Rit LbhÍ nr. 143

„Áhrif ljósmeðferðar í forræktun og lýsingarmeðferð í áframhaldandi ræktun á vöxt, uppskeru og gæði gróðurhúsatómata“

FINAL REPORT

Christina Stadler

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Project leader: Landbúnaðarháskóla Íslands
Keldnaholt
Dr. Christina Stadler
Árleyni 22
112 Reykjavík
Email: christina@lbhi.is
Mobile: 843 5312

Garðyrkjufræðingur: Börkur Halldór Blöndal Hrafnkelsson
Ræktunarstjóri tilraunahús: Elías Óskarsson

Collaborators: Helgi Jóhannesson, Ráðgjafarmiðstöð landbúnaðarins
Tomato growers

Project sponsors: Framleiðnisjóður landbúnaðarins
Hvanneyrargötu 3
311 Borgarnes

Samband Garðyrkjubænda
Bændahöllinni við Hagatorg
107 Reykjavík

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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
ppm parts per million
W Watt
Wh Watt hours

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 regarding the effect of the light treatment in young plant production and the light treatment in continuous production are not yet in place for tomato production and need to be developed. The objective of this study was to test if the light source (HPS or LED) in young plant production and the light treatment in continuous production is affecting growth, yield and quality over the winter of tomatoes and to evaluate the profit margin.

An experiment with ungrafted tomatoes (*Lycopersicon esculentum* Mill. cv. Completo) was conducted from the beginning of November 2020 to the middle of March 2021 in the experimental greenhouse of the Agricultural University of Iceland at Reykir. Tomatoes were grown in rockwool plugs in three replicates with 2,5 tops/m^2 with one top per plant. Four different light treatments for a maximum of 16 hours light were applied: 1. Transplants under top lighting from high-pressure vapour sodium lamps (HPS), continous production under Hybrid top lighting (238 µmol/m^2/s) and interlighting with light emitting diodes (LED) (129 µmol/m^2/s) (HPS, Hybrid+LED), 2. Transplants under top lighting from LEDs, continous production under Hybrid top lighting (249 µmol/m^2/s) and LED interlighting (129 µmol/m^2/s) (LED, Hybrid+LED), 3. Transplants under top lighting from HPS lights, continous production under Hybrid top lighting (365 µmol/m^2/s) (HPS, Hybrid), 4. Transplants under top lighting from LEDs, continous production under Hybrid top lighting (374 µmol/m^2/s) (LED, Hybrid). The day temperature was during the first month 20°C and after that 22°C. The night temperature was during the first month 17°C and after that 20°C. The underheat was 35°C when the experiment started, but was increased to 40°C at the end of November and to 50°C at the beginning of February. 800 ppm CO_2 was applied. Tomatoes received standard nutrition through drip irrigation. The effect of the light source in young plant production and the light treatment in continuous production was tested and the profit margin was calculated.

The light source had an influence on the appearance of the plant: Leaves and clusters were in “Hybrid+LED” longer when plants received HPS lights in young plant production, whereas in “Hybrid” were leaves and clusters longer when grown under LEDs in young plant production. “HPS, Hybrid+LED” had less clusters compared to the other treatments. Therefore, plants might got shocked when light quality changed and reacted with increased or decreased growth during adaption to the new light quality.

Plants that received LED lights in young plant production were about half a week earlier ripe than plants that received HPS lights. This might be caused by the higher leaf temperature of plants that received LEDs. However, at the end of the harvest period was total yield, marketable yield and their number independent of the light treatment. But, the higher yield of green fruits in “LED, Hybrid” and “HPS, Hybrid” compared to “LED, Hybrid+LED” is showing the potential of a possible higher total yield, in case the experiment would have been conducted longer. When considering the marketable yield per cluster, treatments that received LEDs in young plant production had a lower value than plants that received HPS lights in young plant production. Marketable yield was more than 60% for all treatments, whereby “LED, Hybrid+LED” had a lower percentage of 1. class fruits, but a higher percentage of 2. class fruits compared to the other treatments. Consequently, this resulted in the lowest average weight.

Using LEDs in young plant production was associated with about 15% lower daily usage of kWh’s compared to HPS lights in young plant production, but this influence did not have an impact when considering the whole growth period. “Hybrid+LED” used about 21% less energy than “Hybrid”. Light related costs (electricity costs + investment into lights) were calculated higher (12%) for “Hybrid” than “Hybrid+LED” and amounted 50% of total production costs. Used kWh’s were better transferred into yield with “Hybrid+LED” than with “Hybrid” and with HPS lights in young plant production.

With the use of HPS lights in young plant production increased yield by more than 1,1 / 2,0 kg/m^2 (“Hybrid+LED” / “Hybrid”) and profit margin by more than 600 / 1.000 ISK/m^2. However, the marketable yield was low and the profit margin negative. When part of the HPS top lights was replaced by LED interlights, decreased yield by by 1,0 / 0,2 kg/m^2 (HPS / LED lights in young plant production), but profit margin increased by 300 / 800 ISK/m^2. However, calculations scenarios indicating that it would be more economic to use LEDs as top lights in contrast to interlights, as yield might be increased by more than 20%.

Possible recommendations for saving costs other than lowering the electricity costs are discussed. It can be adviced to grow high wire transplants under HPS lights. However, after transplanting seems a Hybrid system recommended, where LEDs are used as top lighting (and not as interlighting) to have a positive effect on yield. Further experiments must show which ratio of LED to HPS lights and which wavelength combinations seems to be suitable for different plant species. So far, a replacement of the HPS lamps by LEDs is not recommended from the economic side and more scientific studies are needed.

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 vetrarræktunar á tómötum og áhrif ljósameðferðar í forræktun og lýsingarmeðferð í áframhaldandi ræktun á gróðurhúsatómata eru ekki til staðar og þarfnast frekari þróunar. Markmiðið var að prófa hvort ljósgjafi (HPS eða LED) í forræktun og lýsingarmeðferð í áframhaldandi ræktun hefði áhrif á vöxt, uppskeru og gæði yfir háveturinn á tómata og hvort það væri hagkvæmt.

Gerð var tilraun með óágrædda tómata (*Lycopersicon esculentum* Mill. cv. Completo) frá byrjum nóvember 2020 og fram í miðjan mars 2021 í tilraunagróðurhúsi Landbúnaðarháskóla Íslands að Reykjum. Tómatarnir voru ræktaðir í steinullarmottum í þremur endurtekningum með 2,5 toppi/m^2 með einum toppi á plöntu. Prófaðar voru fjórar mismunandi ljósameðferðir að hámarki í 16 klst. ljós: 1. Forræktun undir topplýsingu frá háþrýsti-natríumlömpum (HPS), áframhaldandi ræktun undir Hybrid topplýsingu (238 µmol/m^2/s) og millilýsing frá ljósdíóðum (LED) (129 µmol/m^2/s) (HPS, Hybrid+LED), 2. Forræktun undir topplýsingu frá LED ljósum, áframhaldandi ræktun undir Hybrid topplýsingu (249 µmol/m^2/s) og LED millilýsing (129 µmol/m^2/s) (LED, Hybrid+LED), 3. Forræktun undir topplýsingu frá HPS ljósum, áframhaldandi ræktun undir Hybrid topplýsingu (365 µmol/m^2/s) (HPS, Hybrid), 4. Forræktun undir topplýsingu frá LED ljósum, áframhaldandi ræktun undir Hybrid topplýsingu (374 µmol/m^2/s) (LED, Hybrid). Daghiti var í fyrsta mánuði 20°C og eftir það 22°C. Næturhiti var í fyrsta mánuði 17°C og eftir það 20°C. Undirhiti var 35°C í byrjun, en 40°C í lok nóvember og 50°C í byrjun febrúar. 800 ppm voru gefin. Tómatarnir fengu næringu með dropavökvun. Áhrif ljósgjafa í forræktun og lýsingarmeðferð í áframhaldandi ræktun voru prófaðar og framlegð reiknuð út.

Lauf og klasar voru lengur í “Hybrid+LED” þegar plöntur fengu HPS ljós í forræktun, en lengur í “Hybrid” þegar plöntur fengu LED ljós í forræktun. “HPS, Hybrid+LED” var með færri klasa borið saman við hinar meðferðirnar. Þess vegna gætu plöntur orðið fyrir áfalli þegar ljósgæðum er breytt og bregðast við með auknum eða minnkuðum vexti meðan á aðlögun á nýjum ljósgæðum stendur yfir.

Tómatar sem fengu LED ljós í forræktun voru um hálfri viku fyrr þroskaðir en tómatar sem fengu HPS ljós. Þetta gæti orsakast af hærri laufhita plantna sem fengu LED ljós. Hins vegar, í lok uppskerutímabilsins var heildaruppskera, markaðshæfrar

uppskeru og fjöldi þeirra óháð ljósmeðferð. Meiri uppskera grænna tómata í “LED, Hybrid” og “HPS, Hybrid” samanborið við “LED, Hybrid+LED” sýnir möguleika á meiri uppskeru ef tilraunin hefði verið framkvæmd lengur. Þegar miðað er við söluhæfa uppskeru á klasa, höfðu meðferðir sem fengu LED ljós í forræktun lægri gildi en plöntur sem fengu HPS ljós í forræktun. Hlutfall uppskerunnar sem hægt var að selja var meira en 60% fyrir allar meðferðir, þar sem “LED, Hybrid+LED” var með lægra hlutfall af 1. flokks aldinum, en hærra hlutfall af 2. flokks aldinum samanborið við aðrar meðferðir. Þess vegna leiddi þetta til lægri meðalþyngdar.

Með notkun á LED ljósum í forræktun var um 15% minni dagleg notkun á kWh’s miðað við HPS ljós í forræktun, en það hafði ekki áhrif á allt vaxtarskeiðið. “Hybrid+LED” notaði um 21% minni orku en “Hybrid”. Ljósatengdur kostnaður (orkukostnaður + fjárfesting í ljósum) var meira (12%) fyrir “Hybrid” en fyrir “Hybrid+LED” og var 50% af heildarframleislukostnaði. Skilvirkni orkunotkunar var meiri með “Hybrid+LED” en með “Hybrid” og við HPS ljósum í forræktun.

Með HPS ljósi í forræktun jókst uppskera um 1,1 / 2,0 kg/m^2 (“Hybrid+LED” / “Hybrid”) og framlegð um meira en 600 / 1.000 ISK/m^2. En, markaðshæf uppskera var lág og framlegð neikvæð. Þegar hluta HPS toppljósanna var skipt út með LED ljósum, minnkaði uppskera um 1,0 / 0,2 kg/m^2 (HPS / LED ljós í forræktun), en framlegð jókst um 300 / 800 ISK/m^2. Hins vegar, benda útreikningar til þess að það sé hagkvæmara að nota LED sem topplýsingu í stað milliljósa, þar sem uppskera gæti aukist um meira en 20%.

Möguleikar til að minnka kostnað, annað en að lækka rafmagnskostnað eru taldir upp í umræðukaflanum í þessari skýrslu. Það er ráðlagt að rækta forræktunarplöntur undir HPS ljósum. Hins vegar, eftir útplöntun er mælt með Hybrid lýsingu þar sem LED ljós er notað sem topplýsing (en ekki sem millilýsing) til að hafa jákvæð áhrif á uppskeru. Frekari tilraunir verða að sýna fram á hvaða hlutfall LED og HPS ljósa og hvaða litróf fyrir mismunandi plöntu tegundir er mælt með. Það er ekki mælt með því að skipta HPS lömpum út fyrir LED að svo stöddu og þörf er á meiri reynslu á ræktun undir LED ljósi.

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 not (*Stadler*, 2012) or 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). It has been common in Iceland 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). This is especially important as the energy costs having a big share in the 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. 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. The development of flowers and berries and their harvest was delayed by two weeks under LED lights. This was possibly 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 (*Stadler*, 2019; *Stadler*, 2020).

Traditionally, lamps are mounted above the canopy (top lighting), which entails, that lower leaves are receiving limited light. Experiments (*Hovi-Pekkanen & Tahvonen*, 2008; *Grodzinski* et al., 1999; *Rodriguez & Lambeth*, 1975) imply that lower leaves are also able to assimilate quite actively, suggesting that a better utilization could be obtained by using interlighting (lamps in the row) in addition to top lighting. Indeed, the benefits from interlighting in contrast to top lighting alone have been confirmed with different vegetable crops. Interlighting increased first class yield of cucumbers along with increasing fruit quality and decreased unmarketable yield, both in weight and number (*Hovi-Pekkanen & Tahvonen*, 2008). However, only little is known about the impact of the proportion of interlighting to top lighting. A higher light level and interlighting besides top lighting increases energy costs. Therefore is the question if additional purchase of lights is reflected in a better energy use efficiengy. *Hovi-Pekkanen & Tahvonen* (2008) reported that interlighting (compared to top lighting) improved energy use efficiency in lighting.

First experiments with interlighting have been conducted at the Agricultural University of Iceland. The position of the HPS lights had no influence on marketable yield. But HPS top lighting together with interlighting increased unmarketable yield (around 2%

blossom end rot fruits and 2% more fruits with burning damage from the lights) compared to only HPS top lighting (*Stadler* et al., 2010). But, the yield of sweet pepper war significantly less with LED interlighting than with HPS interlighting or 20% less marketable yield (*Stadler*, 2010). On the other hand have LED modules developed in the meantime and therefore, different results might be expected. According to *Davis* & *Burns* (2016) has interlighting in tomatoes proved highly successful and a significant increase in yield was reported. The top light source (LED, HPS) had no influence on marketable yield of tomatoes, but the use of LEDs resulted in an about 40% lower daily usage of kWh´s and with that in lower expenses for the electricity but higher investment costs compared to HPS lighting (*Stadler*, 2020). The yield increased when LED interlighting was added to HPS top lighting, in addition increased the used energy by 8%. The highest yield was reached with Hybrid top lighting and LED interlighting, where the light distribution and used energy was comparable to the before mentioned treatment (*Stadler*, 2020).

However, the requirements to get a good harvest are among others dependent on the quality of the seedlings. 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). The question is, if the above mentioned positive effect of LEDs compared to HPS lights in young plant production, will also positively affect growth, yield and quality of greenhouse grown tomatoes in continuous production under different light treatments. 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).

In addition to the yield is also the quality of the harvest important. Research in the Netherlands has shown that with LED lights was it possible to increase the taste (*Hanenberg* et al., 2016). Experience of the effect of the light source in young plant production and growing tomatoes under Hybrid top lighting without LED interlighting compared to Hybrid top lighting with LED interlighting in continuous production in Iceland is not available and therefore, the effect of light on yield 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 to an appropriate yield of tomatoes.

The objective of this study was to test if (1) the light treatment in young plant production as well as the light treatment in continuous production is affecting growth, yield and quality of tomatoes in continuous production, if (2) this parameter is converted efficiently into yield, and if (3) the profit margin can be improved by the chose of the light source in young plant production and in continous production. This study should enable to strengthen the knowledge on the best method of growing tomatoes and give vegetable growers advice how to improve their production by modifying the efficiency of tomato production.

3 MATERIALS AND METHODS

3.1 Greenhouse experiment

An experiment with ungrafted tomatoes (*Lycopersicon esculentum* Mill. cv. Completo), different light treatments under young plant production and different light treatments at continuing production (see chapter "3.2 Treatments") was conducted at the Agricultural University of Iceland at Reykir during winter 2020/2021.

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).

On 21.09.2020 were seeds of tomatoes sown in rockwool plugs. On 09.11.2020 were four plants with one top/plant planted into rockwool slabs (50 cm x 24 cm x 10 cm). On each bed were six slabs placed in four chambers. Tomatoes were transplanted in rows in three 65 cm high beds (Fig. 1) with 2,5 plants/m^2. Beds were equipped with six slabs respectively 24 tops. Three replicates, one replicate in each bed consisting of two slabs (8 plants) acted as subplots for measurements. Other slabs were not measured. Due to the weekly hanging down were all plants once at the end of the bed.

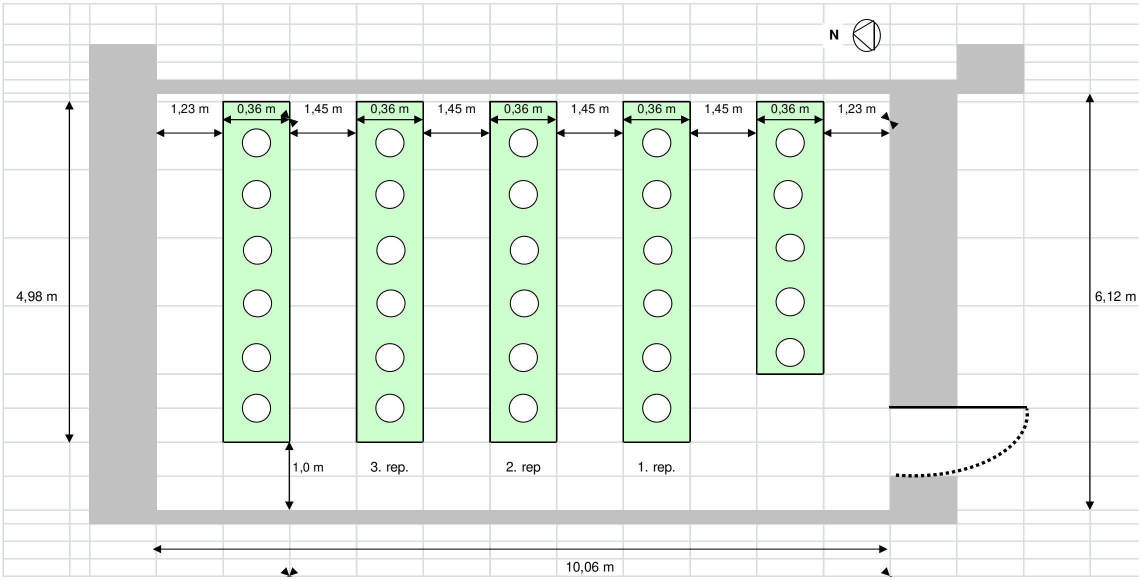

Fig. 1: Experimental design of cabinets.

Regularly were taken shoots of the plants and the plants were deleafed once a week according to 15 leaves per plant. The weekly deleafing was done in the way that most of the time were two leaves of the bottom taken and one top leaf at the upper flowering cluster to create a more open and generative plant habit. That improves light penetration and air circulation and preventing fungal diseases and aphids. The removal of young leaves reduces the total vegetative sink-strength and favours assimilate partitioning into the fruit (*Heuvelink* et al., 2005). Double clusters were removed. Fruits on each clusters were not pruned. Plants were not topped during the experiment to be able to have a “normal” growth until the end of the experiment and conduct measurements.

Wires were placed in 3,5 m height from the floor. For pollination were bumblebees used and the opening of the hives were adjusted as needed. Hives were replaced on average every second week.

Until the 12.12.2020 was the temperature set on 20°C during day and 17°C during night and after that on 22°C / 20°C (day / night). The aim was to reach 20°C at one hour after day starts. At the end of the day was the temperature dropped immediately. Ventilation started at 24°C respectively 26°C. It was heated up with 1,5-2°C per hour. The underheat was set to 35°C in the beginning, increased to 40°C on 23.11.2020 and to 50°C on 03.02.2021. Carbon dioxide was provided (800 ppm CO_2 with no ventilation and 600 ppm CO_2 with ventilation). Installed was a misting system. Humidity was set to 65%. Plant protection was managed by beneficial organisms: En-Strip (Parasitic wasp, *Encarsia Formosa*) was used to prevent whitefly (see details in appendix).

Tomatoes received standard nutrition consisting of “YaraTera™ Ferticare™ Tomato”, calcium nitrate and potassium nitrate according to the following fertilizer plan (Tab. 1).

Tab. 1: Fertilizer mixture.

	Stem solution A (100 l)		**Stem solution B** (100 l)	**Irrigation water**	**Runoff water**
Fertilizer (amount in kg)	YaraTera™ Ferticare™ Tomato	Potassium nitrate	Calcium nitrate	E.C. (mS/cm)	E.C. (mS/cm)
Planting - flowering on 3. cluster	15		19	5	4-6
Flowering on 3.-6. cluster	15	2	19	5	4-6
Flowering from 6. cluster onwards	15	6	18	5	4-6

Plants were irrigated through drip irrigation (4 tubes per slab). The watering was set up that the plants could root well down, which means a low amount of runoff in the first 2-3 weeks. The slabs were watered with an E.C. of 5. The irrigation (100 ml/drip) was arranged to 30% runoff with an E.C. in the drip of 4-6. The first watering was at 5.00 and the last watering was at 17.00. The irrigation interval was variable in accordance to the runoff.

3.2 Treatments

Tomatoes were grown from 09.11.2020 until 17.03.2021 under different lighting regimes in young plant production and in the continuing production in four cabinets at the Agricultural University of Iceland at Reykir:

1. Young plant production under HPS lights
   Hybrid top lighting (50% HPS + 50% LED) + LED interlighting:
   HPS, Hybrid+LED
2. Young plant production under LED lights
   Hybrid top lighting (50% HPS + 50% LED) + LED interlighting:
   LED, Hybrid+LED
3. Young plant production under HPS lights
   Hybrid top lighting (66,6% HPS + 33,3% LED)
   HPS, Hybrid
4. Young plant production under LED lights
   Hybrid top lighting (66,6% HPS + 33,3% LED)
   LED, Hybrid

To test if the light source in young plant production had an influence on the yield of tomatoes were plants that got HPS lights in the young plant production compared to plants that got LED lights in the young plant production (compare 1 and 2, compare 3 and 4). In addition, it was tested if LED interlighting is profitable regarding yield and profit margin or if it would be better to have no LED interlighting and add instead a higher number of HPS top lights (compare 1 and 3, compare 2 and 4).

Used were HPS lights with an electronic ballast and 750 W bulbs (Philips). LED top lights „Green power LED“ deep red / blue types (DR/B) and LED interlights 2,5 m high output (respectively 2,0 m high output at the shelter bed next to the door) were used from the company Signify.

The lamps were distributed in the way that tomatoes 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. 2). HPS lamps were mounted horizontally in 1,4 m distance over the canopy, which corresponds to a height of 4,9 m from the floor. LEDs for top lighting were mounted 4,5 m from the floor. However, due to the roof of the greenhouse were the LEDs over the shelter beds mounted 4,15 m from the floor. The LED interlights were mounted in about 1 m below the top of the plant.

White plastic on the surrounding walls helped to get a higher light level at the edges of the growing area. The µmol level of the top lights in “HPS, Hybrid+LED” and “LED, Hybrid+LED” was lower (238 / 249 µmol/m^2/s) than the µmol level of the top lights in “HPS, Hybrid” and “LED, Hybrid” (365 / 374 µmol/m^2/s). But the interlighting in the before mentioned treatments attributed with 129 µmol/m²/s to an in total comparable light level between all treatments (365-378 µmol/m²/s, Tab. 3). The setup of the HPS lights was corresponding to 120 W/m² (Hybrid+LED) and to 210 W/m² (Hybrid). Light was provided from 05.00-17.00 in the first week after planting, from 05.00-19.00 in the second week, and for 16 hours from 05.00-21.00 from the third week onwards.

Tab. 2: Number of lights and their distribution in the chambers.

Light treatment	Lights	Lights/chamber (no)	Distance between lights
HPS, Hybrid+LED	HPS top lighting	8	3 C profiles with 3 / 2 HPS, 4 m for HPS distance centre centre and 2 m for HPS centre centre
and	LED top lighting	24	8 C profiles with 3 modules, 1,3 m for C profile distance and 1,9 m for modules centre centre
LED, Hybrid+LED	LED interlighting	10	1 m below the top of the plant
HPS, Hybrid and	HPS top lighting	14	3 C profiles with 4 / 5 HPS, 2 m for HPS distance centre centre and 2 m for HPS centre centre
LED, Hybrid	LED top lighting	24	8 C profiles with 3 modules, 1,3 m for C profile distance and 1,9 m for modules centre centre

Tab. 3: Light distribution in the chambers.

Measurement points	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
	(µmol/m²/s)			
1,45 m (floor to top lights)	223	225	307	316
1,95 m (floor to top lights)	223	237	339	350
2,45 m (floor to top lights)	246	254	377	394
2,95 m (floor to top lights)	260	279	438	437
Top lighting (average)	**238**	**249**	**365**	**374**
15 cm from LED interlights	158	155		
20 cm from LED interlights	127	127		
25 cm from LED interlights	103	103		
Interlighting (average)	**129**	**129**		
Total	**367**	**378**	**365**	**374**

3.3 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. The amount of fertilization water (input and runoff) was measured every day.

To be able to determine plant development, in all treatments was the weekly growth, the number of leaves, leaf length, the number of clusters, the number of open flowers, the diameter of head on the highest flowering cluster, the distance between clusters and the length of clusters and total fruits per cluster measured each week on six plants.

During the harvest period were fruits regularly collected (two times per week) in the subplots. Total fresh yield, number of fruits, fruit category (A-class (> 55 mm), B-class (45-55 mm) and not marketable fruits (too little fruits (< 45 mm), fruits with blossom end rot) was determined. At the end of the experiment were on each plant from the subplots the number of immature fruits (green) counted by harvesting five clusters with only green fruits above the last harvested cluster with mature fruits. The marketable yield of the whole chamber was also measured. LED glasses were used for picking to be able to distinguish if fruits were ready for harvesting or not.

