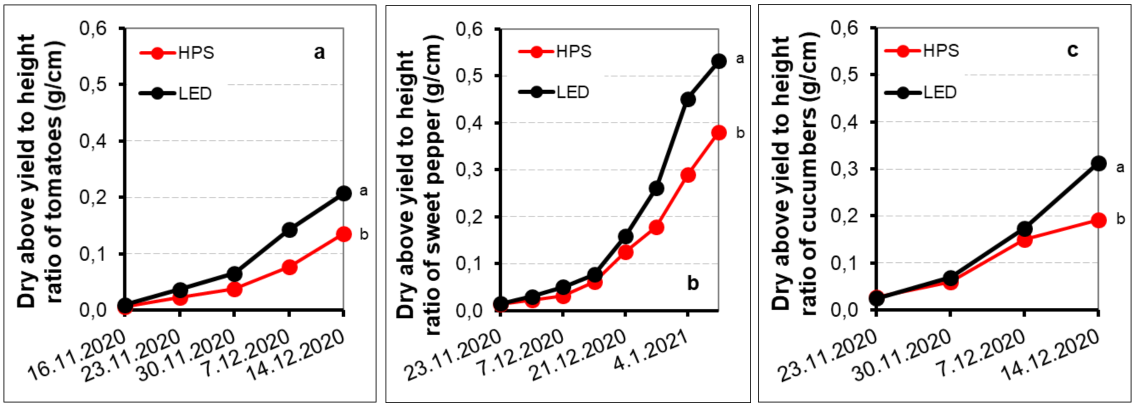

Fig. 21: Dry aboveground yield to height ratio of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.2.6 Dry root yield

The dry root yield included the yield of the roots together with the rockwoll cube. The dry root yield was independent of the light source for tomato and cucumbers. However, for sweet pepper was a significantly higher dry root yield measured under LEDs (Tab. 4)

Tab. 4: Dry root yield of seedlings of tomatoes, sweet pepper and cucumbers under different light sources.

	Tomato	Sweet pepper	Cucumber
Treatment	——— Dry root yield (g/plant) ———		
HPS	51,3 a	50,6 b	47,0 a
LED	50,5 a	54,1 a	47,1 a

Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.3 Interior quality

4.3.3.1 Dry substance of leaves

Dry substance (DS) of the leaves of seedlings of tomatoes, sweet pepper and cucumbers changed little during the young plant production. Leaves seem to have a slightly higher DS under LEDs. However, at the end of young plant production were only for cucumbers significant differences regarding light sources measured (Fig. 22).

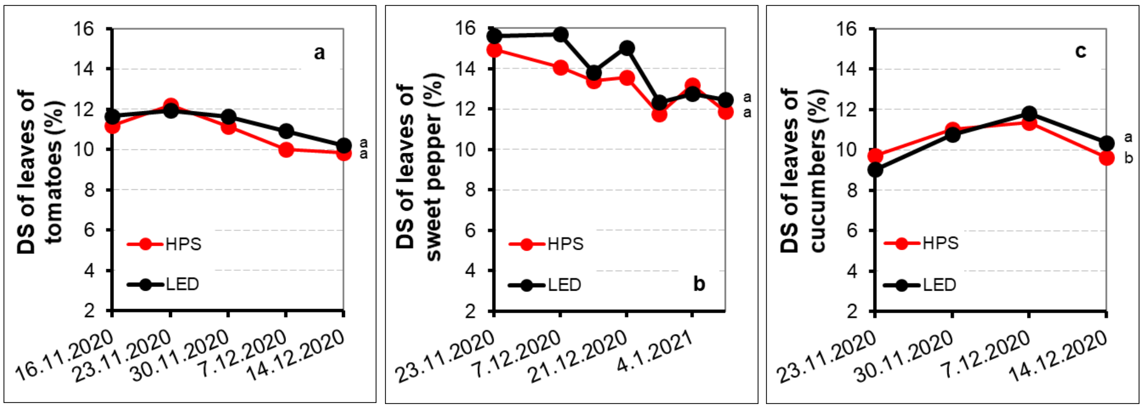

Fig. 22: Dry substance of leaves of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.3.3.2 Dry substance of the stem

The dry substance of the stem of sweet pepper increased during the young plant production, while for tomatoes and cucumbers were little changes during the young plant production observed (Fig. 23). DS of the stem was tendentially (sweet pepper, cucumbers) or even statistically higher (tomatoes) under LEDs.

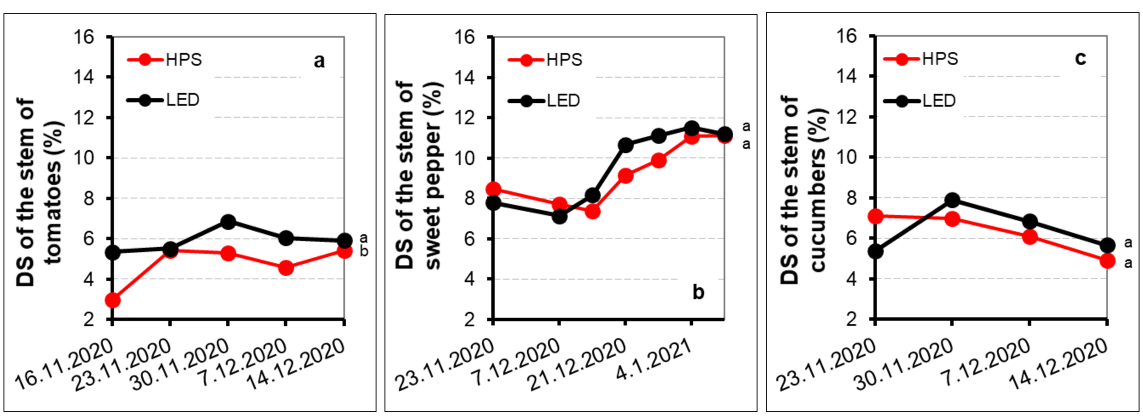

Fig. 23: Dry substance of the stem of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.4 Economics

