Rit LbhÍ nr. 125

„Áhrif LED topplýsingar og LED millilýsingar á vöxt, uppskeru og gæði gróðurhúsatómata"

FINAL REPORT

Christina Stadler

SAMBAND GARÐYRKJUBÆNDA

Framleiðnisjóður landbúnaðarins

SASS

l

Landbúnaðarháskóli Íslands
Agricultural University of Iceland

2020

Landbúnaðarháskóli Íslands, 2020.
Rit LbhÍ nr. 125
ISSN 1670-5785
ISBN 978-9979-881-96-4

Ljósmynd á forsíðu: Christina Stadler

Final report of the research project

„Áhrif LED topplýsingar og LED millilýsingar á vöxt, uppskeru og gæði gróðurhúsatómata“

Duration: 01/08/2019 – 31/12/2020

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

Samtök Sunnlenskra Sveitarfélaga
Austurvegi 56
800 Selfoss

Supply of LED modules and accessories: Philips Research
High Tech Campus 34
5656 AE Eindhoven
The Netherlands

Table of contents

List of figures

List of tables

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 for lighting under LEDs 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 together with LED interlighting 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 end of September 2019 to the beginning of March 2020 in the experimental greenhouse of the Agricultural University of Iceland at Reykir. Tomatoes were grown in pumice 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. high-pressure vapour sodium lamps (HPS, 230 µmol/m^2/s) for top lighting, 2. light emitting diodes (LED, 191 µmol/m^2/s) for top lighting, 3. HPS (220 µmol/m^2/s) top lighting and LED (153 µmol/m^2/s) interlighting (HPS+LED) and, 4. Hybrid (221 µmol/m^2/s) top lighting and LED (148 µmol/m^2/s) interlighting (Hybrid+LED). The day temperature was during the first month 18°C and after that 20°C. The night temperature was during the first month 16°C and after that 17°C. The underheat was 35°C in the light treatments with HPS top lighting, but 40°C in „LED“ to compensate for additional heating by the HPS lamps. Two months after planting was the underheat increased to 45°C, respectively to 55°C. 800 ppm CO_2 was applied. Tomatoes received standard nutrition through drip irrigation. The effect of the light source and LED interlighting was tested and the profit margin was calculated.

The CO_2 amount was higher in the LED top light treatment because of more open windows in the other light treatments. Also, the foor temperature was higher in “LED” due to the fact that the floor temperature was set 5°C / 10°C higher. This setting caused a significantly higher soil temperature in “LED”, whereas the leaf temperature was comparable between light treatments. The temperature and CO_2 advantage might have positively influenced growth and yield of the plants under “LED” even though there were no significant differences in yield, number of first and second class fruits and average fruit size found compared to “HPS”. In contrast, the distance between clusters, the length of clusters and the weekly growth was significantly higher under “HPS” than under “LED”. Also, the dry substance seems to be

increased under “HPS”, while no differences in the sugar content were measured between “HPS” and “LED”.

Using “LED” was associated with about 40 % lower daily usage of kWh’s, resulting in lower expenses for the electricity but higher investment costs compared to “HPS”. With the use of LEDs increased yield by 1,4 kg/m^2 and profit margin by more than 400 ISK/m^2. However, the marketable yield was low and the profit margin for both light sources negative as the light level was low.

Marketable yield increased at a higher light level compared to the lower light level. When LED interlighting was added to HPS top lighting increased the used energy by 8 %, but the energy use efficiency was higher with “HPS+LED” than with “HPS”. The yield increased significantly by 8,6 kg/m^2 and profit margin by more than 4.000 ISK/m^2 compared to “HPS”. The 65 % yield increase was attributed to a significant increased number of marketable fruits and a significant higher average weight.

A further increase of yield by 3,2 kg/m^2 and of profit margin by 500 ISK/m^2 was possible by replacing part of the HPS top lights by LED top lights. The higher yield with “Hybrid+LED” compared to “HPS+LED” was attributed to a higher amount of fruits due to an earlier start of the harvest. “Hybrid+LED” transferred light better into yield than “HPS+LED” even though the LED top lights were turned on 2,5 weeks later and the air temperature was lower compared to “HPS+LED”. The sugar content in the interlighting treatments was comparable.

Marketable yield was about 70 % at the higher light level with LED interlighting compared to 55 % at the lower light level with either LED or HPS top lighting. The yield increase was attributed to an increased proportion of first class fruits and significantly lower proportion of too little fruits.

Possible recommendations for saving costs other than lowering the electricity costs are discussed. From an economic viewpoint, it is not recommended to grow tomatoes at a low light level in winter. With adapted temperature settings was it possible to compensate the additional heating by HPS lights. The tomato yield was positively influenced by a higher light level by adding LED interlighting to top lighting. Before LEDs can be adviced in practice, more scientific studies are needed: Further experiments must show which ratio of LED to HPS lights is recommended and how yield can be optimized with an appropriate ratio of top lighting to interlighting. Therefore, so far a replacement of the HPS lamps by LEDs is not recommended.

YFIRLIT

Vetrarræktun í gróðurhúsum á Íslandi er algjörlega háð aukalýsingu. Viðbótarlýsing getur lengt uppskerutímann og komið í stað innflutnings að vetri til. Fullnægjandi leiðbeiningar vegna vetrarræktunar á tómötum undir LED ljósi eru ekki til staðar og þarfnast frekari þróunar. Markmiðið var að prófa hvort ljósgjafi (HPS eða LED) ásamt LED millilýsingu 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 lok september 2019 og fram í byrjun mars 2020 í tilraunagróðurhúsi Landbúnaðarháskóla Íslands að Reykjum. Tómatarnir voru ræktaðir í vikri í þremur endurtekningum með 2,5 toppi/m^2 með einum toppi á plöntu. Prófaðar voru fjórar mismunandi ljósmeðferðir að hámarki í 16 klst. ljós: 1. topplýsing frá háþrýstinatríumlömpum (HPS, 230 µmol/m^2/s), 2. topplýsing frá ljósdíóðum (LED, 191 µmol/m^2/s), 3. HPS (220 µmol/m^2/s) topplýsing og LED (153 µmol/m^2/s) millilýsing (HPS+LED) og, 4. Hybrid (221 µmol/m^2/s) topplýsing og LED (148 µmol/m^2/s) millilýsing (Hybrid+LED). Daghiti var í fyrsta mánuði 18°C og eftir það 20°C. Næturhiti var í fyrsta mánuði 16°C og eftir það 17°C. Undirhiti var 35°C í klefum við HPS topplýsingu, en 40°C í klefa við LED topplýsingu til að bæta viðbótarhitun sem varð með HPS ljósunum. Tveim mánuðum eftir útplöntun var undirhiti hækkaður í 45°C og 55°C. 800 ppm voru gefin. Tómatarnir fengu næringu með dropavökvun. Áhrif ljósgjafa og LED millilýsingu var prófuð og framlegð reiknuð út.

CO_2 magnið var hærra undir LED topplýsingu vegna þess að gluggarnir í hinum ljós meðferðunum opnuðust meira. Undirhiti var líka hærri í „LED“ vegna þess að undirhiti var settur 5°C / 10°C hærra. Vegna stillingar var jarðvegshiti í „LED“ hærri, en laufhiti var eins á milli ljósmeðferða. Þessi kostur í hitastigi og CO_2 getur líka haft jákvæð áhrif á vöxt plantna og uppskeru undir „LED“, en ljósgjafinn hafði ekki áhrif á markaðshæfni uppskeru, fjölda aldina í fyrsta og annan flokk og meðalþyngd aldina ef borið er saman við „HPS“. Hins vegar var lengd á milli klasa, klasa lengd og vikulegur vöxtur marktækt meiri undir „HPS“. Þurrvigt virðist vera meiri undir „HPS“, en það mældist enginn munur í sykurinnihaldi milli ljósgjafa.

Með notkun „LED“ var um 40 % minni dagleg notkun á kWh, sem leiddi til minni útgjalda fyrir raforku miðað við „HPS“, en hærri fjárfestingarkostnaður er með „LED“.

Þegar LED ljós var notað, þá jókst uppskera um 1,4 kg/m^2 og framlegð um 400 ISK/m^2. En, markaðshæf uppskera var lítil og framlegð því fyrir báða ljósgjafa neikvæð, ljósstig var lágt.

Hægt var að fá meiri markaðshæfa uppskeru við hærra ljósstig. Þegar LED millilýsingu var bætt við HPS topplýsingu jókst orkunotkun hins vegar um 8 %, en skilvirkni orkunotkunar var meiri með „HPS+LED“ en með „HPS“. Uppskera jókst marktækt um 8,6 kg/m^2 og framlegð um meira en 4.000 ISK/m^2 við „HPS+LED“. Ástæðan fyrir 65 % meiri markaðshæfri uppskeru var tölfræðilega marktækt fleiri tómatar og marktækt hærri meðalþyngd.

Til viðbótar við aukna uppskeru um 8,6 kg/m^2 og framlegð um meira en 4.000 ISK/m^2 þegar LED millilýsingu var bætt við HPS topplýsingu, væri hægt að ná frekari aukningu á uppskeru um 3,2 kg/m^2 og framlegð um 500 ISK/m^2 með því að skipta út hluta HPS toppljósanna með LED toppljósum. Ástæðan fyrir meiri uppskeru við „Hybrid+LED“ voru fleiri aldin vegna fyrri uppskeru. Plöntunar nýttu „Hybrid+LED“ betur í uppskeru en „HPS+LED“ jafnvel þó að LED toppljósin væru kveikt 2,5 viku seinna og lofthiti væri lægri miðað við „HPS+LED“. Sykurinnihaldið í meðferðum við LED millilýsingu var sambærilegt.

Hlutfall uppskerunnar sem hægt var að selja var um 70 % við hærra ljósstig með LED millilýsingu en 55 % lægra við ljósstig með annað hvort „LED“ eða „HPS“. Við hærra ljósstig næst hærra hlutfall vegna hærra hlutfalls af fyrsta flokks aldinum og marktækt minna hlutfall af litlum aldinum.

Möguleikar til að minnka kostnað, aðrir en að lækka rafmagnskostnað eru taldir upp í umræðunum í þessari skýrslu. Frá hagkvæmnisjónarmiði er ekki mælt með því að rækta tómata við lítið ljósstig á veturna. Með viðeigandi hitastillingu var samkvæmt þessari tilraun hægt að bæta viðbótarhitun sem varð með HPS ljósum. Tómatauppskera eykst með hærra ljósstigi þegar LED millilýsingu var bætt við topplýsingu. Hins vegar vantar meiri reynslu á ræktun undir LED ljósi: Frekari tilraunir verða að sýna fram á hvaða hlutfall LED og HPS ljósa er mælt með og hvernig hægt er að hámarka uppskeru með viðeigandi hlutfalli af topplýsingu og millilýsingu. Þess vegna er ekki mælt með því að skipta HPS lömpum út fyrir LED að svo stöddu.

2 INTRODUCTION

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

The positive influence of artificial lighting on plant growth, yield and quality of tomatoes (*Demers* et al., 1998a), cucumbers (*Hao* & *Papadopoulos*, 1999) and sweet pepper (*Demers* et al., 1998b) has been well studied. It is often assumed that an increment in light intensity results in the same yield increase. 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*, 2013a).

Supplemental lighting that is normally used in greenhouses has no or only a small amount of UV-B radiation. High pressure sodium (HPS) lamps are the most commonly used type of light source in greenhouse production due to their appropriate light spectrum for photosynthesis and their high efficiency. The spectral output of HPS lamps is primarily in the region between 550 nm and 650 nm and is deficient in the UV and blue region (*Krizek* et al., 1998). However, HPS lights suffer from restricted controllability and dimming range limitations (*Pinho* et al., 2013). In Iceland has it been common to use HPS lamps with electromagnetic ballast. However, HPS lamps with electronic ballast would safe about 8 % energy according to the company Gavita (*Nordby*, oral information). 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 have been successfully cultured under LEDs (e.g. *Philips*, 2017; *Philips*, 2015; *Tamulaitis* et al., 2005; *Schuerger* et al., 1997; *Brown* et al., 1995; *Hoenecke* et al., 1992). However, with HPS was achieved a significantly higher fresh yield of salad in comparison to LEDs. But, two times more kWh was necessary with only HPS lights in comparision with only LEDs. The only use of HPS lights resulted in the highest yield, while the yield with only LEDs was about ¼ less (*Stadler,* 2015). In contrast, the light source did not affect the weight of marketable yield of winter grown strawberries. But, the development of flowers and berries and their harvest was delayed by two weeks under LED lights. This was possibly be related to a higher leaf temperature in the HPS treatment due to additional radiation heating. However, nearly 45 % lower daily usage of kWh's under LEDs were recorded (*Stadler*, 2018). These results are requesting scientific studies with different temperature settings to compensate the additional heating by the HPS lights and the delayed growth and harvest. When the air temperature was adapted was it possible to compensate the additional heating by the HPS lights and prevent a delayed growth and harvest (*Stadler*, 2019).

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 yields 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. But, before LEDs are put into practice on a larger scale, more knowledge must be acquired on effects of LED lighting on crops (*Dueck* et al., 2012b).

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 growing tomatoes under LEDs (top lighting and interlighting) 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) HPS top lighting compared to LED top lighting or in addition LED interlighting is affecting growth, yield and quality of tomatoes, 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 and LED interlighting. 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) and different light treatments (see chapter "3.2 Treatments") was conducted at the Agricultural University of Iceland at Reykir during winter 2019/2020.

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 14.08.2019 were seeds of tomatoes sown in rockwool plugs. On 24.09.2019 were four plants with one top/plant planted into 18 l pots filled with pumice stones. On each bed were six pots 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 pots respectively 24 tops. Three replicates, one replicate in each bed consisting of two pots (8 plants) acted as subplots for measurements. Other pots were not measured. Do to the weekly hanging down were all plants once at the end of the bed.

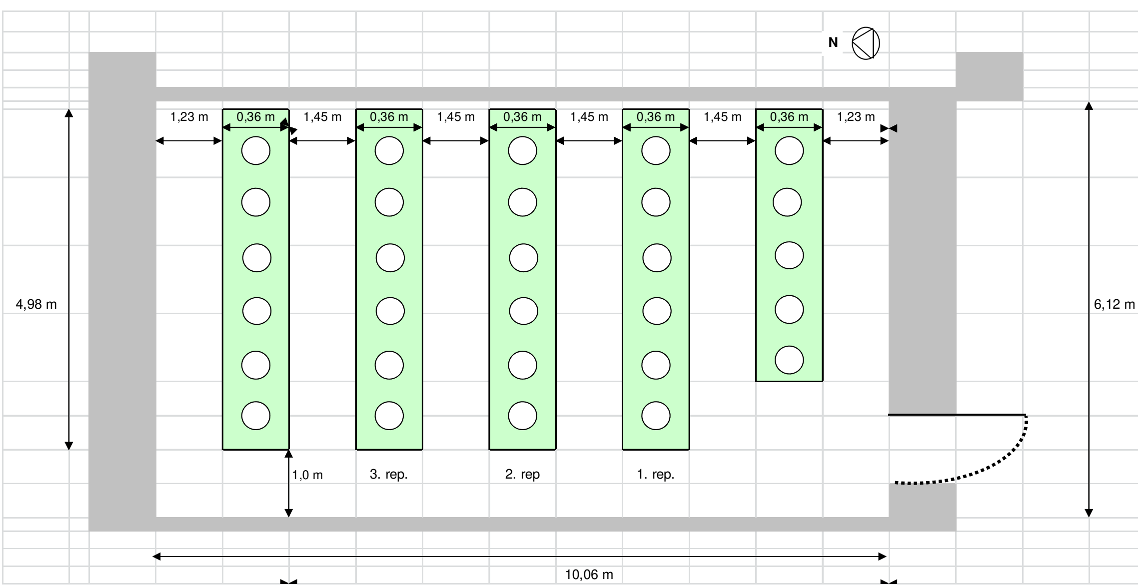

Fig. 1: Experimental design of cabinets.

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 and clusters were pruned to ten fruits. 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 in average every three weeks.

Until the 24.10.2019 was the temperature set on 18°C during day and 16°C during night and after that on 20°C / 17°C (day / night). The aim was to reach 18°C / 20°C at one hour after day starts. At the end of the day was the temperature dropped immediately. Ventilation started at 21°C respectively 23°C. It was heated up with 1,5-2°C per hour. The underheat was set to 35°C in the chambers with HPS top lighting, but to 40°C in the LED top lighting chamber. On 29.11.2019 was the underheat increased to 45°C in the chambers with HPS top lighting and to 55°C it the LED top lighting chamber. 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 70 %. 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.

Fertilizer (amount in kg)	**Stem solution A (100 l)**		**Stem solution B (100 l)**	**Irrigation water**	**Runoff water**
	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 bucket). 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 pumice was 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 half an hour after the lights turned on and the last watering was half an hour before the lights were turned off. The irrigation interval was variable in accordance to the runoff.

3.2 Treatments

Tomatoes were grown from 24.09.2019 until 09.03.2020 under different lighting regimes in four cabinets at the Agricultural University of Iceland at Reykir:

1. Hybrid top lighting (50 % HPS + 50 % LED) + LED interlighting: **Hybrid+LED**
2. HPS top lighting + LED interlighting: **HPS+LED**
3. LED top lighting: **LED**
4. HPS top lighting: **HPS**

In the Hybrid chamber (1) were at the beginning of the experiment only the HPS top lights and the LED interlights turned on, because the connectors for the LED modules were delivered late to Iceland. Immediately, when the connectors arrived, were also the LED lights turned on, which was 2,5 weeks after the start of the experiment.

To test if the light source had an influence on the yield of tomatoes were plants in the LED top lighting chamber (3) compared to plants in the HPS top lighting chamber (4). In addition, it was tested if LED interlighting (2) is profitable regarding yield and profit margin compared to no LED interlighting (4) or if it would be better to decrease the proportion of HPS top lighting and add instead LED top lighting (1).

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, do 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.

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

Light treatment	Lights	Lights/chamber (no)	Distance between lights
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
	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 interlighting	10	1 m below the top of the plant
HPS+LED	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 interlighting	10	1 m below the top of the plant
LED	LED top lighting	36	9 C profiles with 4 modules, 1,1 m for HPS distance centre centre and 1,3 m for HPS centre centre
HPS	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

White plastic on the surrounding walls helped to get a higher light level at the edges of the growing area. In average, the lowest light level was measured under LED top lighting (191 µmol/m^2/s), while the light level under HPS top lighting (230 µmol/m^2/s) was comparable with the top lighting of the other treatments (around 220 µmol/m^2/s). As two treatments (Hybrid+LED, HPS+LED) had in addition to top lighting also LED interlighting (around 150 µmol/m^2/s), was in these chambers the highest light level (around 370 µmol/m^2/s) measured (Tab. 3). The setup of the HPS lights was corresponding to 120 W/m^2 in the Hybrid+LED treatment and to 210 W/m^2 in the HPS+LED and HPS treatment.

Tab. 3: Light distribution in the chambers.

Height (from ground) (m)	Hybrid+LED	HPS+LED	LED	HPS
	(µmol/m²/s)			
1,45	137	131	129	150
1,95	218	227	197	228
2,45	250	236	212	243
2,95	278	288	225	300
Top lighting (average)	**221**	**220**	**191**	**230**
Interlighting (average) (15 cm from the LED lights)	**148**	**153**		
Total	**369**	**373**	**191**	**230**

Light was provided from 05.00-17.00 in the first week after planting, from 05.00-19.00 in the first half of the second week, from 05.00-20.00 in the second half of the second week and for 16 hours from 05.00-21.00 from the third week onwards.

3.3 Measurements, sampling and analyses

Soil temperature and leaf temperature was measured 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.

In treatments with LED modules were LED glasses 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. From the same harvest, the flavour of fresh fruits was examined in a tasting experiment with untrained assessors. Also, 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 less than 3 kWh/m^2 was this value still low (Fig. 2).

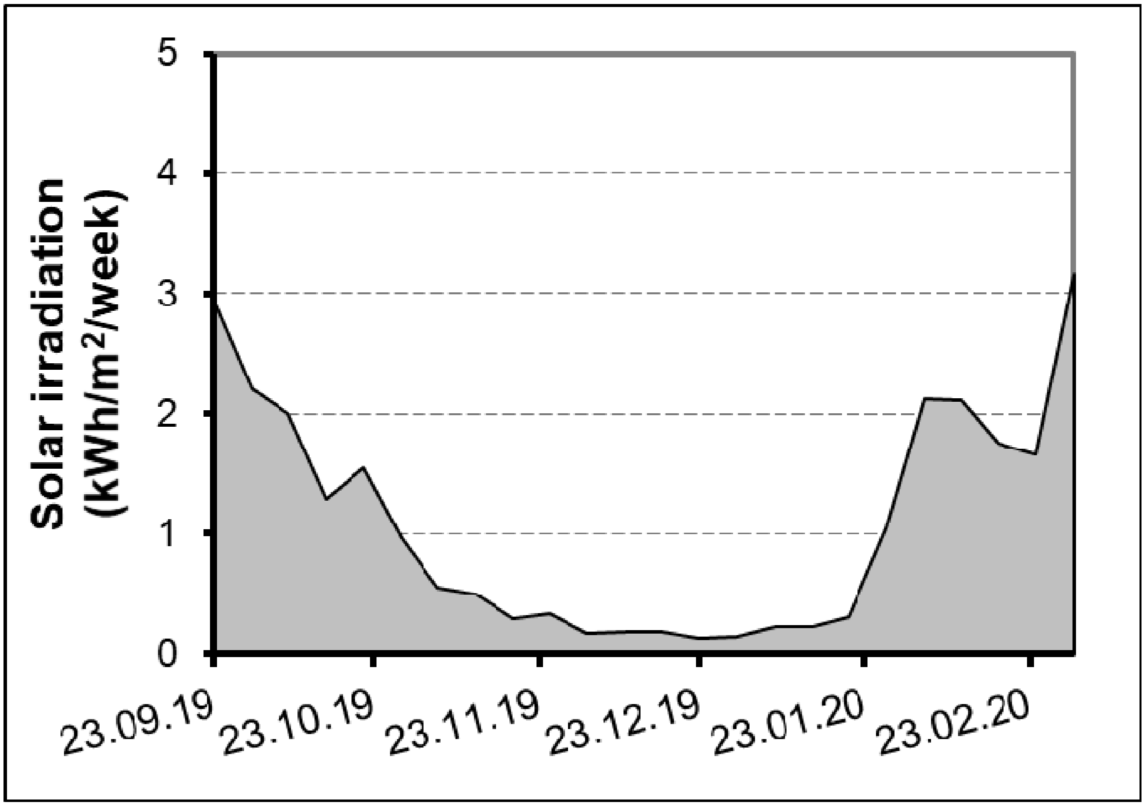

Fig. 2: Time course of solar irradiation.
Solar irradiation was measured every day and values for one week were cumulated.

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 20°C and was very similar between the light treatments. The average air temperature during the day was about 0,5°C higher in the treatment “HPS+LED” compared to the other light treatments. However, the average night temperature was similar between light treatments.

The floor temperature during the day was highest under LED top lighting as in this treatment the floor temperature was set 5°C respectively 10°C higher during the day compared to the other treatments. Differences between the other light treatments were small. The floor temperature during the night was about 1°C lower in the treatment “Hybrid+LED” compared to the other treatments.

The mean CO_2 amount was in average 23-34 ppm higher in the treatment with LED top lighting due to 45 % more often open windows in the other light treatments. One week before harvest started and onwards, was the CO_2 amount comparable between treatments (data not shown). However, before harvest started, differences in the CO_2 amount between treatments were recorded. This was due to more often open windows in the treatments “HPS”, “HPS+LED” and “Hybrid+LED”. Humidity amounted in average 65-71 %.