The interior quality of the fruits was determined. A brix meter (Pocket Refractometer PAL-1, ATAGO, Tokyo, Japan) was used to measure sugar content in the fruits at the beginning, in the middle and at the end of the growth period. Subsamples of the fruits were dried at 105°C for 24 h to measure dry matter yield.

Energy use efficiency (total cumulative yield in weight per kWh) and costs for lighting per kg yield were calculated for economic evaluation and the profit margin was determined.

3.4 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 after transplanting into the cabinets continuously to less than 1 kWh/m^2 at the end of October and was staying at this value until the end of January. With longer days increased solar irradiation naturally continuously, however with up to 3 kWh/m^2 was this value still low (Fig. 2).

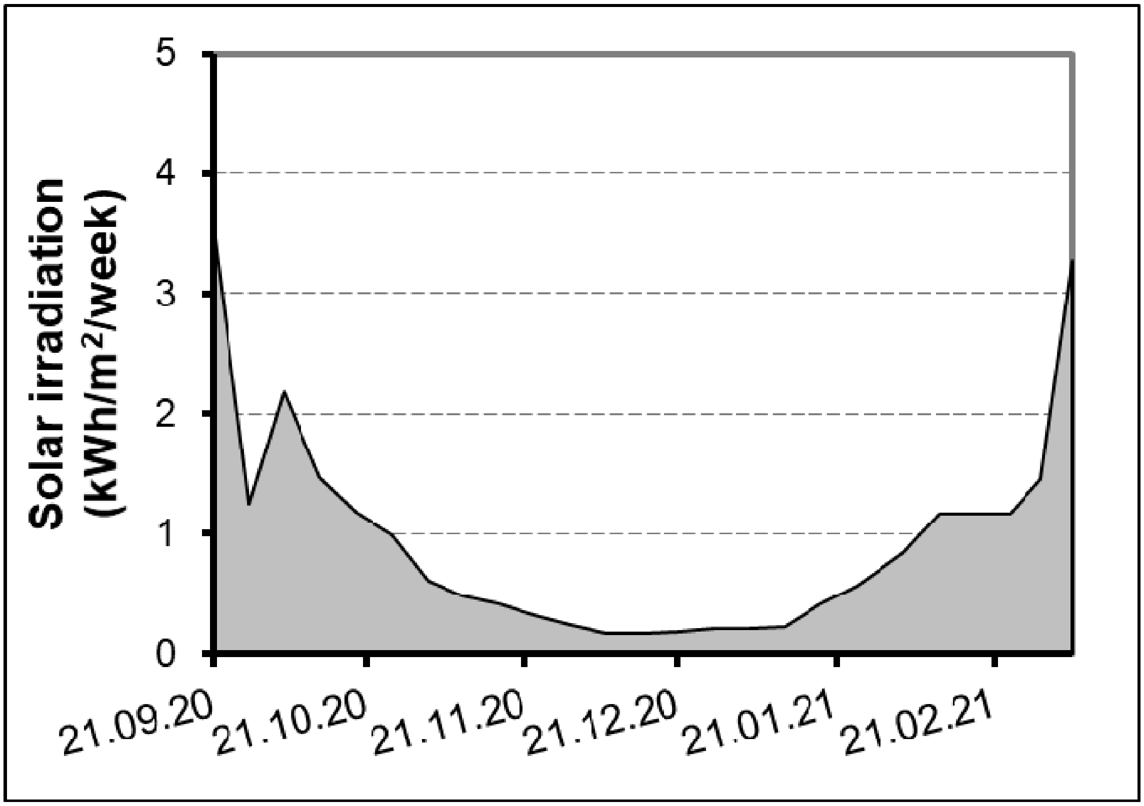

Fig. 2: Time course of solar irradiation.
Solar irradiation was measured every day and values for one week were cumulated.

4.1.2 Chamber settings

The settings in the chambers were regularly recorded. Table 4 shows the average of the air temperature, floor temperature, CO_2 amount, windows opening and humidity.

The average air temperature amounted around 22°C and was very similar between the light treatments. The average air temperature during the day was about 0,5°C lower in the treatment "HPS, Hybrid+LED" compared to the other light treatments. However, the average night temperature was similar between light treatments.

The floor temperature during the day was comparable between the light treatments. The floor temperature during the night was about 1°C higher in the treatment "HPS, Hybrid+LED" compared to the other treatments.

The mean CO_2 amount was 27-44 ppm lower in the treatment "HPS, Hybrid+LED". However, windows were in all light treatments most of the time closed. Humidity amounted 60-69%.

Tab. 4: Chamber settings according to greenhouse computer.

Greenhouse computer data (Average over the experimental period)	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
Air temperature (°C)	21,6	22,0	22,3	22,2
day (°C)	22,6	23,1	23,5	23,5
night (°C)	19,4	19,6	19,7	19,5
Floor temperature day (°C)	45,3	44,9	44,8	45,2
Floor temperature night (°C)	34,1	32,9	32,0	33,0
CO_2 (ppm)	675	713	702	719
Windows opening 1 (%)	0,2	0,3	0,6	0,6
Windows opening 2 (%)	1,7	2,6	3,5	3,7
Humidity (%)	68	62	60	69

4.1.3 Substrate temperature

Substrate temperature was measured weekly at low solar radiation at around noon and fluctuated between 19-24°C. Substrate temperature was on average significantly lower in "HPS, Hybrid" compared to "LED, Hybrid+LED" and "LED, Hybrid". On average amounted this difference 0,4°C (Fig. 3).

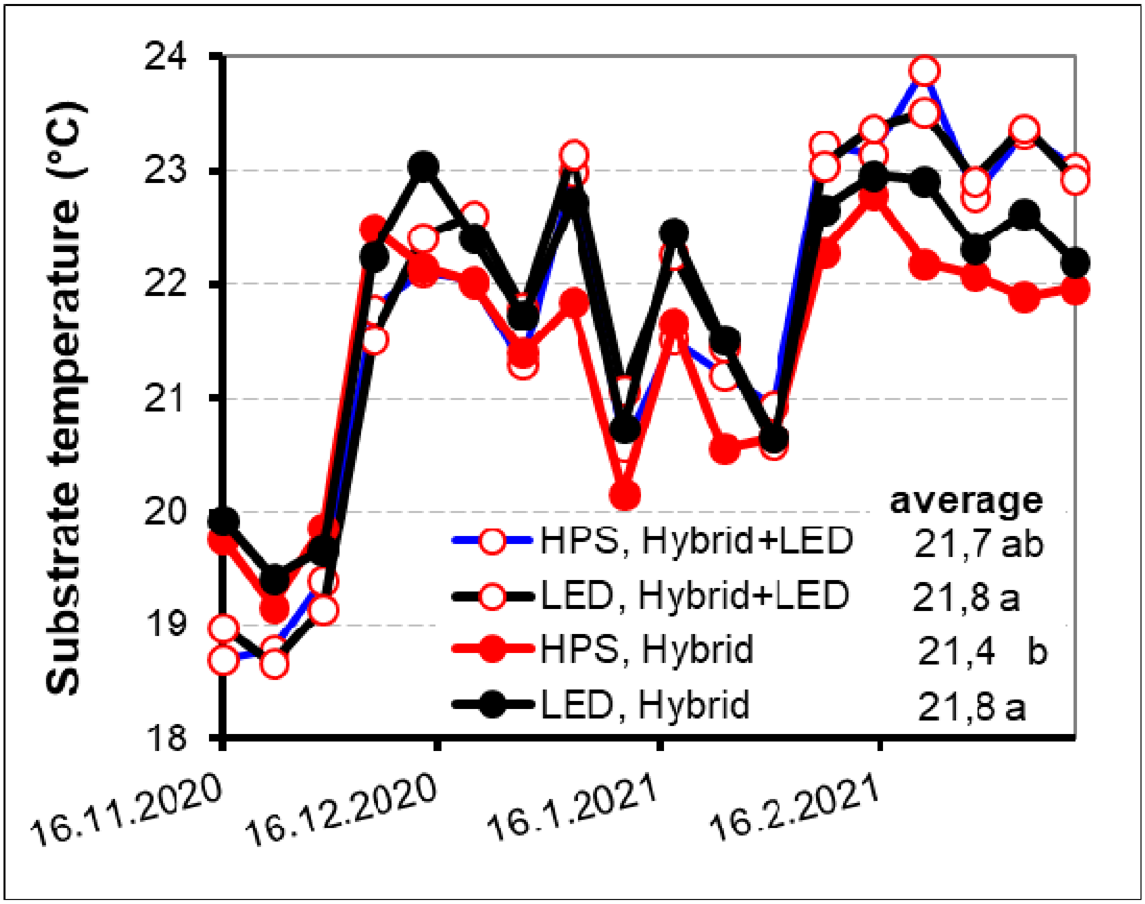

Fig. 3: Substrate temperature.

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

4.1.4 Leaf temperature

Leaf temperature was measured weekly at low solar radiation at around noon and fluctuated between 15-25°C. On average was the leaf temperature significantly higher in treatments that got LEDs in young plant production compared to plants that got HPS lights in young plant production. Regarding the lighting regime in continuous production (“Hybrid+LED” or “Hybrid”) were no significant differences observed (Fig. 4).

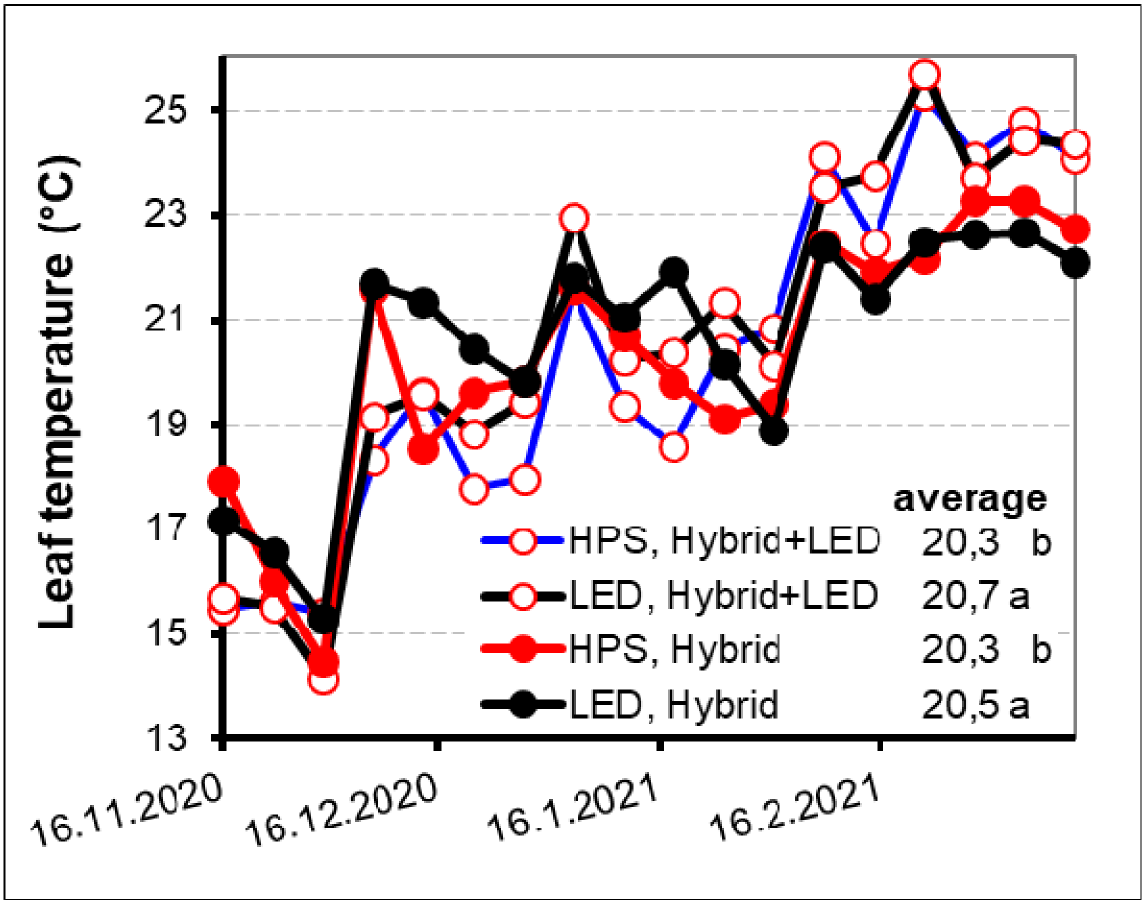

Fig. 4: Leaf temperature.

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

4.1.5 Irrigation of tomatoes

The amount of applied water varied most of the time between 3 and 6 l/m^2 (Fig. 5). By calculating the daily applied water rate per month (Fig. 6) it is getting obvious that all light treatments were watered equally.

E.C. and pH of irrigation water was fluctuating much (Fig. 7). The E.C. of applied water ranged most of the time between 3,0-5,0 and the pH between 5,5-6,0. The E.C. of runoff stayed most of the time between 5,0-8,0 and the pH between 5,5-8,0. The E.C. of the runoff seem to be lowest for “HPS, Hybrid+LED”.

The amount of runoff from applied irrigation fluctuated very much and varied most of the time between 20-50% runoff. It seems to be on average lowest in “HPS, Hybrid” (Fig. 8).

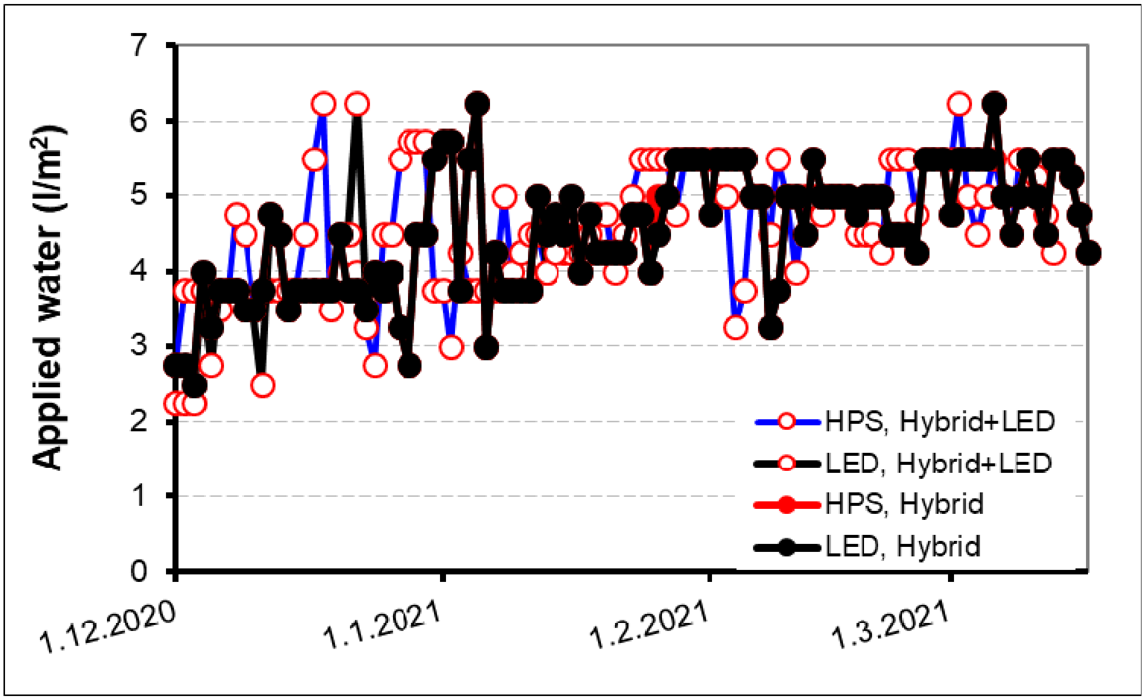

Fig. 5: Daily applied water.

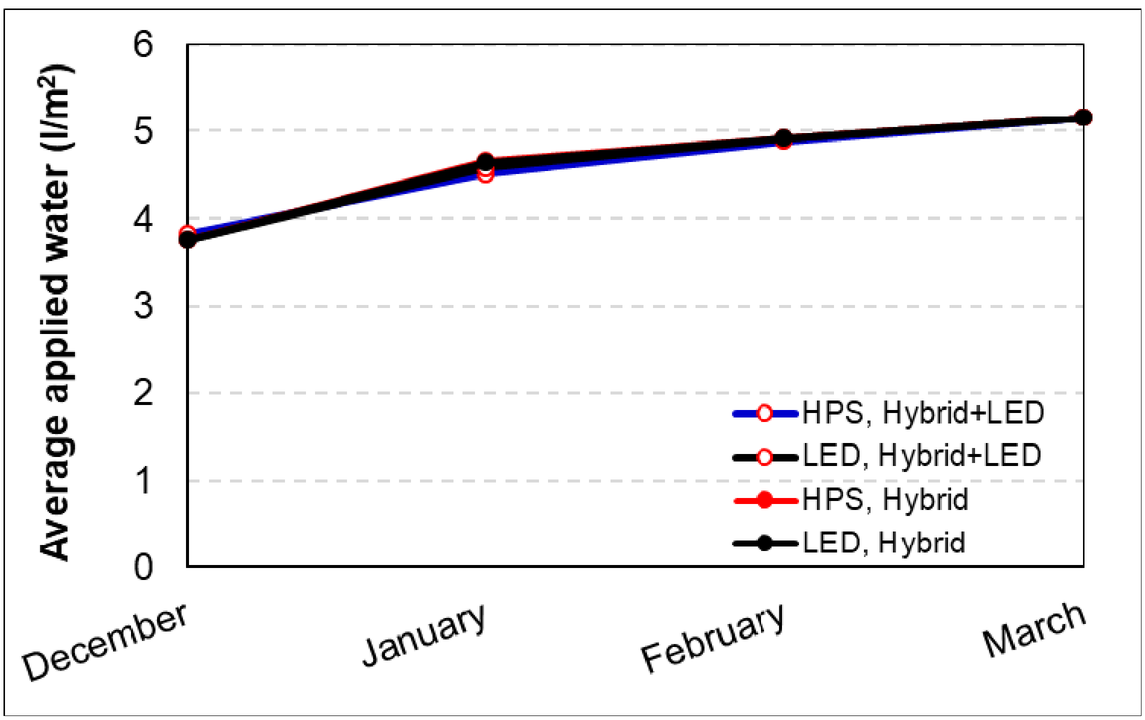

Fig. 6: Average daily applied water in each month.

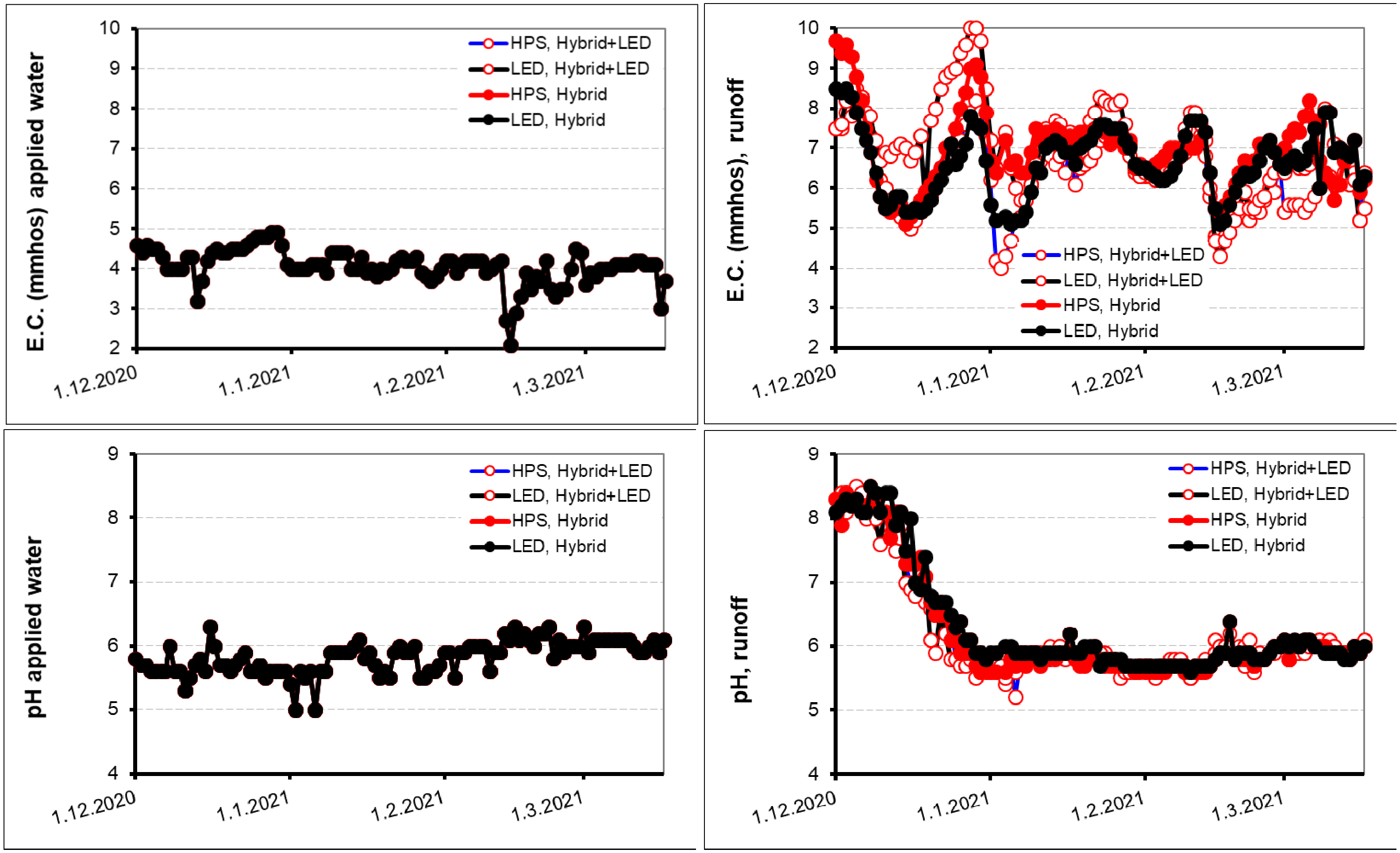

Fig. 7: **E.C. and pH of irrigation water and runoff.**

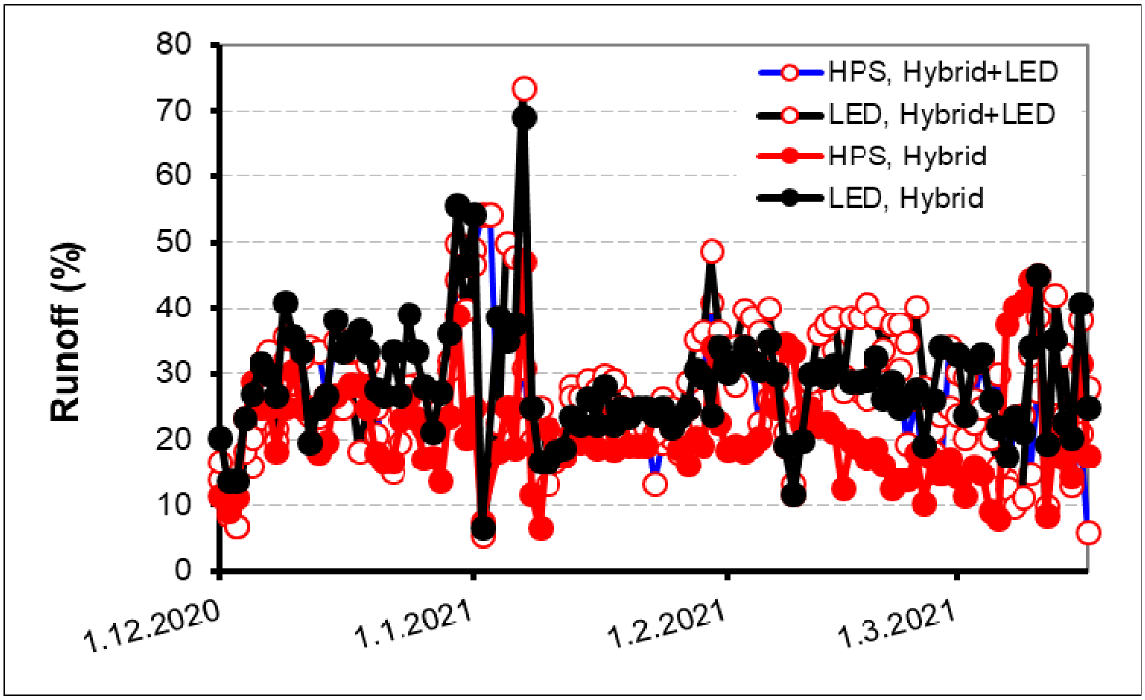

Fig. 8: Proportion of amount of runoff from applied irrigation water.

Plants took up to 4,5 l/m^2. It seems that plants took up most water in the treatment "HPS, Hybrid" (Fig. 9).

