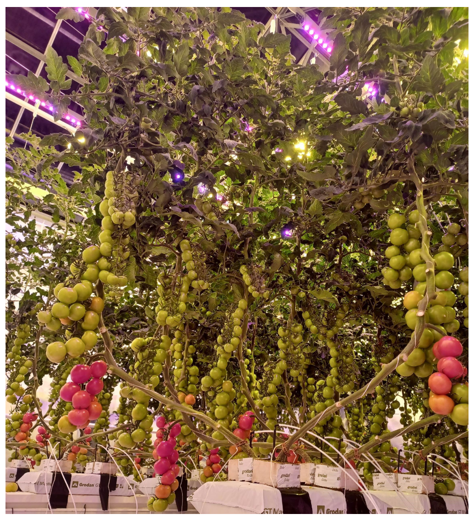
Rit LbhÍ nr. 151

„Áhrif Hybrid topplýsingar og hæð lampanna á vöxt, uppskeru og gæði gróðurhúsatómata“

FINAL REPORT

Christina Stadler



Stjórnarráð Íslands
Matvælaráðuneytið

I

Landbúnaðarháskóli Íslands
Agricultural University of Iceland

2022

Landbúnaðarháskóli Íslands, 2022.
Rit LbhÍ nr. 151
ISSN 1670-5785
ISBN 978-9935-512-25-3

Ljósmynd á forsíðu: Christina Stadler

Final report of the research project

„Áhrif Hybrid topplýsingar og hæð lampanna á vöxt, uppskeru og gæði gróðurhúsatómata“

Duration: 28/09/2021 – 27/09/2022

Project leader: Landbúnaðarháskóli 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: Matvælaráðuneytið (Þróunarsjóði garðyrkjunnar)
Skúlagötu 4
101 Reykjavík

Table of contents

Table of contents I

List of figures III

List of tables IV

Abbreviations IV

1 SUMMARY 1

YFIRLIT 3

2 INTRODUCTION 5

3 MATERIALS AND METHODS 8

3.1 Greenhouse experiment 8

3.2 Treatments 10

3.3 Measurements, sampling and analyses 12

3.4 Statistical analyses 12

4 RESULTS 13

4.1 Environmental conditions for growing 13

4.1.1 Solar irradiation 13

4.1.2 Chamber settings 14

4.1.3 Substrate temperature 14

4.1.4 Leaf temperature 15

4.1.5 Irrigation of tomatoes 16

4.2 Development of tomatoes 20

4.2.1 Plant diseases and pests 20

4.2.2 Height 20

4.2.3 Weekly growth 20

4.2.4 Number of leaves 20

4.2.5 Length of leaves 22

4.2.6 Number of clusters 22

4.2.7 Length of clusters to top 22
4.2.8 Distance between clusters 24
4.2.9 Length of clusters 24
4.2.10 Fruits per cluster 25
4.2.11 Number of open flowers 25
4.2.12 Stem diameter 27
4.2.13 Diameter of the uppermost flowering cluster 27

4.3 Yield 29

4.3.1 Total yield of fruits 29
4.3.2 Marketable yield of tomatoes 30
4.3.3 Outer quality of yield 36
4.3.4 Interior quality of yield – sugar content 37

4.4 Economics 37

4.4.1 Used energy 37
4.4.2 Energy use efficiency 38
4.4.3 Light related costs 39
4.4.4 Costs of electricity in relation to yield 40
4.4.5 Profit margin 40