4.4.1 Used energy

The number of lighting hours is contributing to high annual costs and needs therefore special consideration to consider decreasing lighting costs per kg “yield”. The total hours of lighting and the used kWh’s during the growth period of seedlings of tomatoes, sweet pepper and cucumbers were measured with dataloggers.

The HPS chamber had a daily usage of 118 kWh, while the LED chamber had with 100 kWh 15 % less energy use (Fig. 24). This means that the costs for growing seedlings with HPS lights are higher, due to 18 % higher energy costs.

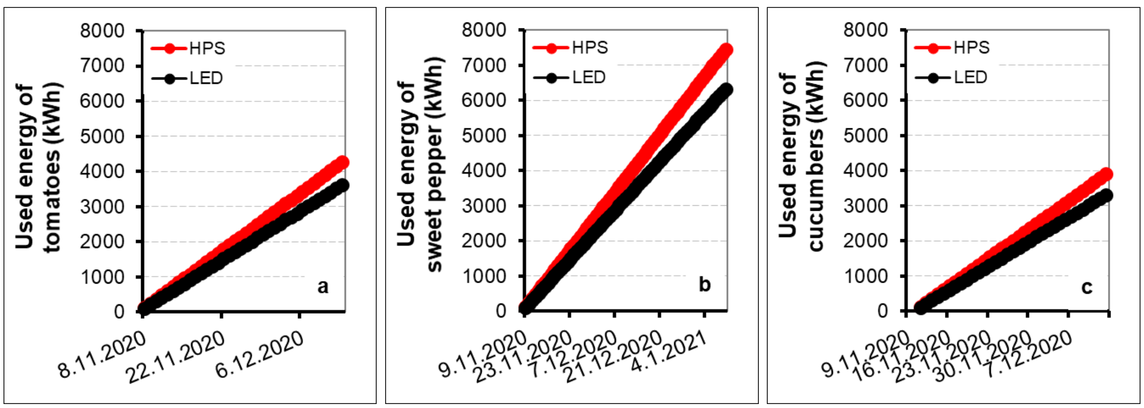

Fig. 26: Used kWh of seedlings of tomatoes (a), sweet pepper (b) and cucumbers (c) under different light sources.

The energy per squaremeter and the power was only a bit lower with LEDs compared to HPS lights (Tab. 4).

Tab. 5: Used energy under different light sources (datalogger values).

	Tomatoes		Sweet pepper		Cucumbers	
Treatment	HPS	LED	HPS	LED	HPS	LED
Energy (kWh)	4.246	3.601	7.443	6.310	3.891	3.300
Energy/m² (kWh/m²)	85	72	149	126	78	66

A relation between yield and kWh was found, a high usage of kWh resulted also in a higher fresh aboveground biomass yield. Thereby was the gradient steeper for HPS lights, meaning more energy was necessary to produce biomass (Fig. 25).