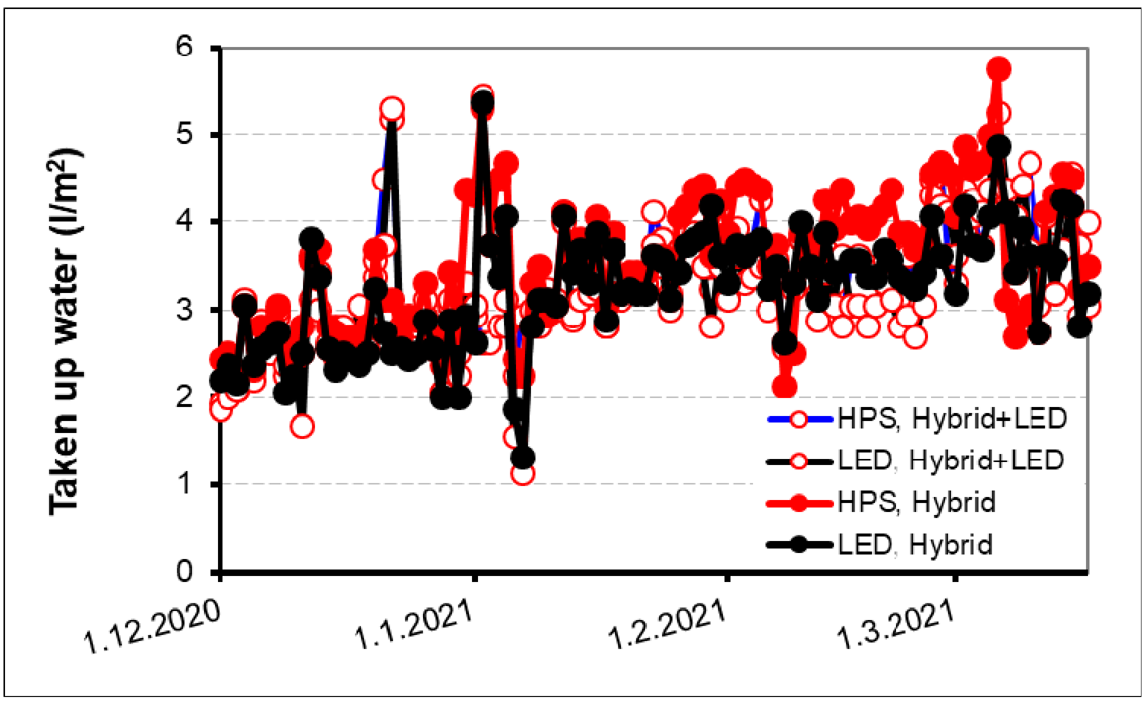

Fig. 9: Water uptake.

4.2 Development of tomatoes

4.2.1 Plant diseases and pests

Neither plant diseases nor pests were observed.

4.2.2 Height

Tomato plants were growing about 2-4 cm per day and reached at the end of the experiment about 4 m (Fig. 10). The height of the plants at the end of the growing period was independent of the light treatment.

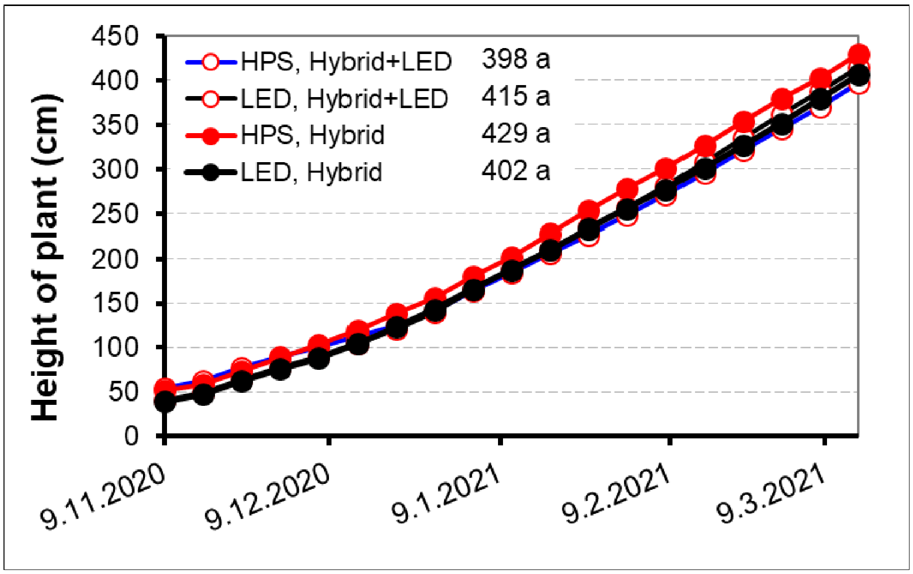

Fig. 10: Height of tomatoes.

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

4.2.3 Weekly growth

All treatments were growing each week on average 19-21 cm (Fig. 11). The weekly growth was independent of the light treatment.

4.2.4 Number of leaves

Plants had on average 15 leaves. However, the treatment “HPS, Hybrid+LED” had on average a significantly lower amount of leaves compared to the other light treatments (Fig. 12).

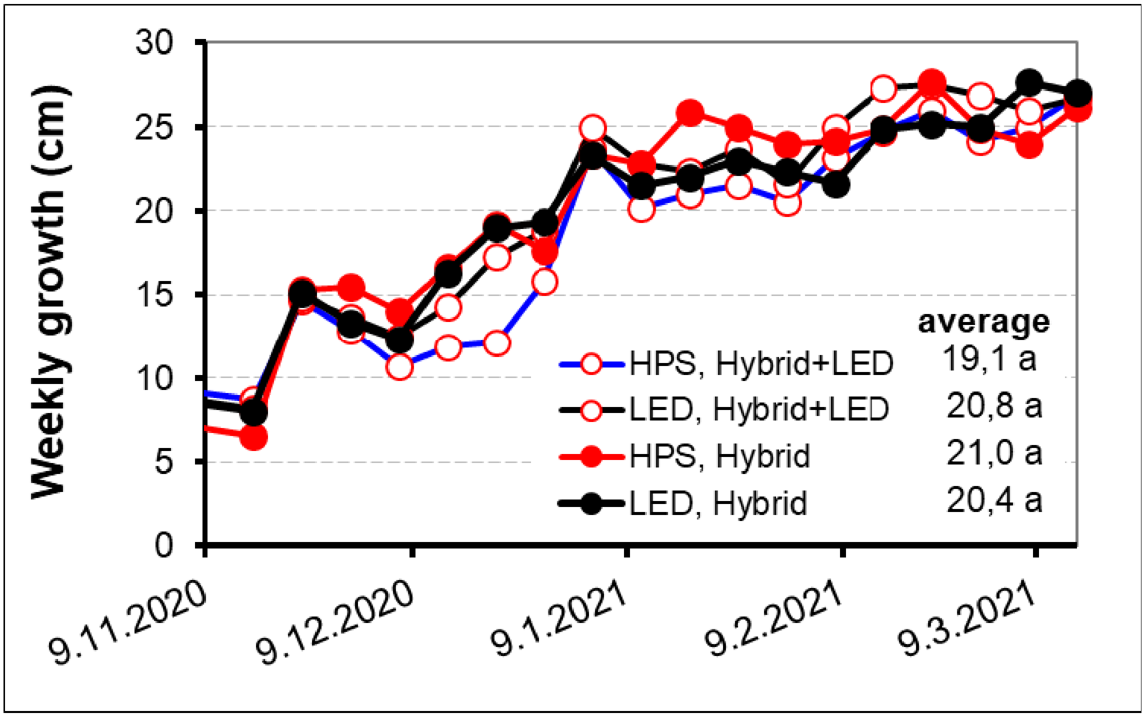

Fig. 11: Weekly growth.

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

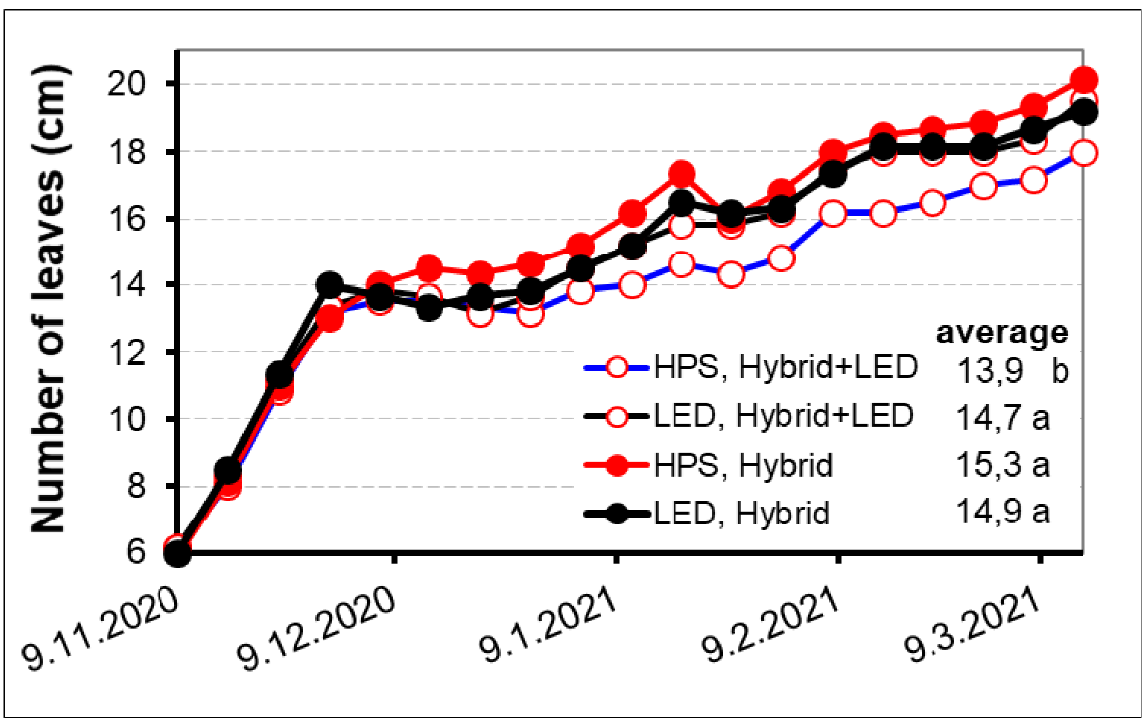

Fig. 12: Number of leaves on the tomato plant.

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

4.2.5 Length of leaves

Length of leaves was staying during the experiment at 42-48 cm (Fig. 13). Young plant production under HPS lights resulted in a significantly higher leaf length compared to young plant production under LEDs when plants received in continuous production “Hybrid+LED”. However, when plants received in continuous production “Hybrid”, was a significant higher leaf length measured when plants were grown in young plant production under LEDs compared to HPS lights. While the continuous light treatment had no influence when plants received HPS lights in young plant production, was a significantly higher leaf length of plants that received LEDs in young plant production measured, when plants were lighted with “Hybrid” instead of “Hybrid+LED” in continuous production.

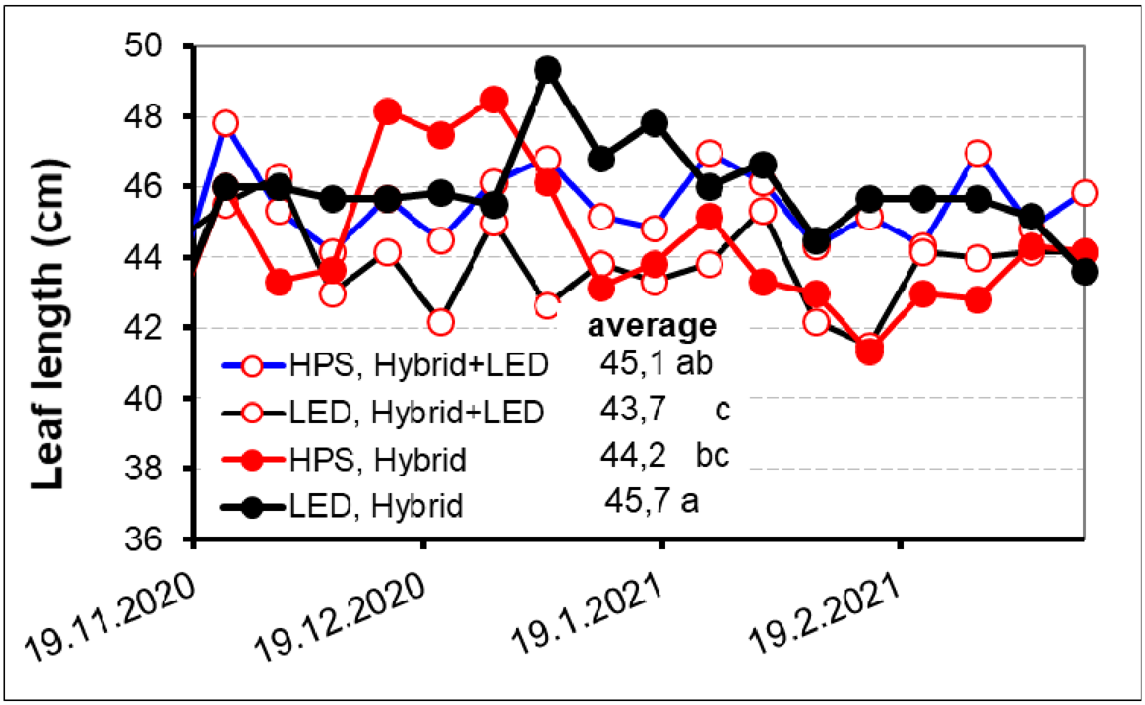

Fig. 13: Length of leaves.

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

4.2.6 Number of clusters

The number of clusters increased with approximately one additional cluster per week. The treatment “HPS, Hybrid+LED” had a significantly lower amount compared to “LED, Hybrid” (Fig. 14).

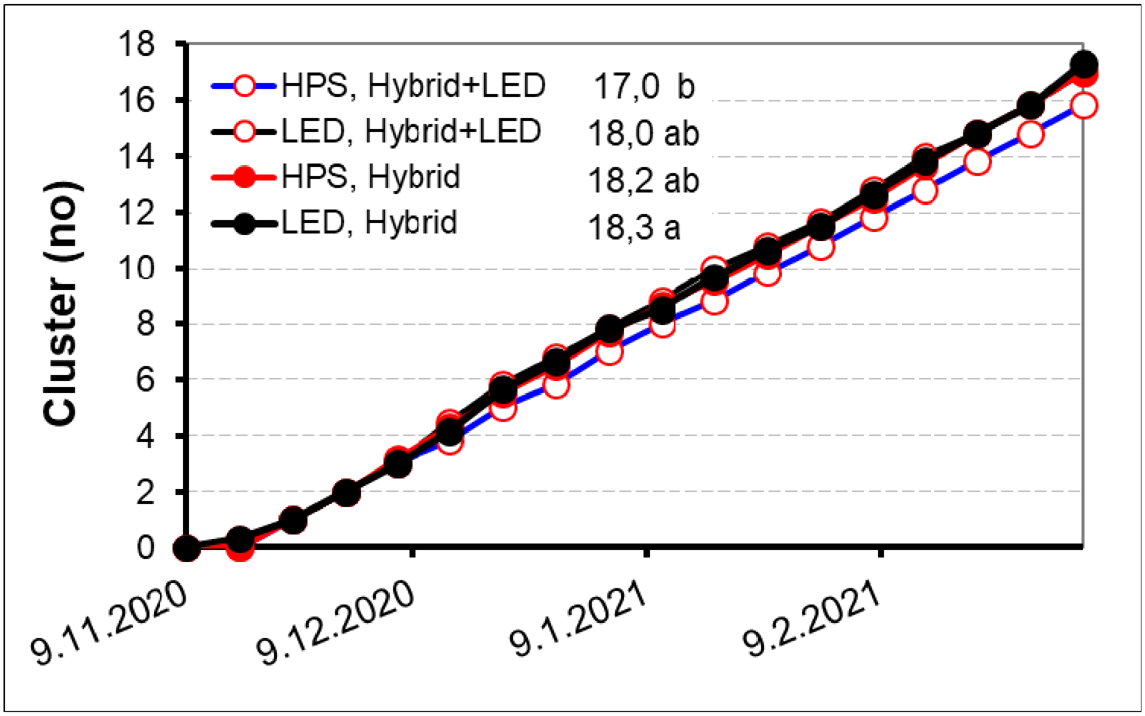

Fig. 14: Number of clusters.

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

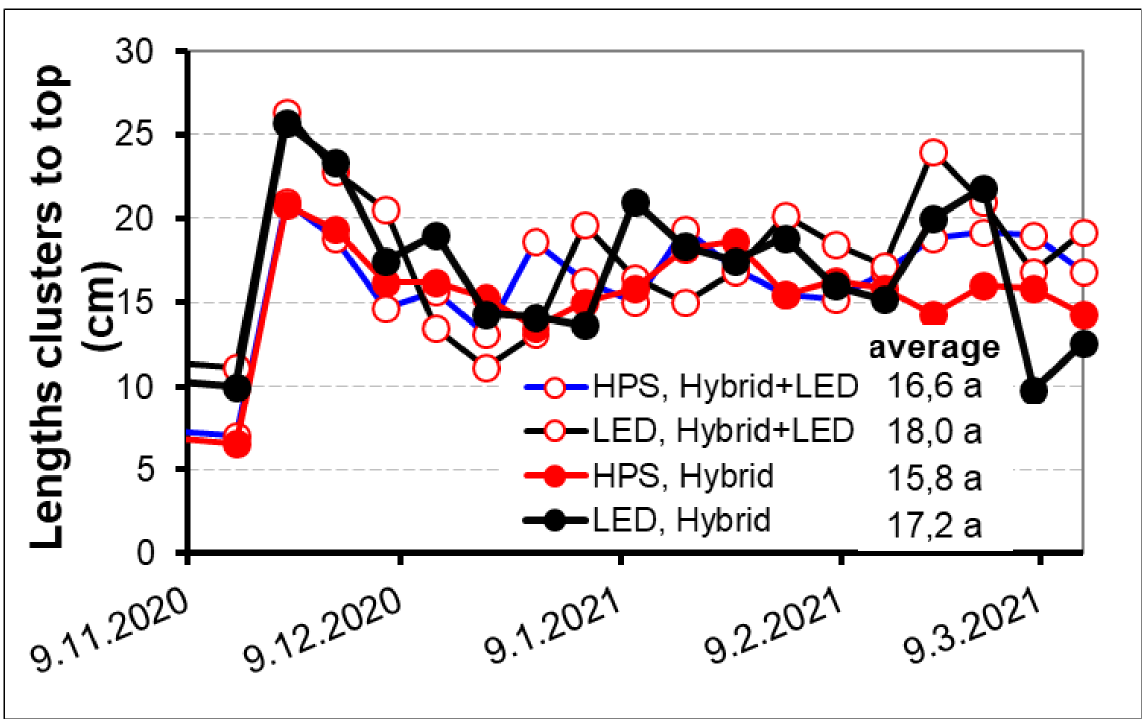

Fig. 15: Length of uppermost flowering cluster to plant top.

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

4.2.7 Length of clusters to top

The length from the uppermost flowering cluster to the top of the plant amounted on average 16-18 cm with no significant differences between light treatments (Fig. 15).

4.2.8 Distance between clusters

The distance between clusters increased from about 20 cm to about 24-26 cm during the growth period. On average amounted the distance 21-22 cm and was independent of the light treatment (Fig. 16). Interestingly, the light treatment under young plant production did not had an influence on the distance between clusters of first clusters.

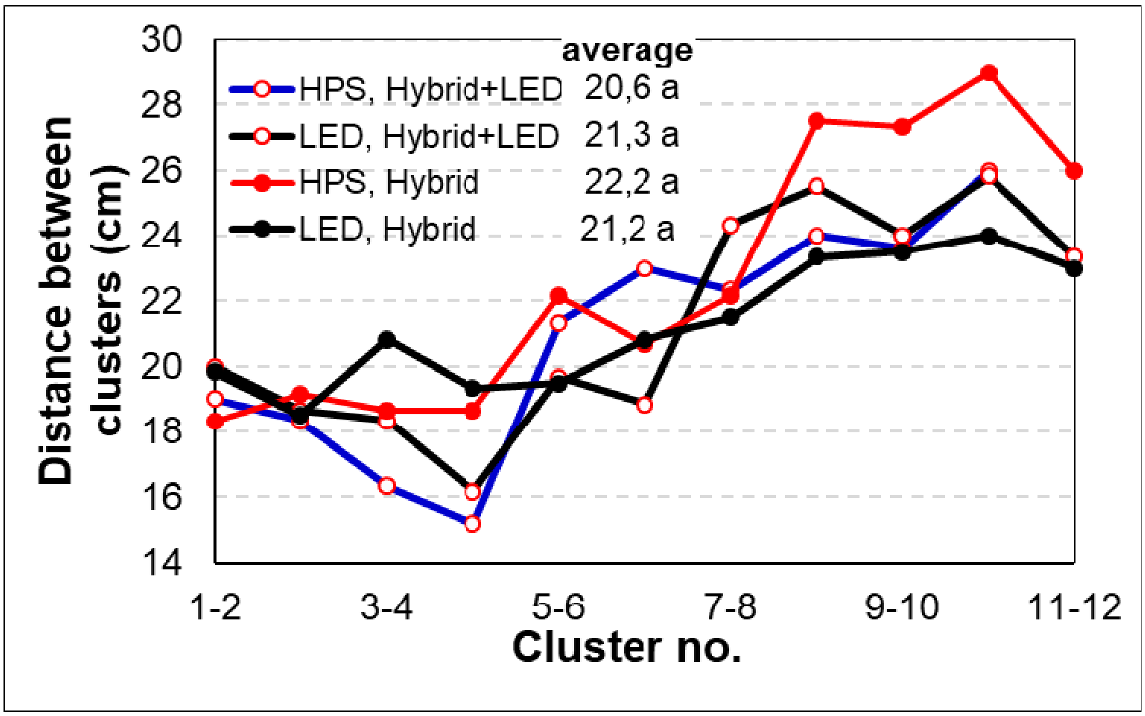

Fig. 16: Distance between clusters.

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

4.2.9 Length of clusters

The length of clusters decreased from about 35 to about 20-25 at the end of the experiment (Fig. 17). The cluster length of the first cluster was not influenced by the light treatment in young plant production. But, plants that were grown in continuous production under “Hybrid+LED” had a significant higher cluster length when grown under HPS lights in young plant production compared to LEDs in young plant production. However, this effect of the light in young plant production was not observed, when plants received later “Hybrid”. For plants that received in young plant production HPS lights was the cluster length independent of the light source in continuous production. However, plants that received in young plant production LEDs had a significantly higher cluster length when grown later under “Hybrid” compared to “Hybrid+LED”.

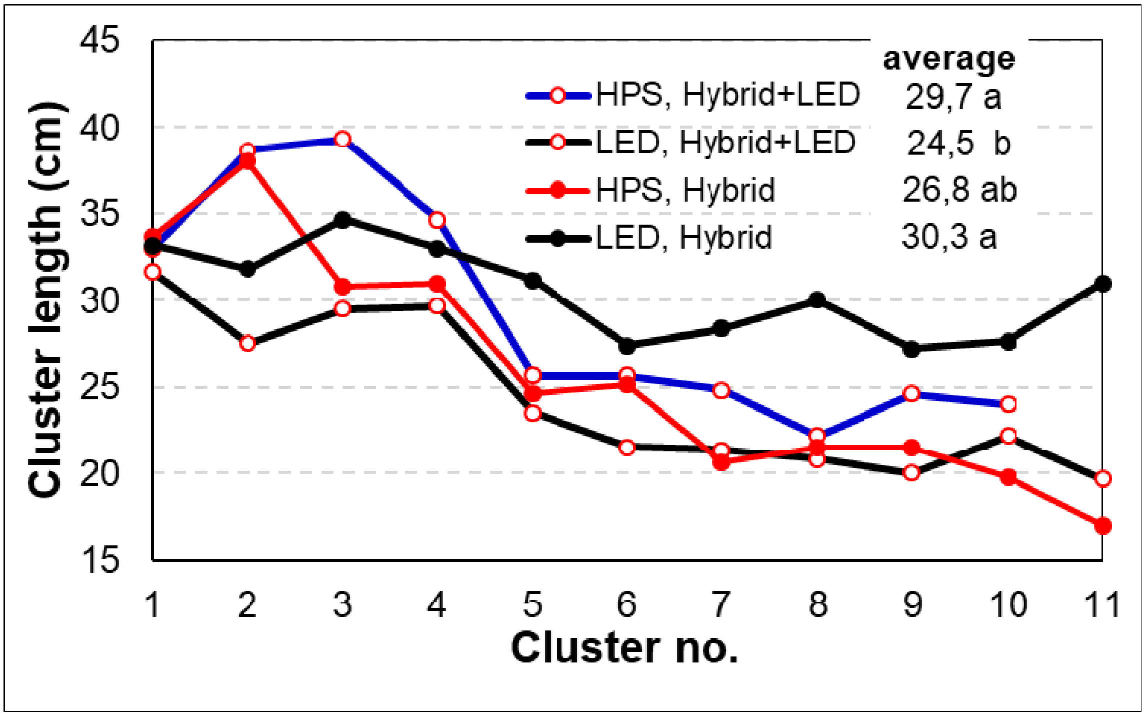

Fig. 17: Length of clusters.