Tab. 4: Chamber settings according to greenhouse computer.

Greenhouse computer data (Average over the experimental period)	Hybrid+LED	HPS+LED	LED	HPS
Air temperature (°C)	20,0	20,2	19,8	19,9
day (°C)	21,3	21,7	21,1	21,3
night (°C)	17,3	17,4	17,3	17,3
Floor temperature day (°C)	41,3	40,5	49,1	41,1
Floor temperature night (°C)	26,0	26,7	27,2	27,1
CO_2 (ppm)	722	737	772	745
Windows opening 1 (%)	5,4	7,5	3,4	6,3
Windows opening 2 (%)	3,1	4,3	2,4	4,2
Humidity (%)	71	65	67	70

4.1.3 Soil temperature

Soil temperature was measured weekly at low solar radiation at around noon and fluctuated between 19-22°C. Soil temperature was in average significantly higher in the LED treatment compared to the other treatments. In average amounted this difference 0,3-0,6°C (Fig. 3).

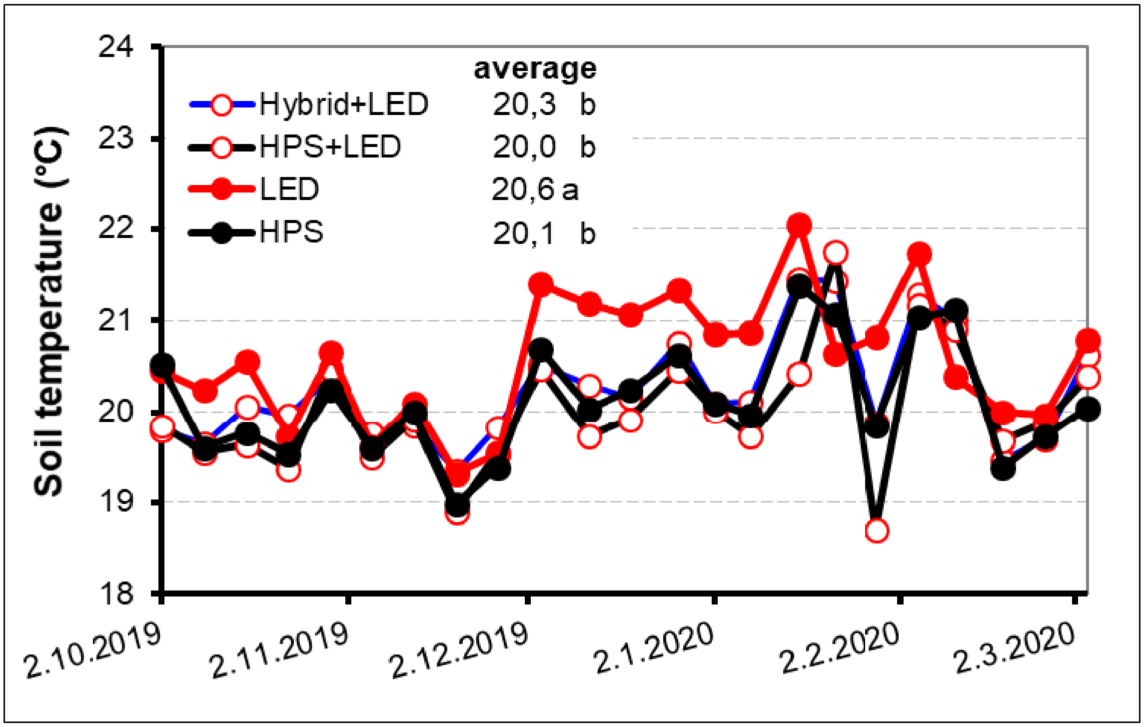

Fig. 3: Soil temperature.

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

4.1.4 Leaf temperature

Leaf temperature was measured weekly at low solar radiation at around noon and fluctuated between 14-20°C. In average was the leaf temperature independent of the light treatment (Fig. 4).

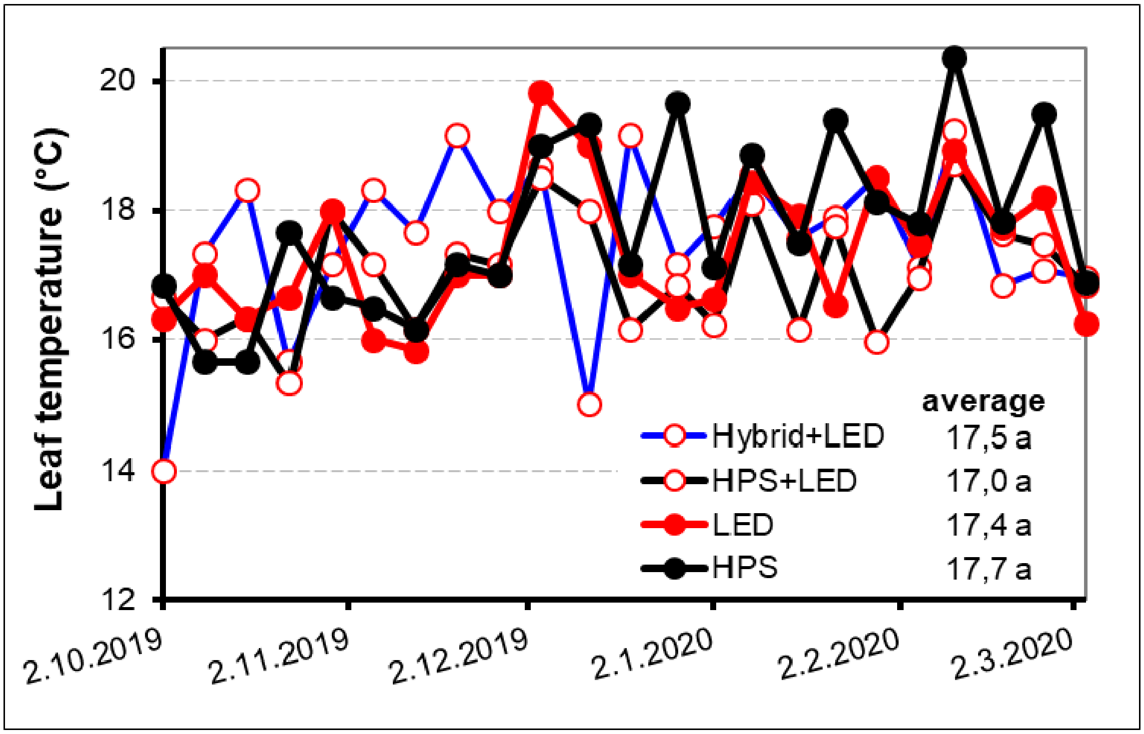

Fig. 4: Leaf temperature.

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

4.1.5 Irrigation of tomatoes

The amount of applied water varied most of the time between 2 and 6 l/m² (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 5,0-7,5 and the pH between 5,0-7,0. The pH of the runoff seem to be lowest for “HPS”.

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

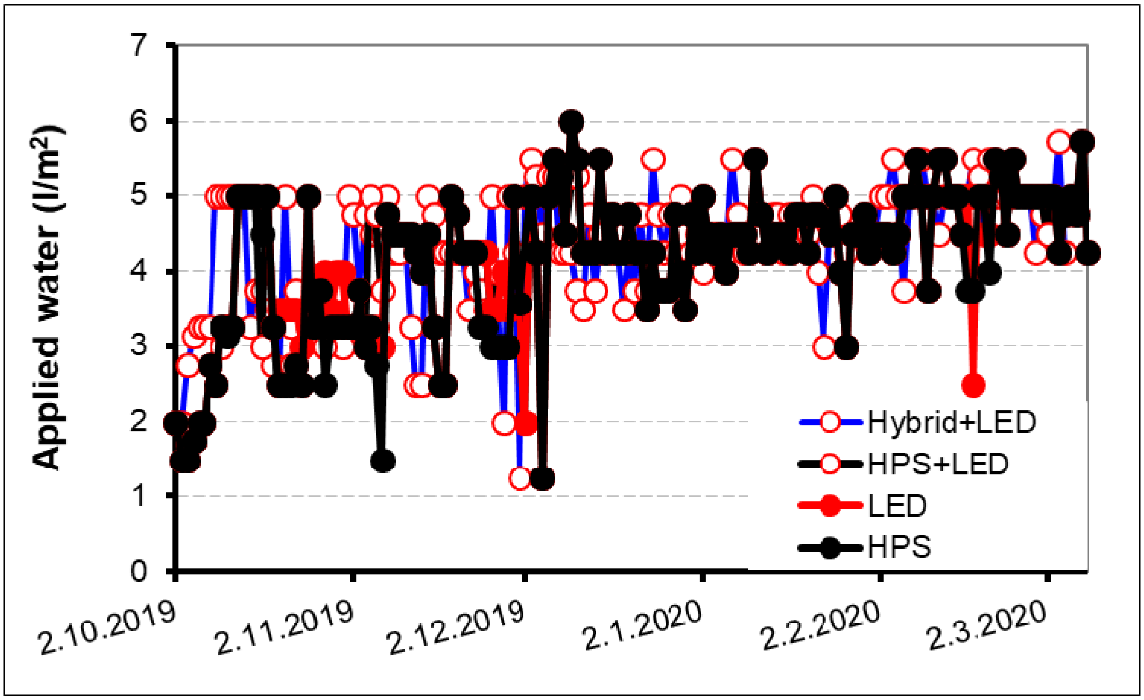

Fig. 5: Daily applied water.

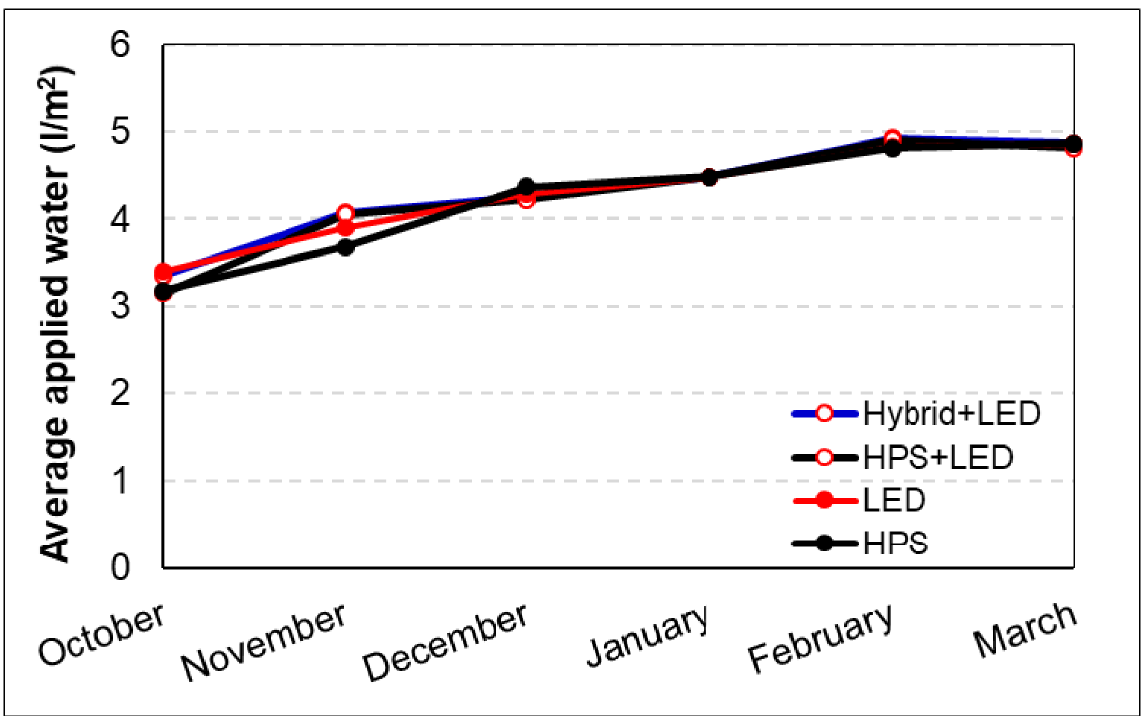

Fig. 6: Average daily applied water in each month.

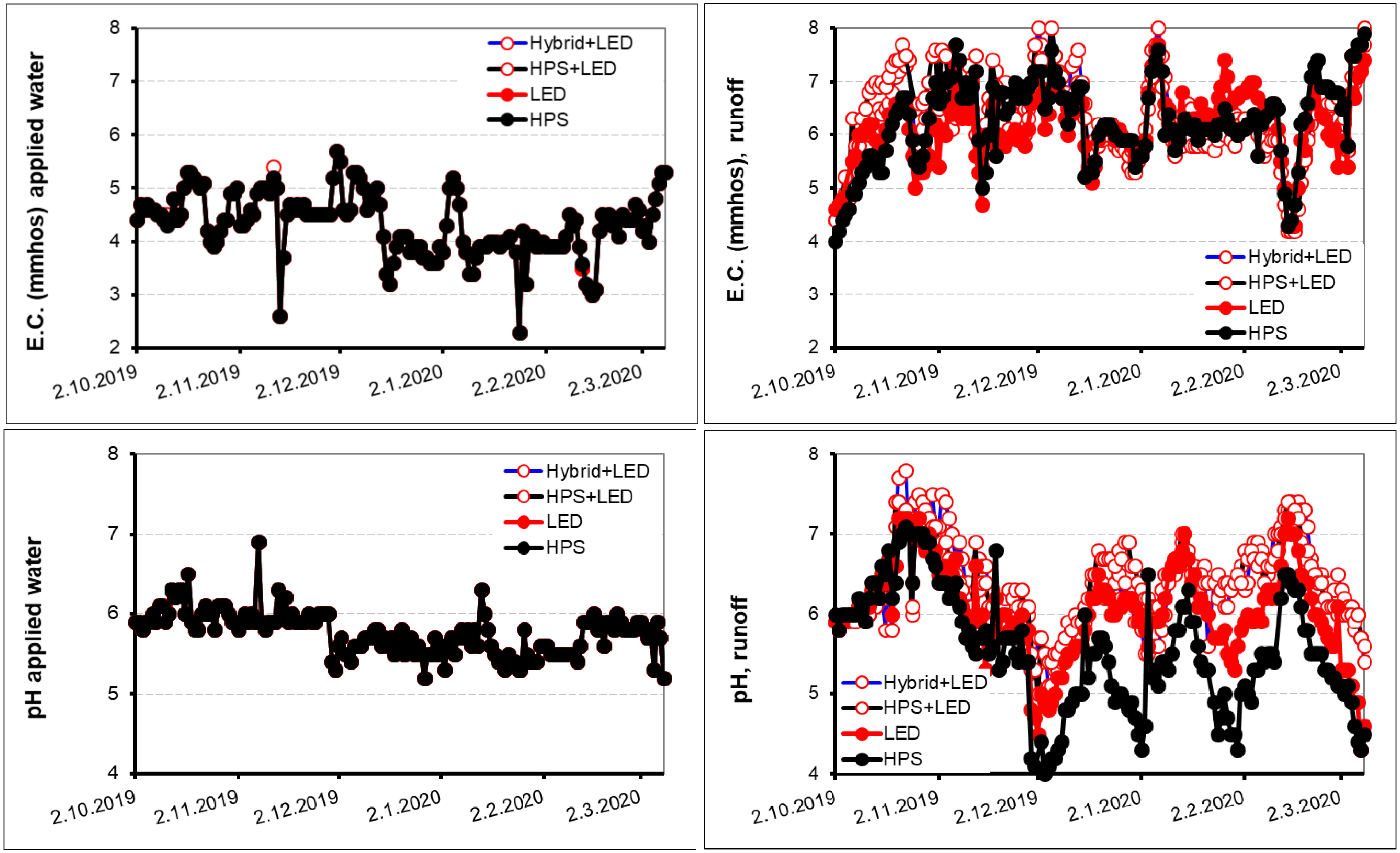

Fig. 7: **E.C. and pH of irrigation water and runoff.**

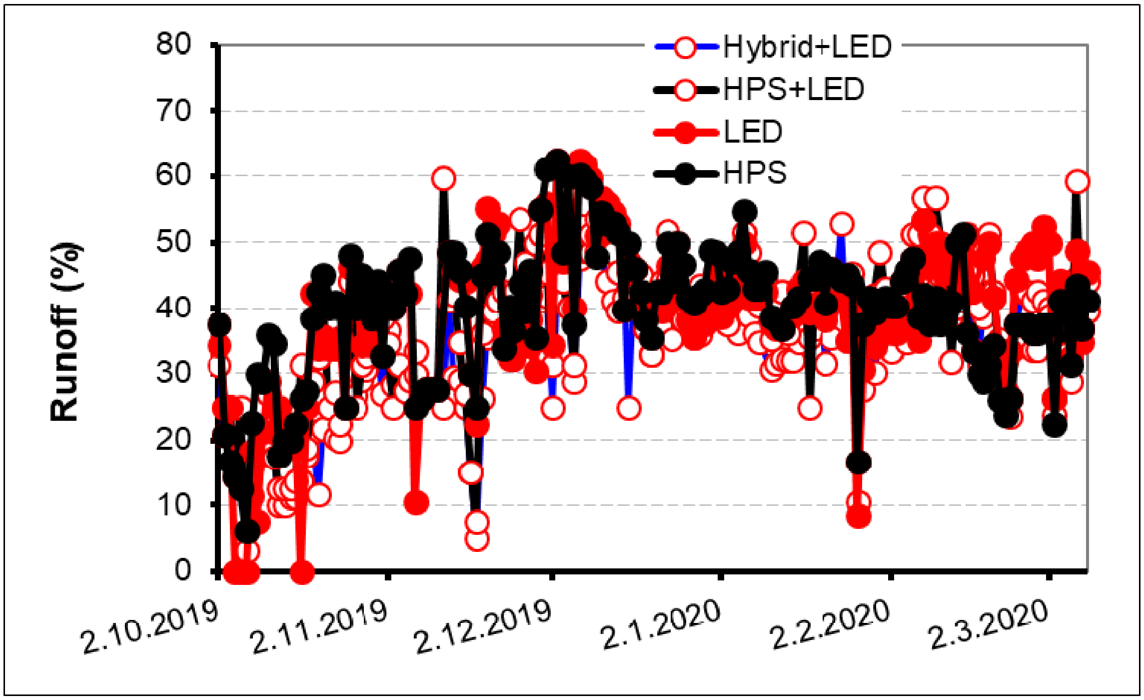

Fig. 8: Proportion of amount of runoff from applied irrigation water.

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

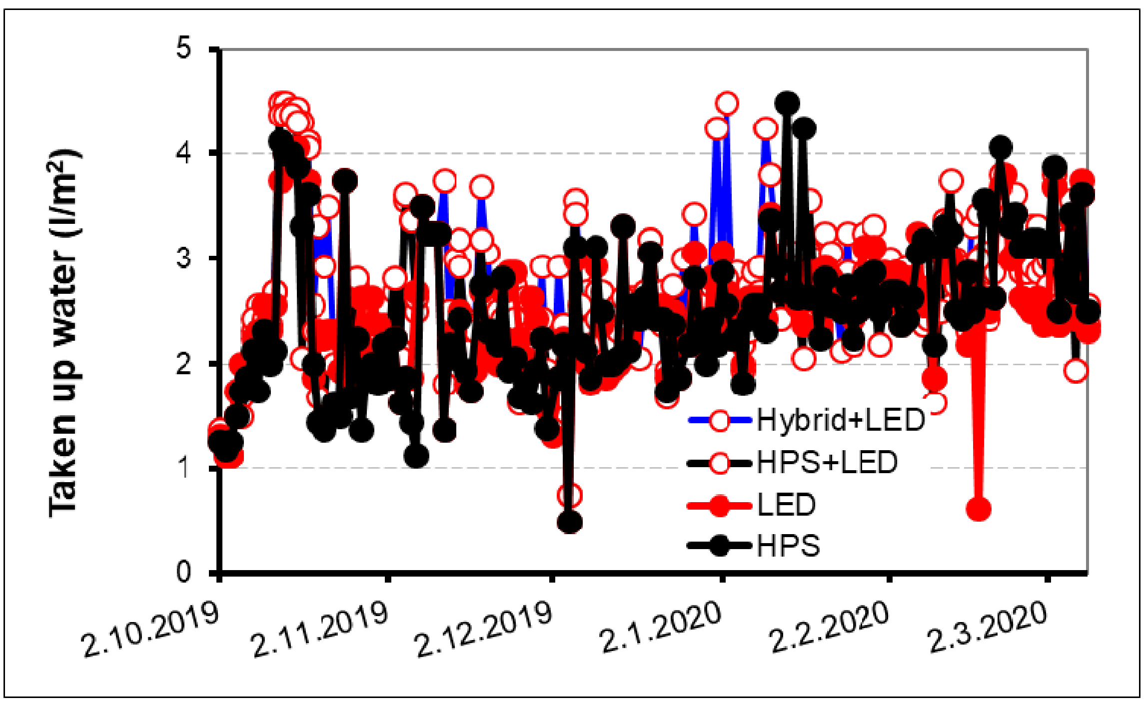

Fig. 9: Water uptake.

4.2 Development of tomatoes

4.2.1 Plant diseases and pests

Neither plant diseases nor pests were observed. However, in the last week of the experiment was a very low amount of white flies observed in “HPS”.

4.2.2 Height

Tomato plants were growing about 2-4 cm per day and reached at the end of the experiment about 5 m (Fig. 10). Plants in the treatment with only HPS top lighting were growing significantly taller than plants in the other treatments were LED lights were only or in addition to HPS lights used.

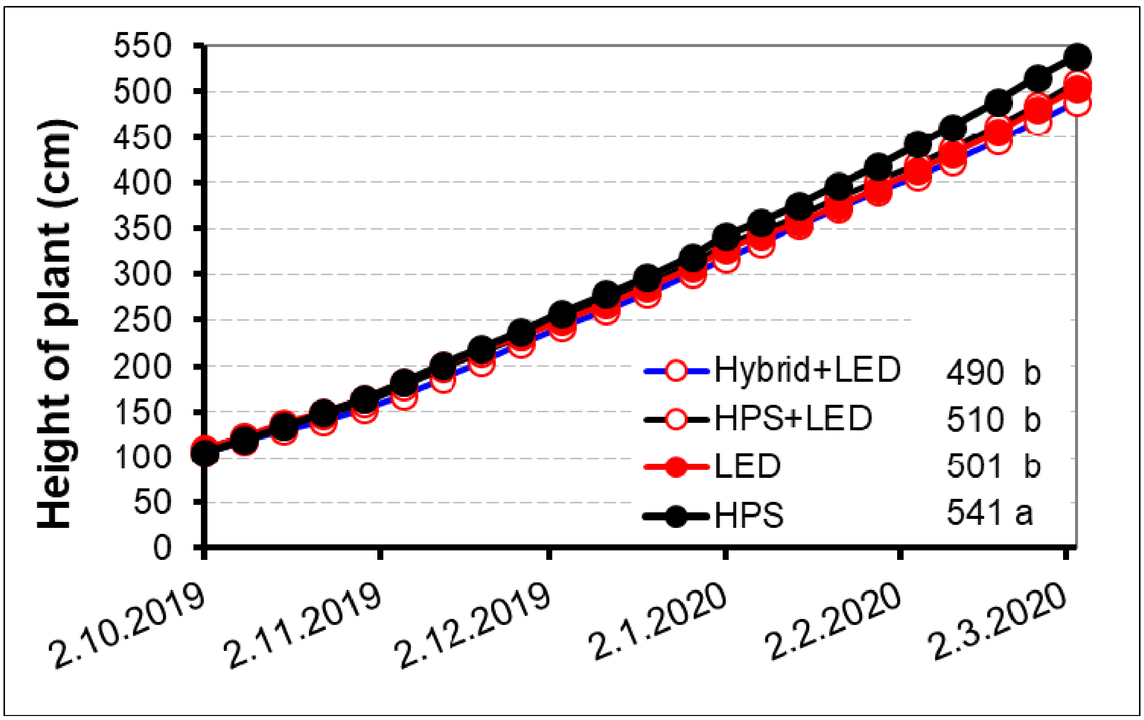

Fig. 10: Height of tomatoes.