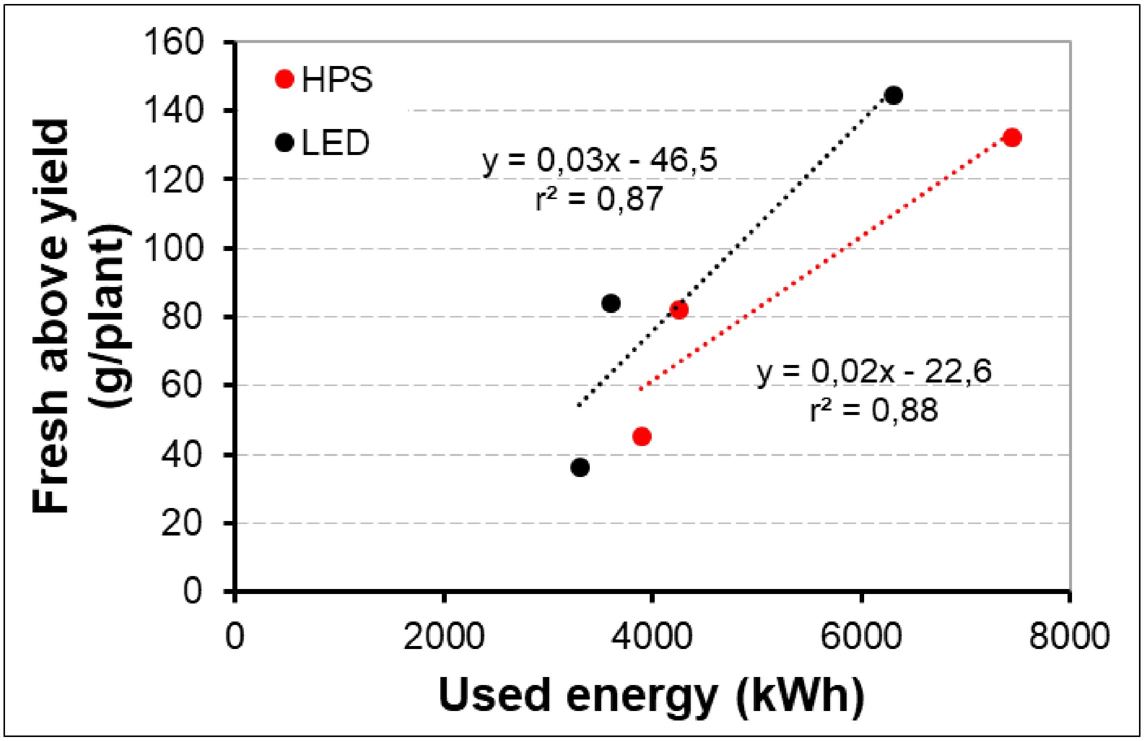

Fig. 25: Relationship between used energy and fresh aboveground biomass yield under different light sources.

4.4.2 Energy use efficiency

Seedlings of tomatoes and sweet pepper transferred the used energy better into yield than seedlings of cucumbers. When seedlings were lightened with LED lights, significantly more (sweet pepper) or tendentially more (tomatoes) fresh biomass yield was reached per kWh compared to HPS lights (Fig. 26). That means that by using LEDs, the kWh's were transferred better into yield for seedlings of sweet pepper and tomatoes. However, for cucumbers was the energy use efficiency independent of the light source.

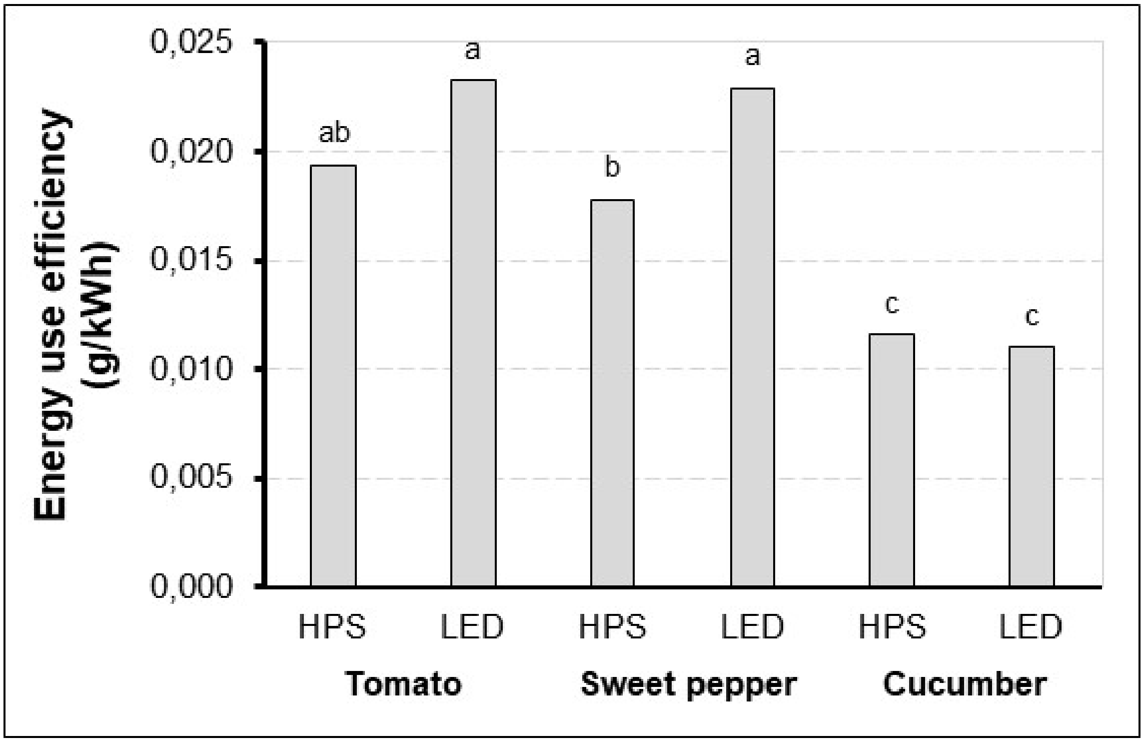

Fig. 26: Energy use efficiency (= fresh above biomass yield per used energy) for seedlings of tomatoes, sweet pepper and cucumbers under different light sources.

4.4.3 Light related costs

Since the application of the electricity law 65/2003 in 2005, the cost for electricity has been split between the monopolist access to utilities, transmission and distribution and the competitive part, the electricity itself. Most growers (95 %) are, due to their location, mandatory customers of RARIK, the distribution system operator (DSO) for most of Iceland except in the Southwest and Westfjords.

The government subsidises the distribution cost of growers that comply to certain criteria's. In recent years, the subsidies fluctuated quite much. In the year 2019 was about 95 % of variable cost of distribution subsidised according to Orkustofnun, which resulted in costs of about 1 ISK/kWh for distribution, while for the sale values amounted 5,77-6,53 ISK/kWh. However, it has to be taken into account that big vegetable growers can get at least 50 % discount on the tariff values. Based on this information, were energy costs for seedling production of tomatoes, sweet pepper and cucumbers calculated (Tab. 6). Costs for electricity were naturally higher for seedlings grown under HPS lights due to the higher use of electricity. However, investment costs into lights were nearly three times higher for LEDs compared to HPS lights. Therefore, in total were light related costs (electricity costs + investment into lights) of seedling production about 25 % higher for LEDs (Fig. 27).