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

4.2.10 Fruits per cluster

Cluster were not pruned. Consequently fluctuated the number of fruits per cluster (Fig. 18). The average number of fruits per cluster was independent of the light treatment in young plant production and also of the light treatment in continuous production. However, it is obvious, that the treatment “LED, Hybrid” had a lower number of fruits at clusters three to six compared to the other light treatments.

The number of not pollinated fruits per cluster was independent of the light treatment in young plant production and of the light treatment in continuous production (Fig. 19). However, it is obvious, that during the whole growing season were most unpollinated flowers counted in the treatment “LED, Hybrid”, followed by “HPS, Hybrid+LED”.

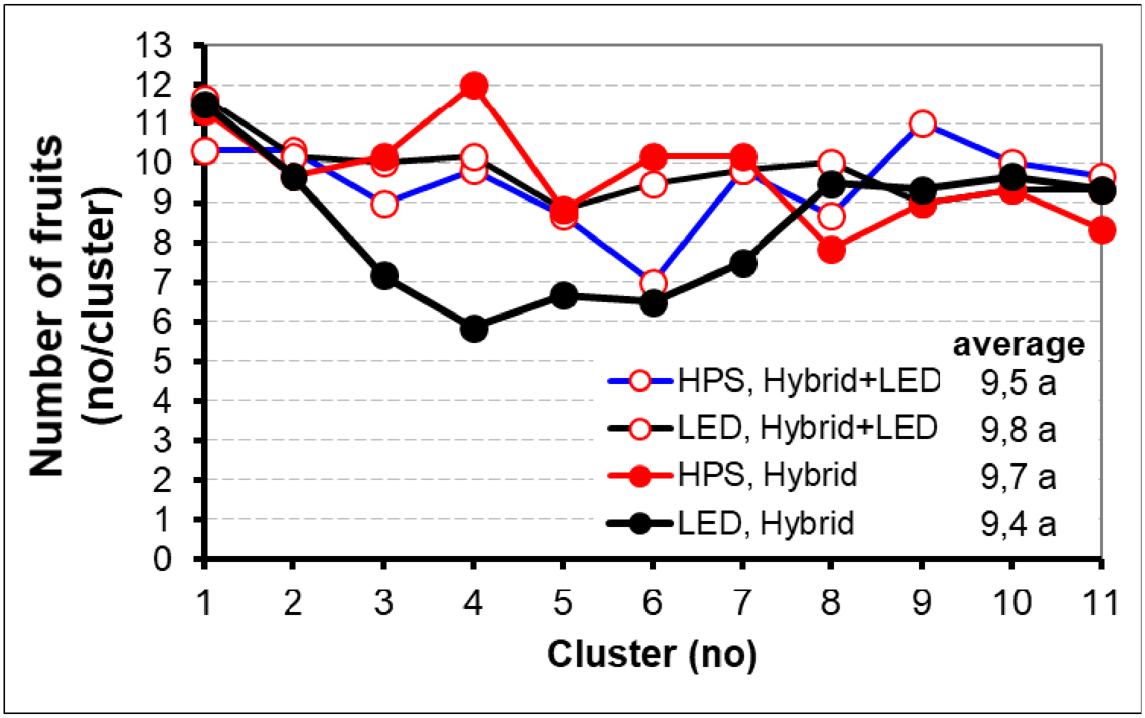

Fig. 18: Number of fruits per cluster.

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

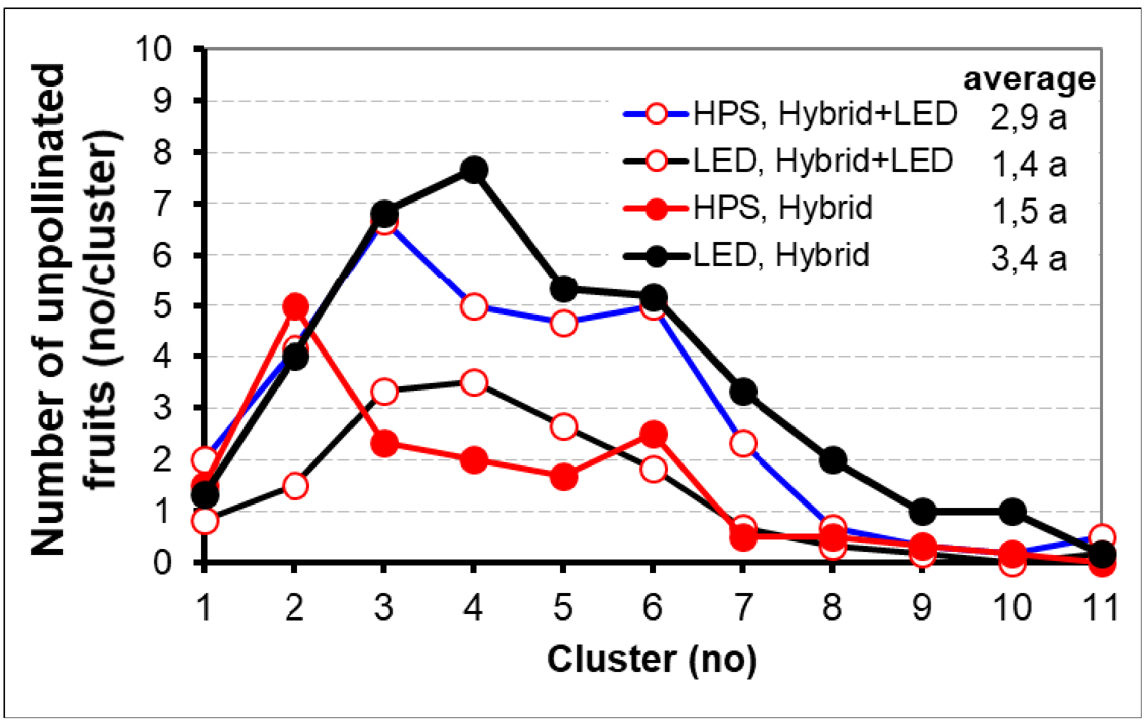

Fig. 19: Number of unpollinated fruits per cluster.

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

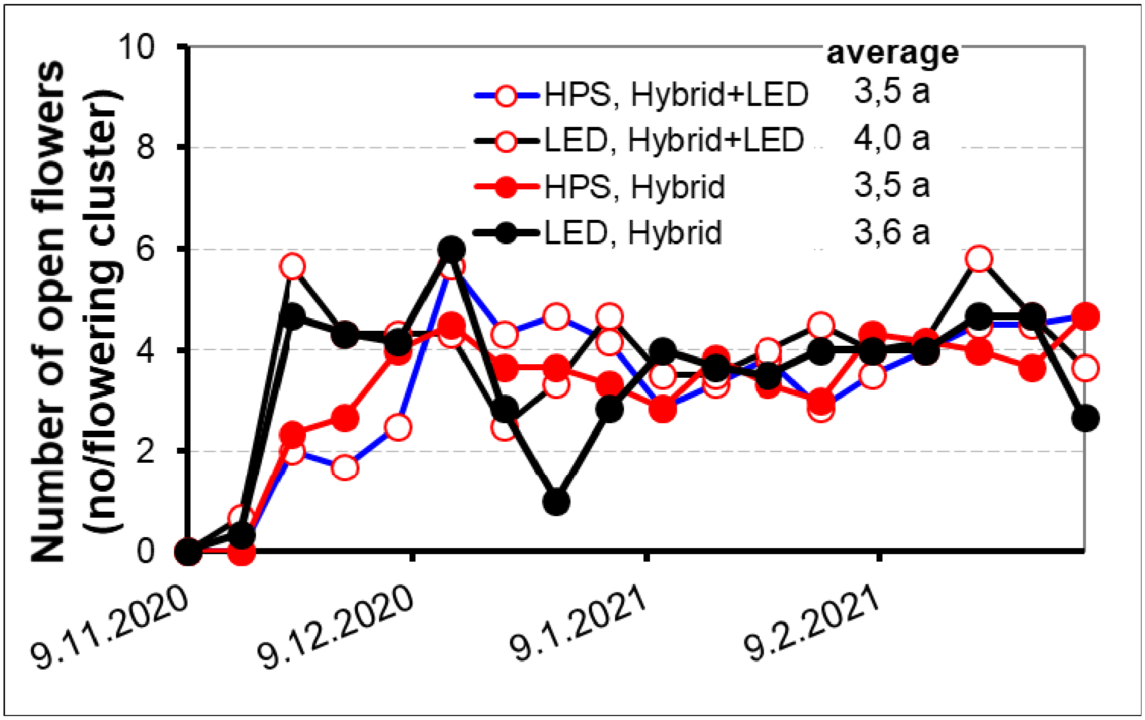

Fig. 20: Number of flowers.

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

4.2.11 Number of open flowers

On the uppermost cluster was the number of open flowers counted. The number of open clusters fluctuated during the growth period at around four open flowers/cluster. On average were no significant differences between the light treatments observed (Fig. 20).

4.2.12 Stem diameter

Stem diameter was varying from 0,6 to 1,4 cm (Fig. 21). On average amounted the diameter of the stem 0,97-1,07 cm and was independent of the light treatment. Plants were most of the time of the growth period weak vegetativ.

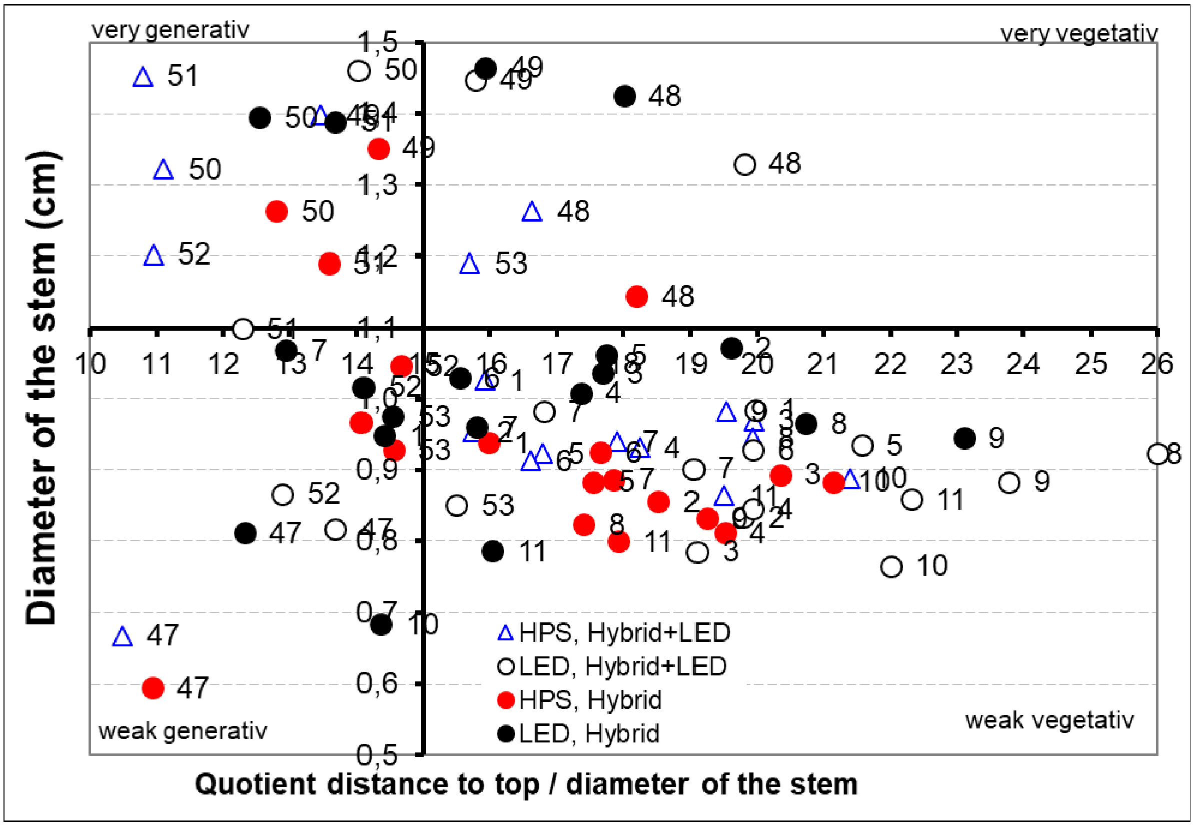

Fig. 21: Stem diameter and quotient lengths to top and stem diameter.
Numbers are representing the week number.

4.3 Yield

4.3.1 Total yield of fruits

The yield of tomatoes included all harvested red fruits during the growth period. The fruits were classified in 1. class (> 55 mm), 2. class (45-55 mm) and not marketable fruits (too little fruits (< 45 mm), fruits with blossom end rot, not well shaped fruits and green fruits at the end of the harvest period).

Cumulative total yield of tomatoes ranged between 22-25 kg/m^2 (Fig. 22). In total was the cumulative total yield of tomatoes independent of the light treatment. However, the 1. class yield, the yield of too little fruits and green fruits was affected by the light treatment, while the 2. class yield was independent of the light treatment. There seem to be a small advantage of “HPS, Hybrid” compared to the other light treatments, even though this difference was not statistically different. The significantly higher yield of green fruits in “LED, Hybrid” and “HPS, Hybrid” compared to “LED, Hybrid+LED” is showing the potential of a possible higher total yield, in case the experiment would have been conducted longer, by increasing fruit size of ripening fruits and with that weight.

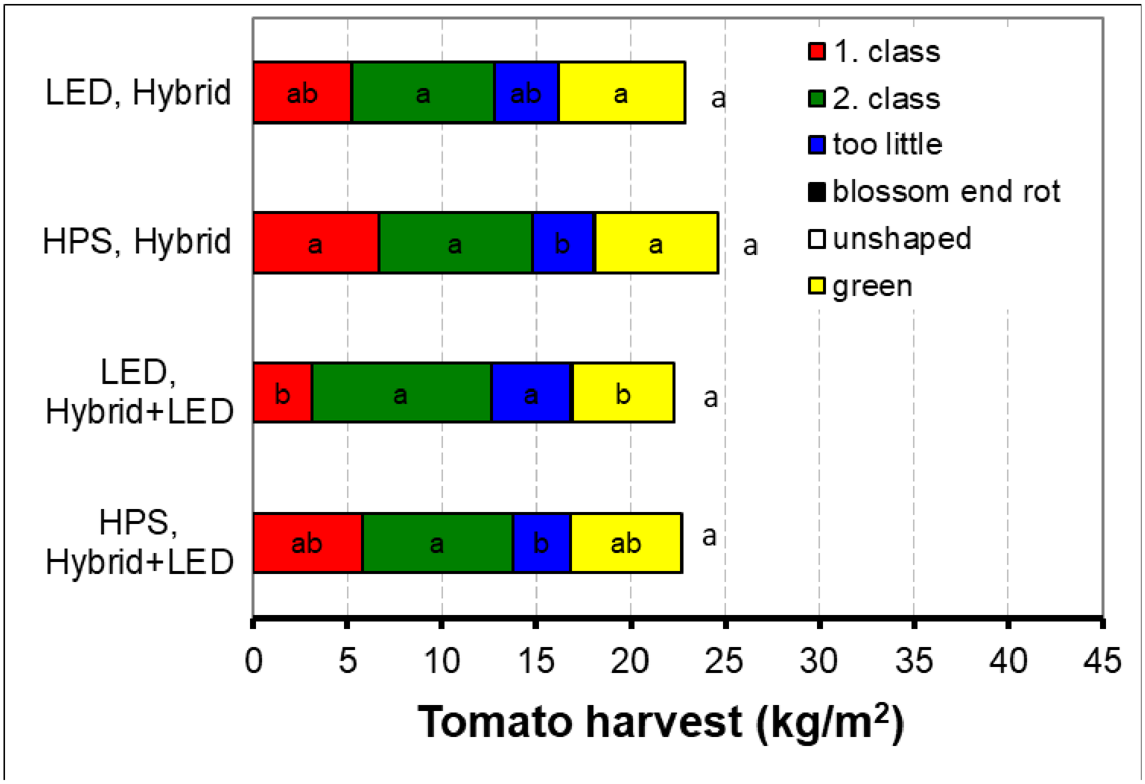

Fig. 22: Cumulative total yield of tomatoes in kg.
Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

Also, the amount of fruits harvested was independent of the light treatment. While the number of green and too little fruits was independent of the light treatment, where in the amount of 1. and 2. class fruits differences between light treatments observed (Fig. 23).

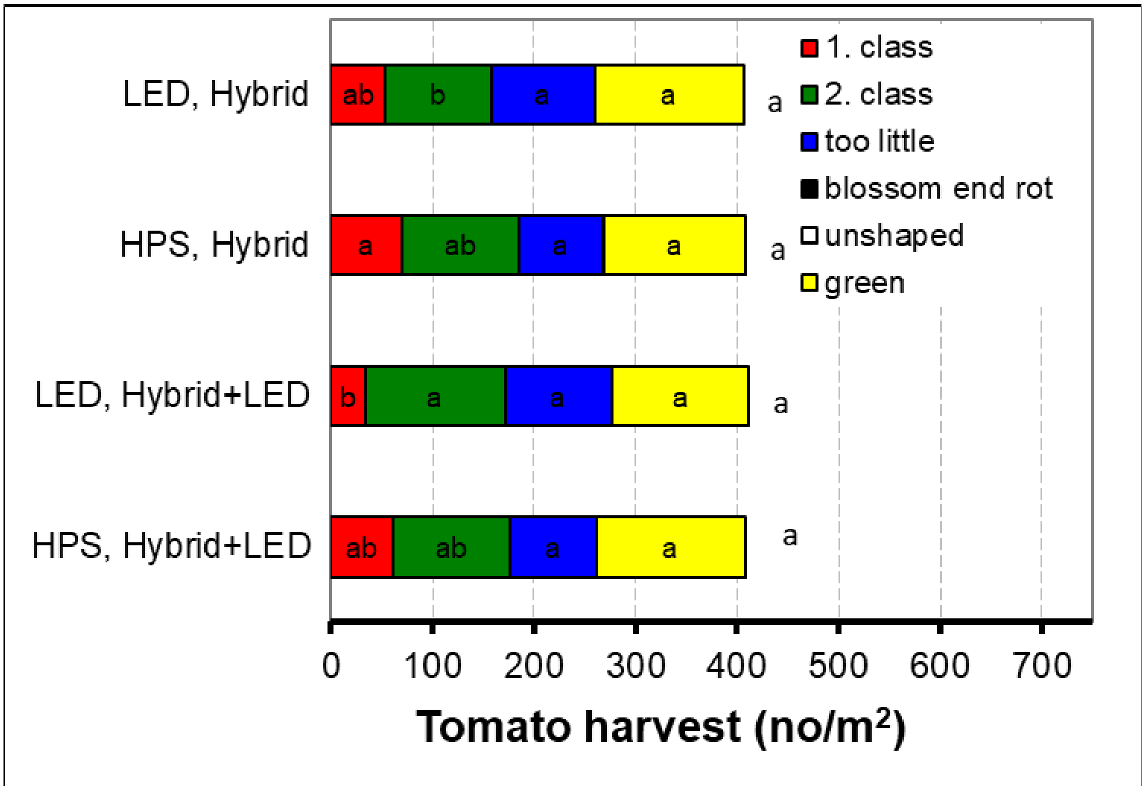

Fig. 23: Cumulative total yield of tomatoes in number.
Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

4.3.2 Marketable yield of tomatoes

At the end of the harvest period amounted marketable yield of tomatoes 13-15 kg/m^2 (Fig. 24). No significant differences between light treatments were observed. The light treatment during young plant production did not matter and also the light treatment at continous production did not have an influence on marketable yield of tomatoes.

Plants that received LED lights in young plant production started to give red fruits about half a week earlier than plants that received HPS lights in young plant production. However, at the end of the harvest period was a small yield advantage observed at light treatments that received HPS lights in young plant production compared to light treatments that received LEDs in young plant production. In the middle of the harvest period was observed an advantage of the treatment „HPS, Hybrid“. However, this advantage decreased at the end of the harvest period.

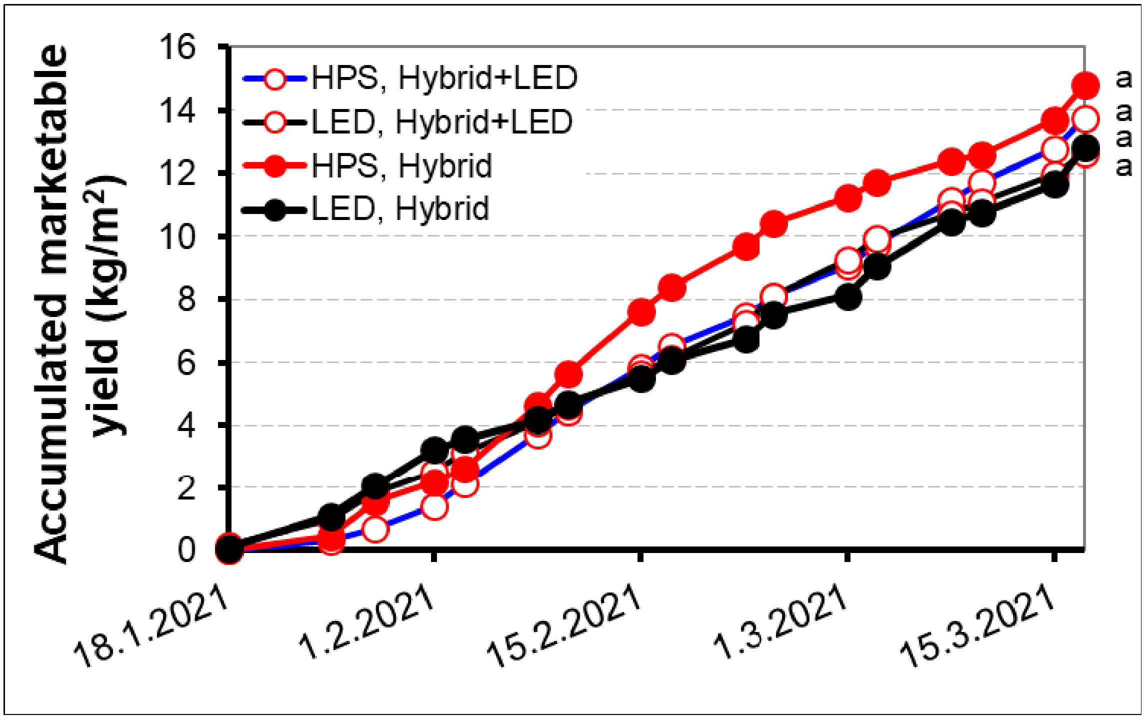

Fig. 24: Time course of marketable yield (1. and 2. class tomatoes).
Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

The 1. class yield amounted 3-6 kg/m^2 at the end of the harvest period (Fig. 25). The 1. class yield was neither affected by the light treatment (HPS versus LED) in young plant production, nor by the light treatment in the continuous production (Hybrid+LED versus Hybrid). However, 1. class yield of “HPS, Hybrid” was two times higher than of “LED, Hybrid+LED” and with that significantly different, but not statistically different to the other two light treatments.

In contrast, the 2. class yield was independent of the light treatment and amounted in all light treatments around 8-10 kg/m^2 (Fig. 26).

Also, the marketable yield of the whole chamber was measured (Fig. 27). A higher marketable yield was reached with “HPS, Hybrid” (4,0 kg/plant) compared to “LED, Hybrid, LED” and “HPS, Hybrid+LED” (3,6 kg/plant) and “LED, Hybrid+LED” (3,4 kg/plant).