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

4.2.3 Weekly growth

All treatments were growing each week in average 17-20 cm (Fig. 11). The treatment “HPS” was growing each week significantly more than the other light treatments.

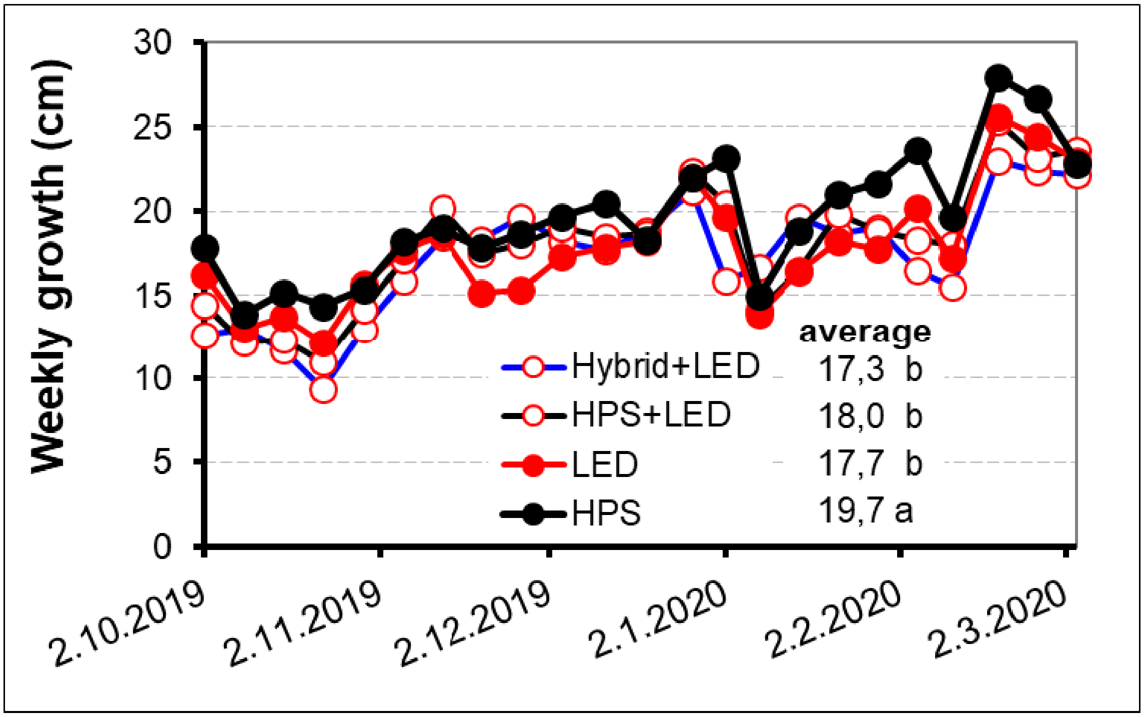

Fig. 11: Weekly growth.

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

4.2.4 Number of leaves

Plants had in average 15 leaves (Fig. 12).

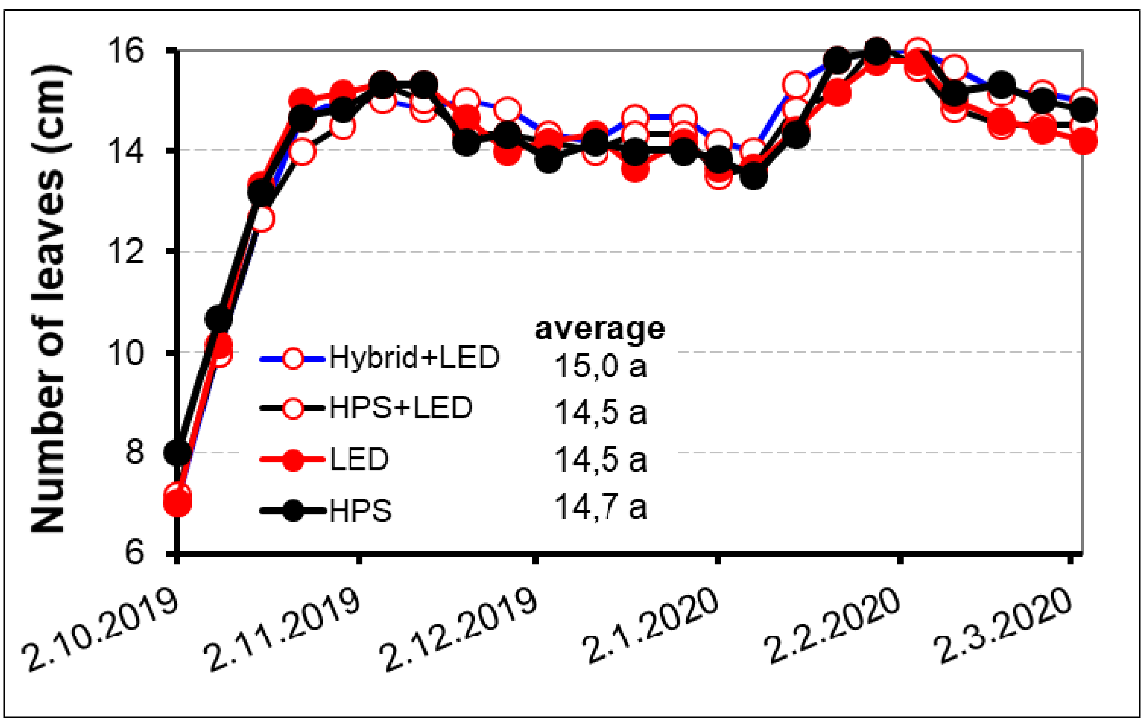

Fig. 12: Number of leaves on the tomato plant.

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

4.2.5 Length of leaves

Lengths of leaves increased until the end of the experiment from about 40 cm to more than 45 cm (Fig. 13). In average were no significant differences in the leaf length between light treatments measured.

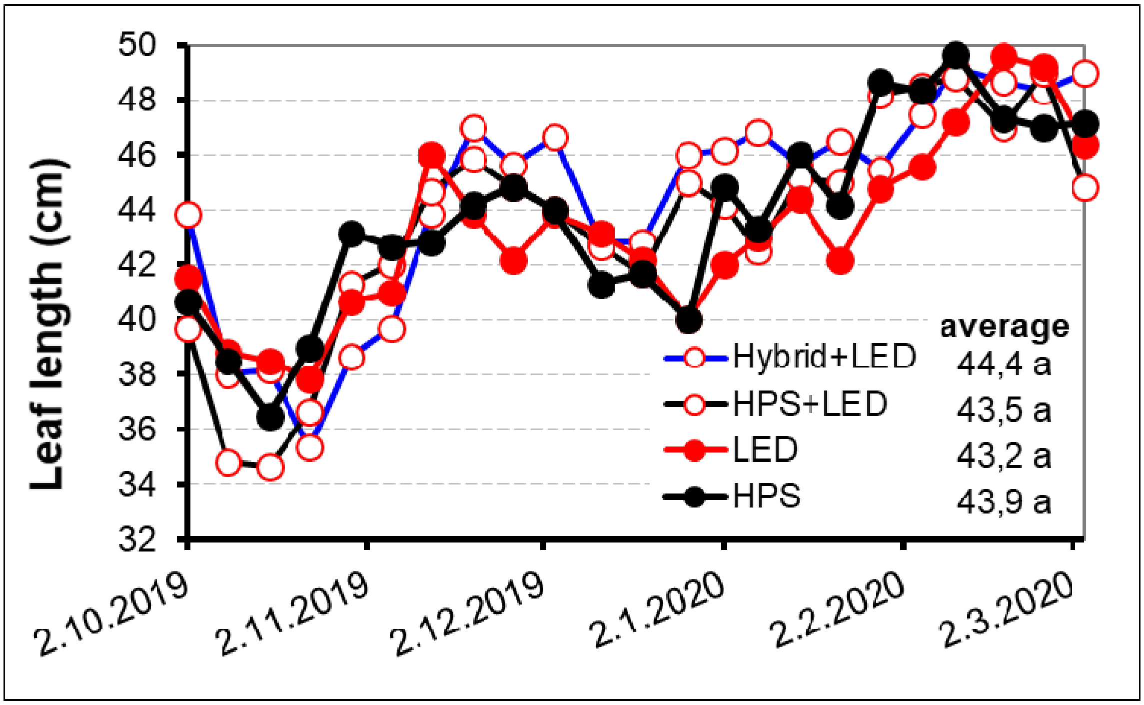

Fig. 13: Length of leaves.

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

4.2.6 Number of clusters

The number of clusters increased with approximately one additional cluster per week. No significant differences in the number of clusters between light treatments were counted (Fig. 14).

In addition, it was observed that there were extra flowers and leaves growing from the receptacle at cluster 1 and 2 in all treatments except in “HPS”. In contrast, in this treatment was only little additional growth at cluster 1 and no additional growth at cluster 2. In all light treatments was no additional growth observed at cluster 3 and also not at the following clusters.

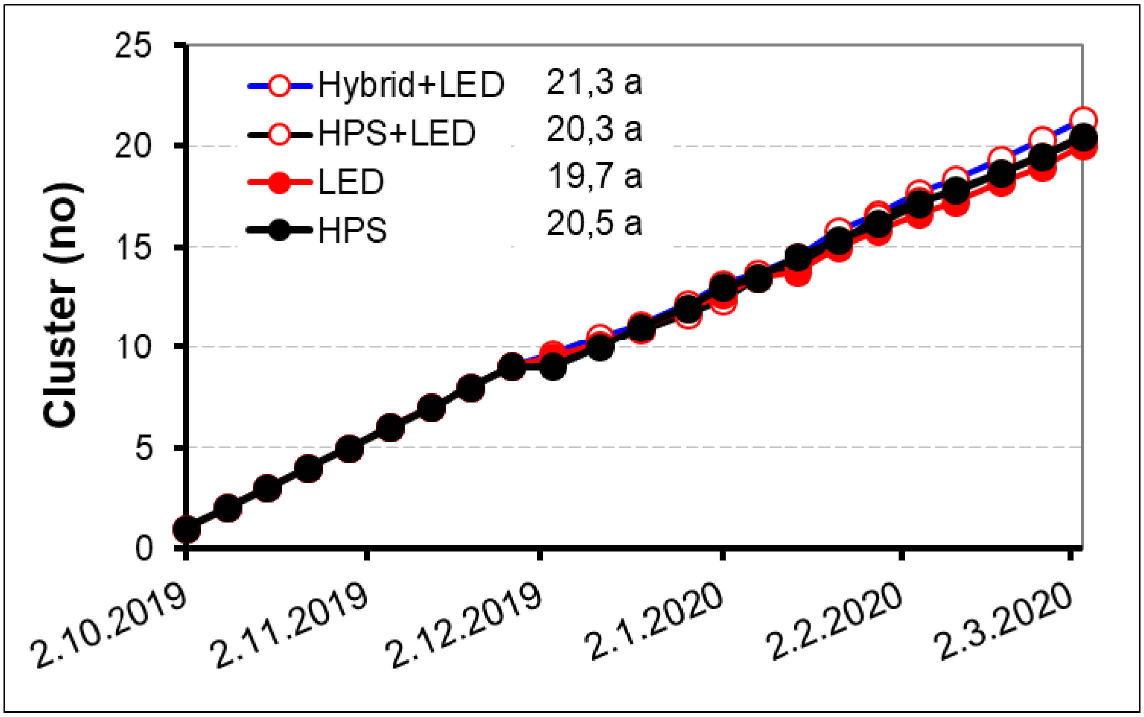

Fig. 14: Number of clusters.

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

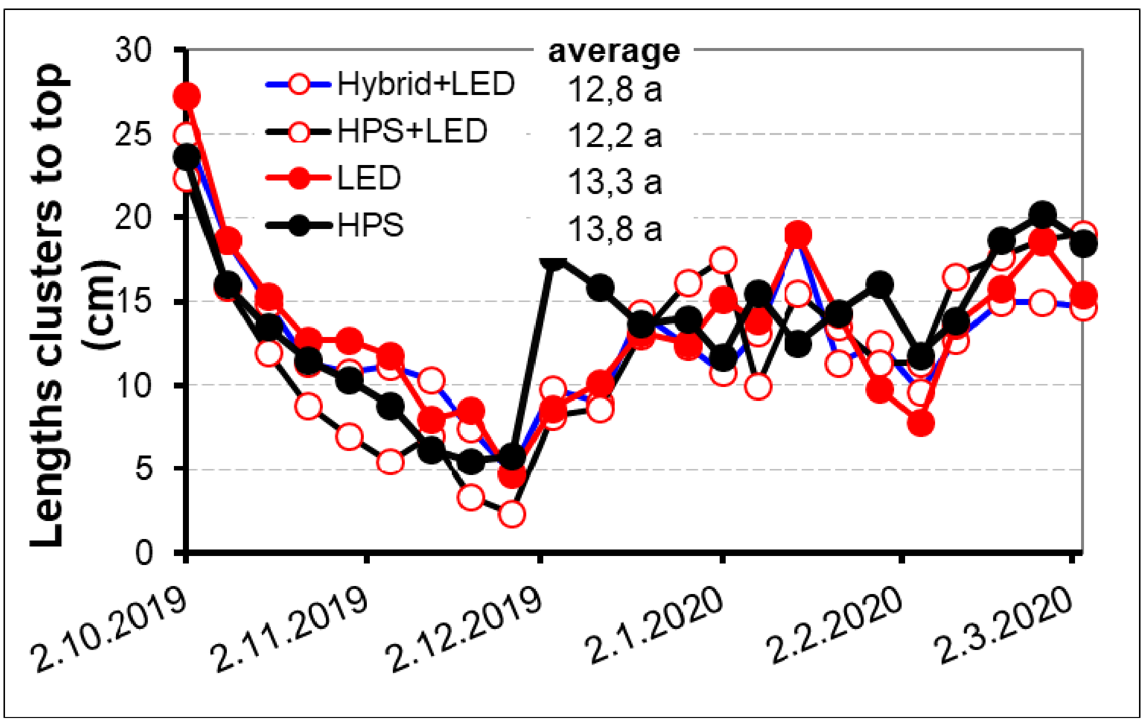

Fig. 15: Lengths of uppermost flowering cluster to plant top.

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

4.2.7 Lengths clusters to top

The lengths from the uppermost flowering cluster to the top of the plant amounted in average 12-14 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 26 cm during the growth period. In average amounted the distance 21-24 cm (Fig. 16). The distance was highest with only HPS top lighting and decreased with LED lighting. Compared to the treatment “HPS” was the distance between clusters significantly decreased with LED top lighting, either in the treatment “LED” or in the treatment “Hybrid+LED”.

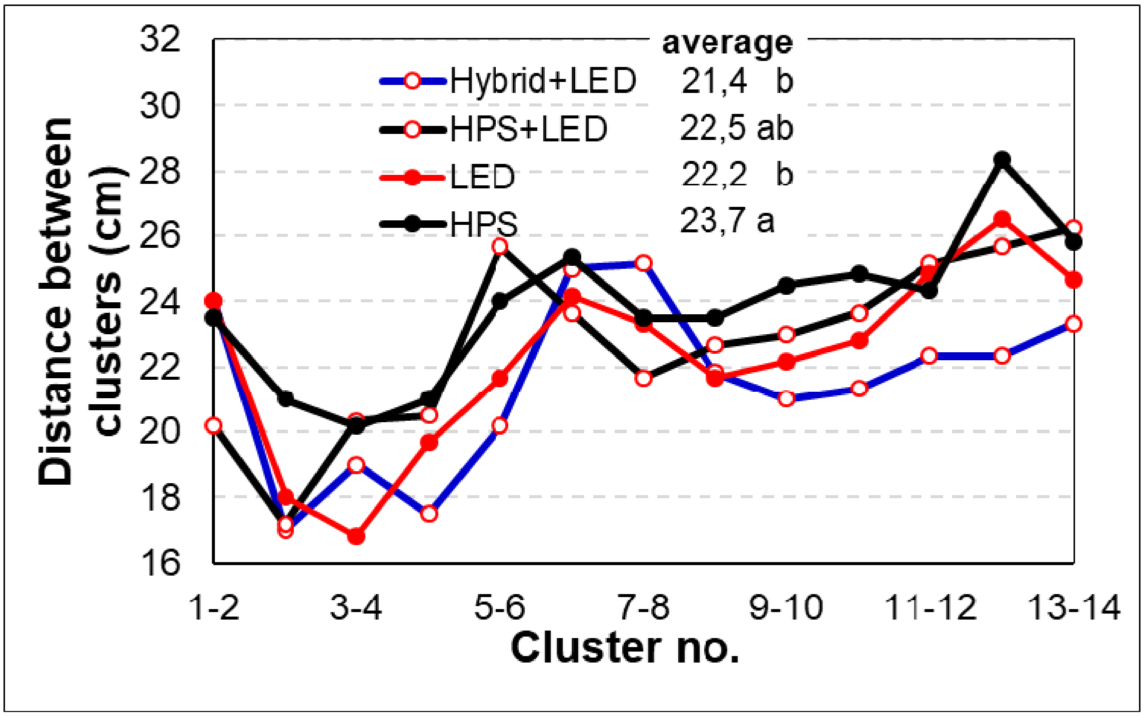

Fig. 16: Distance between clusters.

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

4.2.9 Length of clusters

The length of clusters decreased from about 26 to about 20 at the end of the experiment. The treatment “HPS” and “Hybrid+LED” had a significant higher cluster length compared to the treatment “LED” (Fig. 17).

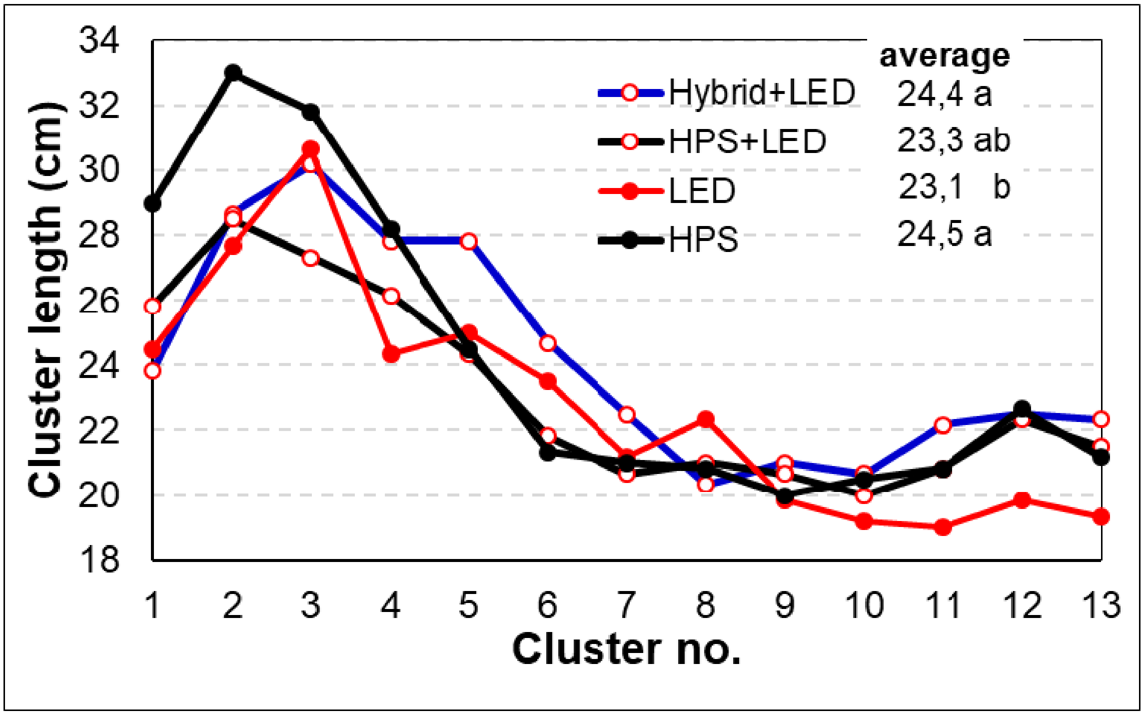

Fig. 17: Length of clusters.

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

4.2.10 Fruits per cluster

Cluster were pruned to 10 fruits per cluster. Consequently fluctuated the number of fruits per cluster around 10 fruits (Fig. 18). It seems that the amount of fruits per cluster decreased slightly at the end of the experiment. In average were no significant differences in the number of fruits per cluster between light treatments measured. The number of not pollinated fruits per cluster was not counted. However, in all light treatments were nearly all fruits pollinated.

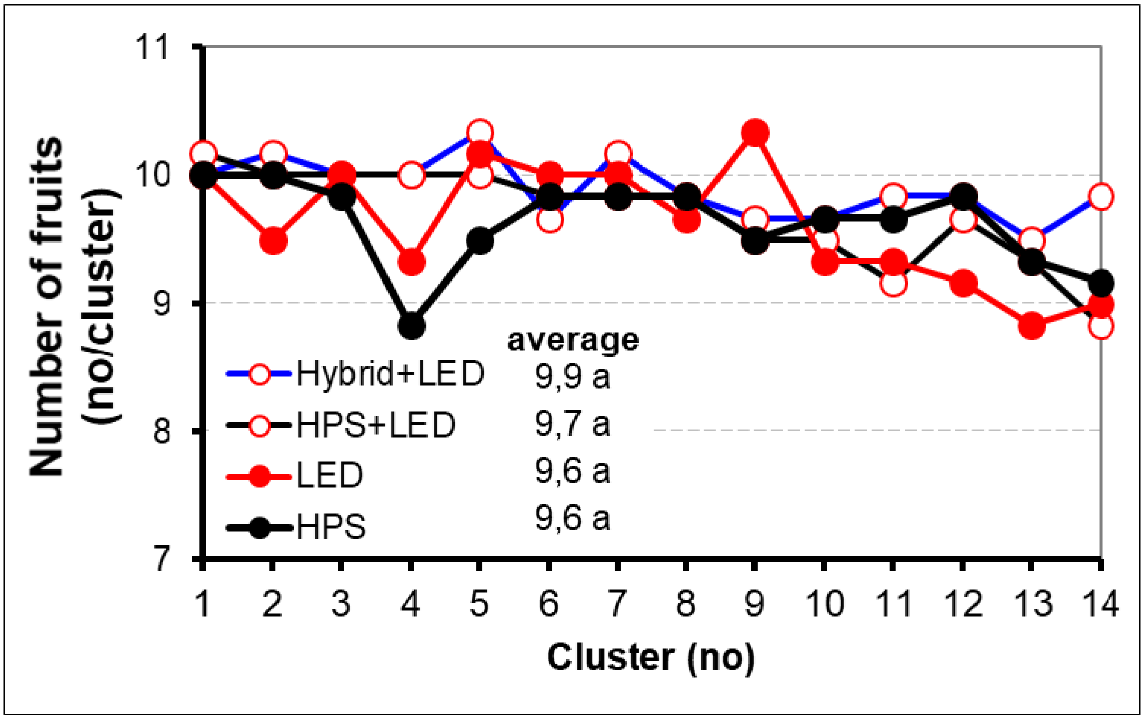

Fig. 18: Number of fruits per cluster.