Tab. 6: Energy costs and investment into lights in seedling production for one growing circle of tomatoes, sweet pepper and cucumbers under different light sources.

	Tomato		Sweet pepper		Cucumber	
Costs (ISK/m²)	HPS	LED	HPS	LED	HPS	LED
Electricity distribution [1]	85	72	149	126	78	66
Electricity sale [2]	490-555	415-470	860-973	727-823	450-509	381-431
∑ Electricity costs	575-640	487-542	1.009-1.122	853-949	528-587	447-497
Lamps [3]	120	483	192	773	96	386
Bulbs [4]	57		91		46	
∑ Investment into lights	**177**	**483**	**283**	**773**	**142**	**386**
Total light related costs	**753-817**	**971-1.025**	**1.292-1.405**	**1.626-1.722**	**670-729**	**833-883**

1 Assumption: In average around 1 ISK/kWh after 95% substitution from the state (according to data from Orkustofnun in the year 2019)

2 Assumption: Around 5,77-6,53 ISK/kWh (according to data from Orkustofnun in the year 2019)

3 HPS lights: 27.100 ISK/lamp, life time: 8 years, LEDs: 50.000 ISK/lamp, life time: 11 years

4 HPS bulbs: 4.000 ISK/bulb, life time: 2 years

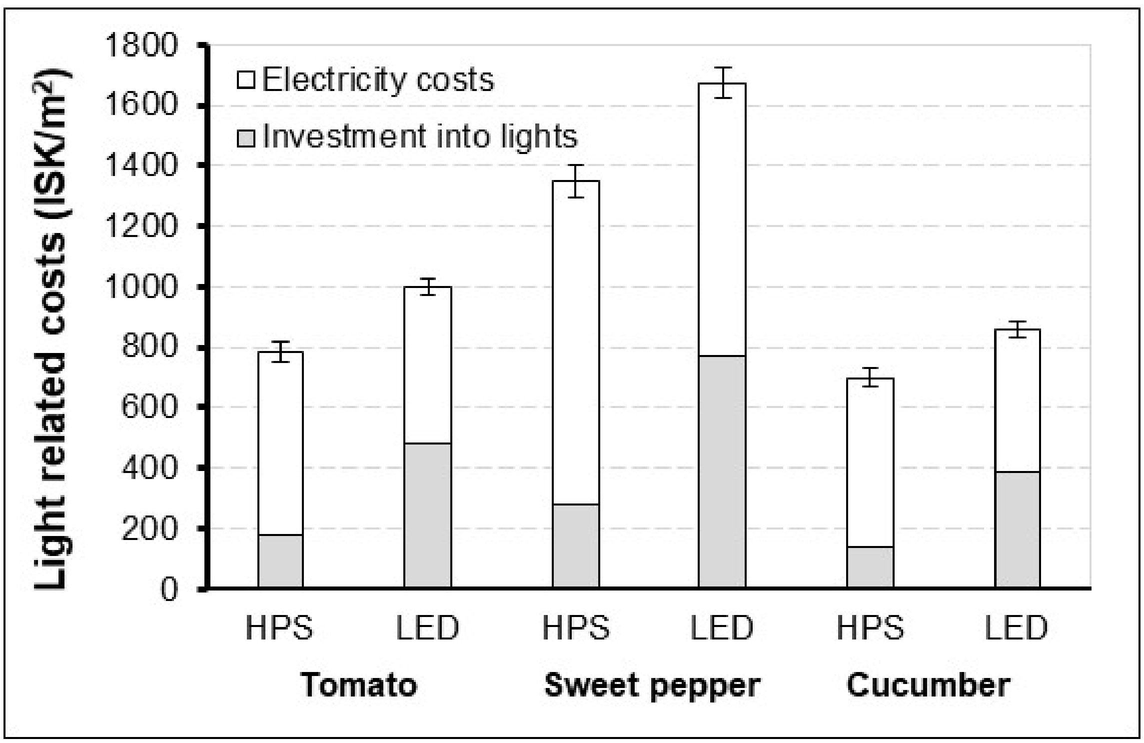

Fig. 27: Light related costs in seedling production for one growing circle of tomatoes, sweet pepper and cucumbers under different light sources.

5 DISCUSSION

In winter production, the success of young plant production strongly depends on supplemental lighting. In this experiment, the effect of two light sources was tested on seedlings of tomatoes, sweet pepper and cucumbers.

5.1 Growth and biomass yield in dependence of the light source

The quality of seedlings of tomatoes, sweet pepper and cucumbers was affected by the light source. Young plants had a lower plant height and were more compact when grown under LEDs compared to HPS lights. This is in accordance with results of *Bergstrand* et al. (2016) and *Hogewoning* et al. (2012) for tomato and cucumber seedlings as well as with results of flower seedlings (*Bergstrand* et al., 2016; *Randall* & *Lopez*, 2014).

No significant differences in stem diameter between lighting sources were found for seedlings of tomatoes and sweet pepper, whereas seedlings of cucumbers had a significantly higher stem diameter under HPS lights than under LEDS. Indeed, also *Hogewoning* (2012) found no significant differences in the stem diameter of tomatoes between light sources. However, the same author also measured, contrary to the presented experiment, no significant differences in the stem diameter of cucumber seedlings between light sources. In contrast, *Bergstrand* et al. (2016) and *Liu* et al. (2019) measured a higher stem diameter of roses and Japanese lady bell transplants, respectively, under LEDs, whereas *Randall* & *Lopez* (2014) reported bigger, equal and smaller stem diameter of flower seedlings depending on the ratio of red:blue in LEDs compared to HPS lights.