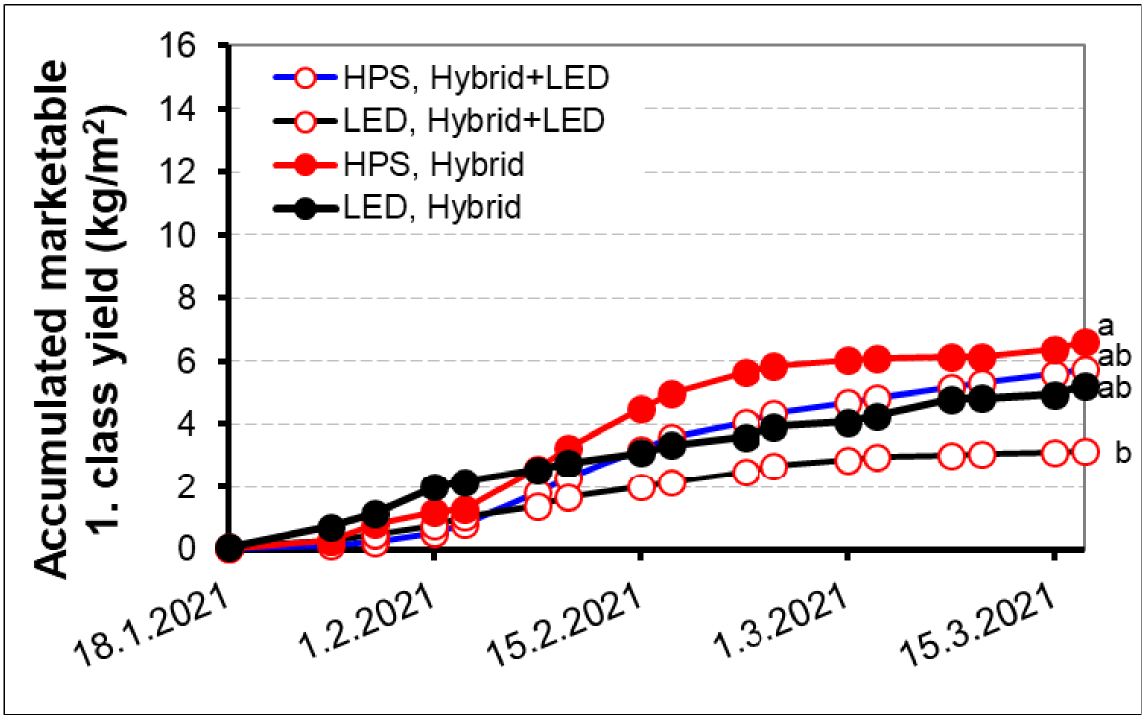

Fig. 25: **Time course of marketable 1. class yield.**
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

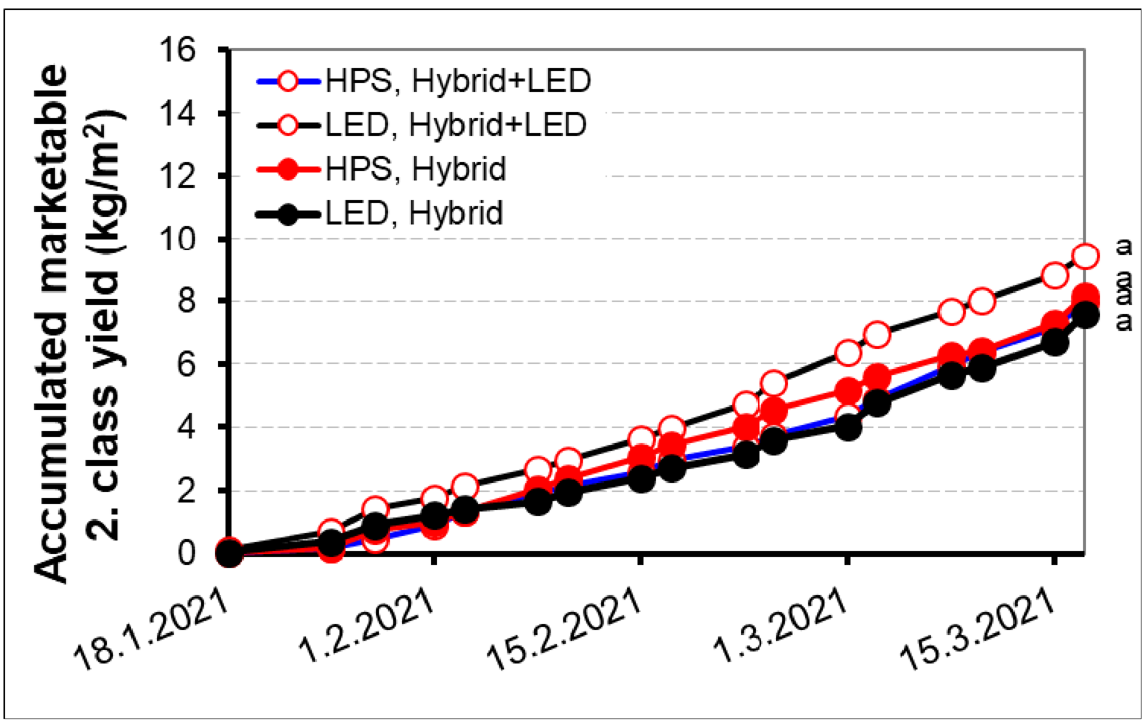

Fig. 26: **Time course of marketable 2. class yield.**
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

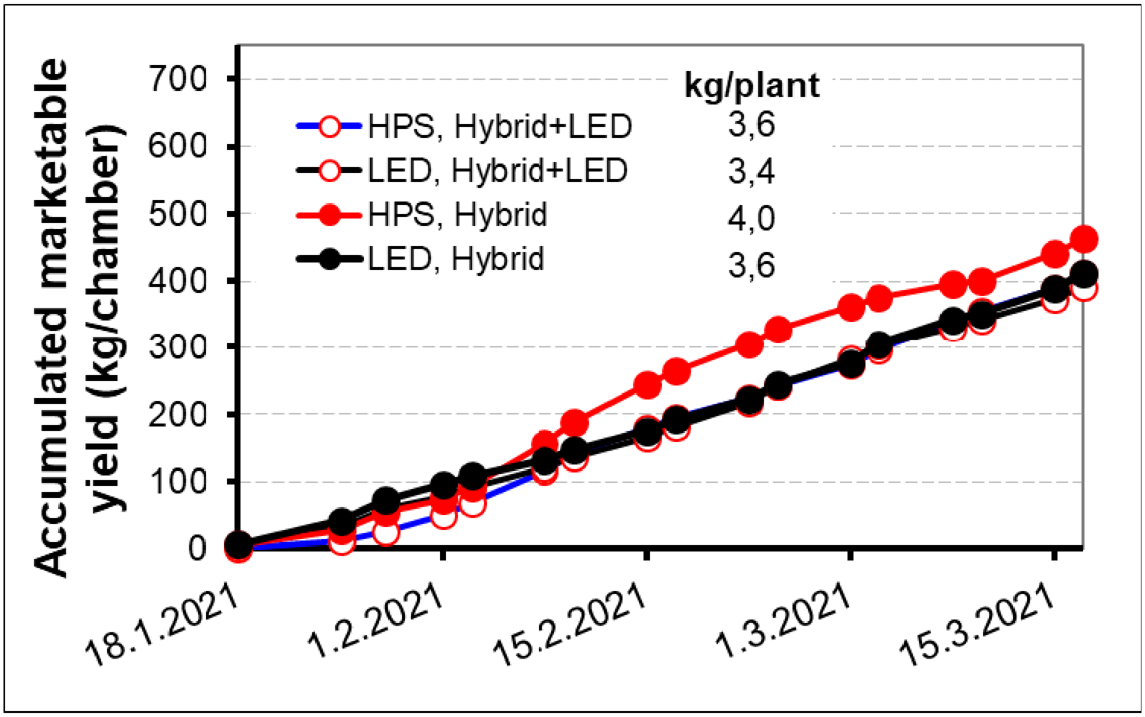

Fig. 27: Time course of marketable yield of tomatoes in the whole chamber.

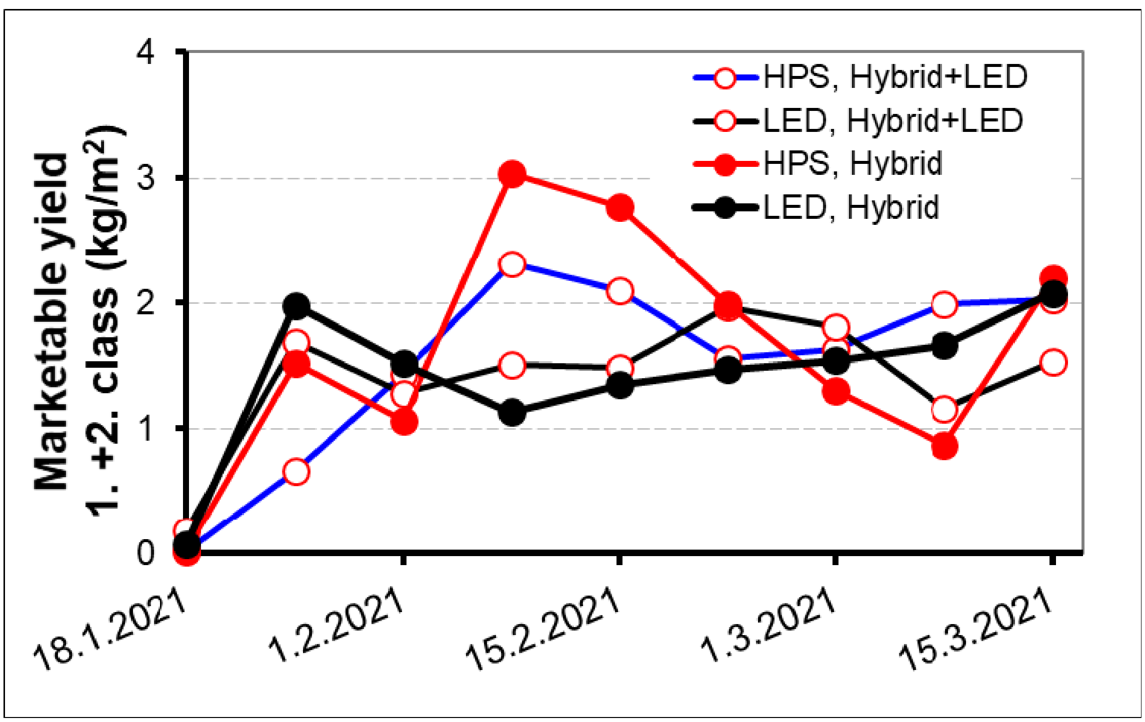

Fig. 28: Time course of marketable yield.

The weekly harvest of 1. class and 2. class fruits amounted 1,0-3,0 kg/m^2, but was most of the time 1,5-2,0 kg/m^2. While all light treatments were more or less with a weekly constant yield, fluctuated the yield of “HPS, Hybrid” quite much (Fig. 28).

But, the number of 1. class fruits was significant higher for “HPS, Hybrid” compared to “LED, Hybrid+LED” (Tab. 5). The number of 1. class fruits was neither influenced by the light treatment in young plant production nor by the light treatment in the continuous production. The number of 2. class fruits was statistically higher in “LED, Hybrid+LED” than in “LED, Hybrid”. When young plant production was under HPS lights was the number of 2. class fruits not affected by the light treatment in continuous production, while, when young plant production was under LEDs was the number of 2. class fruits affected by the light treatment in continuous production (compare “Hybrid” to “Hybrid+LED”). However, the total number of marketable fruits was not significantly different between light treatments regarding young plant production nor regarding continuous production.

Tab. 5: Cumulative total number of marketable fruits.

Treatment	**Number of marketable fruits**		
	1. class (no/m^2)	2. class (no/m^2)	total (1. class + 2. class) (no/m^2)
HPS, Hybrid+LED	61 ab	115 ab	176 a
LED, Hybrid+LED	34 b	137 a	171 a
HPS, Hybrid	69 a	116 ab	185 a
LED, Hybrid	54 ab	104 b	158 a

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

Average fruit size of 1. class tomatoes varyied between 85-105 g / fruit (Fig. 29). On average was the weight of 1. class tomatoes independent of the light source in young plant production. However, when plants received LEDs in young plant production, was a significantly higher average weight of 1. class fruits measured, when lighted with “Hybrid” compared “Hybrid+LED”. But, when plants received HPS in young plant production had the light treatment in continuous production no influence on fruit size.

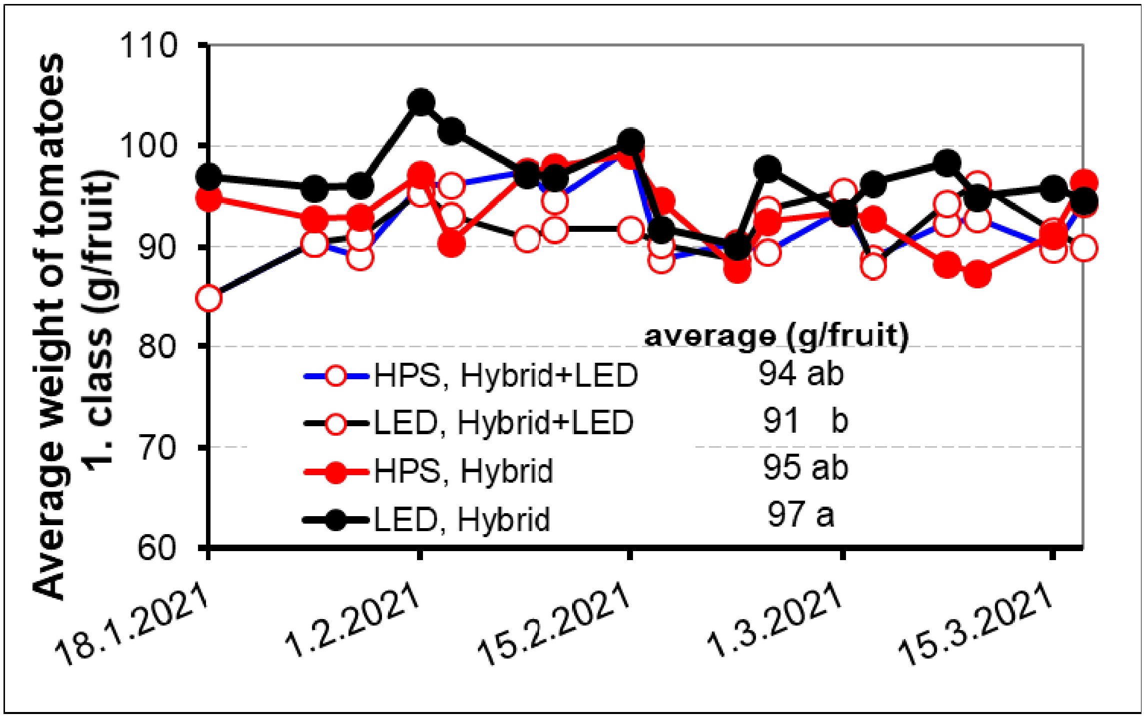

Fig. 29: Average weight of tomatoes (1. class fruits).

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

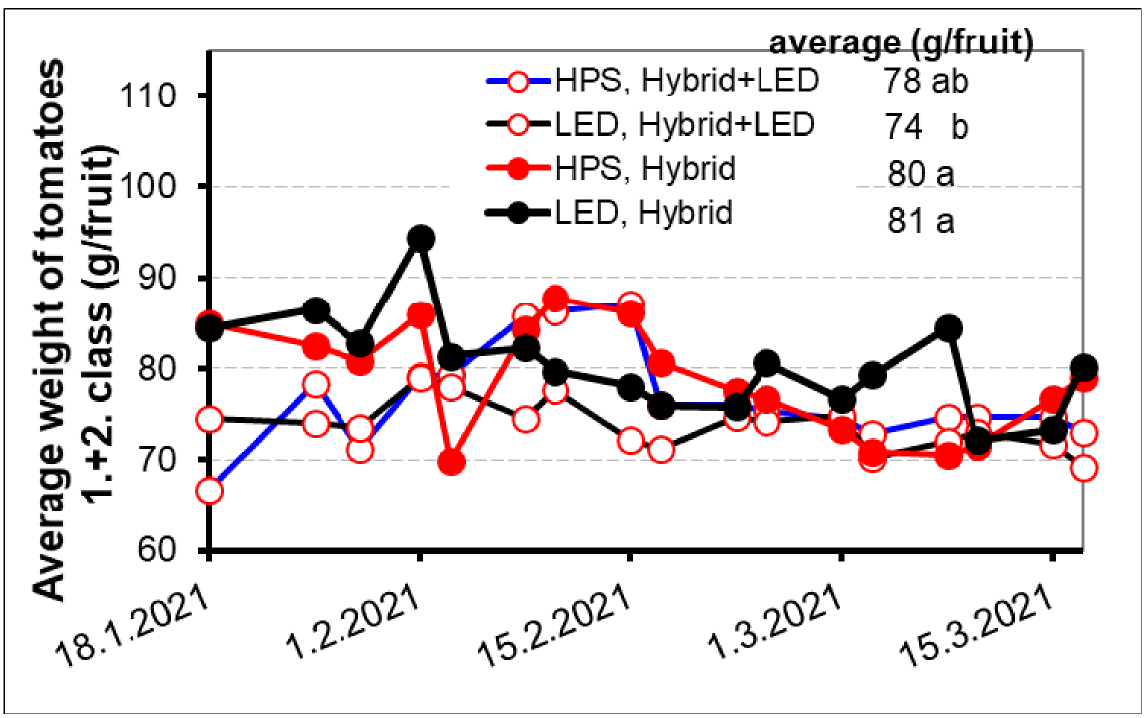

Fig. 30: Average weight of tomatoes (1. and 2. class fruits).

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

Average fruit size of 1. and 2. class tomatoes was varying between 70-90 g / fruit (Fig. 30). It seems that fruit size decreased slightly at proceeded harvest period. The light source in young plant production did not affect average fruit size. But, as for 1. class fruits, was also here an effect of the light source in continuous production observed when lighted with LEDs in young plant production. An additional increase of 7 g was possible with “Hybrid” instead of “Hybrid+LED”. However, this effect was not observed when lighted with HPS lights in young plant production.

4.3.3 Outer quality of yield

Marketable yield was more than 60% of total yield for all light treatments (Tab. 6). While “LED, Hybrid+LED” had a low percentage of 1. class fruits was the proportion of 2. class fruits bigger. The other light treatments had nearly the same percentage of 1. and 2. class fruits. Blossom end rot fruits as well as unshaped fruits had a proportion of zero on total yield. The proportion of green fruits on total yield was in all light treatments very high due to the fact that tomato plants were not topped and allowed to grow “naturally” until the end of the experiment. Therefore, was the amount of green fruits high as new clusters developed until the end of the experiment, which were then harvested as green fruits. The proportion of green fruits was comparable in all light treatments, except “LED, Hybrid+LED” had a lower percentage.

Tab. 6: Proportion of marketable and unmarketable yield.

Treatment	Marketable yield (%)		Unmarketable yield (%)			
	1. class > 55 mm	2. class > 45-55 mm	too little weight	blossom end rot	not well shaped	green
HPS, Hybrid+LED	25 a	35 ab	14 a	0 a	0 a	26 ab
LED, Hybrid+LED	14 b	43 a	19 a	0 a	0 a	24 b
HPS, Hybrid	27 a	33 b	13 a	0 a	0 a	27 ab
LED, Hybrid	23 ab	33 b	15 a	0 a	0 a	29 a

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

4.3.4 Interior quality of yield

4.3.4.1 Sugar content

Sugar content of tomatoes was measured three times during the harvest period. Completo had a sugar content of 3,4-4,0°BRIX. The sugar content was at the two last measurement dates independent of the light treatment. However, at the first measurement date were significant differences between light treatments observed (Fig. 31).

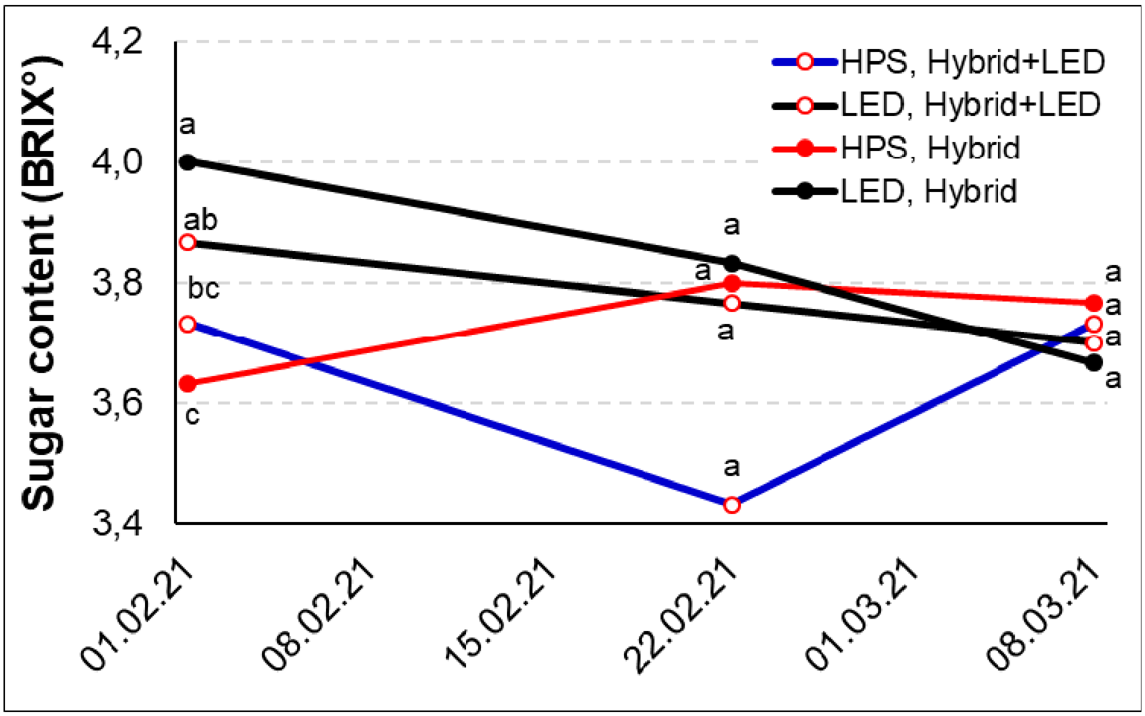

Fig. 31: Sugar content of tomatoes.

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

4.3.4.2 Dry substance of tomatoes

Dry substance (DS) of tomatoes was measured on the same dates as the sugar content and was varying between 4,1% and 4,5% (Fig. 32). The DS content was independent of the light treatment.

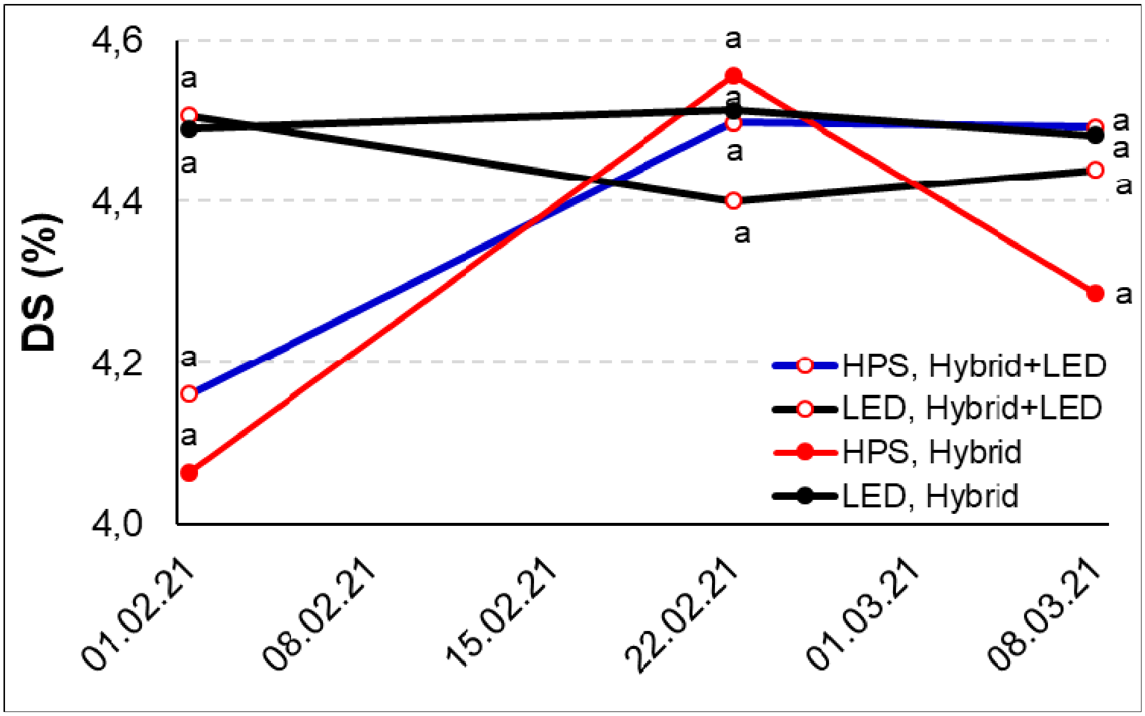

Fig. 32: Dry substance of tomatoes.

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

4.3.4.3 Relationship between dry substance and sugar content

There was no relationship between DS and sugar content of tomatoes (Fig. 33).