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

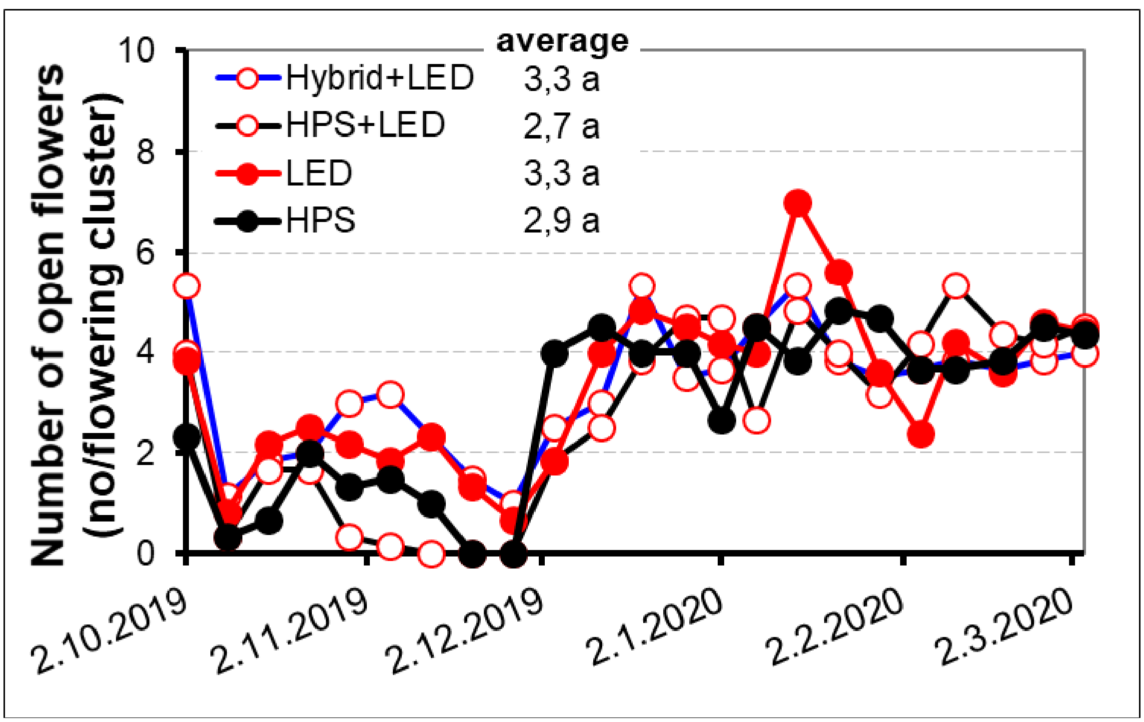

Fig. 19: Number of flowers.

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

4.2.11 Number of open flowers

On the uppermost cluster was the number of open flowers counted. It seems that the number of open clusters increased at the latter part of the experiment and stayed at around 4 open flowers. In average were no significant differences between the light treatments observed (Fig. 19).

4.2.12 Stem diameter

Stem diameter was varying from 0,6 to 1,1 cm (Fig. 20). In average amounted the diameter of the stem 0,78-0,84 cm and was independent of the light treatment. Plants were most of the time of the growth period weak vegetative.

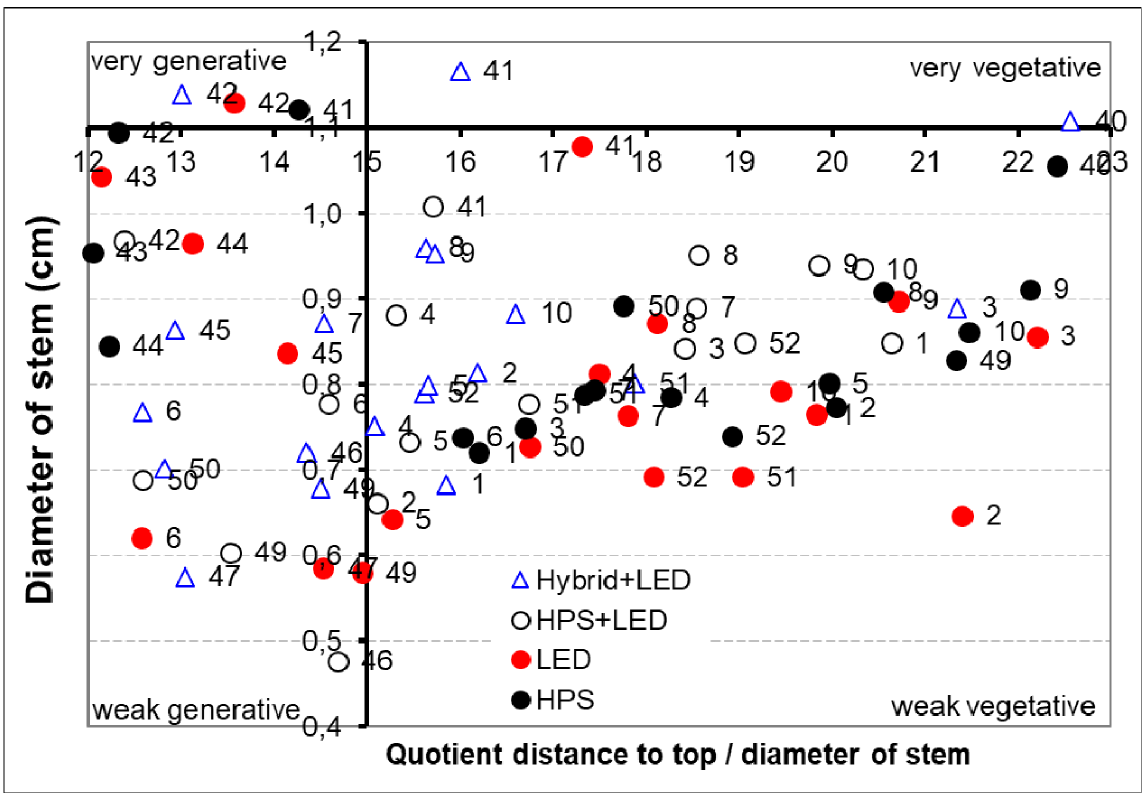

Fig. 20: Stem diameter and quotient lengths to top and stem diameter.
Numbers are representing the week number.

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 24-34 kg/m^2 (Fig. 21). The higher light level (Hybrid+LED, HPS+LED) gave a significantly higher total yield than a lower light level (LED, HPS). In addition, there seem to be a small advantage of Hybrid lighting (Hybrid+LED) compared to “HPS+LED”, even though this difference was not statistically different. Differences in the total yield were mainly attributed to a higher yield of 1. class fruits.

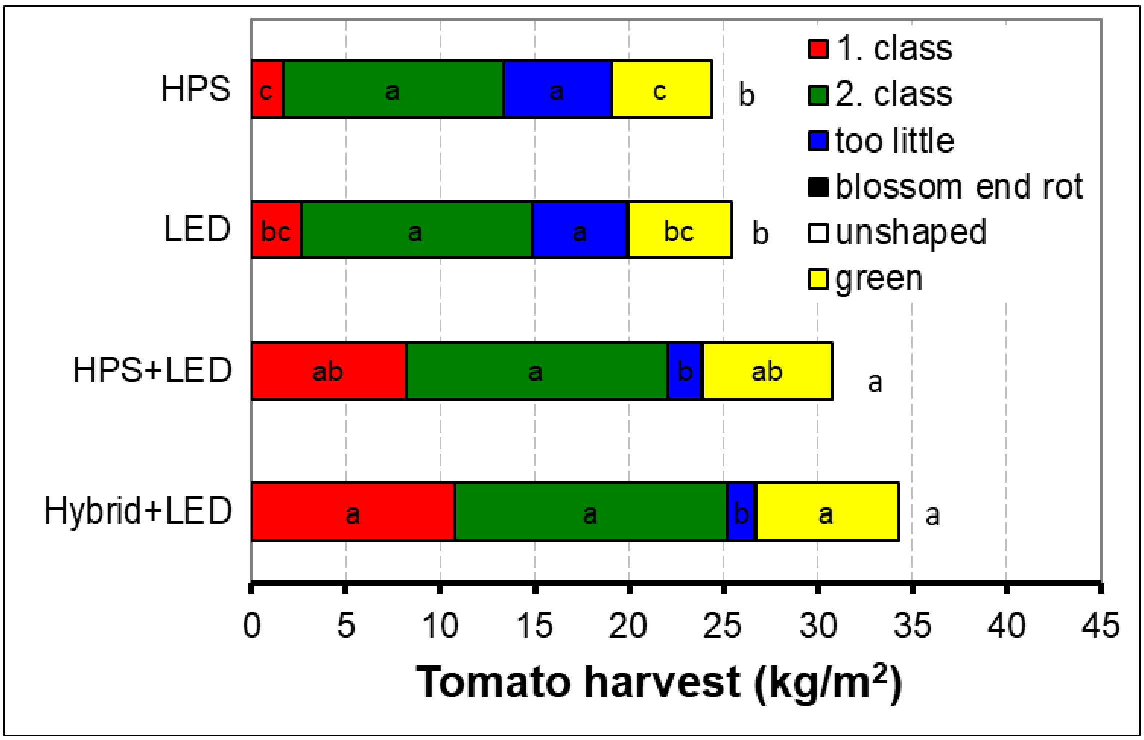

Fig. 21: Cumulative total yield of tomatoes in kg.
Letters indicate significant differences at the end of the experiment (HSD, p ≤ 0,05).

In addition, was a significantly higher amount of fruits harvested in the treatment “Hybrid+LED” compared to “LED” and “HPS”, while “HPS+LED” was not statistically significant from the latter two mentioned treatments (Fig. 22). Again, the higher amount of tomatoes was mainly due to a higher amount of 1. class fruits.

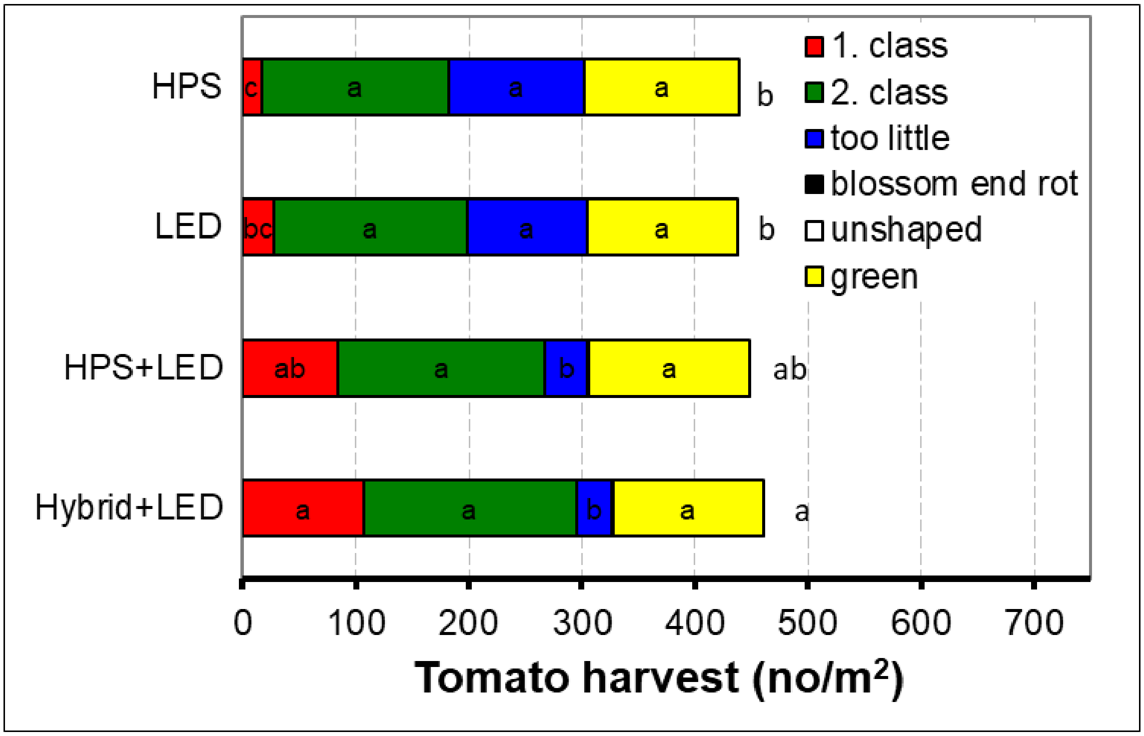

Fig. 22: Cumulative total yield of tomatoes in number.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

4.3.2 Marketable yield of tomatoes

At the end of the harvest period amounted marketable yield of tomatoes 12-25 kg/m^2 (Fig. 23). The marketable yield of tomatoes was significantly higher for the treatments with the higher light level „Hybrid+LED“ with 25 kg/m^2 and „HPS+LED“ with 22 kg/m^2 than for „LED“ with 15 kg/m^2 and „HPS“ with 13 kg/m^2. Differences increased especially at the middle of the harvest period and onwards. The marketable yield of „Hybrid+LED“ was 13 % higher than under „HPS+LED“. No significant differences in the marketable yield were observed between the light sources „LED“ and „HPS“. However, the yield under HPS top lights was 10 % lower compared to LED top lights. By adding LED interlights to HPS top lights (compare „HPS“ with „HPS+LED“) could the marketable yield be increased by 65 %. Tomatoes in the treatment „Hybrid+LED“ were harvested about half a week earlier than the other light treatments.

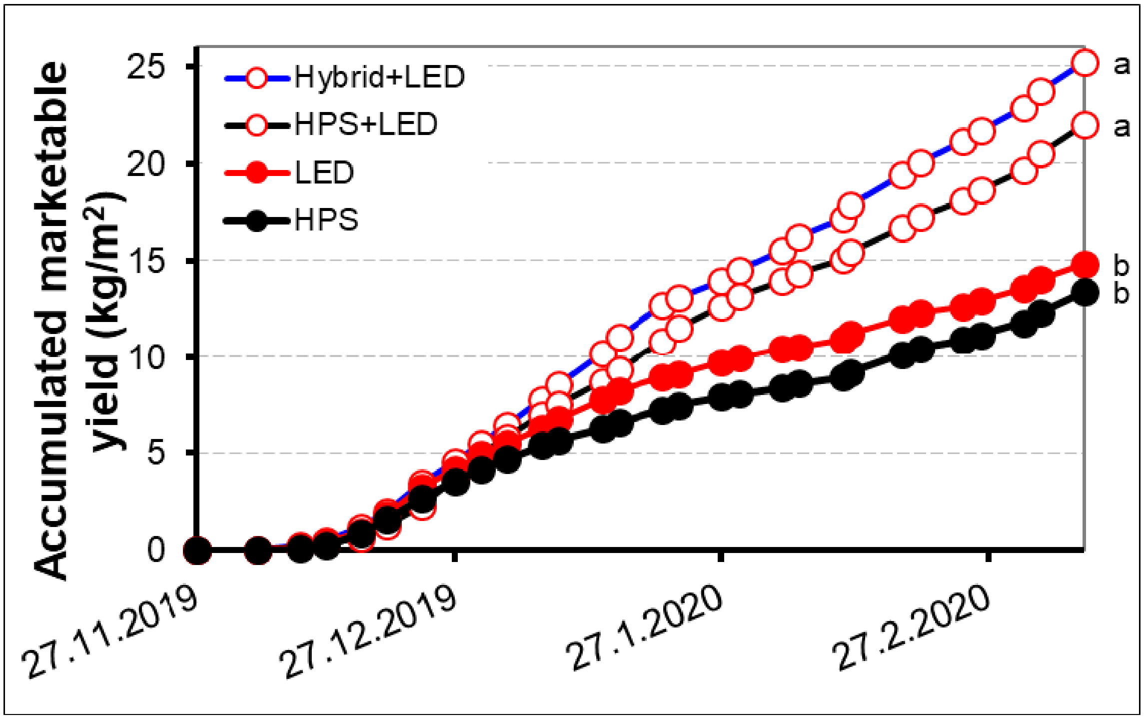

Fig. 23: Time course of marketable yield (1. and 2. class tomatoes).
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

The 1. class yield was low for the treatment “HPS” and “LED” and stayed the whole harvest period at a low value (Fig. 24). Compared to this two light treatments was a significantly higher 1. class yield reached under “Hybrid+LED”. The yield of the treatment “HPS+LED” was statistically significant to the treatment “HPS”, but not to the treatment “LED”.

In contrast, while there were differences in the amount of 1. class yield between the light treatments, was the 2. class yield independent of the light treatment and amounted in all light treatments around 13 kg/m^2 (Fig. 25).

Also, the marketable yield of the whole chamber was measured (Fig. 26). A higher marketable yield was reached with “Hybrid+LED” (6,6 kg/plant) compared to “HPS+LED” (5,5 kg/plant), “LED” (3,8 kg/plant) and “HPS” (3,3 kg/plant).

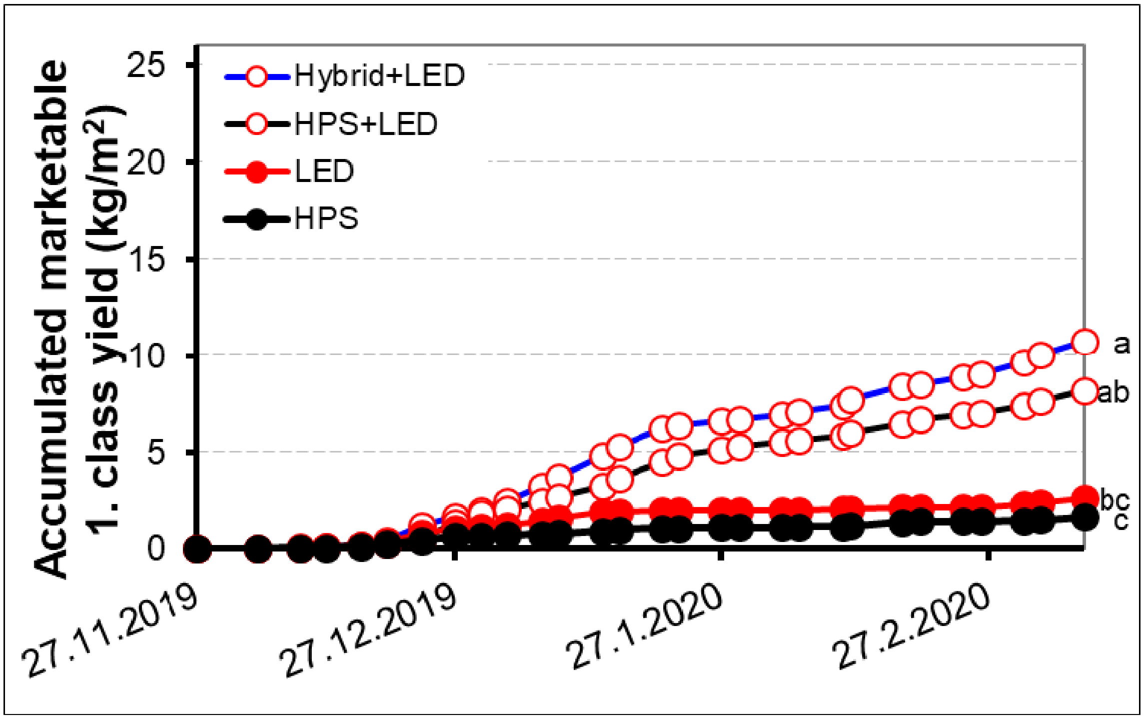

Fig. 24: Time course of marketable 1. class yield.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

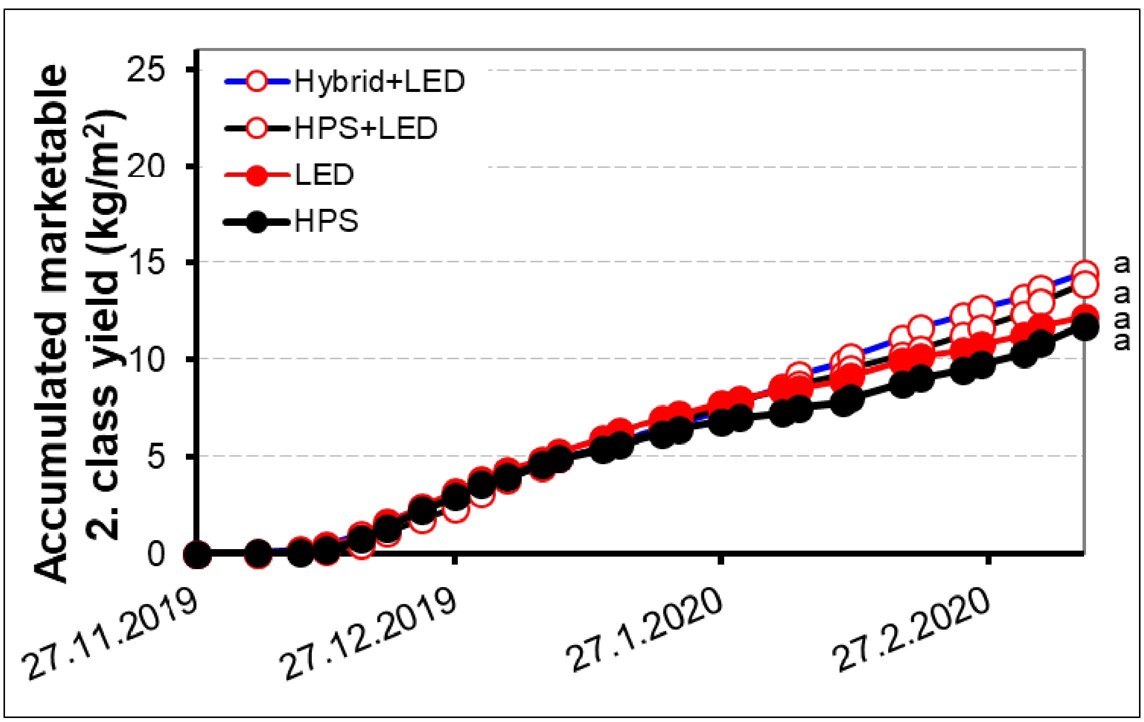

Fig. 25: Time course of marketable 2. class yield.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

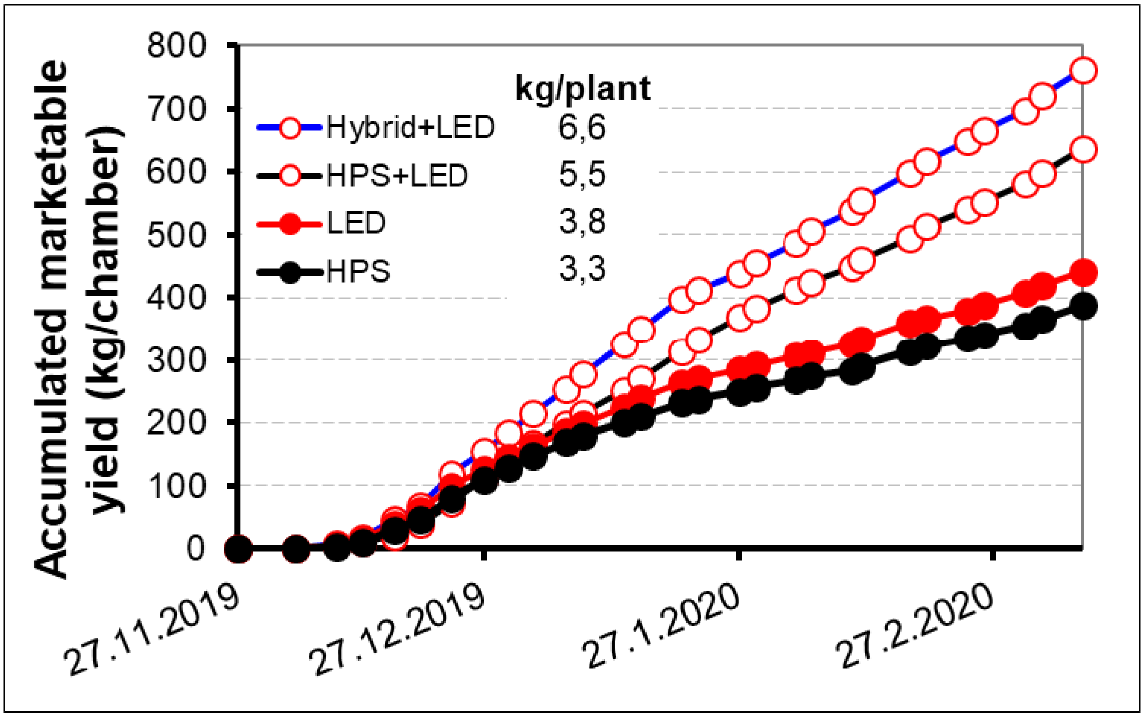

Fig. 26: Time course of marketable yield of tomatoes in the whole chamber.