5 DISCUSSION 46

5.1 Yield in dependence of the light source 46

5.2 Yield in dependence of the height of the light source 51

5.3 Future speculations concerning energy prices 54

5.4 Recommendations for increasing profit margin 55

6 CONCLUSIONS 59

7 REFERENCES 60

8 APPENDIX 65

List of figures

Fig. 1:	Experimental design of cabinets.	8
Fig. 2:	Time course of solar irradiation.	13
Fig. 3:	Substrate temperature.	15
Fig. 4:	Leaf temperature.	16
Fig. 5:	Daily applied water.	17
Fig. 6:	Average daily applied water in each month.	17
Fig. 7:	E.C. and pH of irrigation water and runoff.	18
Fig. 8:	Proportion of amount of runoff from applied irrigation water.	19
Fig. 9:	Water uptake.	19
Fig. 10:	Height of tomatoes.	20
Fig. 11:	Weekly growth.	21
Fig. 12:	Number of leaves on the tomato plant.	21
Fig. 13:	Length of leaves.	22
Fig. 14:	Number of clusters.	23
Fig. 15:	Length of uppermost flowering cluster to plant top.	23
Fig. 16:	Distance between clusters.	24
Fig. 17:	Length of clusters.	25
Fig. 18:	Number of fruits per cluster.	26
Fig. 19:	Number of unpollinated fruits per cluster.	26
Fig. 20:	Number of flowers.	27
Fig. 21:	Stem diameter and quotient lengths to top and stem diameter.	28
Fig. 22:	Diameter of the uppermost flowering cluster.	28
Fig. 23:	Cumulative total yield of tomatoes in kg.	29
Fig. 24:	Cumulative total yield of tomatoes in number.	30
Fig. 25:	Time course of marketable yield (1. and 2. class tomatoes).	31
Fig. 26:	Time course of marketable 1. class yield.	32
Fig. 27	Time course of marketable 2. class yield.	32
Fig. 28:	Time course of marketable yield of tomatoes in the whole chamber.	33
Fig. 29:	Time course of marketable yield.	33
Fig. 30:	Average weight of tomatoes (1. class fruits).	35
Fig. 31:	Average weight of tomatoes (1. and 2. class fruits).	35
Fig. 32:	Sugar content of tomatoes.	37
Fig. 33:	Energy use efficiency (= marketable yield per used energy) for tomatoes under different light treatments.	38
Fig. 34:	Light related costs in tomato production under different light treatments.	40
Fig. 35:	Revenues at different light treatments.	41
Fig. 36:	Variable and fixed costs (without lighting and labour costs).	42

Fig. 37: Division of variable and fixed costs. 43
Fig. 38: Profit margin in relation to the light treatment. 46
Fig. 39: Profit margin in relation to yield with different light sources in tomato production – calculation scenarios. 49
Fig. 40: Profit margin in relation to yield with different heights of the lights in tomato production – calculation scenarios. 51
Fig. 41: Profit margin in relation to light treatment – calculation scenarios. 55

List of tables

Tab. 1: Fertilizer mixture. 9
Tab. 2: Number of lights and their distribution in the chambers. 11
Tab. 3: Light distribution in the chambers. 11
Tab. 4: Chamber settings according to greenhouse computer. 14
Tab. 5: Cumulative total number of marketable fruits. 34
Tab. 6: Proportion of marketable and unmarketable yield. 36
Tab. 7: Used energy under different light treatments (datalogger values). 38
Tab. 8: Energy costs and investment into lights for one growing circle of tomatoes under different light treatments. 39
Tab. 9: Variable costs of electricity in relation to yield. 40
Tab. 10: Profit margin of tomatoes at different light treatments. 44
Tab. 11: Marketable yield per cluster with different light treatments. 52

Abbreviations

E.C.	electrical conductivity
HPS	high-pressure vapour sodium lamps
kWh	kilo Watt hour
LED	light-emitting diodes
pH	potential of hydrogen
ppm	parts per million
W	Watt
Wh	Watt hours

Other abbreviations are explained in the text.

1 SUMMARY

In Iceland, winter production of greenhouse crops is totally dependent on supplementary lighting and has the potential to extend seasonal limits and replace imports during the winter months. Adequate guidelines regarding the effect of the light source and the optimal height of the lights are not yet in place for tomato production and need to be developed. The objective of this study was to test if the light source (HPS or Hybrid) and the height of the lamps is affecting growth, yield and quality over the winter of tomatoes and to evaluate the profit margin.