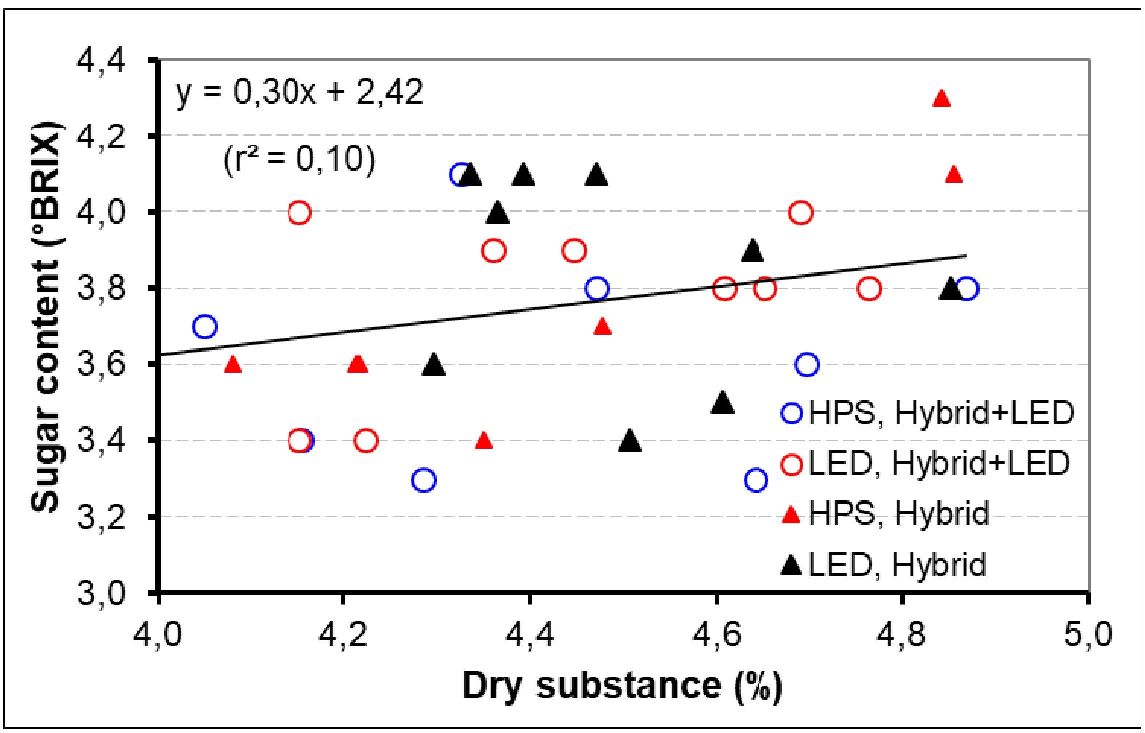

Fig. 33: Relationship between dry substance and sugar content of fruits.

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 and at the continuing growing period after transplanting were measured with dataloggers.

Young plant production of tomatoes resulted in the HPS chamber in a daily usage of 118 kWh, while the LED chamber had with 100 kWh 15% less energy use (Fig. 34a). This means that the costs for growing seedlings with HPS lights are higher, due to 18% higher energy costs. Regarding the continuous production used the treatments “HPS, Hybrid+LED” and “LED, Hybrid+LED” (181 kWh/day) less energy than “HPS, Hybrid” and “LED, Hybrid” (237 kWh/day) (Fig. 34b). The used energy was about 21% lower at treatments with LED interlighting. The light treatment in young plant production did not influence total used energy (Tab. 7).

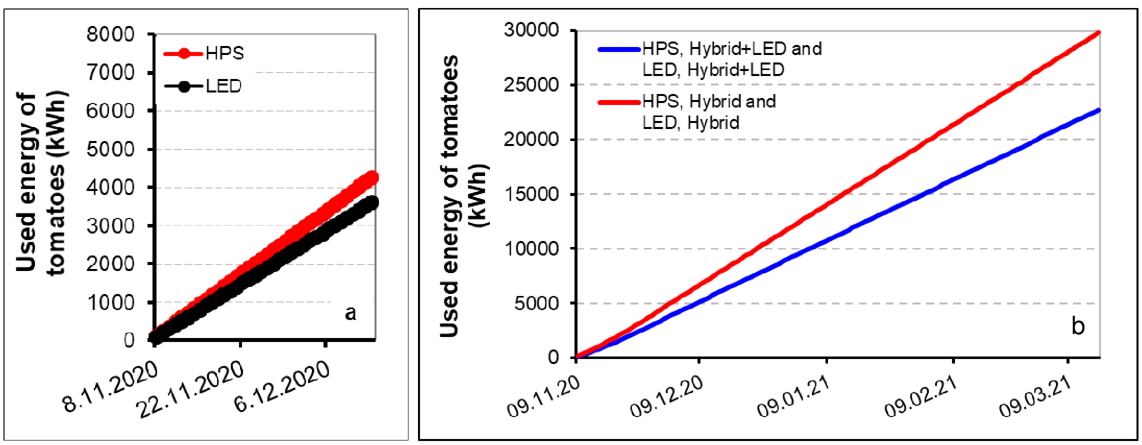

Fig. 34: Used kWh of seedlings of tomatoes (a) and of tomatoes in continuous production (b) under different light sources.

4.4.2 Energy use efficiency

When tomatoes were lightened with “Hybrid+LED” were kWh’s transferred better into yield than with “Hybrid” (Fig. 35). This difference amounted 15-20%. Also, with HPS lights in young plant production was the utilization of kWh’s better transferred into yield compared to LEDs in young plant produciton. This difference amounted 6-12%. However, differences between the treatments were not statistically different.

Tab. 7: Used energy under different light sources (datalogger values).

Treatment	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
Young plant production				
Energy (kWh)	4.246	3.601	4.246	3.601
Energy/m² (kWh/m²)	85	72	85	72
Continous plant production				
Energy (kWh)	22.714	22.708	29.790	29.922
Energy/m² (kWh/m²)	454	454	596	598
Total				
Energy (kWh)	**26.960**	**26.309**	**34.036**	**33.523**
Energy/m² (kWh/m²)	**539**	**526**	**681**	**670**

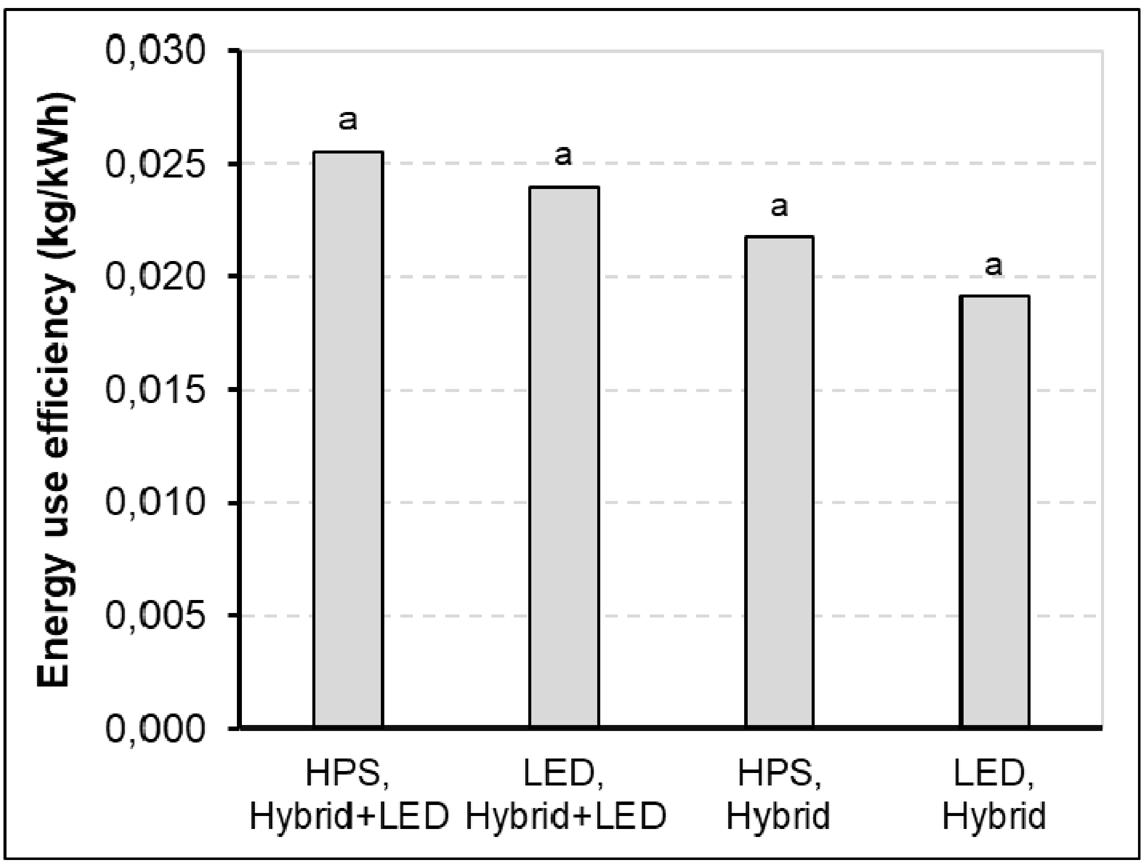

Fig. 35: Energy use efficiency (= marketable yield per used energy) for tomatoes under different light sources.

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 (National Energy Authority of Iceland), 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 and their continuous production calculated (Tab. 8). Costs for electricity were naturally higher for seedlings grown under HPS lights due to the higher use of electricity. Investment costs into lights were nearly three times higher for LEDs compared to HPS lights for young plant production. However, as young plant production did only take a small part into the whole production and investment costs into “Hybrid” and “Hybrid+LED” did not differ much in continuous production, were total investment costs into lights only by 9% increased when plants received LEDs in young plant production compared to HPS lights in young plant production. The selection of “Hybrid+LED” or “Hybrid” did not influence the total investment costs into lights.

In total were light related costs (electricity costs + investment into lights) of seedling production and continuous production about 3% higher for light treatments that received young production under LEDs (“LED, Hybrid+LED,” “LED, Hybrid”), while Hybrid “(HPS, Hybrid”, “LED, Hybrid”) was about 12% more expensive than Hybrid+LED (“HPS, Hybrid+LED”, “LED, Hybrid+LED”) (Fig. 36).

Tab. 8: Energy costs and investment into lights in seedling production and continuous production for one growing circle of tomatoes under different light sources.

Costs (ISK/m²)	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
Young plant production				
Electricity distribution [1]	85	72	85	72
Electricity sale [2]	490-555	415-470	490-555	415-470
∑ **Electricity costs**	575-640	487-542	575-640	487-542
Continous plant production				
Electricity distribution [1]	454	454	596	598
Electricity sale [2]	2.620-2.965	2.620-2.965	3.439-3.892	3.450-3.905
∑ **Electricity costs**	3.074-3.419	3.074-3.419	4.035-4.488	4.048-4.503
Total				
Electricity distribution [1]	**539**	**526**	**681**	**670**
Electricity sale [2]	**3.110-3.520**	**3.035-3.435**	**3.929-4.447**	**3.866-4.375**
∑ Electricity costs	**3.649-4.059**	**3.561-3.961**	**4.610-5.128**	**4.536-5.045**
Young plant production				
Lamps [3]	120	483	120	483
Bulbs [4]	57		57	
∑ **Investment lights**	**177**	**483**	**177**	**483**
Continous plant production				
Lamps [3]	3.032	3.032	2.780	2.780
Bulbs [4]	229	229	401	401
∑ **Investment lights**	3.261	3.261	3.181	3.181
Total				
Lamps [3]	**3.152**	**3.515**	**2.900**	**3.263**
Bulbs [4]	**286**	**229**	**458**	**401**
Total light related costs	**7.087-7.497**	**7.305-7.705**	**7.968-8.486**	**8.200-8.709**

[1] Assumption: On 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

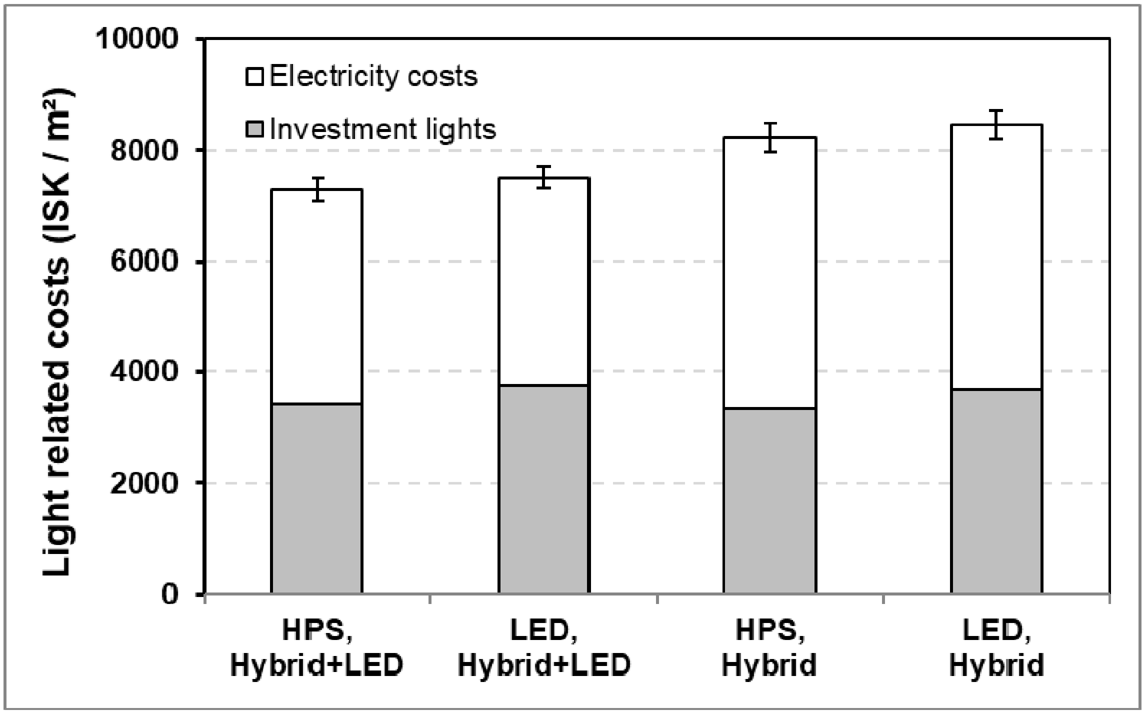

Fig. 36: Light related costs in seedling production + continuous production of tomatoes under different light sources.

4.4.4 Costs of electricity in relation to yield

Costs of electricity in relation to yield for wintergrown tomatoes were calculated (Tab. 9). The costs of electricity per kg yield increased by 6% / 14% when LEDs were used in young plant production (compare "HPS, Hybrid+LED" with "LED, Hybrid+LED" and "HPS, Hybrid" with "LED, Hybrid"). Also, the costs of electricity in relation to yield increased by 17% / 25% with the selection of only Hybrid top lighting compared to Hybrid top lighting together with LED interlighting (compare "HPS, Hybrid+LED" with "HPS, Hybrid" and "LED, Hybrid+LED" with "LED, Hybrid").

Tab. 9: Variable costs of electricity in relation to yield.

Treatment	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
Yield (kg/m^2)	13,7	12,6	14,8	12,8
Electricity costs (ISK/kg yield)	266-296	283-314	311-346	354-394

4.4.5 Profit margin

The profit margin is a parameter for the economy of growing a crop. It is calculated by substracting the variable costs from the revenues. The revenues itself, is the product of the price of the sale of the fruits and kg yield. For each kg of tomatoes, growers are getting about 560 ISK from Sölufélag garðyrkjumanna (SfG, The Horticulturists' Sales Company) and in addition 130 ISK from the government. Therefore, the revenues increased with more yield (Fig. 37). The light source in continuous production had a small influence on the revenue, whereas a higher profit margin was reached by having HPS lights in young plant production.

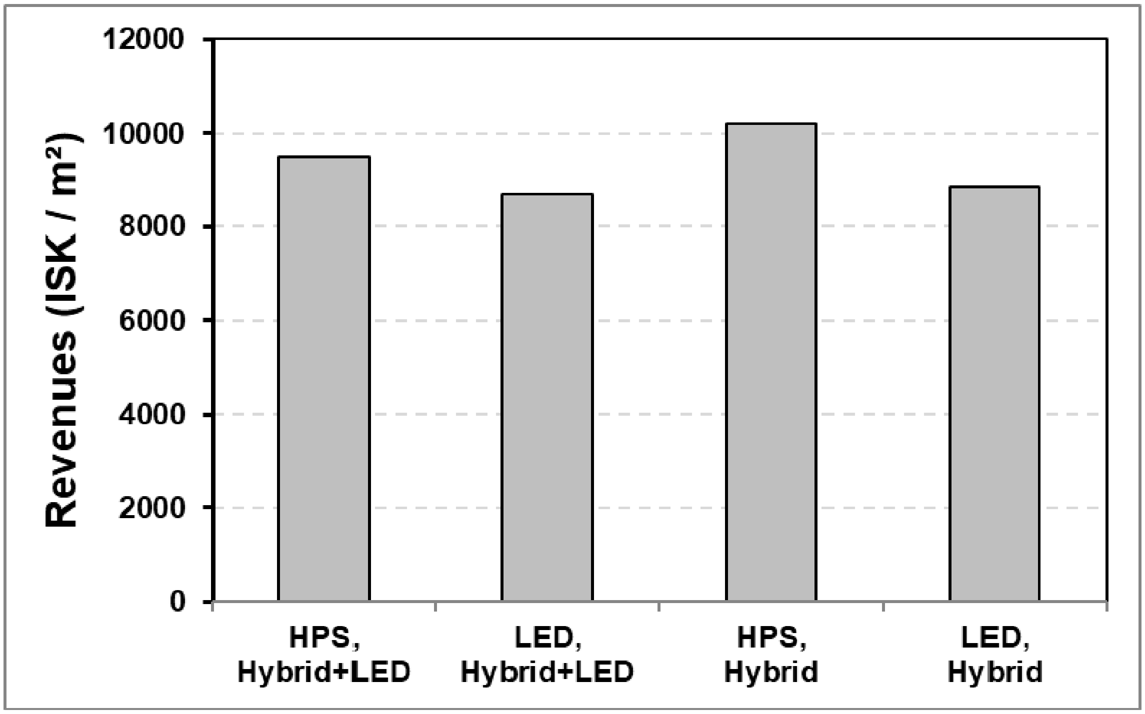

Fig. 37: Revenues at different treatments.

When considering the results of previous chapter, one must keep in mind that there are other cost drivers in growing tomatoes than electricity alone (Tab. 10). Among others, this are e.g. the costs for seeds and seedling production (≈ 400 ISK/m^2) and transplanting (≈ 400 ISK/m^2), costs for gutters (≈ 100 ISK/m^2), and watering system (≈ 350 ISK/m^2), costs for plant nutrition (≈ 330 ISK/m^2), costs for plant protection and bumblebees, CO_2 transport (≈ 200 ISK/m^2), liquid CO_2 (≈ 1.600 ISK/m^2), the rent of the tank (≈ 460 ISK/m^2), the rent of the green box (≈ 100 ISK/m^2), material for packing (≈ 500 ISK/m^2), packing costs with the machine from SfG (≈ 200 ISK/m^2) and transport costs from SfG (≈ 150 ISK/m^2) (Fig. 38).

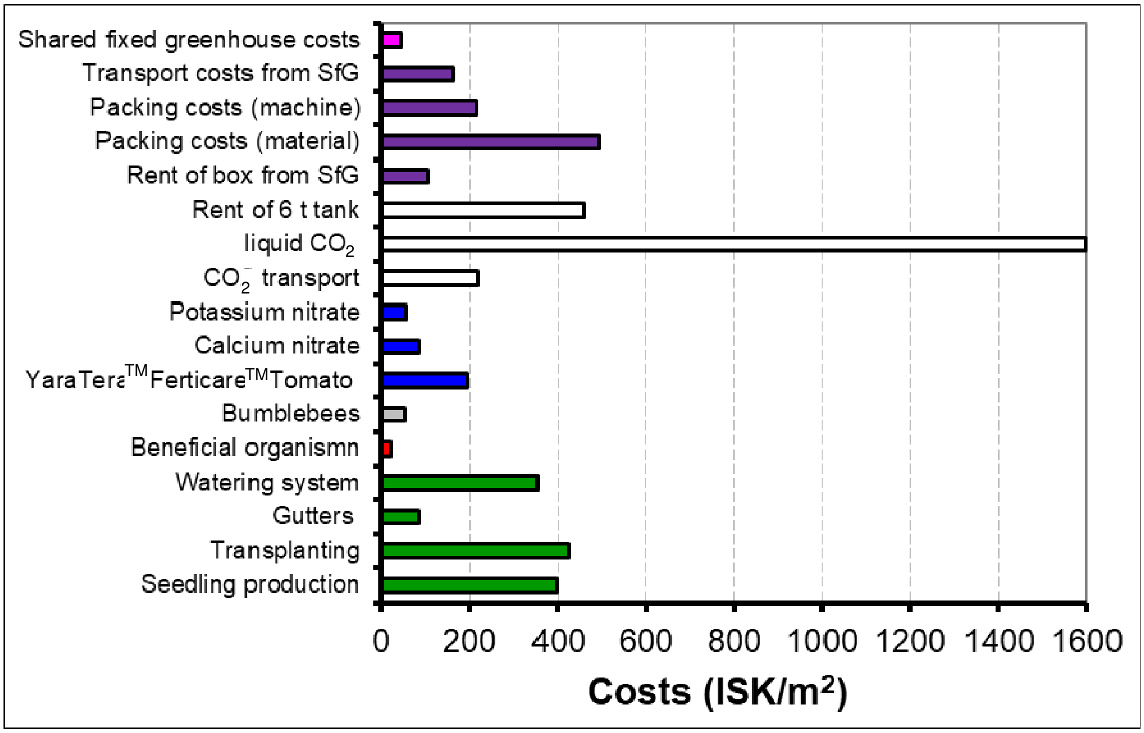

Fig. 38: Variable and fixed costs (without lighting and labour costs).

However, in Fig. 38 three of the biggest cost drivers are not included and these are investment in lamps and bulbs, electricity and labour costs. These costs are also included in Fig. 39 and it is obvious, that especially the electricity and the investment in lamps and bulbs as well as the CO_2 and labour costs are contributing much to the variable and fixed costs beside the costs for seedling production, transplanting and cultivation and the costs for packing and marketing. The proportion of the variable and fixed costs is mainly the same for all light treatments. Attention has to be payed on the big proportion of more than 50% of light related costs (electricity + investment into lamps and bulbs) on total production costs. With a higher use of LED lights decreased the costs for electricity (“HPS, Hybrid+LED”, “LED, Hybrid+LED”) from 33% to 28%, but in contrast, the costs for the investment into lamps and bulbs increased from 22% to 24%. The proportion of the other costs is comparable for all light treatments.

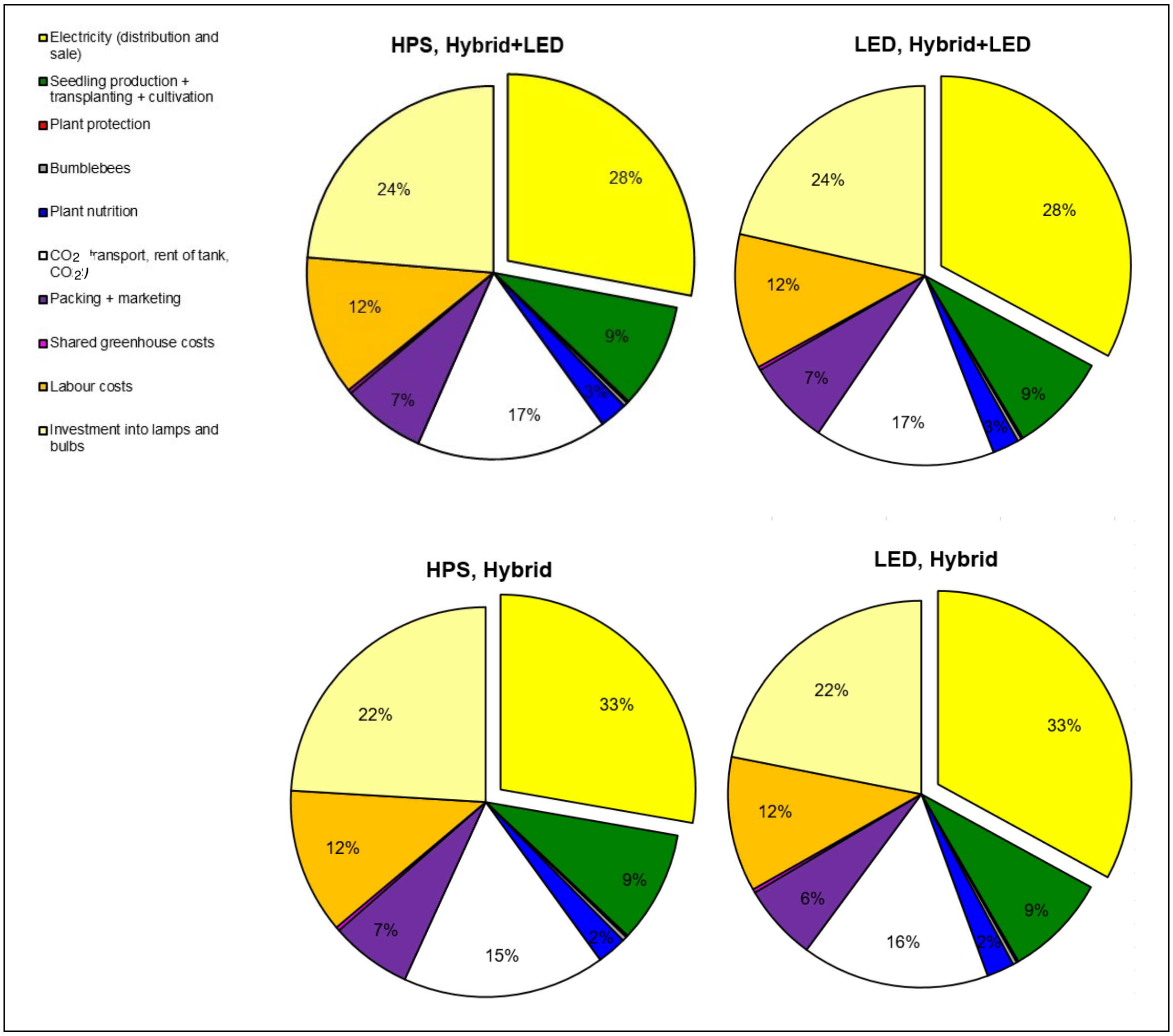

Fig. 39: Division of variable and fixed costs.