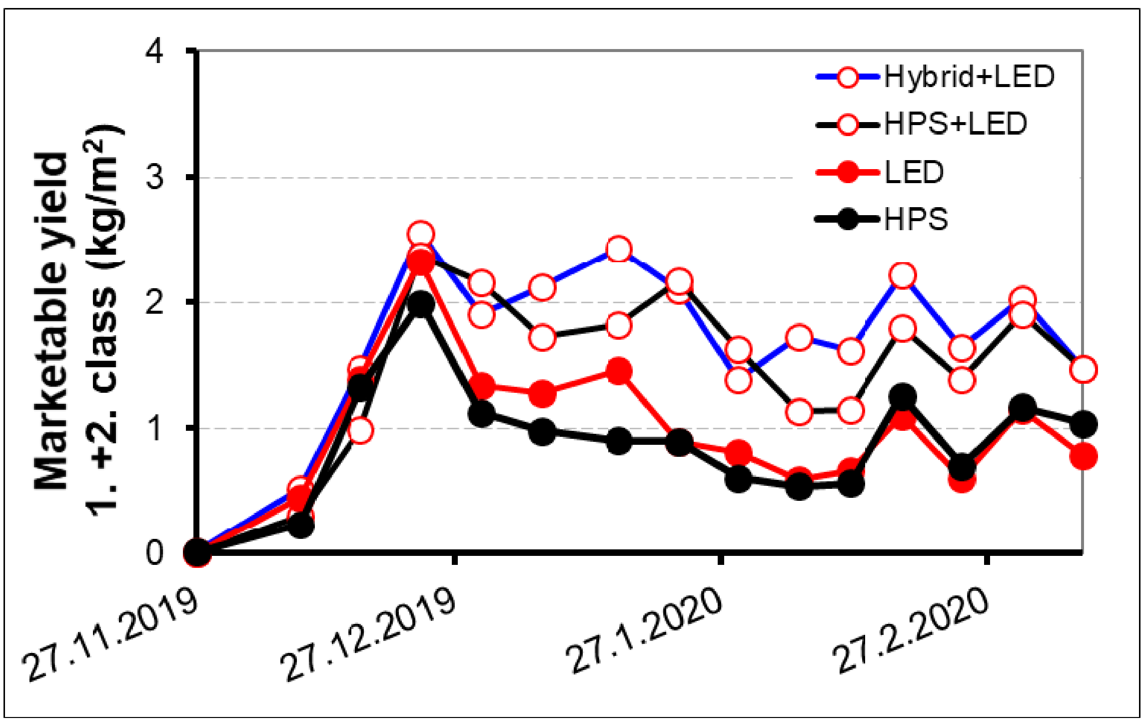

Fig. 27: Time course of marketable yield.

The weekly harvest of 1. class and 2. class fruits amounted between 1,5-2,5 kg/m^2 for the higher light level treatments “Hybrid+LED” and “HPS+LED”, but 0,5-1,5 kg/m^2 for the lower light level treatments “LED” and “HPS” (Fig. 27).

The number of 1. class fruits was significant higher for “Hybrid+LED” and “HPS+LED” than for “HPS” (Tab. 5), while no significant differences between “HPS” and “LED” were observed. The number of 2. class fruits was statistically independent of the light treatment. The total number of marketable fruits was significantly higher for the treatments with LED interlighting than for only LED or HPS top lighting.

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)
Hybrid+LED	107 a	188 a	295 a
HPS+LED	84 ab	184 a	268 a
LED	28 bc	171 a	199 b
HPS	18 c	165 a	183 b

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

Average fruit size of 1. class tomatoes varyied between 85-105 g / fruit (Fig. 28). In average was the weight of 1. class tomatoes independent of the light source when HPS and LED top lighting are compared. Fruits under “HPS” were signifycantly lighter than in the higher light level treatments with interlighting, meaning adding LED interlights to HPS top lights significantly increased fruit size. Fruit size under “LED” was significantly lower than under “Hybrid+LED” but not significanty different from “HPS+LED”.

Average fruit size of 1. and 2. class tomatoes was varying between 75-95 g / fruit (Fig. 29). It seems that fruit size decreased until the beginning of February and increased after that. The light source (either HPS or LED as top lighting) did not affect average fruit size. When LED interlights were added to HPS top lights was average fruits size significantly increased by nearly 10 g. An additional increase of 4 g was possible with Hybrid lighting. However, these two treatments with LED interlighting were not statistically different.

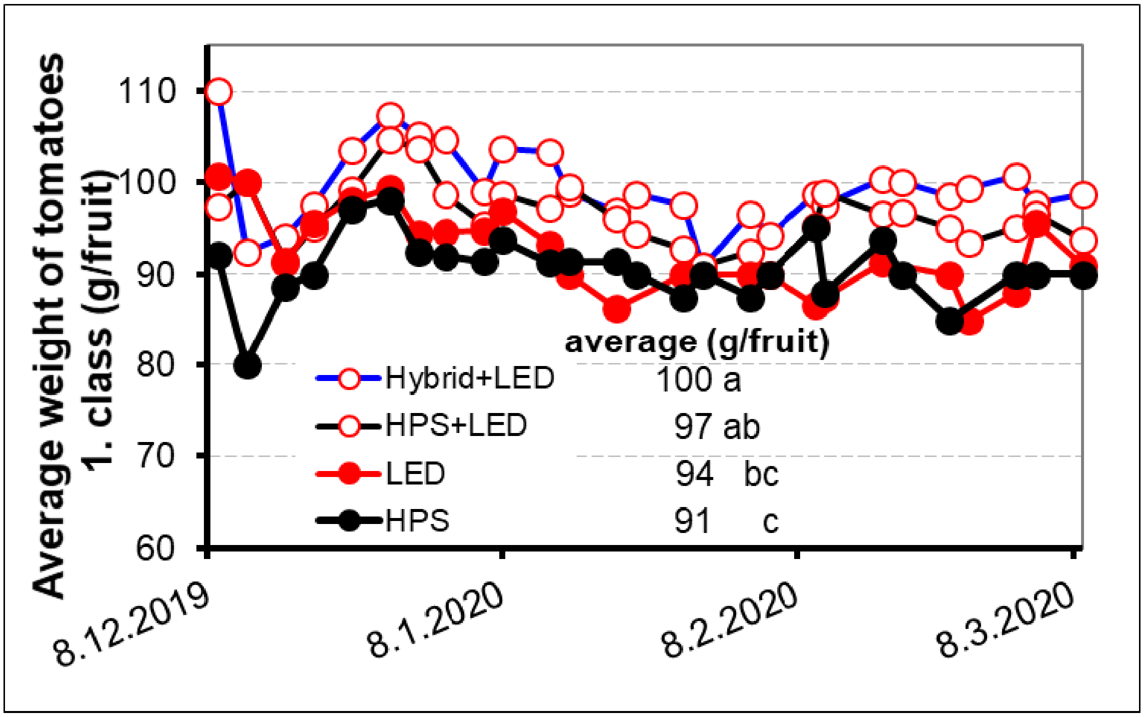

Fig. 28: Average weight of tomatoes (1. class fruits).

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

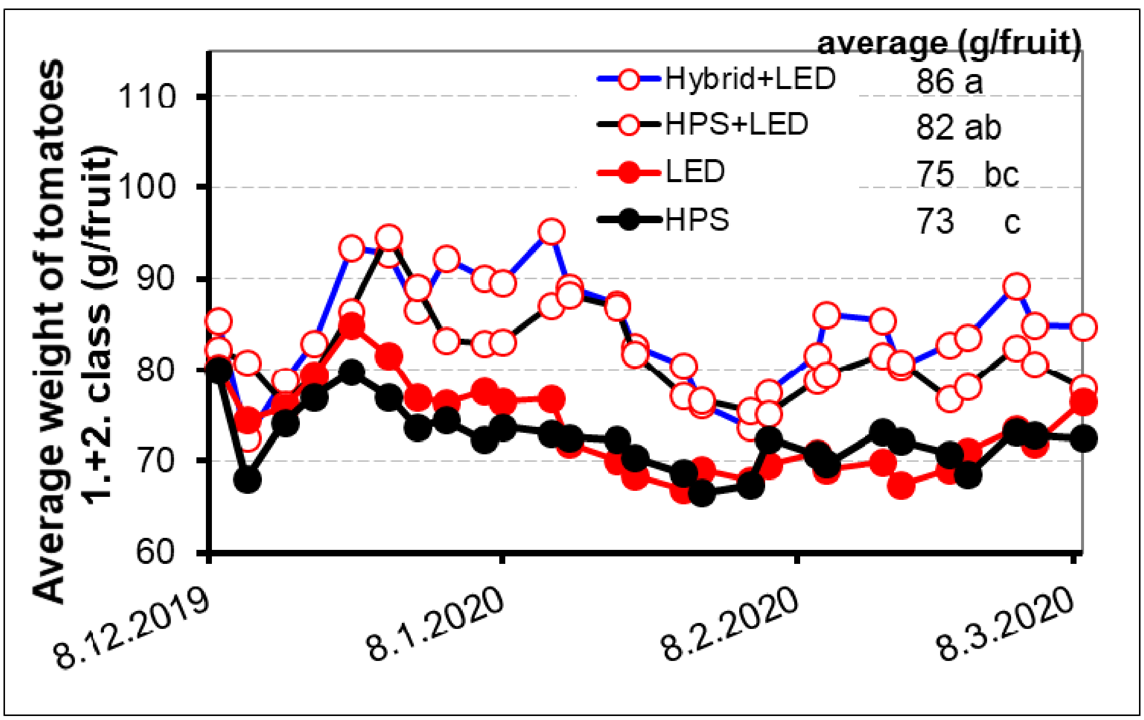

Fig. 29: Average weight of tomatoes (1. and 2. class fruits).

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

4.3.3 Outer quality of yield

Marketable yield was more than 70 % of total yield for light treatments with LED interlighting, but around 55 % with either only LED or HPS top lighting (Tab. 6). This difference was due to an increased proportion of 1. class fruits and a significantly lower proportion of too little fruits for the treatments with LED interlighting compared to “HPS” or “LED”, while the proportion of 2. class fruits was independent of the light treatment. 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. Naturally, 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 the same in all light treatments, which is indicating appropriate sampling.

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
Hybrid+LED	31 a	43 a	4 b	0 a	0 a	22 a
HPS+LED	26 ab	46 a	6 b	0 a	0 a	22 a
LED	10 bc	48 a	20 a	0 a	0 a	22 a
HPS	7 c	48 a	23 a	0 a	0 a	22 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 at three times during the harvest period. Completo had a sugar content of 3,4-3,9°BRIX. The sugar content was at all measurement dates independent of the light treatment (Fig. 30).

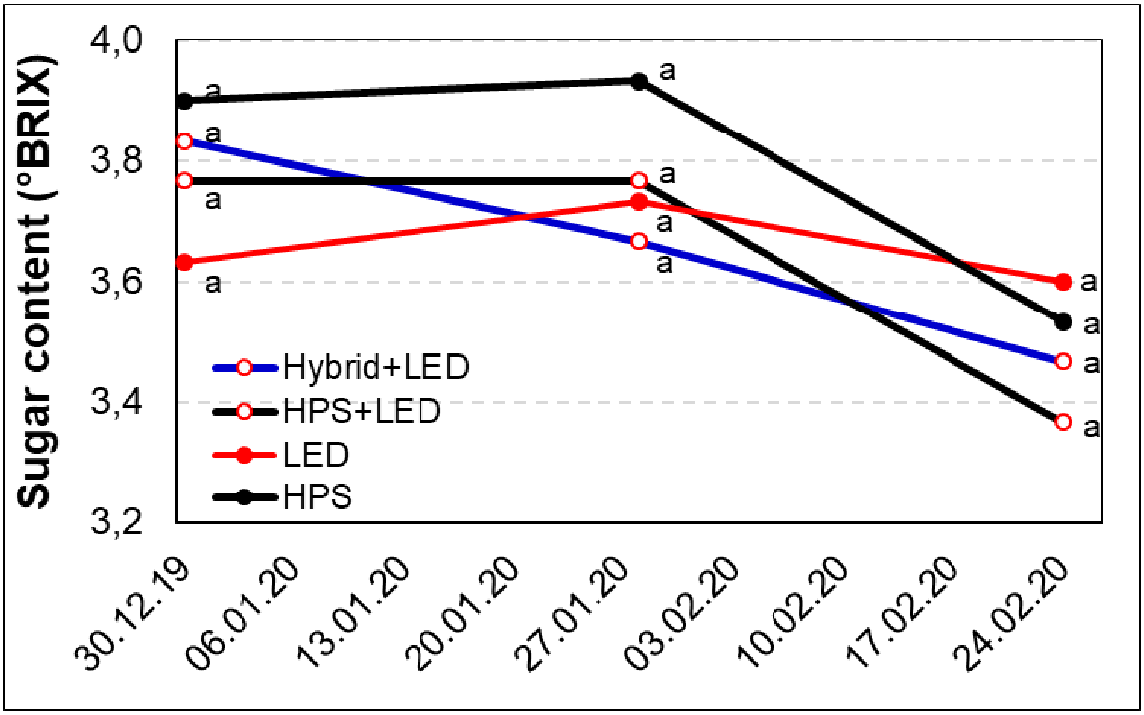

Fig. 30: Sugar content of tomatoes.

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

4.3.4.2 Taste of tomatoes

The taste of tomatoes, subdivided into sweetness, flavour and juiciness was tested by untrained assessors on 28.01.2020. The rating within the same sample was varying very much and therefore, same light treatments resulted in a high standard deviation. It seems that "HPS" was rated sweeter than the other light treatments, while the flavour and the juiciness was rated more or less the same between the different light treatments (Fig. 31).

4.3.4.3 Dry substance of tomatoes

Dry substance (DS) of tomatoes was measured on the same dates as the sugar content and was varying between 4,3 % and 4,8 % (Fig. 32). The DS content was most of the time independent of the light treatment. It seems that fruits under "LED" had a tendentially lower DS content.

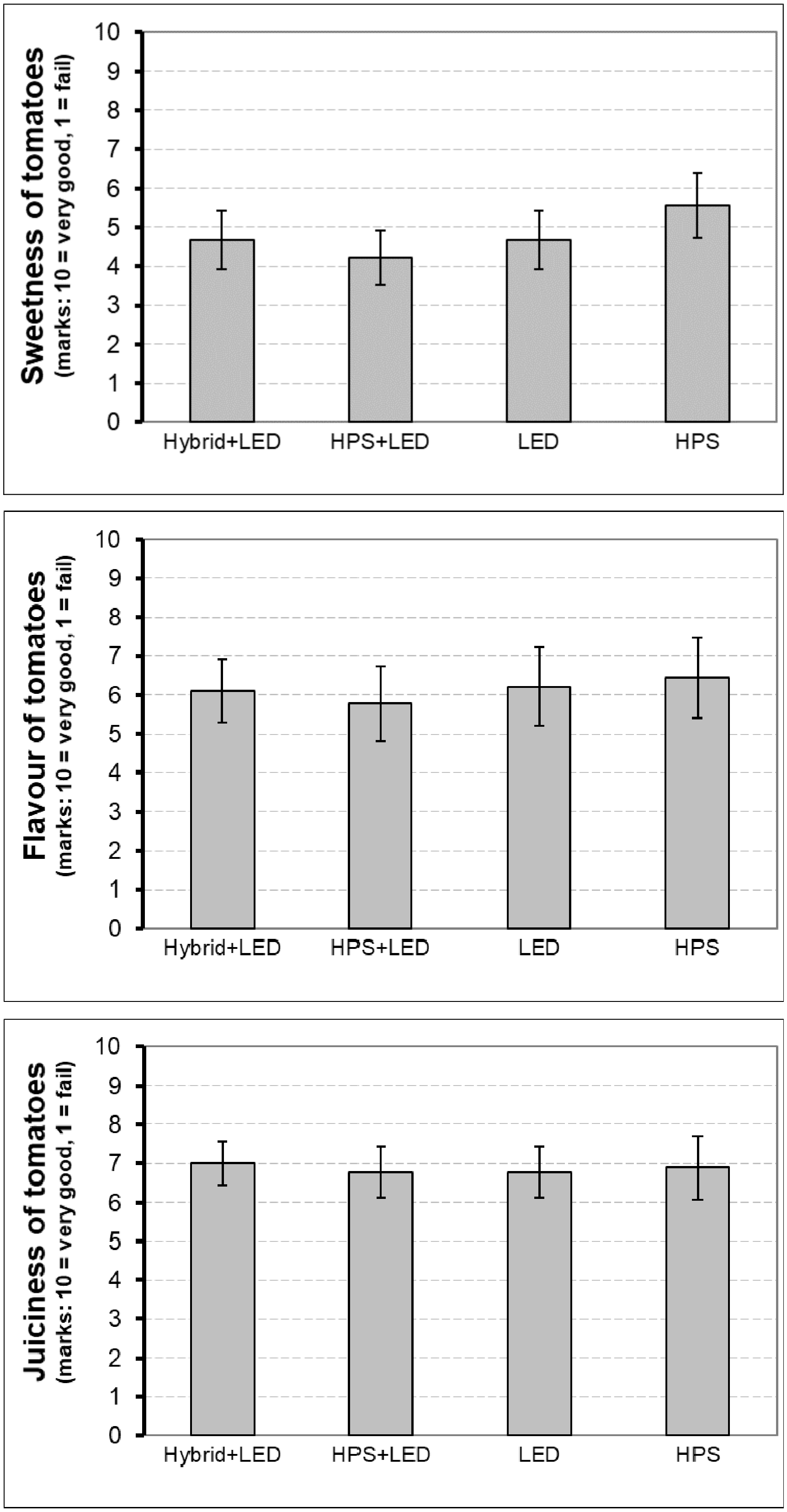

Fig. 31: Sweetness, flavour and juiciness of tomatoes.

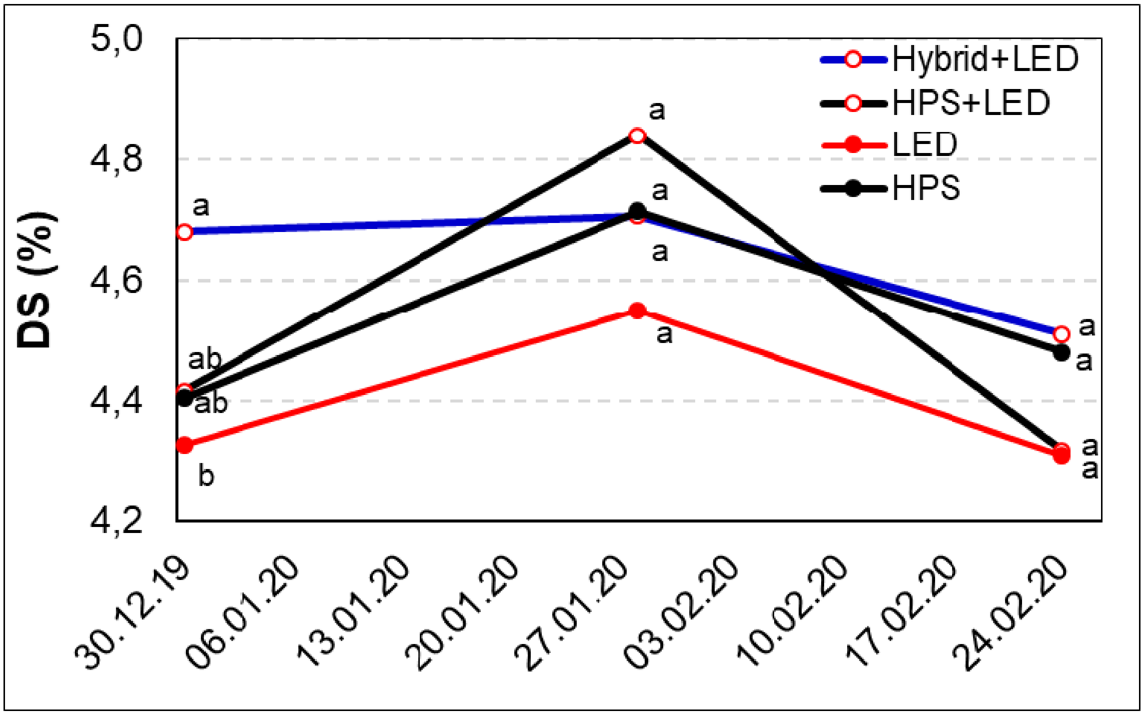

Fig. 32: Dry substance of tomatoes.

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

4.3.4.4 Relationship between dry substance and sugar content

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

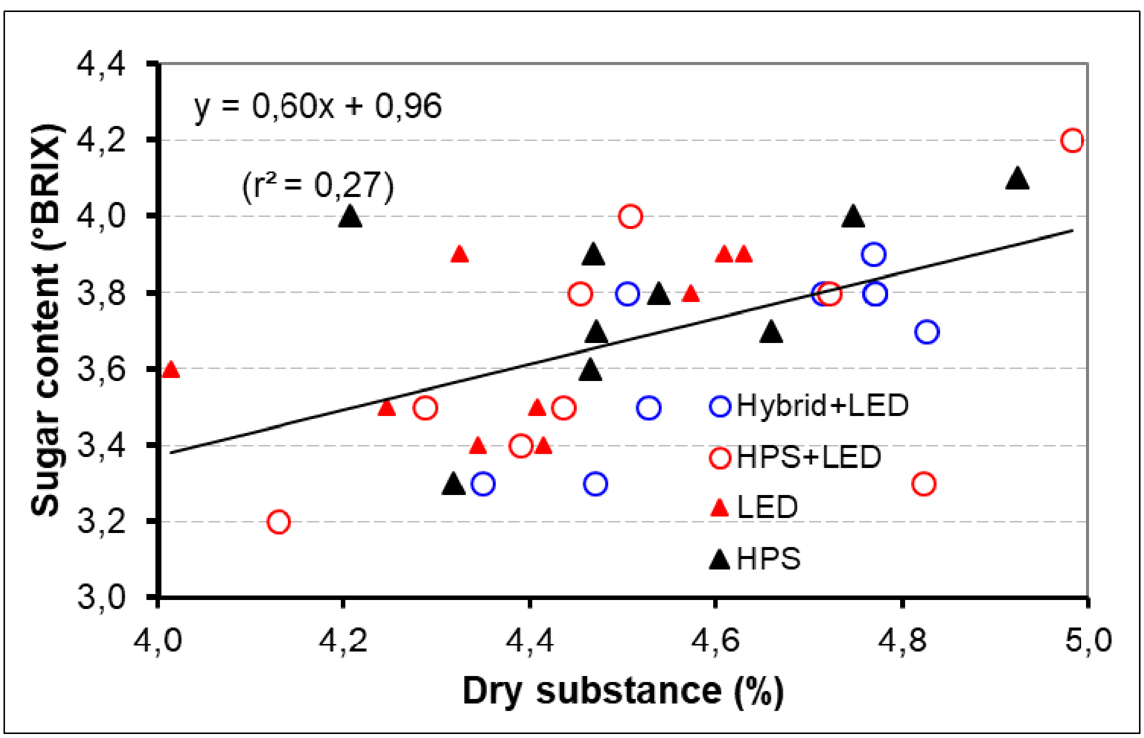

Fig. 33: Relationship between dry substance and sugar content of fruits.