An experiment with ungrafted tomatoes (*Lycopersicon esculentum* Mill. cv. Completo) was conducted from the beginning of November 2021 to the middle of March 2022 in the experimental greenhouse of the Agricultural University of Iceland at Reykir. Tomatoes were grown in rockwool plugs in three replicates with 2,5 tops/m^2 with one top per plant. Three different light treatments for a maximum of 16 hours light were applied: 1. HPS top lighting (1000 W bulbs), HPS lamps in 4,5 m height from the floor (HPS, 472 µmol/m^2/s), 2. Hybrid top lighting (2:1, HPS:LED, 750 W HPS bulbs), HPS in 4,9 m and LEDs in 4,5 m height from the floor (Hybrid high, 373 µmol/m^2/s), 3. Hybrid top lighting (2:1, HPS:LED, 750 W HPS bulbs), HPS lights and LEDs in 4,5 m height from the floor (Hybrid, 454 µmol/m^2/s). The day temperature was set on 20°C. The night temperature was during the first two months 20°C and after that 17°C. The underheat was 35°C when the experiment started, but was increased to 50°C after one month and to 55°C at the end of February. The heating pipes were set to 45°C in the middle of January. 800 ppm CO_2 was applied. The tomatoes received standard nutrition through drip irrigation. The effect of the light source and the height of the lamps were tested and the profit margin was calculated.

The light source had an influence on the appearance of the plant: The height of the plant, the weekly growth and the distance between the clusters was significantly higher in “HPS” compared to “Hybrid”. In contrast, the above mentioned parameters were not affected by the height of the Hybrid lights.

The tomatoes that were lighted with the light source mounted 1,0 m over the plant canopy were about half a week earlier ripe than fruits that received lights from Hybrid lights that were 1,4 m away. This might be caused by the higher substrate temperature of plants where the light was mounted closer to the plants. At the end of

the harvest period was total yield and their number as well as marketable yield significantly higher where the Hybrid lights were in less distance to the plants. The reason for the higher yield was a significantly higher first class yield due to heavier fruits, whereas the number of marketable fruits was independent of the height of the Hybrid lights. In contrast, total yield, marketable yield, their number and average weight was not affected by the light source.

Marketable yield was around 70% for all light treatments, whereby the percentage of 1. class fruits, 2. class fruits, too small fruits and green fruits was independent of the light treatment.

Using Hybrid lights was associated with the same daily usage of kWh's compared to HPS lights. Light related costs (electricity costs + investment into lights) were calculated higher (6%) for "Hybrid" than "HPS" and amounted 46% of total production costs. Used kWh's were better transferred into yield with "Hybrid" than with "Hybrid high", while the light source had no effect on this parameter.

When the distance between Hybrid lights and plant canopy was reduced from 1,4 m to 1,0 m, yield was increased by 4,2 kg/m^2 and profit margin by 2.500 ISK/m^2. An additional increase could be reached by replacing Hybrid lights by HPS lights with 1000 W bulbs instead of 750 W bulbs to reduce investment costs. Then, the profit margin increased by 1.600 ISK/m^2 compared to Hybrid lights, while yield stayed comparable.

Possible recommendations for saving costs other than lowering the electricity costs are discussed. To be able to get a higher photosynthetic photon flux density the distance between lights and plant canopy could be lowered to one meter to be able to have a positive influence on yield and profit margin. It can be adviced to grow high wire plants under HPS top lights and invest rather in buying HPS lights with 1000 W than in LEDs for top lighting. So far, a replacement of the HPS lamps by LEDs is not recommended from the economic side and more scientific studies are needed.