A detailed composition of the variable costs at each treatment is shown in Tab. 10.

Tab. 10: Profit margin of tomatoes at different light treatments.

Treatment	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
Marketable yield (kg/m²)	13,7	12,6	14,8	12,8
Sales				
SfG (ISK/kg) [1]	560	560	560	560
Government (ISK/kg) [2]	130	130	130	130
Revenues (ISK/m²)	**9.484**	**8.700**	**10.198**	**8.836**
Variable and fixed costs (ISK/m²)				
Electricity distribution [3]	539	526	681	670
Electricity sale [4]	3.110-3.520	3.035-3.435	3.929-4.447	3.866-4.375
Seeds [5]	267	267	267	267
Grodan small [6]	13	13	13	13
Grodan big [7]	118	118	118	118
Slab [8]	339	339	339	339
Strings [9]	84	84	84	84
Gutters [10]	85	85	85	85
Watering system	353	353	353	353
Beneficial organismn [11]	22	22	22	22
Bumblebees [12]	50	50	50	50
YaraTera™Ferticare™ Tomato[13]	196	196	197	197
Potassium nitrate [14]	82	83	83	83
Calcium nitrate [15]	53	54	54	54
CO_2 transport [16]	219	219	219	219
Liquid CO_2 [17]	1.599	1.599	1.599	1.599
Rent of CO_2 tank [18]	460	460	460	460
Rent of box from SfG [19]	107	98	115	99
Packing material [20]	504	462	542	469
Packing (labour + machine) [21]	220	202	236	205
Transport from SfG [22]	167	153	180	156
Shared fixed costs [23]	43	43	43	43
Lamps [24]	3.032	3.032	2.780	2.780
Bulbs [25]	229	229	401	401
∑ variable costs	**11.890-12.300**	**11.720-12.120**	**12.847-13.365**	**12.630-13.139**
Revenues -∑ variable costs	**-2.406--2.816**	**-3.020--3.420**	**-2.649--3.167**	**-3.793--4.302**
Working hours (h/m²)	0,83	0,81	0,85	0,81
Salary (ISK/h)	2.017	2.017	2.017	2.017
Labour costs (ISK/m²)	1.672	1.634	1.707	1.641
Profit margin (ISK/m²)	**-4.078--4.488**	**-4.654--5.054**	**-4.356--4.874**	**-5.434-5.943**

1 Price winter 2020/2021: 560 ISK/kg
2 Price for 2019: 130 ISK/kg
3 Assumption: On average around 1 ISK/kWh after 95% substitution from the state (according to data from Orkustofnun in the year 2019)
4 Assumption: Around 5,77-6,53 ISK/kWh (according to data from Orkustofnun in the year 2019)
5 86.000 ISK / 1.000 Completo seeds
6 36x36x40mm, 1.100 ISK / 220 Grodan small
7 27/35, 38 ISK / 1 Grodan big
8 50x24x10cm, 437 ISK/slab
9 27 ISK / string
10 4.388 ISK / m gutter; assumption: 10 years life time, 1,33 circles / year
11 3.354 ISK / unit parasitic wasps (*Encarsia formosa*), twice
12 6.783 ISK / unit bumble bees
13 6.750 ISK / 25 kg YaraTera™ Ferticare™ Tomato
14 5.225 ISK / 25 kg Potassium nitrate
15 2.350 ISK / 25 kg Calcium nitrate
16 CO_2 transport from Rvk to Hveragerði / Flúðir: 8,0 ISK/kg CO_2
17 Liquid CO_2: 47,0 ISK/kg CO_2
18 Rent for 6 t tank: 83.600 ISK/mon, assumption: rent in relation to 1.000 m^2 lightened area
19 100 ISK / box
20 Packing costs (material):
Costs for packing of tomatoes (1,00 kg): Platter: 21 ISK / kg,
plastic film: 7 ISK / kg,
label: 2 ISK / kg
21 Packing costs (labour + machine): 16 ISK / kg
22 Transport costs from SfG: 9,8 ISK / kg
23 94 ISK/m^2/year for common electricity, real property and maintenance
24 HPS lights: 27.100 ISK/lamp, life time: 8 years
LED top lights: 50.000 ISK/lamp, life time: 11 years
LED interlights lights: 38.000 ISK/lamp, life time: 11 years
25 HPS bulbs: 4.000 ISK/bulb, life time: 2 years

The profit margin was dependent on the light treatment and was varying between -4.300 to -5.700 ISK/m^2 (Fig. 40). The light source in young plant production influenced profit margin: The profit margin was lower under treatments that received LEDs in young plant production (-4.900 to -5.700 ISK/m^2) than under treatments that received HPS lights in young plant production (-4.300 to -4.600 ISK/m^2). That means HPS lights in young plant production increased profit margin in continuous production by nearly 600 ISK/m^2, respectively by more than 1.000 ISK/m^2 compared to LEDs. When some of the Hybrid top lights were replaced by LED interlights increased profit margin by 300 ISK/m^2, respectively 800 ISK/m^2 and reached -4.300 ISK/m^2 instead of -4.600 ISK/m^2, respectively -4.900 ISK/m^2 instead of -5.700 ISK/m^2. However, it has to be taken into account that the profit margin depends much on the actual price of the LEDs.

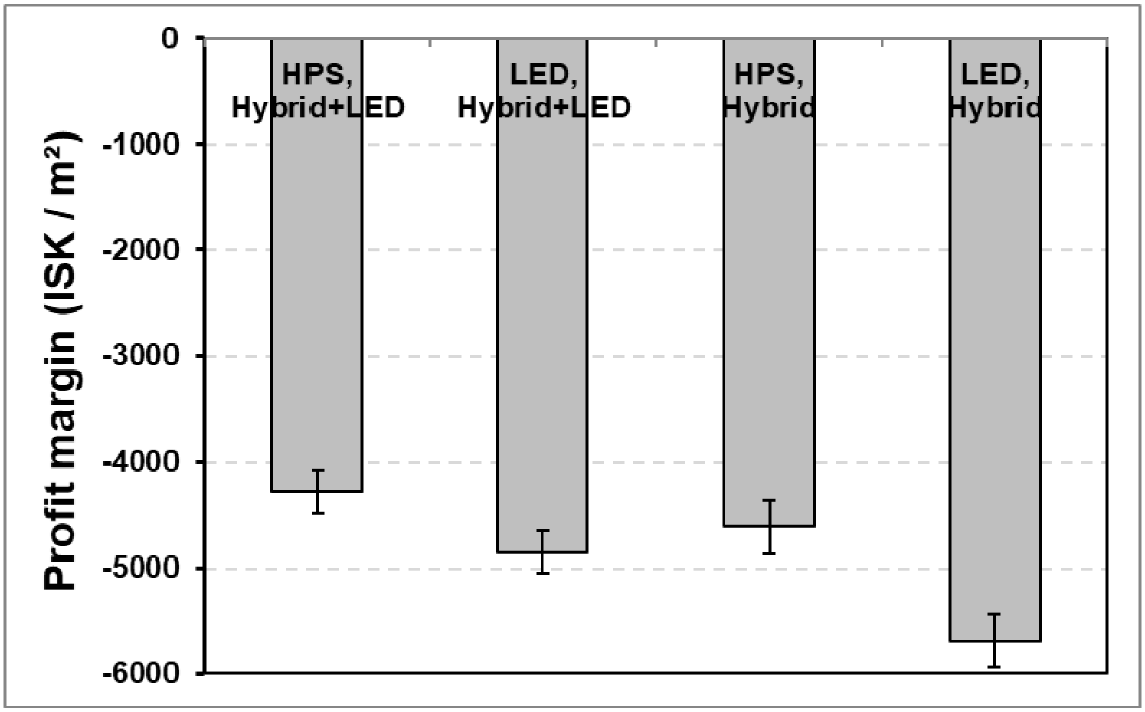

Fig. 40: Profit margin in relation the light treatment.

5 DISCUSSION

In winter production, the success of vegetable growing strongly depends on supplemental lighting. In this experiment, the effect of two light sources in young plant production in continuous production and the effect of the light treatment in continuous production was tested on tomatoes.

5.1 Yield in dependence of the light source in young plant production

When tomatoes were lighted either with HPS or LED top lights in young plant production, the total and marketable yield of tomatoes and their number was independent of the light source, which was in accordance to *Stadler* (2020). However, harvest started half a week earlier when tomatoes received LEDs in young plant production. Also, strawberry plants under HPS lights showed a delayed growth that was one week behind the development of strawberries treated with LEDs and increased temperature (*Stadler*, 2019), while strawberries in the LED treatment were delayed when temperature settings were the same (*Stadler*, 2018). The marketable yield of the strawberry variety Magnum under HPS lights was significantly higher than under LEDs and increased temperature, while there were no significant yield differences between light sources for the strawberry variety Sonata (*Stadler*, 2019). Also, *Stadler* (2018) reported no yield differences between HPS and LED lights for strawberries under same temperature settings. However, despite of the earlier harvest of tomatoes that received LEDs in young plant production, was this advantage not reflected in a higher marketable yield. Furthermore, when the marketable yield per cluster was calculated, treatments that received LEDs in young plant production had a lower value despite of the earlier harvest (Tab. 11).

Tab. 11: Marketable yield per cluster with different light treatments.

Treatment	HPS, Hybrid+LED	LED, Hybrid+LED	HPS, Hybrid	LED, Hybrid
Yield (kg/m^2)	13,7	12,6	14,8	12,8
Harvested clusters (no/m^2)	23	26	25	25
Yield (kg/cluster)	0,60	0,48	0,60	0,51

The higher leaf temperature in treatments that received LED lights in young plant production might be related to different thickness of leaves between light sources and might have positively influenced development and leading to an earlier harvest of half a week compared to treatments that received HPS lights in young plant production. In contrast, *Särkka* et al. (2017) reported that cucumber leaf temperature was lower (4-5°C at the centre parts of leaf blades, 3-4°C at the top of the canopy) with only LED lights (top and interlighting) and there was a lower temperature difference between night and day compared to the other light treatments (HPS top and HPS interlights, HPS top and LED interlights). This resulted in reduced leaf appearance rate, flower initiation rate, increased fruits abortion rate, whereas stem elongation and leaf expansion was increased compared to full HPS (HPS top and HPS interlights) and Hybrid (HPS top and LED interlights) lighting. The lower temperature might have decreased fruit growth of cucumbers in the LED treatment through reduced cell growth and indirectly through sink strength. Also, *Hernández* & *Kubota* (2015) attributed the 28% greater shoot dry mass of cucumber transplants, the 28-32% higher shoot fresh weight and the 9-12% higher leaf number under HPS lights compared to the LED treatments (blue LED, red LED) to the higher canopy air temperature. 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. The authors 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.

It seems to be necessary to increase the floor temperature or day temperature, to compensate for additional radiation heat of the HPS lights and prevent with that a harvest delay under LED lights as it was observed from *Stadler* (2018) when temperature settings were the same between the HPS and the LED treatment. Indeed, *van Delm* et al. (2016) concluded that the regulation of temperature and lighting strategy seems to be important for plant balance between earliness and total yield.

While light quality did not affect yield, it had an influence on the appearance of the plant. The length of the leaves and the cluster lengths was influenced by the lighting source: The length of the leaves and clusters was in treatments with “Hybrid+LED” longer for plants that received HPS lights in young plant production, whereas in treatments with “Hybrid” were longer leaves and clusters measured when grown under LEDs in young plant production. Therefore, plants might get shocked when coming into an other light treatment and while adapting to the new light spectrum, plants might react with increased or decreased growth. In contrast, the distance between clusters was not influenced by the light treatment in young plant production. *Stadler* (2020) reported that the distance between clusters and the length of clusters was significantly highest under HPS top lighting. Tomato plants were growing significant more each week and showed consequently significantly tallest plants when compared to LED top lighting. Also, *Trouwborst* et al. (2010) measured a lower plant length of cucumbers under LEDs. Tomatoes that received LEDs in young plant production were more compact than tomatoes that received HPS lights in young plant production (*Stadler*, 2021). The less compactness of plants that recieved HPS lights in young plant production had an impact after transplanting, as these plants allowed faster working in continuous production. In addition, the risk of breaking the stem when tiding plants up was reduced.

With LED lighting LED glasses need to distinguish between ripe and not ripe fruits. For strawberries was the maintenance of the crop and the harvest more difficult due to an other vision under LED lights compared to the commonly used HPS lights (*Stadler* & *Hrafnkelsson*, 2019). However, this effect was much less pronounced under tomatoes.

The DS of tomatoes and their BRIX content was not influenced by the light treatment used in young plant production and in continuous production. In contrast, tomatoes and strawberries seems to have a higher DS under HPS than under LED lights (*Stadler*, 2020; *Stadler*, 2019). *Dzakovich* et al. (2015) did not reveal any significant differences when analysing the quality of tomatoes in response to supplemental lighting with HPS or LED lamps. In contrast, according to *Philips* (2018) were strawberries sweeter under LEDs compared to HPS lights and also *Hanenberg* et al. (2016) mentioned that it was possible to increase the taste of strawberries by using LED lights.

The use of HPS lights in young plant production resulted in a nearly 600 ISK/m^2 (Fig. 41a), respectively more than 1.000 ISK/m^2 (Fig. 41b) higher profit margin than the use of LEDs in young plant production. The yield was increased by 1,1 kg/m^2 (Fig. 41a), respectively 2,0 kg/m^2 (Fig. 41b). When the yield of the LED treatment would have been 1 kg/m^2 higher (Fig. 41a), respectively nearly 2 kg/m^2 (Fig. 41b) higher, would the profit margin have been comparable to the treatments that received HPS lights in young plant production. However, the profit margin was for both light sources negative. To be able to get a positive profit margin would a yield increase be necessary: Yield must reach more than 21 kg/m^2.

In contrast to the presented results, reported *Dueck* et al. (2012b) 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. Also, *Särkka* et al. (2017) mentioned that the electrical use efficiency (kg yield J^{-1}) increased when HPS light was replaced with LEDs in cucumbers. When LED lights and interlights were used was the light use efficiency (g fruit FW mol^{-1} PAR) highest, but resulted in a fewer number of fruits in mid-winter particularly and the lowest yield potential. 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.

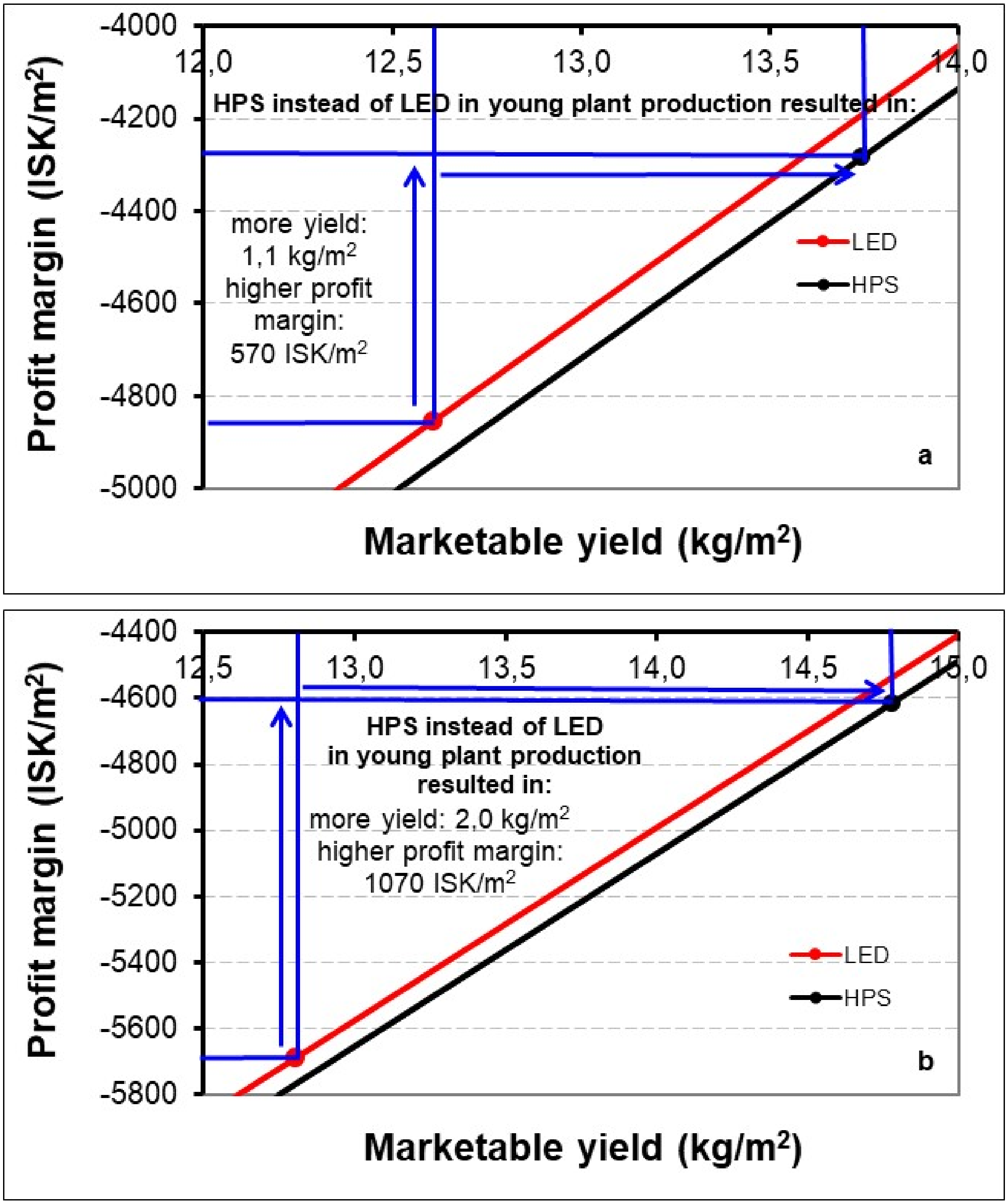

Fig. 41: Profit margin in relation to yield with different light sources in young plant production and either Hybrid+LED (a) or Hybrid (b) in continuous production – calculation scenarios.

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.

5.2 Yield in dependence of the light source in continuous production

Top lighting is creating a strong light gradient along the canopy of tomatoes and therefore is irradiance at the bottom of the canopy quite low. By LED interlighting is it possible to diminish the strong light gradient along the canopy and provide adequate illumination along the canopy (*Davis & Burns*, 2016; *Bantis* et al., 2018). LED interlighting in contrast to no LED interlighting strongly modulated the light spectral composition from the top to the bottom of the tomato canopy by reducing the FR:R ratio at the middle and low positions in the canopy and was associated with greener leaves and higher photosynthetic light use efficiency in the leaves in the lower canopy when compared to the ratio in the treatment with no LED interlighting (*Paponov* et al., 2020). Also, *Tewolde* et al. (2018) used a treatment with no artificial lighting as a control and measured that supplemental LED interlighting improved the light distribution within the plant profile and yield increased by 27% at winter (*Tewolde* et al., 2018).

The light treatment in continuous production did not affect the total and marketable yield of tomatoes and their number. The marketable yield was increased by 8% when Hybrid top lighting without LED interlighting was used in treatments that received HPS lights in young plant production ("HPS, Hybrid") compared to "HPS, Hybrid+LED". However, this yield increase was not statistically different and neither statistically related to a higher number of fruits nor to a higher average weight. When plants were lighted with LEDs in young plant production, was the marketable yield comparable between light treatments in continuous production as the tendentially lower number of harvested fruits with only Hybrid lighting ("LED, Hybrid") was compensated by a significantly higher average weight compared to the treatment with LED interlighting ("LED, Hybrid+LED"). But, tomatoes that received "Hybrid" in continuous production had tendentially, respectively significantly a higher yield of green tomatoes than in treatments that received "Hybrid+LED". This could reflect the possibility of a higher yield in "Hybrid" treatments in case the experiment would have been conducted longer and with that recommending rather Hybrid top lighting without LED interlighting. The higher average weight of "LED, Hybrid" compared to "LED, Hybrid+LED" is supporting this recommendation. However, the development of "HPS, Hybrid+LED" was delayed compared to the other clusters and among others resulting in one less cluster compared to the other treatments. This might be related to the fact, that plants were "used" to HPS lights in young plant production, but when they received more LED lights than HPS lights in continuous production got plants shocked and time passed to adapt to the other light quality in continuous production. This might have resulted in the delayed growth. When the marketable yield per cluster was set into relation to the number of harvested clusters (Tab. 11), the marketable yield per cluster was not influenced by LED interlighting in continuous production, indicating that no advantage with LED interlighting is gained. In addition, attention has to be payed to the high number of unpollinated flowers in "HPS, Hybrid+LED" and "LED, Hybrid" compared to the other treatments, eventhough differences were not different. Assuming the number of unpollinated flowers would have been lower in these treatments, a higher yield could be expected.

The replacement of part of the HPS top lights by LED interlights in continuous production resulted in more than 300 ISK/m^2 (Fig. 42a), respectively more than 800 ISK/m^2 (Fig. 42b) higher profit margin. The yield was decreased by 1,0 kg/m^2 (Fig. 42a), respectively by 0,2 kg/m^2 (Fig. 42b). As LED interlighting did not result in a yield increase and profit margin did not increase that much, it is not paying off to have LED interlighing and it can be rather recommended to lighten tomatoes with Hybrid top lights without LED interlights.

As in this year and in the previous year (*Stadler*, 2020) was Hybrid top lighting together with LED interlighting ("Hybrid+LED") used as a reference, was it possible to draw conclusions regarding if it would be better to use LED interlighting ("HPS+LED") or if it would be better to shift the LED interlighting up as LED top lighting ("Hybrid")

(Tab. 12). It could be clearly shown, that using the LEDs as toplights would give a more than 20% higher yield than using the LEDs as LED interlights.

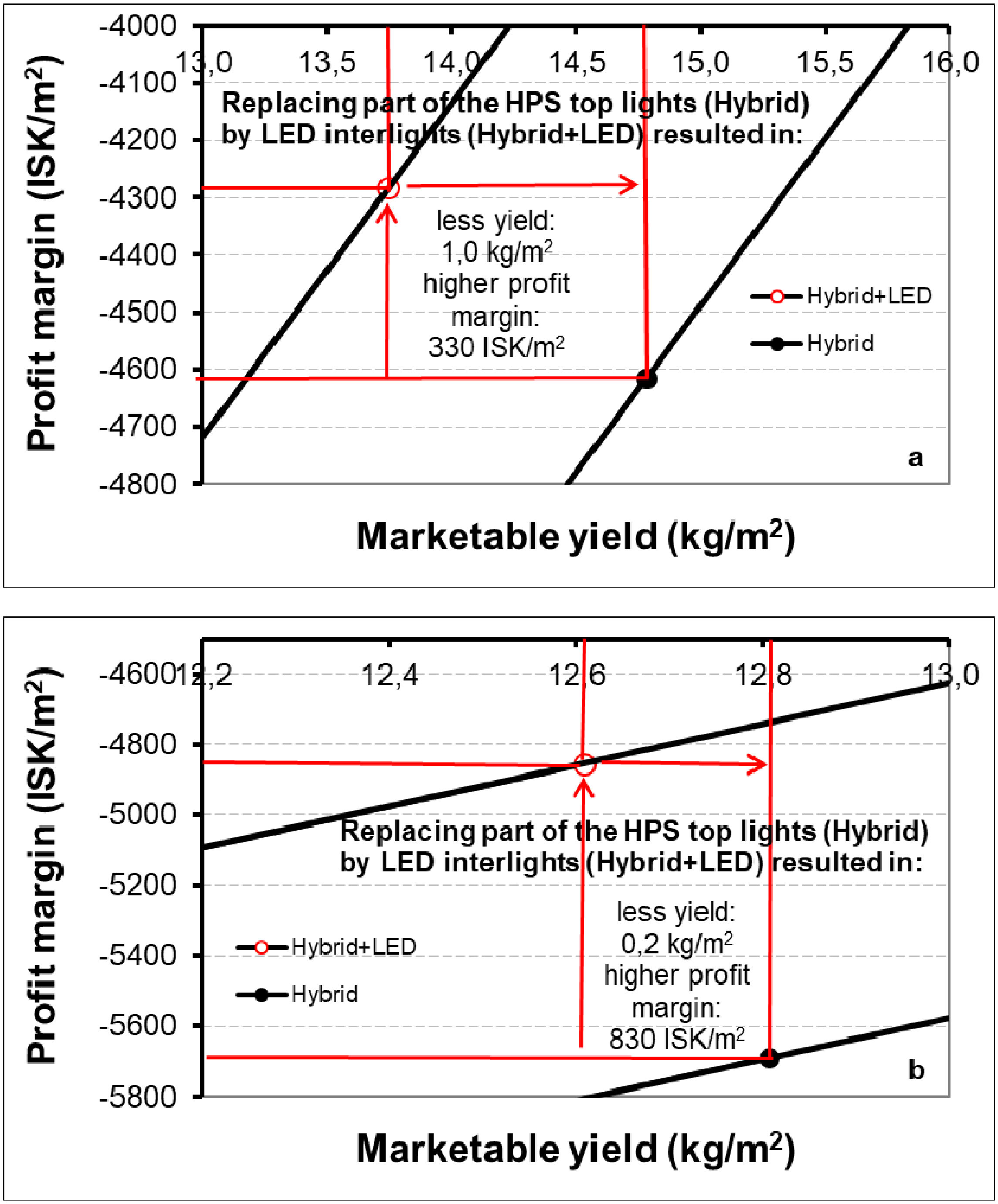

Fig. 42: Profit margin in relation to yield with Hybrid top lighting with(out) LED interlighting in continuous production and either HPS (a) or LED (b) lights in young plant production – calculation scenarios.