4.4 Economics

4.4.1 Lighting hours

The number of lighting hours is contributing to high annual costs and needs therefore special consideration to consider decreasing lighting costs per kg marketable yield. The total hours of lighting during the growth period of tomatoes were both simulated and measured with dataloggers.

"HPS" had a daily usage of 170 kWh (Fig. 34), while "LED" had with 105 kWh 39 % less daily usage. When LED interlighting was added to HPS top lighting increased the used energy by 8 % (compare HPS with HPS+LED). The treatments "Hybrid+LED" (181 kWh/day) and "HPS+LED" (185 kWh/day) were nearly comparable regarding the used energy.

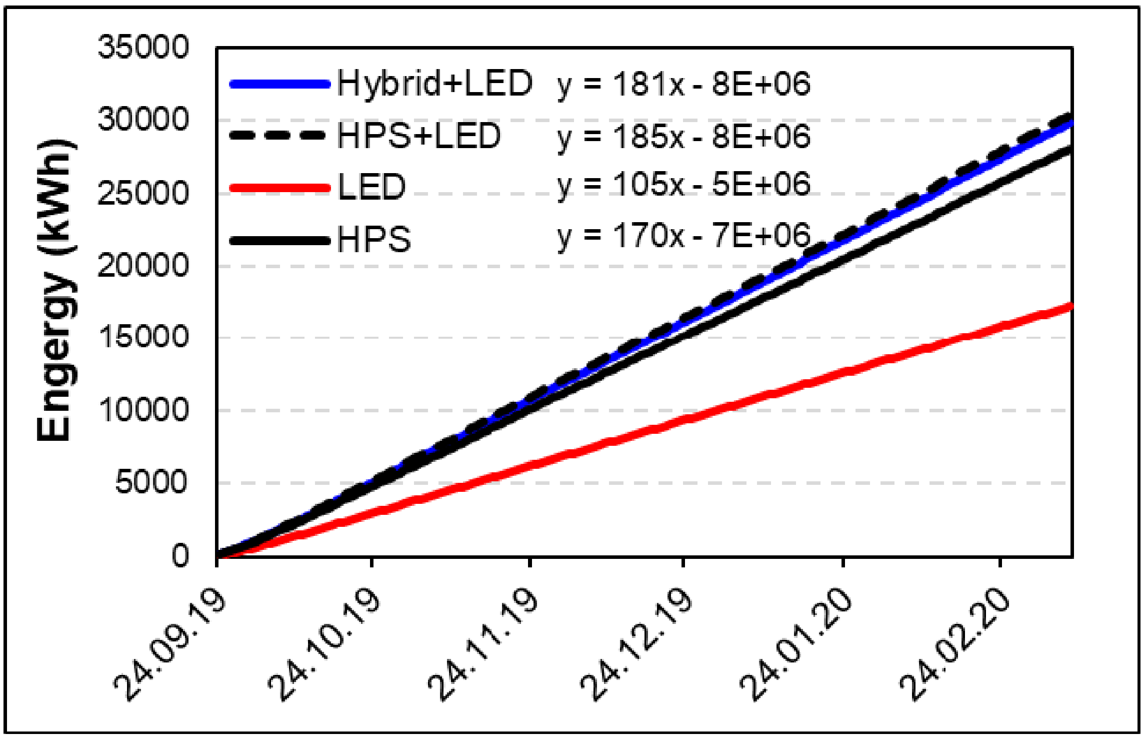

Fig. 34: Used kWh in the different chambers.

The simulated value was calculated according to the lighting hours written down. The measured lighting hours were comparable between the different light treatments (Tab. 7).

For calculation of the power, different electric consumptions were made, because the actual consumption is higher than the nominal value of the bulb: one was based on the power of the lamps (nominal Watts, 0 % more power consumption), one with 6 % more power consumption and one with 10 % more power consumption. The power and the energy was comparable between measured and simulated values.

Tab. 7: Lighting hours, power and energy in the cabinets.

Treatment	Hours	Power	Energy	Energy/m²
	h	W	kWh	kWh/m²
Hybrid+LED				
Measured values	2.613	229	29.873	597
Simulated values				
0 % more power consumption (nominal)	2.617	220	28.784	576
6 % more power consumption	2.617	233	30.511	610
10 % more power consumption	2.617	242	31.633	633
HPS+LED				
Measured values	2.618	232	30.434	609
Simulated values				
0 % more power consumption (nominal)	2.617	228	29.831	597
6 % more power consumption	2.617	242	31.621	632
10 % more power consumption	2.617	251	32.814	656
LED				
Measured values	2.618	132	17.262	345
Simulated values				
0 % more power consumption (nominal)	2.617	122	15.962	319
6 % more power consumption	2.617	129	16.920	338
10 % more power consumption	2.617	134	17.558	351
HPS				
Measured values	2.620	214	28.085	562
Simulated values				
0 % more power consumption (nominal)	2.617	210	27.476	550
6 % more power consumption	2.617	223	29.125	582
10 % more power consumption	2.617	231	30.224	604

4.4.2 Energy use efficiency

When tomatoes were only lightened with HPS top lighting were kWh's transferred worst into yield. The energy use efficiency increased when HPS top lighting was replaced by LED top lighting (Fig. 35). The difference amounted 44 %. The energy use efficiency was with "Hybrid+LED" comparable to the one of LED top lighting. However, when the number of HPS lights increased (HPS+LED) was the utilization of kWh's not as good transferred into yield compared to the two other before mentioned treatments.

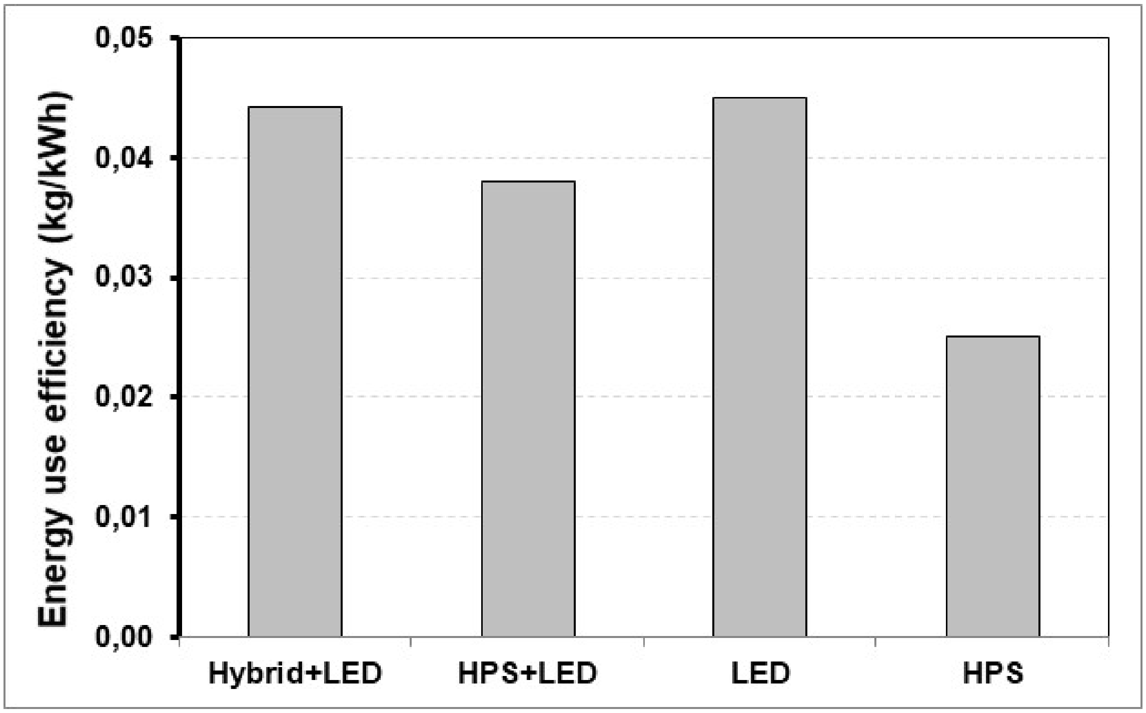

Fig. 35: Yield per kWh.

4.4.3 Energy prices

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 are, due to their location, mandatory customers of RARIK, the distribution system operator (DSO) for most of Iceland except in the Southwest and Westfjords (*Eggertsson*, 2009).

RARIK offers basically three types of tariffs:

a) energy tariffs, for smaller customers, that only pay fixed price per kWh,
b) "time dependent" tariffs (tímaháður taxti, Orkutaxti TT000) with high prices during the day (09.00-20.00) at working days (Monday to Friday) but much lower during the night and weekends and summer, and
c) demand based tariffs (afltaxti AT000), for larger users, who pay according to the maximum power demand.

In the report, only afltaxti is used as the two other types of tariffs are not economic. Since 2009, RARIK has offered special high voltage tariffs ("VA410" and "VA430") for large users, that must either be located close to substation of the transmission system operator (TSO) or able to pay considerable upfront fee for the connection.

Costs for distribution are divided into an annual fee and costs for the consumption based on used energy (kWh) and maximum power demand (kW) respectively the costs at special times of usage. The annual fee is pretty low for “VA210” and “VA230” when subdivided to the growing area and is therefore not included into the calculation. However, the annual fee for “VA410” and “VA430” is much higher. Growers in an urban area in “RARIK areas” can choose between different tariffs. In the report, only the possibly most used tariffs “VA210” and “VA410” in urban areas and “VA230” and “VA430” in rural areas are considered.

The government subsidises the distribution cost of growers that comply to certain criteria’s. In recent years, the subsidies fluctuated quite much. Currently 85,7 % and 87,7 % of variable cost of distribution for urban and rural areas respectively are subsidised. In 2019 this values amounted 82 % and 86,1 % for urban and rural areas respectively. However, in 2018 the values were 64,8 % respectively 69,2 % and in 2017 87 % respectively 92 %. This amount can be expected to change in the future. Since 2019 also the annual fee is subsidised.

Based on this percentage of subsidy and the lighting hours (Tab. 7), for the cabinets the energy costs per m^2 during the time of the experiment for the growers were calculated (Tab. 8a, Tab. 8b).

The energy costs per kWh are for distribution after subsides 0,65 ISK/kWh for „VA210“ and 1,12 ISK/kWh for „VA230“, 0,54 ISK/kWh for „VA410“ and 0,80 ISK/kWh for „VA430“. The energy costs for sale are for „Afltaxti“ 5,39 ISK/kWh and for „Orkutaxti“ 7,93 ISK/kWh.

Cost of electricity was comparable between real and calculated values (Tab. 8a, Tab. 8b). In general, tariffs for large users rendered lower cost. Costs of electricity for “LED” were lower than for “HPS”. When LED interlight was added to HPS top light, increased the costs of electricity slightly. Costs for the treatments “Hybrid+LED” and “HPS+LED” were similar.

Tab. 8a: Costs for consumption of energy for distribution and sale of energy for lighting with Hybrid+LED and HPS+LED.

	Costs for consumption							
	Energy ISK/kWh				**Energy costs with subsidy per m²** ISK/m²			
Treat-ment	Hybrid+LED		HPS+LED		Hybrid+LED		HPS+LED	
	real	calculated	real	calculated	real	calculated	real	calculated
DISTRIBUTION								
RARIK Urban					85,7 % subsidy from the state			
VA210	0,65	0,65	0,65	0,65	386	373 396 411	393	387 410 426
VA410	0,54	0,55	0,54	0,55	324	314 333 345	330	325 345 358
RARIK Rural					87,7 % subsidy from the state			
VA230	1,12	1,12	1,12	1,12	669	646 685 711	681	670 710 737
VA430	0,80	0,80	0,80	0,80	478	461 489 508	486	478 507 526
SALE								
Afltaxti	5,39	5,44	5,39	5,44		3.129		3.243
Orkutaxti	7,93	7,13	7,93	7,13	3.221	3.317	3.279	3.438
						3.442		3.567

Comments: The first number for the calculated value is with 0 % more power consumption, the second value with 6 % more power consumption and the last value with 10 % more power consumption.

Prices are from April 2020.

Tab. 8b: Costs for consumption of energy for distribution and sale of energy for lighting with LED and HPS.

	Costs for consumption							
	Energy ISK/kWh				Energy costs with subsidy per m^2 ISK/m^2			
Treat-ment	LED		HPS		LED		HPS	
	real	calculated	real	calculated	real	calculated	real	calculated
				DISTRIBUTION				
RARIK Urban					85,7 % subsidy from the state			
VA210						207		356
	0,65	0,65	0,65	0,65	223	219	363	378
						228		392
VA410						174		300
	0,54	0,55	0,54	0,55	186	185	305	318
						191		330
RARIK Rural					87,7 % subsidy from the state			
VA230						358		617
	1,12	1,12	1,12	1,12	387	380	629	654
						394		679
VA430						256		440
	0,80	0,80	0,80	0,80	276	271	449	467
						281		484
				SALE				
Afltaxti	5,39	5,44	5,39	5,44		1.735		2.987
Orkutaxti	7,92	7,13	7,93	7,13	1.861	1.839	3.027	3.166
						1.909		3.286

Comments: The first number for the calculated value is with 0 % more power consumption, the second value with 6 % more power consumption and the last value with 10 % more power consumption.

Prices are from April 2020.

4.4.4 Costs of electricity in relation to yield

Costs of electricity in relation to yield for wintergrown tomatoes were calculated (Tab. 9). While for the distribution several tariffs were possible, for the sale only the cheapest tariff was considered.

The costs of electricity per kg yield decreased by nearly 45 % when LEDs were used as top lighting instead of HPS lights. When LED interlights were added to HPS top lights were costs of electricity per kg yield decreased by nearly 35 % (compare HPS with HPS+LED) due to yield increase. A further nearly 15 % decrease of costs of electricity per yield was reached by replacing part of the HPS top lights by LED top lights (compare Hybrid+LED with HPS+LED).

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

	Variable costs of electricity per kg yield ISK/kg							
Treatment	Hybrid+LED		HPS+LED		LED		HPS	
Yield kg/m²	25,2		22,0		14,8		13,4	
	real	calculated	real	calculated	real	calculated	real	calculated
Urban area (Distribution + Sale)								
VA210	143	139 147 153	167	165 175 182	141	131 139 144	253	250 264 274
VA410	141	137 145 150	164	162 172 178	138	129 137 142	249	245 260 270
Rural area (Distribution + Sale)								
VA230	154	150 159 165	180	178 189 196	152	141 150 156	273	269 285 296
VA430	147	142 151 157	171	169 179 186	144	135 143 148	259	256 271 281

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 550 ISK from Sölufélag garðyrkjumanna (SfG) and in addition 130 ISK from the government. Therefore, the revenues increased with more yield (Fig. 36). The light source (compare HPS and LED) had a small influence on the revenue. However, by adding LED interlighting to HPS top lighting could the revenue be increased. The revenue was highest in “Hybrid+LED”.

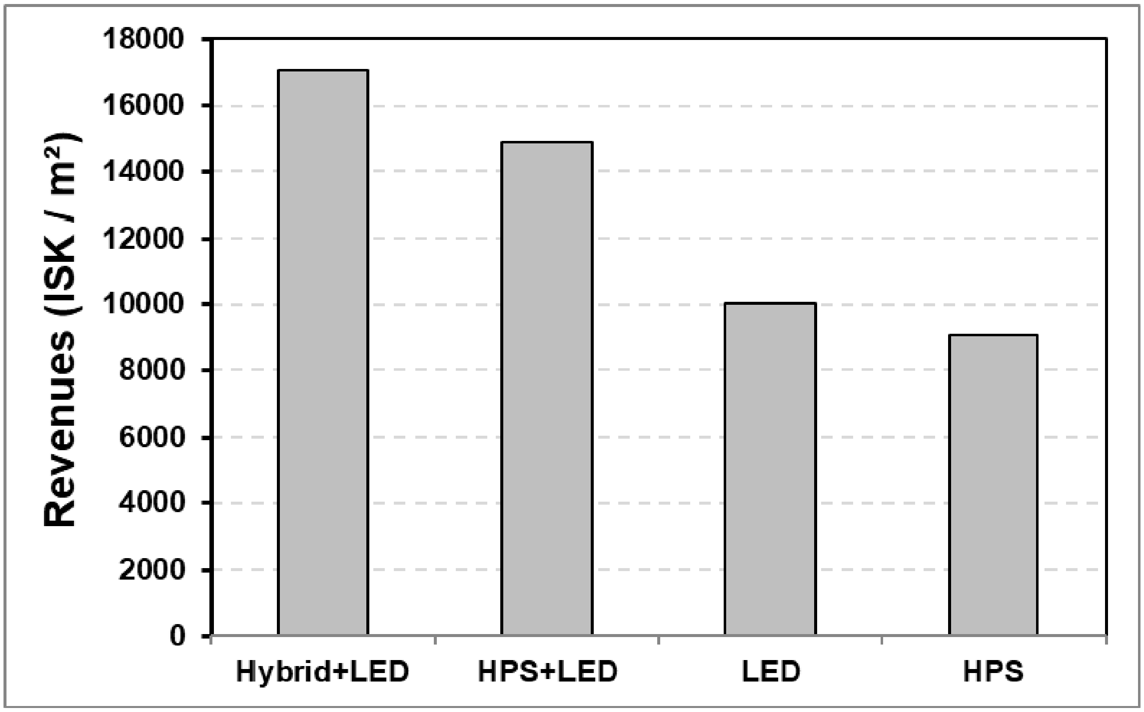

Fig. 36: Revenues at different treatments.

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 (≈ 300 ISK/m^2), costs for gutters (≈ 100 ISK/m^2), and watering system (≈ 350 ISK/m^2), costs for plant nutrition (≈ 400 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 (≈ 400 ISK/m^2), the rent of the green box (≈ 150 ISK/m^2), material for packing (≈ 700 ISK/m^2), packing costs with the machine from SfG (≈ 300 ISK/m^2) and transport costs from SfG (≈ 200 ISK/m^2) (Fig. 37).

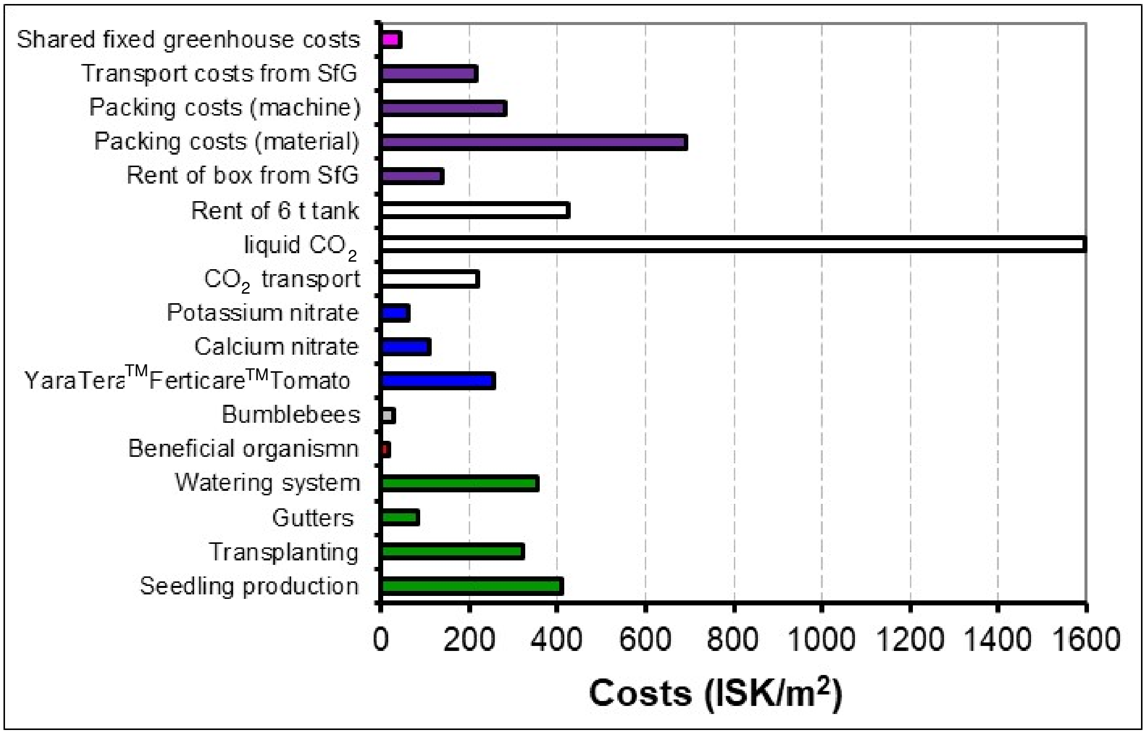

Fig. 37: Variable and fixed costs (without lighting and labour costs).

However, in Fig. 37 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. 38 and it is obvious, that especially the electricity and the investment in lamps and bulbs as well as the 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 and CO_2 costs. The proportion of the variable and fixed costs is mainly the same for treatments that have HPS top lights. However with a higher light level (Hybrid+LED, HPS+LED) increased naturally the proportion of the costs for electricity and investment into lamps and bulbs from 42 % (HPS) to 44 % (HPS+LED), respectively to 48 % (Hybrid+LED), meaning that with a high light level was nearly half of the variable and fixed costs in the category lights (electricity + investment into lamps and bulbs). The proportion of electricity could be reduced by 13 % when instead of HPS lights (31 %), LED lights (18 %) were used. In contrast, then the proportion of investment into lamps and bulbs increased by 14 % with LED lights (HPS: 11 %, LED: 25 %). Therefore, the proportion in the category “lights” (“electricity” and “investment into lamps and bulbs”) on total costs was not different between “HPS” and “LED”.