The aboveground fresh and dry biomass yield was independent of the light source for seedlings of tomatoes and sweet pepper. Biomass production under LEDs might have been stimulated by extra shoots coming out of the axil and with that suppressing an otherwise possible advantage of HPS lights, as it was obverved for seedlings of cucumbers. The biomass of the root (together with the cube) was indepent of the light source for seedlings of tomatoes and cucumbers, but a significantly higher dry root weight was measured for sweet pepper under LEDs compared to HPS lights. This was in accordance to *Hogewoning* (2012) who reported that total dry weight of seedlings of tomatoes was independent of the light source.

Also, *Bergstrand* et al. (2016) measured that fresh and dry weight of roses was unaffected by the lamp type. In contrast, in grafted tomatoes seedlings (*Wei* et al., 2018) and Japanese lady bell (*Liu* et al., 2019) was biomass improved under LEDs compared to HPS lights. *Hernández* & *Kubota* (2015) attributed the 28 % greater shoot dry mass of cucumber transplants and the 28-32 % higher shoot fresh weight under HPS lights compared to the LED treatments (blue LED, red LED) to the higher leaf temperature. This is in agreement with the presented experiment where the higher substrate temperature and leaf temperature in the HPS treatment might have influenced positively biomass yield of cucumber seedlings grown under HPS lights. Indeed, *Davis* & *Burns* (2016) reported that in all experiments that compare HPS and LED light there is a need to assess the differences in plant temperature to ensure that any effect of temperature can be seperated from the effects of light on plants responses. *Van Delm* et al. (2016) assumed that the regulation of temperature and lighting strategy seems to be important for plant balance between earliness and total yield. *Davis* & *Burns* (2016) concluded that the switch from HPS to LED lighting would require a period of learning to develop protocols for correct management of plant irrigation and growth. For example, *Kowalczyk* et al. (2018) draw the conclusion to increase the density of cucumbers when providing LED lighting.

For sweet pepper was the number of leaves at the end of the seedling production significantly increased by the use of LEDs compared to HPS lights. This might be a result of the stimulation of additional growth through LEDs. But, this light source effect was not observed before division of the stem into two tops and was then – like for seedlings of tomatoes and cucumbers – independent of the light source. In contrast, *Wei* et al., (2018) reported that leaf number of grafted tomato seedlings was the greatest under LEDs compared to HPS lights. *Hernández* & *Kubota* (2015) counted a 9-12 % greater leaf number of cucumbers and a greater LAI under HPS lights compared to LEDs and attributed this effect to the higher air temperature under HPS lights and to the greater growth rate of the plants grown under HPS lights due to the higher leaf temperature caused by the infrared radiation produced by the fixture. In the presented experiment might the higher LAI of the biggest cucumber leaf under HPS lights have attributed to the significantly higher biomass yield compared to seedlings grown under LEDs. However, for tomatoes was the higher LAI of the biggest tomato leaf under HPS lights not resulting in a higher biomass yield under HPS lights. Indeed, also *Bergstrand* et al., (2016) reported that LAI was lower for seedlings of tomatoes and roses grown under LEDs. Again, the additional growth of seedlings of sweet pepper might caused that the LAI of the biggest leaf was not, like for seedlings of tomatoes and cucumbers, higher under HPS lights.

The dry aboveground yield to height ratio was for all seedlings the highest under LEDs compared to HPS lights. Also, *Wei* et al., (2018) reported that scion dry weight to height ratio were the greatest for grafted tomato seedlings grown under LEDs compared to HPS lights.

Hernández & *Kubota* (2015) recommend the use of red LED supplemental light to increase cucumber transplant compactness. Also, *Randall* & *Lopez* (2014) concluded that most transplants that were grown under LEDs with both red and blue light were with a comparable or better quality than plants that were grown under HPS lights. However, do to experience in the presented experiment may too compact plants after grown under LEDs, despite of an otherwise good quality, not be of advantage after transplanting: The compact plants under LEDs hampered working with these high wire plants after transplanting. The tiding of the plants took more time due to the shorter distance between leaves and due to the removing of additional shoots out of the axils. In contrast, the bigger distances between leaves of transplants grown under HPS lights allowed faster working and reduced the risk of breaking the stem when tiding plants up. Therefore, a young plant production for high wire crops only under LEDs can not be recommended. At least hybrid lighting should be applied to seedlings that require later a high wire culture to ensure not too compact transplants. However, for herbs, flowers and not high wire vegetables might LEDs increase quality of transplants due to their characteristic compact growth and make with that transport of transplants more secure by reducing the risk of bending of the stem.