Tab. 12: Comparision of yield with different treatments and calculation scenarios regarding placement of LED lights.

Treatment	Ratio HPS / LED + LED (%)	Yield (kg/m^2)	Yield increase (kg/m^2)	Yield increase (%)
Experiment 2019/2020 (young plant production was under HPS lights)				
Hybrid+LED	33,3 / 33,3 + 33,3	25,2	3,2	15
HPS+LED	66,6 / 0 + 33,3	22,0		
Experiment 2020/2021 (young plant production was under HPS lights)				
Hybrid+LED	33,3 / 33,3 + 33,3	13,7		
Hybrid	66,6 / 33,3 + 0	14,8	1,1	8
Calculation scenarios				
Hybrid	66,6 / 33,3 + 0	14,8 [1]	2,8	23
HPS+LED	66,6 / 0 + 33,3	12,0 [2]		

[1] yield value from the experiment 2020/2021 was used

[2] yield value was calculated taking values from experiment 2019/2020 into account

There were no differences in BRIX content regarding different light treatments in continuous production measured. Indeed, also *Kowalczyk* et al. (2018) found that taste desirability were similarly high for cucumbers irrespectively of HPS top lighting, HPS top lighting + LED interlighting or LED top lighting + LED interlighting.

Adding LED modules as a light source for interlighting raises questions about the optimal light spectrum within the crop. LED for interlighting provides possibilities for lighting with efficient spectra for photosynthesis and plant development. It was reported for tomatoes that interlighting with varying red (627 nm), blue (450 nm) or far-red (730 nm) ration altered leaf photosynthesis and stomatal properties but did not affect plant productivity expressed by fruit number and total fruit fresh weight (*Gomez & Mitchell*, 2016). Also, in the presented experiment were found no significant marketable yield differences in weight and number depending on if LED interlighting was used or not. The optimum light spectrum for various plant growth processes such as leaf and fruit growth may be different, as manipulating light spectral distribution with LEDs in the verticale profile of the canopy has a large influence on plant growth and development (*Guo* et al., 2016).

Dueck et al. (2012a) compared the effect of top lighting and interlighting with HPS and/or LEDs on the production of tomatoes. The amount of energy required per kg of harvested tomatoes was highest for the LED treatment and Hybrid system with LED top lighting. Also, *Stadler* (2020) reported that the electricity per yield was increased by 15% by replacing part of the HPS top lights by LED top lights („Hybrid+LED“). In cucumbers, LED interlighting increased light use efficiency, mainly by increasing light reaching the inter canopy, compared with HPS top lights (*Hao* et al., 2014). Moreover, the response of cucumbers to LED interlighting could be optimized by using proper crop management (e.g. plant density) and ratio of top light / interlight. This was in agreement with the presented results, where the costs of electricity per kg of tomatoes increased with the use of LEDs in young plant production and with Hybrid top lighting in continuous production, whereas lower values were calculated for HPS in young plant production and Hybrid top lighting together with LED interlighting in continuous production. Also, “Hybrid+LED” transferred the used kWh’s better into yield than “Hybrid”. In addition, with HPS lights in young plant production was the utilization of kWh´s better transferred into yield compared to LEDs in young plant production. This seems to be contrary to findings of *Stadler* (2021) in young plant production of tomatoes, sweet pepper and cucumbers, where a better transformation of energy was reached under LEDs. However, values were related to biomass production, whereas in the presented experiment results were related to yield production. In case biomass production would also have been obtained here, comparable results as for young plant production might be possible.

Särkka et al. (2017) concluded that at the current stage of LED technology, the best lighting solution for high latitude winter growing appears to be HPS top lights combined with LED interlights. However, a solution for the near future could be a combination of LED and HPS as top lights to be able to maintain a suitable temperature, but reduce energy use. According to the presented results it is recommended to use no LED interlighting, but HPS and LED lights as top lighting as lighting source for tomato production. This is in accordance with *Dueck* et al. (2012a) who 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 Future speculations concerning energy prices

When tomatoes were grown under HPS lights in young plant production, were the energy costs 18% higher compared to young plant production under LEDs. When plants were lighted in continuous production with “Hybrid+LED” were energy costs reduced by 21% compared to “Hybrid”. In contrast, *Stadler* (2020) reported higher savings with LED top lighting without compromising yield of tomatoes: Using LEDs was associated with about 40% lower daily usage of kWh’s, resulting in lower expenses for the electricity compared to the use of HPS top lights. With the use of LED top lights were energy costs (distribution + sale) per kg yield lowered by 45% compared to the use of HPS lights. However, the investment into LEDs was nearly dobble as high as for the HPS lights. Meaning the higher price of the LEDs compensated their lower use of electricity (*Stadler*, 2020). In contrast, in the presented experiment were the investment costs into lights 9% higher under treatments that received LEDs in young plant production (“LED, Hybrid+LED”, “LED, Hybrid”) than for plants that recieved HPS lights in young plant production (“HPS, Hybrid+LED”, “HPS, Hybrid”). The total light related costs were for “Hybrid” about 12% higher than for “Hybrid+LED”.

In terms of the economy of lighting it is also worth to make some future speculations about possible developments also regarding the fluctuation of the subsidy. So far, the lighting costs (electricity + bulbs) are contributing to a big part of the production costs of tomatoes. In the past and present, there have been and there are still a lot of discussions (for example in Bændablaðið, 10. tölublað 2020, blað nr. 563) concerning the energy prices. Therefore, it is necessary to highlight possible changes in the energy prices (Fig. 43). So far, the lighting costs are contributing to about 1/3 of the production costs.

The white columns are representing the profit margin according to Fig. 40. Where to be assumed, that growers would get no subsidy from the state for the distribution of the energy, that would result in a profit margin of -7.500 to -9.700 ISK/m^2 (black columns, Fig. 43). Without the subsidy of the state, probably less Icelandic growers would produce tomatoes over the winter months. When it is assumed that the energy costs, both in distribution and sale, would increase by 25%, but growers would still get the subsidy, then the profit margin would range between -5.200 to -6.900 ISK/m^2 (dotted columns). When it is assumed that growers have to pay 25% less for the energy, the profit margin would increase to -3.300 to -4.500 ISK/m² (gray columns). From these scenarios, it can be concluded that from the grower's side it would be preferable to get subsidy to be able to get a higher profit margin and grow tomatoes over the winter. It is obvious that actions must be taken, that growers are also producing during the winter at low solar irradiation.

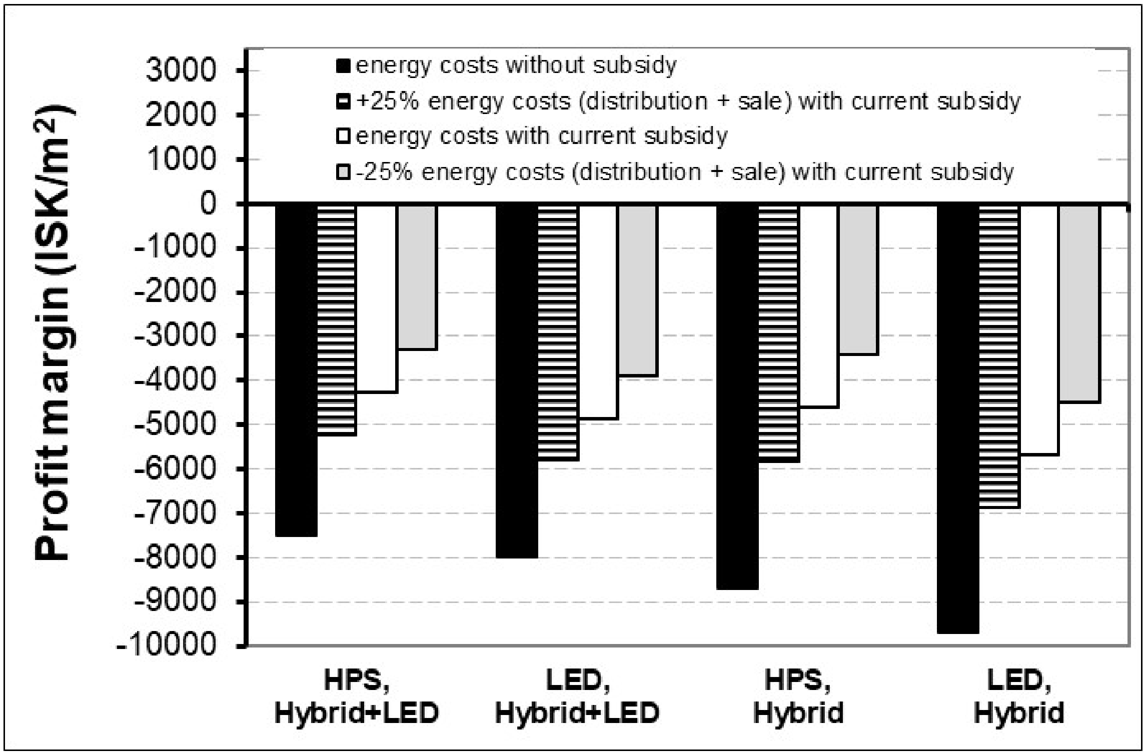

Fig. 43: Profit margin in relation to treatment – calculation scenarios.

5.5 Recommendations for increasing profit margin

The current economic situation for growing tomatoes necessitate for reducing production costs to be able to heighten profit margin for tomato production. On the other hand, growers have to think, if tomatoes should be grown during low solar irradiation and much use of electricity.

It can be suggested, that growers can improve their profit margin of tomatoes by:

1. Getting higher price for the fruits
   It may be expected to get a higher price, when consumers would be willing to pay even more for Icelandic fruits than imported ones. Growers could also get a higher price for the fruits with direct marketing to consumers (which is of

course difficult for large growers). They could also try to find other channels of distribution (e.g. selling directly to the shops and not over SfG).

2. Decrease plant nutrition costs

   Growers can decrease their plant nutrition costs by mixing their own fertilizer. When growers would buy different nutrients separately for a lower price and mix out of this their own composition, they would save fertilizer costs. However, this takes more time and it is more difficult to perform this task by employees. At low solar irradiation, watering with a scale can save up to 20% of water – and with that plant nutrition costs – with same yield when compared to automatic irrigation (*Stadler*, 2013). It is profitable to adjust the watering to the amount of last water application (*Yeager* et al., 1997).

3. Lower CO_2 costs

   The costs of CO_2 are pretty high. Therefore, the question arises, if it is worth to use that much CO_2 or if it would be better to use less and get a lower yield but all together have a possible higher profit margin. The CO_2 selling company has currently a monopoly and a competition might be good.

4. Decrease packing costs

   The costs for packing (machine and material) from SfG and the costs for the rent of the box are high. Costs could be decreased by using cheaper packing materials. Also, packing costs could be decreased, when growers would due the packing at the grower's side.

5. Efficient employees

   The efficiency of each employee has to be checked regularly and growers will have an advantage to employ faster workers. Growers should also check the user-friendliness of the working place to perform only minimal manual operations. Very often operations can be reduced by not letting each employee doing each task, but to distribute tasks over employees. In total, employees will work more efficiently due to the specialisation.

6. Decrease energy costs

- Lower prices for distribution and sale of energy (which is not realistic)
- Growers should decrease artificial light intensity at increased solar irradiation, because this would possibly result in no lower yield (*Stadler* et al., 2010).
- 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.
- Growers can save up to 8% of total energy costs when they would divide the winter lighting over all the day. That means growers should not let all lamps be turned on at the same time. This would be practicable, when they would grow in different independent greenhouses. Of course, this is not so easy realisable, when greenhouses are connected together, but can also be solved there by having different switches for the lamps to be able to turn one part of the lamps off at a given time. Then, plants in one compartment of the greenhouse would be lightened only during the night. When yield would be not more than 2% lower with lighting at nights compared to the usual lighting time, dividing the winter lighting over all the day would pay off. However, a tomato experiment showed that the yield was decreased by about 15% when tomatoes got from the beginning of November to the end of February light during nights and weekends (*Stadler*, 2012). This resulted in a profit margin that was about 18% lower compared to the traditional lighting system and therefore, normal lighting times are recommended.
- Also, growers could decrease the energy costs by about 6% when they would lighten according to 100 J/cm^2/cluster and 100 J/cm^2 for plant maintenance (*Stadler*, 2012). This would mean that especially at the early stage after transplanting, plants would get less hours light. Also at high

natural light, lamps would be turned off. In doing so, compared to the traditional lighting system, profit margin could be increased by about 10% (assuming similar yield).

- 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 lights are used effectively and that they are replacing their bulbs before the expensive season is starting.
- *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.
- Replacing part of the HPS lights by LEDs can reduce electricity consumption. To be able to get no delay in the harvest, environmental settings need to be adapted to the use of this light source.
- The use of a high light level is required for getting a high yield and with that a positive profit margin.

6 CONCLUSIONS

The development of tomato plants was affected by the selection of the lighting source for young plant production. Plants that received LEDs in young plant production gave earlier ripe tomatoes. However, this was not resulting in a yield advantage, but rather in a decreased yield when the marketable yield per harvested cluster was calculated. In addition, plants that received LEDs in young plant production were to compact and therefore, young plant production under HPS can be recommended.

In continuous production gave “Hybrid+LED” no optimization in yield. The slightly higher profit margin compared to “Hybrid” was not justifying the use of LED interlights despite of 21% lower energy costs. However, shifting LED interlights up as LED toplights would result in a yield increase of more than 20% when 2/3 of the top lights would be HPS lights. Therefore, LED interlights can not be adviced. Further experiments must show more details which ratio of LED to HPS lights is recommended.

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. However, replacing a small part of the HPS top lights by LED top lights could have a positive influence on yield. Growers should pay attention to possible reduction in their production costs for tomatoes other than energy costs.

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8 APPENDIX

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	**tasks**	**observations problems**	**tasks**	**observations problems**	**tasks**	**observations problems**	**tasks**	**observations problems**
9.11	transplanting, light from 5-17, 20°C/17°C (day/night), ventilation 24°C, underheat 35°C, 400 ppm CO_2, humidity 65%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)	transplants are taller under HPS lights for seedling production	transplanting, light from 5-17, 20°C/17°C (day/night), ventilation 24°C, underheat 35°C, 400 ppm CO_2, humidity 65%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)	clusters seem to be further developed under LEDs for seedling production	transplanting, light from 5-17, 20°C/17°C (day/night), ventilation 24°C, underheat 35°C, 400 ppm CO_2, humidity 65%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)	transplants are taller under HPS lights for seedling production	transplanting, light from 5-17, 20°C/17°C (day/night), ventilation 24°C, underheat 35°C, 400 ppm CO_2, humidity 65%, 300 ml H_2O/plant per day (100 ml watering with 3 h in between)	clusters seem to be further developed under LEDs for seedling production
10.11		plants are de-veloping roots		plants are dev-eloping roots		plants are de-veloping roots		plants are de-veloping roots
11.11								
12.11								
13.11								
14.11								
15.11								
16.11	weekly measurements, measured leaf + soil temperature, light from 5-19, 600 ppm CO_2, last watering 2 h before night		weekly measurements, measured leaf + soil temperature, light from 5-19, 600 ppm CO_2, last watering 2 h before night	more than 10 plants have open flowers	weekly measurements, measured leaf + soil temperature, light from 5-19, 600 ppm CO_2, last watering 2 h before night		weekly measurements, measured leaf + soil temperature, light from 5-19, 600 ppm CO_2, last watering 2 h before night	more than 10 plants have open flowers
17.11								
18.11								

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	**tasks**	**observations problems**	**tasks**	**observations problems**	**Date**	**tasks**	**observations problems**	**tasks**
19.11		more than 10 plants have open flowers				more than 10 plants have open flowers		
20.11								
21.11								
22.11								
23.11	weekly measurements, measured leaf + soil temperature light from 5-21, 800 ppm CO_2, underheat 40°C	plants look very compact in the uppermost 15 cm with 3 clusters	weekly measurements, measured leaf + soil temperature light from 5-21, 800 ppm CO_2, underheat 40°C	plants look less compact than in the first chamber	weekly measurements, measured leaf + soil temperature light from 5-21, 800 ppm CO_2, underheat 40°C	plants look less compact than in the first chamber	weekly measurements, measured leaf + soil temperature light from 5-21, 800 ppm CO_2, underheat 40°C	plants look less compact than in the first chamber
24.11		problems with the heat		problems with the heat		problems with the heat		problems with the heat
25.11	En-Strip put out	problems with the heat	En-Strip put out	problems with the heat	En-Strip put out	problems with the heat	En-Strip put out	problems with the heat
26.11		problems with the heat		problems with the heat		problems with the heat		problems with the heat
27.11		problems with the heat		problems with the heat		problems with the heat		problems with the heat
28.11		problems with the heat		problems with the heat		problems with the heat		problems with the heat
29.11		problems with the heat		problems with the heat		problems with the heat		problems with the heat
30.11		problems with the heat		problems with the heat		problems with the heat		problems with the heat

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	**tasks**	**observations problems**	**tasks**	**observations problems**	**Date**	**tasks**	**observations problems**	**tasks**
1.12	weekly measurements, measured leaf + soil temperature, removed leaf behind the 3. cluster, deleafed 2 leaves from the bottom, new hive	problems with the heat	weekly measurements, measured leaf + soil temperature, removed leaf behind the 3. cluster, deleafed 2 leaves from the bottom, new hive	problems with the heat	weekly measurements, measured leaf + soil temperature, removed leaf behind the 3. cluster, deleafed 2 leaves from the bottom, new hive	problems with the heat	weekly measurements, measured leaf + soil temperature, removed leaf behind the 3. cluster, deleafed 2 leaves from the bottom, new hive	problems with the heat
2.12	3 h between waterings (6 min)	problems with the heat	3 h between waterings (6 min)	problems with the heat	3 h between waterings (6 min)	problems with the heat	3 h between waterings (6 min)	problems with the heat
3.12		problems with the heat		problems with the heat		problems with the heat		problems with the heat
4.12	due to the problems with the heat was lighting changed to 03-19	nights have been cold	due to the problems with the heat was lighting changed to 03-19	nights have been cold	due to the problems with the heat was lighting changed to 03-19	nights have been cold	due to the problems with the heat was lighting changed to 03-19	nights have been cold
5.12	2 h between waterings (6 min)		2 h between waterings (6 min)		2 h between waterings (6 min)		2 h between waterings (6 min)	
6.12	1 h between waterings (3 min)		1 h between waterings (3 min)		1 h between waterings (3 min)		1 h between waterings (3 min)	
7.12	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
8.12	removed leaf behind the 4. cluster, deleafed 2 leaves from the bottom		removed leaf behind the 4. cluster, deleafed 2 leaves from the bottom		removed leaf behind the 4. cluster, deleafed 2 leaves from the bottom		removed leaf behind the 4. cluster, deleafed 2 leaves from the bottom	
9.12								
10.12								
11.12								

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	tasks	observations problems	tasks	observations problems	Date	tasks	observations problems	tasks
12.12	weekly measurements, measured leaf + soil temperature, 22°C / 20°C (day/night), ventilation 26°C		weekly measurements, measured leaf + soil temperature, 22°C / 20°C (day/night), ventilation 26°C		weekly measurements, measured leaf + soil temperature, 22°C / 20°C (day/night), ventilation 26°C		weekly measurements, measured leaf + soil temperature, 22°C / 20°C (day/night), ventilation 26°C	
13.12								
14.12								
15.12	removed leaf behind the cluster		removed leaf behind the cluster		removed leaf behind the cluster		removed leaf behind the cluster	
16.12	deleafed 2 leaves from the bottom, new hive		deleafed 2 leaves from the bottom, new hive		deleafed 2 leaves from the bottom, new hive		deleafed 2 leaves from the bottom, new hive	
17.12								
18.12								
19.12								
20.12								
21.1	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
22.12	removed leaf behind the cluster, deleafed 2 leaves from the bottom		removed leaf behind the cluster, deleafed 2 leaves from the bottom		removed leaf behind the cluster, deleafed 2 leaves from the bottom		removed leaf behind the cluster, deleafed 2 leaves from the bottom	
23.12								
24.12								
25.12								
26.12								
27.12								

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	**tasks**	**observations problems**	**tasks**	**observations problems**	**Date**	**tasks**	**observations problems**	**tasks**
28.12	weekly measurements, measured leaf + soil temperature	plants look more compact than in the 2. chamber, bad pollination	weekly measurements, measured leaf + soil temperature	bad pollination	weekly measurements, measured leaf + soil temperature	bad pollination	weekly measurements, measured leaf + soil temperature	bad pollination
29.12								
30.12	new hive		new hive		new hive		new hive	
31.12								
1.1								
2.1								
3.1								
4.1	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
5.1	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	bad pollination	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	bad pollination
6.1				tomatoes start to get red				tomatoes start to get red
7.1								
8.1								
9.1								
10.1								
11.1	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
12.1								
13.1	new hive, En-Strip put out		new hive, En-Strip put out		new hive, En-Strip put out		new hive, En-Strip put out	
14.1								
15.1								
16.1								
17.1								

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	**tasks**	**observations problems**	**tasks**	**observations problems**	**Date**	**tasks**	**observations problems**	**tasks**
18.1	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
19.1	deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom	
20.1								
21.1								
22.1								
23.1								
24.1								
25.1	harvest, weekly measurements, measured leaf + soil temperature, 1 h between waterings (4 min)	bad pollination, plants start to get yellow in the top	harvest, weekly measurements, measured leaf + soil temperature, 1 h between waterings (4 min)	ec of hatt, bad pollination, plants start to get yellow in the top	harvest, weekly measurements, measured leaf + soil temperature, 1 h between waterings (4 min)	ec of hatt, bad pollination, plants start to get yellow in the top	harvest, weekly measurements, measured leaf + soil temperature, 1 h between waterings (4 min))	ec of hatt, bad pollination, plants start to get yellow in the top
26.1								
27.1	new hive		new hive		new hive		new hive	
28.1	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
29.1	additional watering		additional watering		additional watering		additional watering	
30.1								
31.1								
1.2	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
2.2	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	tasks	observations problems	tasks	observations problems	Date	tasks	observations problems	tasks
3.2	harvest, underheat 50°C, stopped with additional watering		harvest, underheat 50°C, stopped with additional watering		harvest, underheat 50°C, stopped with additional watering		harvest, underheat 50°C, stopped with additional watering	
4.2								
5.2								
6.2								
7.2								
8.2	harvest, weekly measurements, measured leaf + soil temperature	bees not very active	harvest, weekly measurements, measured leaf + soil temperature	enough bees for pollination	harvest, weekly measurements, measured leaf + soil temperature	enough bees for pollination	harvest, weekly measurements, measured leaf + soil temperature	enough bees for pollination
9.2								
10.2	harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom	
11.2								
12.2	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
13.2								
14.2								
15.2	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
16.2	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
17.2	harvest, new hive		harvest, new hive		harvest, new hive		harvest, new hive	
18.2								
19.2	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
20.2								
21.2								

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	tasks	observations problems	tasks	observations problems	Date	tasks	observations problems	tasks
22.2	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
23.2	deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom		deleafed 3 leaves from the bottom	
24.2	harvest		harvest		harvest		harvest	
25.2								
26.2							not working LED top light changed in the shelter bed	
27.2								
28.2								
1.3	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
2.3								
3.3	harvest		harvest		harvest		harvest	
4.3								
5.3								
6.3								
7.3								
8.3	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
9.3								
10.3	harvest		harvest		harvest		harvest	
11.3								
12.3								
13.3								
14.3								

	HPS, Hybrid+LED		LED, Hybrid+LED		HPS, Hybrid		LED, Hybrid	
Date	**tasks**	**observations problems**	**tasks**	**observations problems**	**Date**	**tasks**	**observations problems**	**tasks**
15.3	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
16.3								
17.3	final harvest		final harvest		final harvest		final harvest	