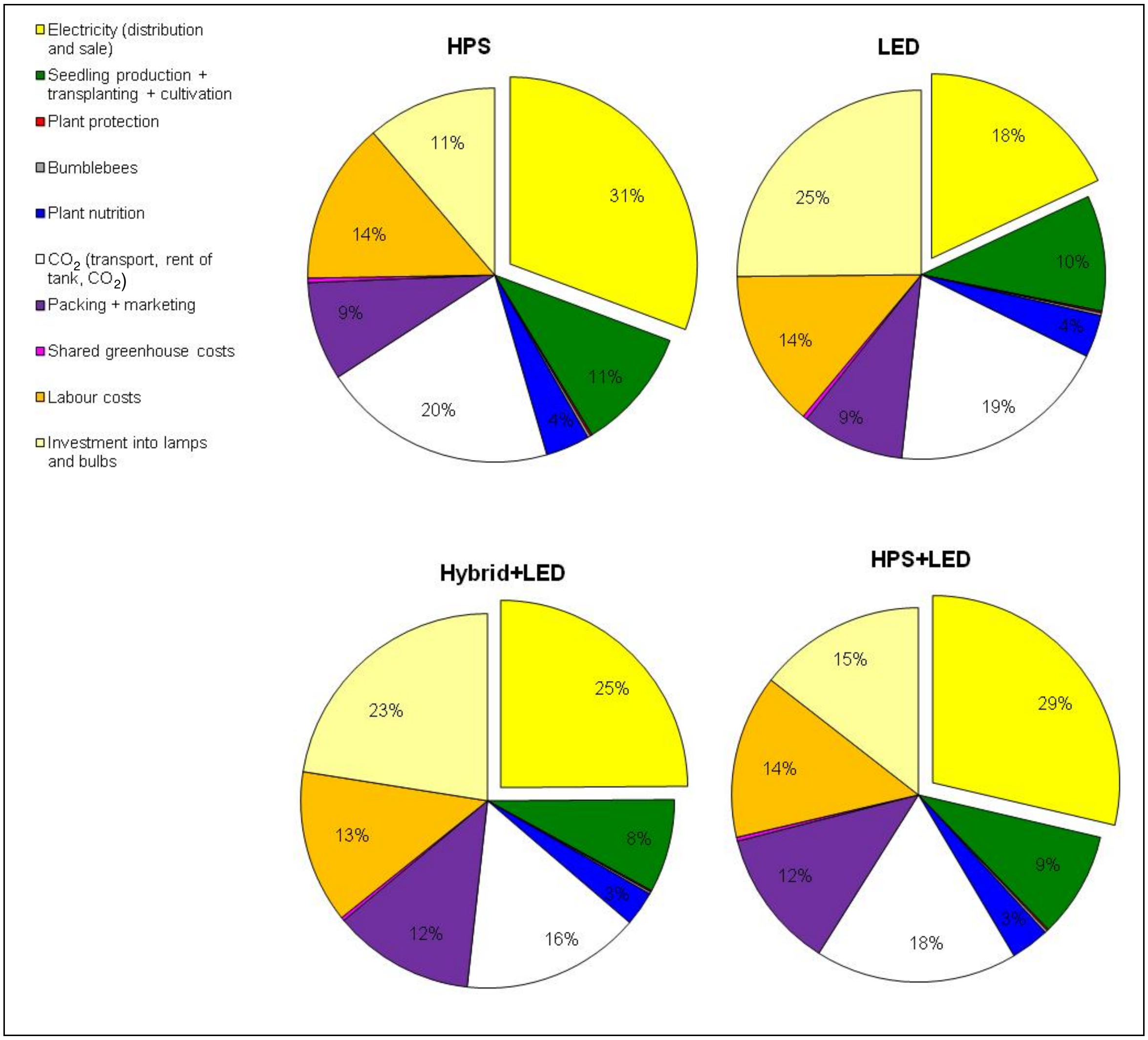

Fig. 38: Division of variable and fixed costs.

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

Tab. 10: Profit margin of tomatoes at different treatments (urban area, VA210).

Treatment	Hybrid+LED	HPS+LED	LED	HPS
Marketable yield (kg/m²)	25,2	22,0	14,8	13,4
Sales				
SfG (ISK/kg) [1]	547	547	547	547
Government (ISK/kg) [2]	130	130	130	130
Revenues (ISK/m²)	**17.060**	**14.894**	**10.020**	**9.072**
Variable and fixed costs (ISK/m²)				
Electricity distribution [3]	386	393	223	363
Electricity sale	3.221	3.279	1.861	3.027
Seeds [4]	277	277	277	277
Grodan small [5]	13	13	13	13
Grodan big [6]	121	121	121	121
Pumice [7]	225	225	225	225
Pots [8]	20	20	20	20
Strings [9]	78	78	78	78
Gutters [10]	85	85	85	85
Watering system	353	353	353	353
Beneficial organismn [11]	19	19	19	19
Bumblebees [12]	28	28	28	28
YaraTera™Ferticare™ Tomato	259	256	258	252
Potassium nitrate [14]	62	61	61	60
Calcium nitrate [15]	111	109	110	107
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]	426	426	426	426
Rent of box from SfG [19]	184	160	108	98
Packing material [20]	923	806	542	491
Packing (labour + machine) [21]	378	330	222	201
Transport from SfG [22]	287	251	169	153
Shared fixed costs [23]	43	43	43	43
Lamps [24]	3.032	1.456	2.906	842
Bulbs [25]	229	401		401
∑ variable costs	**12.576**	**11.006**	**9.964**	**9.499**
Revenues -∑ variable costs	**4.484**	**3.888**	**56**	**-428**
Working hours (h/m²)	1,02	0,97	0,85	0,82
Salary (ISK/h)	1.878	1.878	1.878	1.878
Labour costs (ISK/m²)	1.916	1.815	1.590	1.546
Profit margin (ISK/m²)	**2.568**	**2.072**	**-1.534**	**-1.974**

1 price winter 2019/2020: 547 ISK/kg

2 price for 2019: 130 ISK/kg

3 assumption: urban area, tariff "VA210", no annual fee (according to datalogger values)

4 89.430 ISK / 1.000 Completo seeds

5 36x36x40mm, 1.100 ISK / 220 Grodan small

[6] 27/35, 39 ISK / 1 Grodan big
[7] 20.000 ISK/m^3
[8] 335 ISK / pot; assumption: 10 years life time, 1,33 circles / year
[9] 25 ISK / string
[10] 4.388 ISK / m gutter; assumption: 10 years life time, 1,33 circles / year
[11] 2.776 ISK / unit parasitic wasps (*Encarsia formosa*), twice
[12] 5.684 ISK / unit bumble bees
[13] 6.400 ISK / 25 kg YaraTera™ Ferticare™ Tomato
[14] 4.450 ISK / 25 kg Potassium nitrate
[15] 2.250 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: 77.400 ISK/mon, assumption: rent in relation to 1.000 m^2 lightened area
[19] 94 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): 15 ISK / kg
[22] transport costs from SfG: 9,2 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 -2.200 to 2.600 ISK/m^2 (Fig. 39). The light source had an influence on profit margin: The profit margin was lower under “HPS” (-1.900 to -2.200 ISK/m^2) than under “LED” (-1.500 to -1.700 ISK/m^2). That means LED top lighting increased the profit margin by more than 400 ISK/m^2. However, when LED interlighting was added to HPS top lighting, increased profit margin by 4.000 ISK/m^2 and reached 1.800-2.100 ISK/m^2. An even 500 ISK/m^2 higher profit margin (2.300-2.600 ISK/m^2) could be reached when part of the HPS top lights was replaced by LED top lights. However, it has to be taken into account that the profit margin depends much on the actual price of the LEDs. A larger use (higher tariff: “VA 410” compared to “VA 210”, “VA 430” compared to “VA 230”), did nearly not influence the profit margin, however there was a small advantage of a higher tariff in rural areas. It did not matter if the greenhouse is situated in an urban or rural area, the profit margin was comparable. However, at the lower tariff there was a surprisingly small advantage of urban areas due to the state subsidies (Fig. 39).

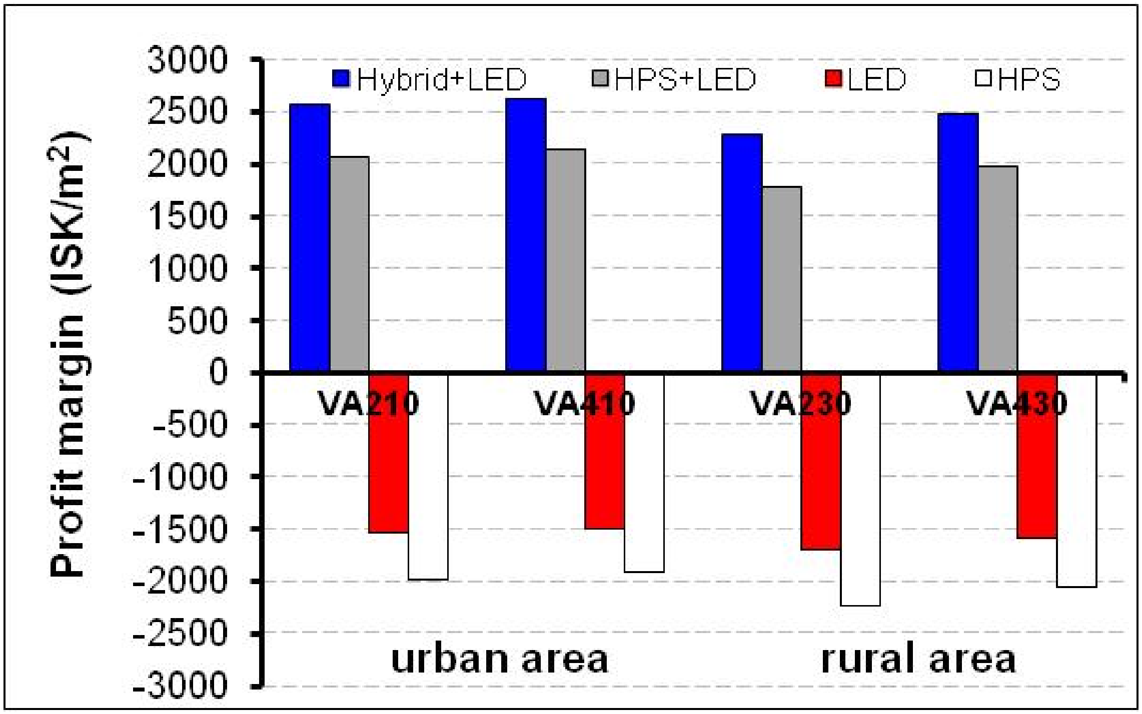

Fig. 39: Profit margin in relation to tariff and treatment.

5 DISCUSSION

In winter production, the success of vegetable growing strongly depends on supplemental lighting. In this experiment, the effect of two light sources for top lighting and the effect of LED interlighting and a higher light level was tested on tomatoes.

5.1 Yield in dependence of the light source

When tomatoes were lighted either with HPS or LED top lights, the development and the marketable yield of tomatoes, the number of first and second class fruits and the average fruit size was independent of the light source. In contrast, 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.

The higher soil temperature in the LED top lighting treatment, due to the higher floor temperature and the higher CO_2 amount before harvest, might have positive influenced development and yield, even though the yield was not significant different from the HPS top lighting treatment. However, 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 very 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.

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 throught 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.

While light quality did not affect yield, it had an influence on the appearance of the plant. 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 significanty tallest plants compared to LED top lighting. Also, *Trouwborst* et al. (2010) measured a lower plant length of cucumbers under LEDs.

With LED lighting are 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.

Tomatoes seems to have a higher DS under HPS than under LED lights. This was also observed with strawberries (*Stadler*, 2019), but the light source did not affect juiciness. Tomatoes under HPS, were rated sweeter, however no differences in the BRIX content were measured. Indeed, *Stadler* (2019) reported the same for strawberries. *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 presented results show that LED top lighting resulted in energy savings 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.

The use of LEDs resulted in a more than 400 ISK/m^2 higher profit margin than the use of HPS lights (Fig. 40). The yield was increased by 1,4 kg/m^2. When the yield of the HPS treatment would have been nearly 1 kg/m^2 higher, would the profit margin have been comparable to the one of the LED treatment. 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: In the case of HPS lights by more than 3,5 kg/m^2 and in the case of LEDs by nearly 3,0 kg/m^2.

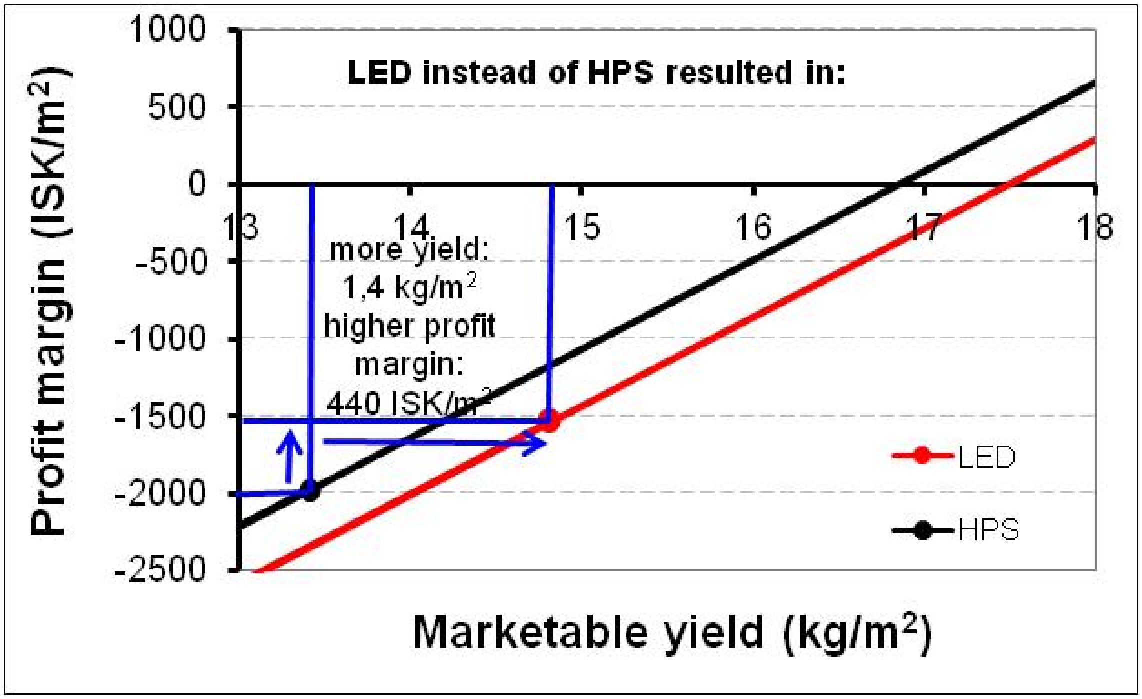

Fig. 40: Profit margin in relation to yield with different light sources for top lighting – calculation scenarios (urban area, VA210).

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.

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 LED interlighting and the light source for top lighting

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).

A higher light intensity by using LED interlighting in addition to top lighting is associated with higher expenses for the electricity. Thus, it is necessary that the higher use of electricity is paying off by obtaining a higher yield. It was possible to enhance tomato productivity significantly at a higher light level: Adding LED interlighting to HPS top lighting increased productivity, yield was increased by 8,6 kg/m^2 and profit margin by more than 4.000 ISK/m^2 (Fig. 41). Therefore, LED interlighting can be recommended. The yield increase corresponded to 65 % yield increase due to an increase of 46 % in the amount of marketable fruits (1. class fruits) and an increase of 12 % in the amount of the average weight of marketable fruits, while number of clusters and fruits per cluster was not affected. This resulted in about 70 % of marketable fruits at the higher light level with LED interlighting compared to only 55 % at the lower light level with either LED or HPS top lighting and no LED interlighting due to an increased proportion of 1. class fruits and a significantly lower proportion of too little frutis. Also, *Paponov* et al. (2020) mentioned that supplemental LED interlighting increased tomato yield by 21 %. However, in contrast to the presented experiment was this attributed to an increase in the mean weight of the fruits (8,5 %) and a larger number of clusters (9,9 %), while the fruit number per cluster changed only slightly. The authors assumed that a higher root pressure contributes to the utimately higher fruit weight of fruits with LED interlighting. Also, *Moerkens* et al. (2016) reported, that HPS top lighting together with LED interlighting resulted in a 20 % higher yield for two tomato cultivars compared with HPS top lighting only.

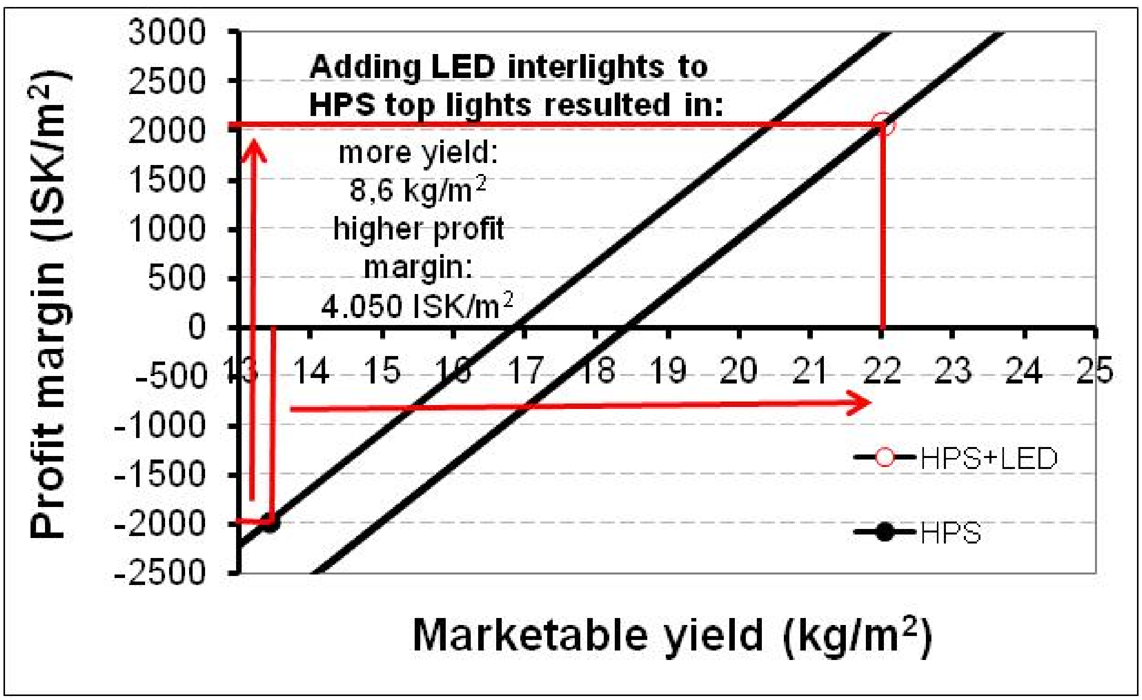

Fig. 41: Profit margin in relation to yield with HPS top lighting with(out) LED interlighting – calculation scenarios (urban area, VA210).

Among that was it possible to increase the yield by further 3,2 kg/m^2 and the profit margin by 500 ISK/m^2 by replacing part of the HPS top lights by LED top lights (Fig. 42). Therefore, also Hybrid top lighting can be recommended. The higher yield at Hybrid lighting was attributed to a higher amount of fruits which was caused among others by an earlier start of the harvest.

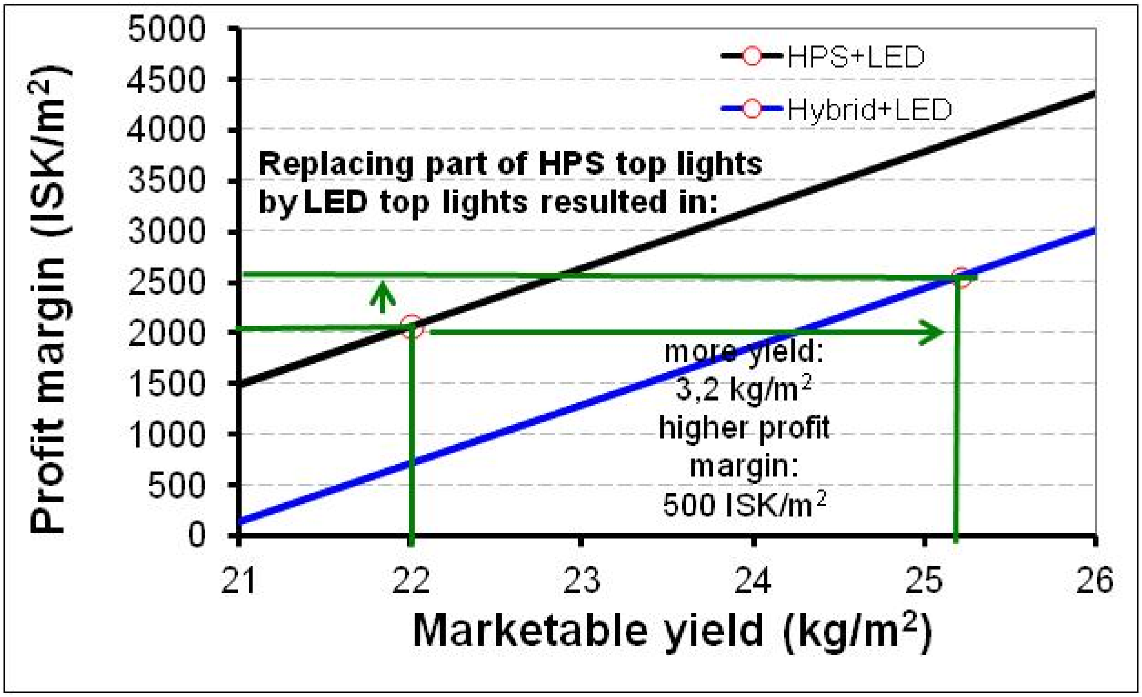

Fig. 42: Profit margin in relation to yield with LED interplanting and different light sources for top lighting – calculation scenarios (urban area, VA210).

Marcelis et al. (2006) reported that generally, it can be said that 1 % increase of light intensity is resulting in a yield increase of 0.7-1.0 % for fruit vegetables. These values are in accordance with the present findings: A 1 % increase of µmol/m^2/s (compare HPS with HPS+LED) resulted in a yield increase of 1 %. In earlier experiments, where the light intensity (W/m^2) of HPS top lights was increased, were values of 0.7 % reported (*Stadler*, 2013b). Therefore, it can be concluded that the higher value with LED interlighting (1 %) compared to the only use of HPS top lights (0.7 %) appears to be caused by an even better transformation of light into yield, presuming that µmol/m^2/s would have shown same values as W/m^2 at different light intensities with HPS top lights. Again, the assumed better transformation of light into yield with LED lights might be confirmed by an even higher yield when part of the HPS top lights was replaced by LED top lights (compare HPS+LED with Hybrid+LED), as µmol/m^2/s was quite similar between these two treatments.

In previous experiments, where the effect of a higher light intensity was tested without interlighting, the reason for the higher yield at the higher light intensity was mainly an increased number of sweet pepper (*Stadler*, 2010) and tomatoes (*Stadler*, 2013a; *Stadler* 2013b). However, in the literature there are also other explanations for a higher yield. For example, pulled *Lorenzo* & *Castilla* (1995) in their conclusion a higher LAI together with a higher yield; i.e. higher values of LAI in the high density treatment lead to an improved radiation interception and, subsequently, to higher biomass and yield of sweet pepper than in the low density treatment. Also, *Hidaka* et al. (2013) concluded that accelerated photosynthesis promoted plant growth of strawberries, as manifested by increases in leaf weight and LAI, leading to increased fruits weight, number of fruits and marketable yield. The LAI was not observed in the presented experiment, but the number of leaves was counted and the leaf length measured and both were independent of the light treatment. However, more factors than only light might have influenced yield: The temperature was in average 0,5°C lower in "Hybrid+LED" compared to "HPS+LED". In addition, the LED top lights in the Hybrid+LED treatment were not turned on during the first 2,5 weeks. These factors might have influenced yield, but the influence of each factor is unknown. With same temperature between the interlighting treatments and no delay in the LED top lights might even have been a higher yield in the treatment "Hybrid+LED" possible.

Regarding taste and BRIX content were no differences between the interlighting treatments found. 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). 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).

Even though, used energy increased by 8 % by adding interlighting to HPS top lighting, was the energy use efficiency higher with interlighting. Adding LED interlighting to HPS top lighting decreased electricity per yield by nearly 35 % compared to only top lighting and a further increase by 15 % was possibe by replacing part of the HPS top lights by LED top lights (Hybrid+LED). Also, *Hao* et al. (2014) reported that LED interlighting of cucumber increased light use efficiency, mainly by increasing light reaching the inter canopy, compared with HPS top lights. 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.

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. Also, *Dueck* et al. (2012a) suggested that a combination of HPS and LEDs as top lighting is the most promising alternative for greenhouse grown tomatoes in the Netherlands when taking into consideration different production parameters and costs for lighting and heating. Also, *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.

5.3 Future speculations concerning energy prices

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 between 64,8-87,0 % in urban areas and 69,2 and 92,0 % in rural areas in the years 2017-2020. 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 when HPS lights were used.