The presented results of the measurement parameters on the seedlings have shown very clearly that different species may react different to the kind of supplemental lighting. This is in agreement to results of *Hernández & Kubota* (2014) who reported that the growth of tomato plants under 100 % red LEDs was comparable to that under HPS lights, but the growth of cucumber plants was higher under HPS than 100 % red LED lighting. Also, *Treder* et al. (2016) reported that tomatoes respond differently than cucumbers to different light treatments. This is indicating that the selection of the kind of supplemental lighting for seedlings is species specific. Indeed, *Gómez* and *Mitchell* (2015) concluded that LEDs are a promising supplemental lighting technology for propagating greenhouse crops, however, spectral-quality effects on plant growth and development remains to be optimized. However, the presented results indicate the possibility of same reactions on light sources within the same plant family. Both, for seedlings of tomatoes and sweet pepper were the following characteristics independent of the light source: Diameter of the stem, width of the biggest leaf, fresh yield of leaves, fresh and dry aboveground yield. But, this characteristics were for cucumbers significantly higher under HPS lights compared to LEDs. This is indicating that the reaction of the source of supplemental light might be similar within the same family, nightshades (*Solanceae*). Therefore, it can be expected that also other nightshades might react in the same way as tomatoes and sweet pepper, whereas different plant families (*Solanceae* versus *Cucurbitaceae*) might show a different or contrary reaction to the light source. Therefore, the selection of the kind of supplemental lighting for seedlings might be with a regularity within plant families. Among that, may the used type of LED and their wavelength (ratio red:blue) in other experiments explain possible controversial results within same plant families.

So far, limited information is available comparing HPS supplemental lighting with LED supplemental lighting in terms of plant growth and development (*Hernández* & *Kubota*, 2015). Reported results are controversial, first because of different plant species and cultivars are used and second due to various experimental conditions. Therefore, it is concluded by different authors (*Bantis* et al., 2018; *Gómez* et al., 2013; *Hernández* & *Kubota*, 2015; *Singh* et al., 2015), that more detailed scientific studies are necessary to understand the effect of different spectra using LEDs on plant physiology and to investigate the responses to supplemental light quality of economically important greenhouse crops and validate the appropriate and ideal wavelength combinations for important plant species. Therefore, before LEDs are put into practice on a larger scale, more knowledge must be acquired on effects of LED lighting on crops (*Dueck* et al., 2012b).

5.2 Electricity consumption in dependence of the light source

The presented results show that LED lights resulted in energy savings without compromising biomass of tomatoes and sweet pepper, whereas for cucumbers was the biomass significantly lower. Using LEDs was associated with about 15 % lower daily usage of kWh's, resulting in 15 % lower expenses for the electricity compared to the use of HPS lights. However, the investment into LEDs was nearly three times as high as for the HPS lights. Meaning the total light related costs were higher for LED lighted seedlings than HPS lighted ones, as the higher price of the LEDs compensated not their lower use of electricity. The energy use efficiency was independent of the light source for seedlings of cucumbers, whereas higher values were calculated for sweet pepper and tomatoes under LEDs. In contrast, *Hernández* & *Kubota* (2015) reported that HPS had a higher energy use efficiency than LEDs.

It has to be mentioned, that HPS lights with an electronic ballast were put up for this experiment. According to Gavita is this kind of HPS lights saving about 8 % of energy compared to the before used HPS lights with an electromagnetic ballst. In addition, are the new screens giving a better reflection of the light. This might explain that the energy savings are pretty low when using LEDs instead of HPS lights. In contrast to the presented results, decreased energy consumption from the LEDs by 59 %, 55 % and 48 % for the 100:0, 85:15, and 70:30 red:blue LEDs, respectively, compared with HPS lights (*Randall* & *Lopez*, 2014). *Dueck* et al. (2012b) reported that the production under LEDs was lower than under HPS, but LEDs saved 30 % of dehumidification and heat energy and 27 % of electricity relative to the crop grown with HPS lights. However, the high capital cost is still an important aspect delaying the LED technology in horticultural lighting. *Singh* et al. (2015) showed that the introduction of LEDs allows, despite of high capital investment, reduction of the production cost of vegetables and ornamental flowers in the long-run (several years), due to the LEDs' high energy efficiency, low maintenance cost and longevity.

To grow high wire transplants under hybrid lighting could be a solution to save energy and get not too compact plants. Also, *Dueck* et al. (2012a) suggested that a combination of HPS and LEDs as top lighting is the most promising alternative for greenhouse grown tomatoes in the Netherlands when taking into consideration different production parameters and costs for lighting and heating.

5.3 Recommendations for decreasing energy costs

It can be suggested, that growers can reduce energy costs in seedling production by:

- Lower prices for distribution and sale of energy (which is not realistic)
- Growers should check if they are using the right RARIK tariff and the cheapest energy sales company tariff. Unfortunately, it is not so easy, to say, which is the right tariff, because it is grower dependent.
- Growers should check if they are using the power tariff in the right way to be able to get a lowered peak during winter nights and summer (max. power -30 %). It is important to use not so much energy when it is expensive, but have a high use during cheap times.
- For large growers, that are using a minimum of 2 GWh it could be recommended to change to "stórnotendataxti" in RARIK and save up to 35 % of distribution costs.
- It is expected that growers are cleaning their lamps to make it possible, that all the light is used effectively and that they are replacing their bulbs before the expensive season is starting.
- An investment into HPS lights with an electronic ballast would save about 8 % of electricity costs compared to HPS lights with an electromagnetic ballast.
- *Aikman* (1989) suggests to use partially reflecting material to redistribute the incident light by intercepting material to redistribute the incident light by intercepting direct light before it reaches those leaves facing the sun, and to reflect some light back to shaded foliage to give more uniform leaf irradiance.
- The use of LED lights instead of HPS lights can reduce electricity consumption by 15 %. To be able to get no delay in the growth, environmental settings need to be adapted to the use of this light source.