YFIRLIT

Vetrarræktun í gróðurhúsum á Íslandi er algjörlega háð aukalýsingu. Viðbótarlýsing getur lengt uppskerutímann og komið í stað innflutnings að vetri til. Fullnægjandi leiðbeiningar fyrir vetrarræktun á tómötum og áhrif ljósgjafa og besta millibils milli ljóss og plantna á gróðurhúsatómata eru ekki til staðar og þarfnast frekari þróunar. Markmiðið var að prófa hvort ljósgjafi (HPS eða Hybrid) og hæð lampanna hefðu áhrif á vöxt, uppskeru og gæði yfir háveturinn á tómata og hvort það væri hagkvæmt.

Gerð var tilraun með ógrædda tómata (*Lycopersicon esculentum* Mill. cv. Completo) frá byrjun nóvember 2021 og fram í miðjan mars 2022 í tilraunagróðurhúsi Landbúnaðarháskóla Íslands á Reykjum. Tómatarnir voru ræktaðir í steinullarmottum í þremur endurtekningum með 2,5 toppi/m^2 með einum toppi á plöntu. Prófaðar voru þrjár mismunandi ljósameðferðir að hámarki í 16 klst. ljós: 1. HPS topplýsingu (1000 W perur), ljós í 4,5 m hæð frá gólfi (HPS, 472 µmol/m^2/s), 2. Hybrid topplýsingu (2:1, HPS:LED, 750 W HPS perur), HPS í 4,9 m og LEDs í 4,5 m hæð frá gólfi (Hybrid high, 373 µmol/m^2/s), 3. Hybrid topplýsingu (2:1, HPS:LED, 750 W HPS perur), HPS ljós og LEDs í 4,5 m hæð frá gólfi (Hybrid, 454 µmol/m^2/s). Daghiti var 20°C. Næturhiti var fyrstu tvo mánuðina 20°C og eftir það 17°C. Undirhiti var 35°C í byrjun, en 50°C eftir mánuð og 55°C í lok febrúar. Um miðjan janúar voru hitarör stillt á 45°C. 800 ppm voru gefin. Tómatarnir fengu næringu með dropavökvun. Áhrif ljósgjafa og hæð lampanna voru prófaðar og framlegð reiknuð út.

Ljósgjafar höfðu áhrif á plönturnar: Hæð plöntunnar, lengdavöxtur vikunnar og millibil milli klasa var marktækt lengri þegar plönturnar fengu HPS ljós miðað við Hybrid ljós. En hins vegar hafði hæð Hybrid lampanna ekki áhrif á ofangreindar breytur.

Tómatar sem fengu ljós frá ljósgjafa sem var 1,0 m fyrir ofan plöntuþekju, þroskuðust um hálfri viku fyrr en tómatar sem fengu ljós frá Hybrid ljósi sem var í 1,4 m fyrir ofan plönturnar. Þetta gæti orsakast af hærri hita í ræknunarefni plantna þar sem ljós var í minni fjárlægð frá plöntunum. Í lok uppskerutímabilsins var heildaruppskera, fjöldi uppskorinna aldina og markaðshæfrar uppskeru marktækt meiri þegar Hybrid ljós var í minnni fjarlægð frá plöntunum. Meiri uppskeru má rekja til þess að fyrsta flokks uppskera var marktækt meiri vegna meira þyngdar aldins, á meðan fjöldi markaðshæfrar aldina var óháð hæð frá Hybrid ljósum. Hins vegar var heildaruppskera, markaðshæfrar uppskeru, fjölda uppskorinna aldina og meðalþyngd aldina ekki háð ljósgjafa.

Hlutfall uppskerunnar sem hægt var að selja var um 70% fyrir allar ljósameðferðir án þess að tillit væri tekið til mismunar milli meðferða á 1. flokks aldina, 2. flokks aldina, of lítilla aldina og grænna aldina.

Dagleg notkun á Hybrid ljósum var sú sama í kWh's sem og HPS ljós. Ljósatengdur kostnaður (orkukostnaður + fjárfesting í ljósum) var hærri (6%) fyrir "Hybrid" en fyrir "HPS" og var 46% af heildarframleiðslukostnaði. Skilvirkni orkunotkunar var meiri með "Hybrid" en með "Hybrid high", á meðan ljósgjafi hafði engin áhrif á þessar breytur.