The white columns are representing the profit margin according to Fig. 30. 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 -4.100 to 300 ISK/m^2 (black columns, Fig. 43). Without the subsidy of the state, probably less Icelandic grower 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 -2.800 to 1.700 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 -1.100 to 3.500 ISK/m^2 (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. Referring to the constant fluctuation of the subsidy between the years 2017 to 2020, it is obvious that actions must be taken, that growers are also producing during the winter at low solar irradiation. It is also showing clearly, that it is only paying of to produce strawberries during the winter in Iceland, when a high yield is guarantied and this is only possible when a high light level is applied to tomatoes that is consequently causing high expenses of energy.

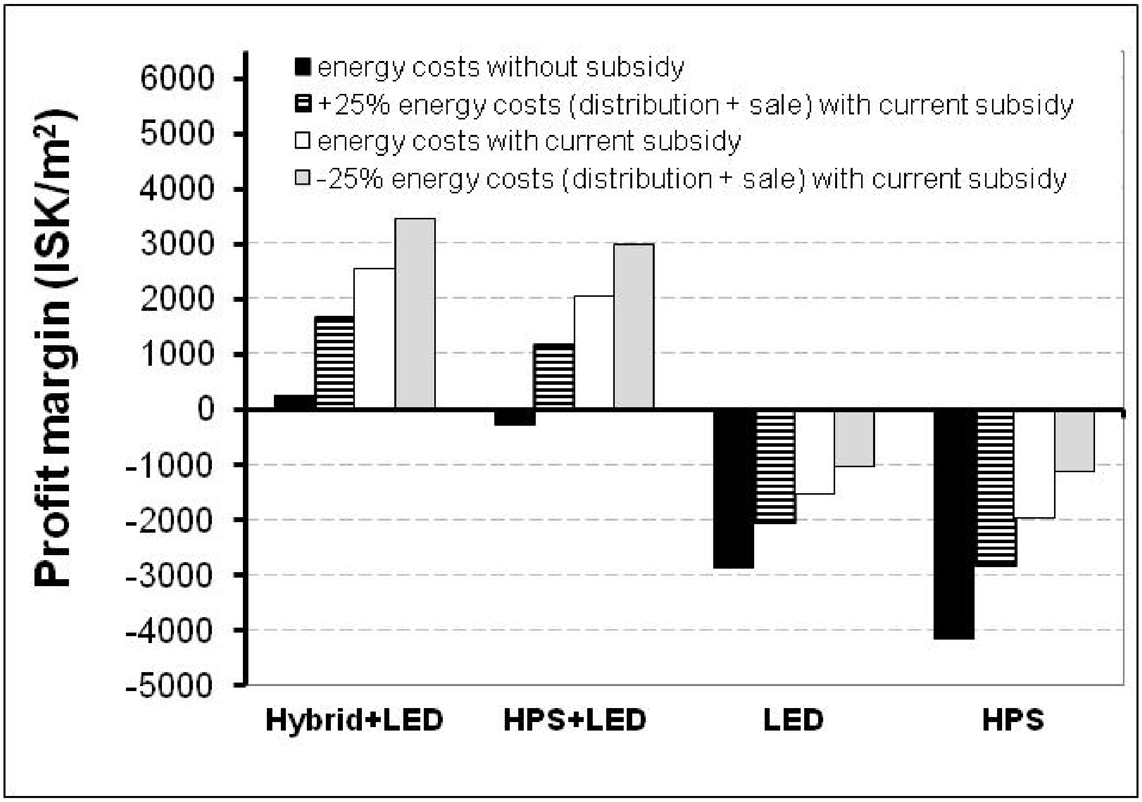

Fig. 43: Profit margin in relation to treatment – calculation scenarios (urban area, VA210).

Also, the use of LEDs are showing the possibility to increase profit margin compared to HPS lights in case subsidy would be lowered or energy costs increased. This is getting especially important as the reduction of the subsidy fluctuated much in the past years. Due to a lower use of electricity by the LED lights would a reduction of the subsidy became less appearent than with the use of HPS lights. However, the tested light level with HPS or LED top lighting was to low for getting a high yield and therefore, a positive profit margin.

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 side, 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*, 2013a). 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 light is 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.
- The use of LED lights instead of HPS lights can reduce electricity consumtion by more than 40 %. 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 and the tomato yield was not influenced by the light source for top lighting. The reduction of the lighting costs per yield by 45 % with the use of LEDs instead of HPS lights was accompanied by a high increase of the investion costs. However, at a low light level was the yield very low and a negative profit margin was calculated. Therefore, growing tomatoes at a low light level can not be recommended. The tomato yield was positively influenced by a higher light level by adding LED interlighting to top lighting and can therefore be advised. Further experiments must show which ratio of LED to HPS lights is recommended and how yield can be optimized with an appropriate ratio of top lighting to interlighting.

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

7 REFERENCES

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

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

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

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

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

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

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

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

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

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

DZAKOVICH MP, GOMEZ C, MITCHELL CA, 2015: Tomatoes grown with light-emitting diodes or high-pressure sodium supplemental light have similar fruit-quality attributes. HortScience, 50 (10), 1498-1502.

EGGERTSSON H, 2009: Personal communication (Notice in writing) from Haukur Eggertsson, Orkustofnun, October 2009.

GÓMEZ C, MITCHELL CA, 2016: Physiological and productivity responses of high-wire tomato as affected by supplemental light source and distribution within the canopy. JASHS 141: 196-208.

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

GRODZINSKI B, SCHMIDT JM, WATTS B, TAYLOR J, BATES S, DIXON MA, STAINES H, 1999: Regulating plant/insect interactions using CO2 enrichment in model ecosystems. Adv. Space Res. 24, 281-291.

GUO X, HAO X, KHOSLA S, KUMAR KGS, CAO R, BENNETT N, 2016: Effect of LED interlighting combined with overhead HPS light on fruits yield and quality of year-round sweet pepper in commercial greenhouse. Acta Hortic 1134: 71-78.

HANENBERG MAA, JANSE J, VERKERKE W, 2016: LED light to improve strawberry flavour, quality and production. Acta Hortic. 1137, 207-212.

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

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

HEUVELINK E, BAKKER MJ, ELINGS A, KAARSEMAKER R, MARCELIS LFM, 2005: Effect of leaf area on tomato yield. Acta Hort. 691, 43-50.

HIDAKA K, DAN K, IMAMURA H, MIYOSHI Y, TAKAYAMA T, SAMESHIMA K, KITANO M, OKIMURA M, 2013: Effect of supplemental lighting from different light sources on growth and yield of strawberry. Environ. Control Biol. 51, 41-47.

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

HOVI-PEKKANEN T, TAHVONEN R, 2008: Effects of interlighting on yield and external fruit quality in year-round cultivated cucumber. Sci. Hortic. 116, 152-161.

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

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

LORENZO P, CASTILLA N, 1995: Bell pepper response to plant density and radiation in unheated plastic greenhouse. Acta Hort. 412, 330-334.

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

MOERKENS R, VANLOMMEL W, VANDERBRUGGEN R, VAN DELM T, 2016: The added value of LED assimilation light in combination with high pressure sodium lamps in protected tomato crops in Belgium. Acta Hortic. 1134. DOI 10.17660/ActaHortic.2016.1134.16.

PAPONOV M, KECHASOV D, LACEK J, VERHEUL MJ, PAPONOV IA, 2020: Supplemental light-emitting diode inter-lighting increases tomato fruit growth through enhanced photosynthetic light use efficiency and modulated root activity. Frontiers in Plant Science 10: 1656. Doi: 10.3389/fpls.2019.01656.

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

PHILIPS, 2017: Higher yields of better quality tomatoes. http://images.philips.com/is/content/Philips Consumer/PDFDownloads/Global/ Case-studies/CSLI20170119_001-UPD-en_AA-PHIL_164209_CaseStudy_ MartinSigg.pdf visited: 01.02.2017.

PHILIPS, 2018: Strawberries ahead of the rest. http://www.lighting.philips.com/main/cases/cases/horticulture/welroy-fruit. visited: 11.09.2018.

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

RODRIGUEZ BP, LAMBETH VN, 1975: Artificial lighting and spacing as photosynthetic and yield factors in winter greenhouse tomato culture. J. Amer. Soc. Hort. Sci. 100, 694-697.

SÄRKKA L, JOKINEN K, OTTOSEN CO, KAUKORANTA T, 2017: Effects of HPS and LED lighting on cucumber leaf photosynthesis light quality penetration and temperature in the canopy, plant morphology and yield. Agricultural and Food Science 26, 102-110.

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

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

STADLER C, 2010: Effects of plant density, interlighting, light intensity and light quality on growth, yield and quality of greenhouse sweet pepper. Final report, Rit LbhÍ nr. 30.

STADLER C, 2012: Effects of lighting time and light intensity on growth, yield and quality of greenhouse tomato. Final report, Rit LbhÍ nr. 40.

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

STADLER C, 2013b: Áhrif ljósstyrks, ágræðslu og umhverfis á vöxt, uppskeru og gæði gróðurhúsatómata. Final report, Rit LbhÍ nr. 45.

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

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

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

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

STADLER C, HRAFNKELSSON BH BI, 2019: Vinnuskilyrði undir LED-ljósum. Bændablaðið 532, 41.

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

TEWOLDE FT, SHIINA K, MARUO T, TAKAGAKI M, KOZAI T, YAMORI W, 2018: Supplemental LED inter-lighting compensated for a shortage of light for plant growth and yield under the lack of sunshine. PLoS ONE 13(11): e0206592. DOI: 10.1371/journal.pone.0206592.

TROUWBORST G, OOSTERKAMP J, HOGEWONING SW, HARBINSON J, VAN IEPEREN W, 2010: The responses of light interception, photosynthesis and fruit yield of cucumber to LED-lighting within the canopy. Physiol. Plant 138, 289-300.

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

YEAGER TH, GILLIAM CH, BILDERBACK TE, FARE DC, NIEMIERA AX, TILT KM, 1997: Best management practices guide for producing container-grown plants. Southern Nurs. Assoc., Marietta, GA.

8 APPENDIX

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
24.9	transplanting, light from 5-17	plants were tall and therefore difficult to plant (planting was deleayed because the connection for the LED modules did not yet arrive, therefore was only the HPS top light and LED interlights turned on)	transplanting, light from 5-17	plants were tall and therefore difficult to plant	transplanting, light from 5-17	plants were tall and therefore difficult to plant	transplanting, light from 5-17	plants were tall and therefore difficult to plant
25.9	weekly measurements, LED interlights in 90 cm height		weekly measurements, LED interlights in 90 cm height		weekly measurements		weekly measurements	
26.9								
27.9								
28.9								
29.9								
30.9	pollinated by hand		pollinated by hand		pollinated by hand		pollinated by hand	
1.10	light from 5-19, En-Strip put out, 3 h between waterings (3 min)		light from 5-19, En-Strip put out, 3 h between waterings (3 min)		light from 5-19, En-Strip put out, 3 h between waterings (3 min)		light from 5-19, En-Strip put out, 3 h between waterings (3 min)	
2.10	weekly measurements, measured leaf + soil temperature heating pipe temp. increased by 5 °C	heating pipe temperature was lower despite same settings within treatments	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
3.10								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	tasks	observations	tasks	observations	tasks	observations	tasks	observations
4.10	light from 5-20		light from 5-20		light from 5-20		light from 5-20	
5.10								
6.10								
7.10	2 h between waterings (3 min)		2 h between waterings (3 min)		2 h between waterings (3 min)		2 h between waterings (3 min)	
8.10	hive set in and opend for 2 h		hive set in and opend for 2 h		hive set in and opend for 2 h		hive set in and opend for 2 h	
9.10	light from 5-21, weekly measure-ments, measured leaf + soil tempe-rature, 1 h be-tween waterings (2 min)	heating pipe temperature was higher compared to the other chambers	light from 5-21, weekly measure-ments, measured leaf + soil tempe-rature,1 h be-tween waterings (2 min)		light from 5-21, weekly measure-ments, measured leaf + soil tempe-rature, 1 h be-tween waterings (2 min)		light from 5-21, weekly measure-ments, measured leaf + soil tem-perature, 1 h be-tween waterings (2 min)	
10.10	connection for LEDs came + was set up, heating pipe temp. de-creased by 5 °C							
11.10	LED interlighting was turned on							
12.10								
13.10								
14.10								
15.10								
16.10	weekly measure-ments, measured leaf + soil tempe-rature, hive open for 30 min		weekly measure-ments, measured leaf + soil tempe-rature, hive open for 30 min		weekly measure-ments, measured leaf + soil tempe-rature, hive open for 30 min		weekly measure-ments, measured leaf + soil tempe-rature, hive open for 30 min	
17.10	removed the 3. leaf below the highest cluster, hive open for 1 h		removed the 3. leaf below the highest cluster, hive open for 1 h		removed the 3. leaf below the highest cluster, hive open for 1 h		removed the 3. leaf below the highest cluster, hive open for 1 h	
18.10								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
19.10								
20.10								
21.10								
22.10	pruning clusters		pruning clusters		pruning clusters		pruning clusters	
23.10	weekly measurements, measured leaf + soil temperature	shoots growing from the receptacle at cluster 1	weekly measurements, measured leaf + soil temperature	shoots growing from the receptacle at cluster 1, CO_2 is too low	weekly measurements, measured leaf + soil temperature	shoots growing from the receptacle at cluster 1	weekly measurements, measured leaf + soil temperature	shoots growing from the receptacle at cluster 1
24.10	deleafed 2 leaves from the bottom, 0,5 h between waterings (2 min)	much pollination	deleafed 2 leaves from the bottom, 0,5 h between waterings (2 min)	much pollination, CO_2 repaired	deleafed 2 leaves from the bottom, 0,5 h between waterings (2 min)	much pollination	deleafed 2 leaves from the bottom, 0,5 h between waterings (2 min)	much pollination
25.10	removed the 3. leaf below the highest cluster, 50 min between waterings (2 min), day / night temperature (20 / 17°C)		removed the 3. leaf below the highest cluster, 50 min between waterings (2 min), day / night temperature (20 / 17°C)		removed the 3. leaf below the highest cluster, 50 min between waterings (2 min), day / night temperature (20 / 17°C)		removed the 3. leaf below the highest cluster, 50 min between waterings (2 min), day / night temperature (20 / 17°C)	
26.10								
27.10								
28.10								
29.10	pruning clusters		pruning clusters		pruning clusters		pruning clusters	
30.10	weekly measurements, measured leaf + soil temperature, height LED interlighting is good	little development since last week, 15 leaves on plant (waiting with deleaving til next week)	weekly measurements, measured leaf + soil temperature, height LED interlighting is good	little development since last week, 15 leaves on plant (waiting with deleaving til next week)	weekly measurements, measured leaf + soil temperature	little development since last week, 15 leaves on plant (waiting with deleaving til next week)	weekly measurements, measured leaf + soil temperature	little development since last week, 15 leaves on plant (waiting with deleaving til next week)
31.10	removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster	
1.11								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
2.11								
3.11								
4.11								
5.11	deleafed 2 leaves from the bottom, pruning clusters		deleafed 2 leaves from the bottom, pruning clusters		deleafed 2 leaves from the bottom, pruning clusters		deleafed 2 leaves from the bottom, pruning clusters	
6.11	hive open for 3 h, weekly measurement, measured leaf + soil temperature, height interlighting is good	extra flowers and leaves were growing from the receptacle at cluster 1 and 2	hive open for 3 h, weekly measurement, measured leaf + soil temperature, height interlighting is good	extra flowers and leaves were growing from the receptacle at cluster 1 and 2	hive open for 3 h, weekly measurement, measured leaf + soil temperature	extra flowers and leaves were growing from the receptacle at cluster 1 and 2	hive open for 3 h, weekly measurement, measured leaf + soil temperature	little additonal growth at cluster 1 and no additional growth at cluster 2
7.11	removed the 3. leaf below the highest cluster, 0,5 h between waterings (2 min)		removed the 3. leaf below the highest cluster, 0,5 h between waterings (2 min)		removed the 3. leaf below the highest cluster, 0,5 h between waterings (2 min)		removed the 3. leaf below the highest cluster, 0,5 h between waterings (2 min)	
8.11								
9.11								
10.11								
11.11								
12.11	deleafed 2 leaves from the bottom, 40 min between waterings (2 min)		deleafed 2 leaves from the bottom, 40 min between waterings (2 min)		deleafed 2 leaves from the bottom, 40 min between waterings (2 min)		deleafed 2 leaves from the bottom, 40 min between waterings (2 min)	
13.11	weekly measurements, measured leaf + soil temperature, height LED interlighting increased to 1,15 m		weekly measurements, measured leaf + soil tempa-rature, height LED interlighting increased to 1,15 m		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
14.11	pruning clusters, removed the 3. leaf below the highest cluster		pruning clusters, removed the 3. leaf below the highest cluster		pruning clusters, removed the 3. leaf below the highest cluster		pruning clusters, removed the 3. leaf below the highest cluster	

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
15.11								
16.11								
17.11								
18.11	0,5 h between waterings (2 min)		0,5 h between waterings (2 min)		0,5 h between waterings (2 min)		0,5 h between waterings (2 min)	
19.11	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
20.11	weekly measure-ments, measured leaf + soil tempe-rature, 40 min between water-ings (2 min), LED interlighting in-creased to 1,45 m	fruits on the 2.+3. cluster looking same size as fruits on 1. cluster	weekly measure-ments, measured leaf + soil tempe-rature, 40 min between water-ings (2 min), LED interlighting in-creased to 1,45 m	fruits on the 2.+3. cluster looking same size as fruits on 1. klasa	weekly measure-ments, measured leaf + soil tempe-rature, 40 min between waterings (2 min)		weekly measure-ments, measured leaf + soil tempe-rature, 40 min between waterings (2 min)	
21.11	removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster	
22.11								
23.11	40 min between waterings (2 min)		40 min between waterings (2 min)		50 min between waterings (2 min)		50 min between waterings (2 min)	
24.11								
25.11	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
26.11								
27.11	weekly measure-ments, measured leaf + soil tempe-rature, height in-terlighting is good	biggest fruits compared to the other treatments	weekly measure-ments, measured leaf + soil tempe-rature, height in-terlighting is good		weekly measure-ments, measured leaf + soil tempe-rature		weekly measure-ments, measured leaf + soil tempe-rature	smalles fruits compared to the other treatments
28.11	removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster	
29.11	underheat increased to 45°C		underheat increased to 45°C		underheat increased to 55°C		underheat increased to 45°C	

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
30.11								
1.12								
2.12	deleafed 2 leaves from the bottom, 30 min between waterings (2 min)		deleafed 2 leaves from the bottom, 30 min between waterings (2 min)		deleafed 2 leaves from the bottom, 30 min between waterings (2 min)		deleafed 2 leaves from the bottom, 30 min between waterings (2 min)	
3.12								
4.12	weekly measure-ments, measured leaf + soil tempe-rature, harvest, new hive, removed the 3. leaf below the highest cluster, 40 min between waterings (2 min), height interlighting is good		weekly measure-ments, measured leaf + soil tempe-rature, harvest, new hive, remo-ved the 3. leaf below the highest cluster, 40 min between waterings (2 min), height interlighting is good		weekly measure-ments, measured leaf + soil tempe-rature, harvest, new hive, removed the 3. leaf below the highest cluster, 40 min between waterings (2 min)		weekly measure-ments, measured leaf + soil tempe-rature, harvest, new hive, removed the 3. leaf below the highest cluster, 40 min between waterings (2 min)	
5.12		too high pH (ammonium free fertilizer used)		too high pH (ammonium free fertilizer used)		too high pH (ammonium free fertilizer used)		too high pH (ammonium free fertilizer used)
6.12								
7.12								
8.12								
9.12	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	
10.12								
11.12	35 min between waterings (2 min)		35 min between waterings (2 min)		35 min between waterings (2 min)		35 min between waterings (2 min)	

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
12.12	harvest, weekly measurements, measured leaf + soil temperature, removed the 3. leaf below the highest cluster, height interlighting is good		harvest, weekly measurements, measured leaf + soil temperature, removed the 3. leaf below the highest cluster, height interlighting is good		harvest, weekly measurements, measured leaf + soil temperature, removed the 3. leaf below the highest cluster		harvest, weekly measurements, measured leaf + soil temperature, removed the 3. leaf below the highest cluster	
13.12								
14.12								
15.12								
16.12	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	
17.12								
18.12								
19.12	harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, vikulegar mælingar (B, C), measuring leaf + soil temperature		harvest, vikulegar mælingar (B, C), measuring leaf + soil temperature	
20.12								
21.12								
22.12								
23.12	harvest		harvest		harvest		harvest	
24.12								
25.12	new hive		new hive		new hive		new hive	
26.12								
27.12	harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom	
28.12								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
29.12								
30.12	harvest, BRIX measurements, pollinated by hand, hive open for 3,5 h		harvest, BRIX measurements, pollinated by hand, hive open for 3,5 h		harvest, BRIX measurements, pollinated by hand, hive open for 3,5 h		harvest, BRIX measurements, pollinated by hand, hive open for 3,5 h	
31.12								
1.1								
2.1	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	
3.1	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
4.1								
5.1								
6.1	harvest		harvest		harvest		harvest	
7.1								
8.1	harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom	
9.1								
10.1								
11.1								
12.1								
13.1	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	
14.1								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	tasks	observations	tasks	observations	tasks	observations	tasks	observations
15.1	harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out		harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out		harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out		harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out	
16.1								
17.1								
18.1								
19.1								
20.1	harvest, hive open for 1,5 h		harvest, hive open for 1,5 h		harvest, hive open for 1,5 h		harvest, hive open for 1,5 h	
21.1	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
22.1	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	
23.1	removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster	
24.1								
25.1								
26.1								
27.1	harvest, BRIX measurements, deleafed 2 leaves from the bottom		harvest, BRIX measurements, deleafed 2 leaves from the bottom		harvest, BRIX measurements, deleafed 2 leaves from the bottom		harvest, BRIX measurements, deleafed 2 leaves from the bottom	
28.1	removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster		removed the 3. leaf below the highest cluster	
29.1	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	
30.1								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	tasks	observations	tasks	observations	tasks	observations	tasks	observations
31.1								
1.2	CO_2 empty		CO_2 empty		CO_2 empty		CO_2 empty	
2.2								
3.2	harvest, deleafed 3 leaves from the bottom		harvest, deleafed 3 leaves from the bottom		harvest, deleafed 3 leaves from the bottom		harvest, deleafed 3 leaves from the bottom	
4.2								
5.2	harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature	small amount of white flies has been seen
6.2	CO_2 filled		CO_2 filled		CO_2 filled		CO_2 filled	
7.2								
8.2								
9.2								
10.2	harvest		harvest		harvest		harvest	
11.2	harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out		harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out		harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out		harvest, weekly measurements, measured leaf + soil temperature, En-Strip put out	
12.2								
13.2								
14.2								
15.2								
16.2								
17.2	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	
18.2								
19.2	harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature	
20.2								

	Hybrid+LED		HPS+LED		LED		HPS	
Date	tasks	observations	tasks	observations	tasks	observations	tasks	observations
21.2								
22.2								
23.2								
24.2	harvest, BRIX measurements, deleafed 2 leaves from the bottom		harvest, BRIX measurements, deleafed 2 leaves from the bottom		harvest, BRIX measurements, deleafed 2 leaves from the bottom		harvest, BRIX measurements, deleafed 2 leaves from the bottom	
25.2								
26.2	harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature	
27.2								
28.2								
29.2								
1.3								
2.3	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	
3.3								
4.3	harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature		harvest, weekly measurements, measuring leaf + soil temperature	
5.3								
6.3								
7.3								
8.3								
9.3	final harvest		final harvest		final harvest		final harvest	