6 CONCLUSIONS

The development of seedlings of tomatoes, sweet pepper and cucumbers was influenced by the light source. Different species acted differently to the kind of supplemental lighting, but species of same families seem to react more similar than species of different families. The quality of transplants was affected by the selection of the light source and had also an impact after transplanting. In conclusion, the results indicate that growing high wire seedlings only under LEDs is not recommended due to the too compact growth. However, for seedlings that require no high wire system like flowers and herbs might the quality be increased when grown under only LEDs.

The reduction of the lighting costs by 15 % with the use of LEDs instead of HPS lights was accompanied by a high increase of the investion costs. The energy consumption was better transferred into biomass yield, when sweet pepper and tomatoes were grown under LEDs, while the energy use efficiency was independent of the light source for cucumbers.

Further experiments must show which ratio of LED to HPS lights is recommended for seedlings of high wire crops and how the quality of high wire transplants can be optimized by establishing species related recommendations regarding the best selection of the light source.

However, the high capital cost is an important aspect delaying the LED technology in horticultural lighting as long as more knowledge is available to different plant species. So far, a replacement of the HPS lamps by LEDs is not recommended from the economic side. Growers should pay attention to possible reduction of energy costs by other than exchanging HPS lights by LEDs.

7 REFERENCES

AIKMAN DP, 1989: Potential increase in photosynthetic efficiency from the redistribution of solar radiation in a crop. J. Exp. Bot. 40, 855-864.

BANTIS F, SMIRNAKOU S, OUZOUNIS T, KOUKOUNARAS A, NTAGKAS N, RADOGLOU K, 2018: Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). Sci. Hortic 235, 437-451.

BERGSTRAND KJ, MORTENSEN LM, SUTHAPARAN A, GISLEROD HR, 2016: Acclimatisation of greenhouse crops to differing light quality. Scientia Horticulturae 204, 1-7.

BLANCO FF & FOLEGATTI MV, 2003: A new method for estimating the leaf area index of cucumber and tomato plants. Horticultura Brasileira 21, 666–669.

BROWN CS, SCHUERGER AC, SAGER JC, 1995: Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. J. Amer. Soc. Hort. Sci. 120, 808-813.

BULA RJ, MORROW EC, TIBBITTS TW, BARTA DJ, IGNATIUS RW & MARTIN TS, 1991: Light-emitting diodes as a radiation source for plants. HortScience 26, 203-205.

DAVIS PA, BURNS C, 2016: Photobiology in protected horticulture. Foot and Energy Security 5(4), 223-238.

DE RUITER, without year: Completo https://www.deruiterseeds.com/en-uk/products.html/tomato/completo visited 29.04.2020.

DEMERS DA, DORAIS M, WIEN CH, GOSSELIN A, 1998a: Effects of supplemental light duration on greenhouse tomato (*Lycopersicon esculentum* Mill.) plants and fruit yields. Sci. Hortic. 74, 295-306.

DEMERS DA, GOSSELIN A, WIEN HC, 1998b: Effects of supplemental light duration on greenhouse sweet pepper plants and fruit yields. J. Amer. Hort. Sci. 123, 202-207.

DUECK TA, JANSE J, EVELEENS BA, KEMPKES FLK, MARCELIS LFM, 2012b: Growth of tomatoes under hybrid LED and HPS lighting. Acta Hortic. 952, 335-342.

DUECK TA, JANSE J, LI T, KEMPKES F, EVELEENS B, 2012a: Influence of diffuse glass on the growth and production of tomato. Acta Hortic. 956, 75-82.

ENZA ZADEN, without year: Gialte https://www.enzazaden.com/uk/products-and-services/our-products/Pepper/Gialte visited 20.01.2021.

GÓMEZ C, MITCHELL CA, 2015: Growth responses of tomato seedlings to different spectra of supplemental lighting. HortScience 50 (1), 112-118.

GÓMEZ C, MORROW RC, BOURGET CM, MASSA G, MITCHELL CA, 2013: Comparison of intracanopy light-emitting diode towers and overhead high-pressure sodium lamps for supplemental lighting of greenhouse-grown tomatoes. HortTechnology 23 (1), 93-98.

HAO X, PAPADOPOULOS AP, 1999: Effects of supplemental lighting and cover materials on growth, photosynthesis, biomass partitioning, early yield and quality of greenhouse cucumber. Sci. Hortic. 80, 1-18.

HERNÁNDEZ R, KUBOTA C, 2014: LEDs supplemental lighting for vegetable transplant production: Spectral evaluation and comparisons with HID technology. ActaHortic 1037: 829-835.

HERNÁNDEZ R, KUBOTA C, 2015: Physiological, morphological, and energy-use efficiency comparisons of LED and HPS supplemental lighting for cucumber transplant production. HortScience 50 (3), 351-357.

HOENECKE ME, BULA RJ, TIBBITTS TW, 1992: Importance of “blue” photon levels for lettuce seedlings grown under red-light-emitting diodes. HortScience 27, 427-430.

HOGEWONING SW, TROUWBORST G, MEINEN E, VAN IEPEREN, 2012: Finding the optimal growth-light spectrum for greenhouse crops. Acta Hort. 956, 357-363.

KOWALCZYK K, GAJC-WOLSKA J, BUJALSKI D, MIRGOS M, NIEDZINSKA M, MAZUR K, ZOLNIERCZYK P, SZATKOWSKI D, CICHON M, LECZYCKA N, 2018: The effect of supplemental assimilation lighting with HPS and LED lamps on the cucumber yielding and fruit quality in autumn crop. Acta Sci. Pol. Hortorum Cultus, 17(4), 193-200. DOI: 10.24326/asphc.2018.4.17.

KRIZEK DT, MIRECKI RM, BRITZ SJ, HARRIS WG, THIMIJAN RW, 1998: Spectral properties of microwave sulfur lamps in comparison to sunlight and high pressure sodium/metal halide lamps. Biotronics 27, 69-80.

LIU Y, REN X, J BR, 2019: Supplementary light source affect growth, metabolism, and physiology of Adenophora triphylla (Thunb.) A.DC. seedings. BioMed Research International, 6283989. doi: 10.1155/2019/6283989. eCollection 2019.

MARCELIS LFM, BROEKHUIJSEN AGM, MEINEN E, NIJS EHFM, RAAPHORST MGM, 2006: Quantification of the growth response to light quality of greenhouse grown crops. Acta Hort. 711, 97-104.

NUNHEMS, 2018: Providing both high production and high resistance. https://www.hortidaily.com/article/6042837/providing-both-high-production-and-high-resistance/ visited 20.1.2021.

PHILIPS, 2015: The ideal replacement for the incandescent lamp. http://www.lighting.philips.com/b-dam/b2b-li/en_AA/Experience/cases/Brookberries/PHIL_143918_CaseStudy_Brookberries_UK.pdf visited: 01.02.2017.

PHILIPS, 2017: Higher yields of better quality tomatoes. http://images.philips.com/is/content/Philips Consumer/PDFDownloads/Global/Case-studies/CSLI20170119_001-UPD-en_AA-PHIL_164209_CaseStudy_MartinSigg.pdf visited: 01.02.2017.

PINHO P, HYTÖNEN T, RANTANEN M, ELOMAA P, HALONEN L, 2013: Dynamic control of supplemental lighting intensity in a greenhouse environment. Lighting Res. Technol. 45, 295-304.

RANDALL WC, LOPEZ RG, 2014: Comparision of supplemental lighting from high-pressure sodium lamps and light-emitting diodes during bedding plant seedling production. HortScience 49 (5): 589-595.

RODRÍGUEZ PADRÓN R, LOPES S, SWAROWSKY A, CERQUERA R, NOGUEIRA C, MAFFEI M, 2016: Non-destructive models to estimate leaf area on bell pepper crop. Ciência Rural. 46, 1938-1944. 10.1590/0103-8478cr20151324.

SCHUERGER AC, BROWN CS, STRYJEWSKI EC, 1997: Anatomical features of pepper plants (Capsicum annum L.) grown under red light-emitting diodes supplemented with blue or far-red light. Ann. Bot. 79, 273-282.

SINGH D, BASU C, MEINHARDT-WOLLWEBER M, ROTH B, 2015: LEDs for energy efficient greenhouse lighting. Renewable and Sustainable Energy Reviews 49, 139-147.

STADLER C, 2013: Áhrif ljósstyrks, rótarbeðsefnis, vökvunar og umhirðu á vöxt, uppskeru og gæði gróðurhúsatómata. Final report, Rit LbhÍ nr. 43.

STADLER C, 2015: Áhrif LED lýsingar á vöxt, uppskeru og gæði gróðurhúsasalats að vetri. Final report, Rit LbhÍ nr. 61.

STADLER C, 2018: Áhrif LED lýsingar á vöxt, uppskeru og gæði gróðurhúsajarðarberja að vetri. Final report, Rit LbhÍ nr. 103.

STADLER C, 2019: Áhrif LED lýsingar og viðeigandi hitastillingar á vöxt, uppskeru og gæði gróðurhúsajarðarberja að vetri. Final report, Rit LbhÍ nr. 117.

STADLER C, 2020: Áhrif LED topplýsingar og LED millilýsingar á vöxt, uppskeru og gæði gróðurhúsatómata. Final report, Rit LbhÍ nr. 125.

STADLER C, HELGADÓTTIR Á, ÁGÚSTSSON, M, RIIHIMÄKI MA, 2010: How does light intensity, placement of lights and stem density affect yield of wintergrown sweet pepper? Fræðaþing landbúnaðarins, 227-232.

TAMULAITIS G, DUCHOVSKIS P, BLIZNIKAS Z, BREIVE K, ULINSKAITE R, BRAZAITYTE A, NOVICKOVAS A, ZUKAUSKAS A, 2005: High-power light-emitting diode based facility for plant cultivation. J. Phys. D: Appl. Phys. 38, 3182-3187.

TREDER J, BORKOWSKA A, TREDER W, KLAMKOWSKI K, 2016: "The effects of LEDs on growth and morphogenesis of vegetable seedlings cultivated in growth chambers," 2016 IEEE Lighting Conference of the Visegrad Countries (Lumen V4), Karpacz, 2016, 1-4.

VAN DELM T, MELIS P, STOFFELS K, VANDERBRUGGEN R, BAETS W, 2016: Advancing the strawberry season in Belgian glasshouses with supplemental assimilation lighting. Acta Hortic. 1134, 147-154.

WEI H, HU J, LIU C, WANG M, ZHAO J, KANG DI, JOENG BR, 2018: Effect of supplementary light source on quality of grafted tomato seedlings and expression of two photosynthetic genes. Agronomy 8, 207; doi: 10.3390/agronomy8100