Þegar millibil milli Hybrid ljósa og plöntuþekju var minnkað úr 1,4 m í 1,0 m jókst uppskera um 4,2 kg/m^2 og framlegð um 2.500 ISK/m^2. Að auki var hægt að fá betri niðurstöður með því að skipta Hybrid ljósum út fyrir HPS ljós og nota 1000 W perur í staðinn fyrir 750 W perur til að lækka fjárfestingarkostnað í ljósum. Þá jókst framlegð um 1.600 ISK/m^2 á meðan uppskera breyttist ekki.

Möguleikar á að lækka kostnað, með öðrum hætti en að lækka rafmagnskostnað eru taldir upp í umræðukaflanum í þessari skýrslu. Þar er ráðlegt að minnka hæð milli plöntunnar og ljós í einn metra til að fá hærri µmol tölu sem mun leiða til hærri uppskeru og framlegðar. Mælt er með því að rækta tómata undir HPS ljósi og fjárfesta frekar í að kaupa HPS ljós með 1000 W perum en LEDs fyrir topplýsingu. Ekki mælt með því að skipta HPS lömpum út fyrir LED að svo stöddu og þörf er á meiri reynslu á ræktun undir LED ljósi.

2 INTRODUCTION

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

The positive influence of artificial lighting on plant growth, yield and quality of tomatoes (*Demers* et al., 1998a), cucumbers (*Hao* & *Papadopoulos*, 1999) and sweet pepper (*Demers* et al., 1998b) has been well studied. It is often assumed that an increment in light intensity results in the same yield increase (*Marcelis* et al., 2006). Indeed, yield of sweet pepper in the experimental greenhouse of the Agricultural University of Iceland at Reykir increased with light intensity (*Stadler* et al., 2010). However, with tomatoes, a higher light intensity resulted not (*Stadler*, 2012) or in only a slightly higher yield (*Stadler*, 2013).

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

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

Traditionally, lamps are mounted above the canopy (top lighting), which entails, that lower leaves are receiving limited light. Experiments (*Hovi-Pekkanen & Tahvonen*, 2008; *Grodzinski* et al., 1999; *Rodriguez & Lambeth*, 1975) imply that lower leaves are also able to assimilate quite actively, suggesting that a better utilization could be obtained by using interlighting (lamps in the row) in addition to top lighting. Indeed, the benefits from interlighting in contrast to top lighting alone have been confirmed with different vegetable crops. Interlighting increased first class yield of cucumbers along with increasing fruit quality and decreased unmarketable yield, both in weight and number (*Hovi-Pekkanen & Tahvonen*, 2008).

Experiments with interlighting have been conducted at the Agricultural University of Iceland. The position of the HPS lights had no influence on marketable yield. But HPS top lighting together with interlighting increased unmarketable yield (around 2% blossom end rot fruits and 2% more fruits with burning damage from the lights) compared to only HPS top lighting (*Stadler* et al., 2010). But the yield of sweet pepper war significantly less with LED interlighting than with HPS interlighting or 20% less marketable yield (*Stadler*, 2010). According to *Davis* & *Burns* (2016) interlighting in tomatoes has proved highly successful and a significant increase in yield was reported. The top light source (LED, HPS) had no influence on marketable yield of tomatoes, but the use of LEDs resulted in about 40% lower daily usage of kWh´s and with that in lower expenses for the electricity but higher investment costs compared to HPS lighting (*Stadler*, 2020). The yield increased when LED interlighting was added to HPS top lighting, in addition increased the used energy by 8%. The highest yield was reached with Hybrid top lighting and LED interlighting, where the light distribution and used energy was comparable to the before mentioned treatment (*Stadler*, 2020). When part of the HPS top lights was replaced by LED interlights decreased yield and it was concluded that it would be more economic to use LEDs as top lights (360 µmol/m^2/s, Hybrid lighting (HPS:LED, 2:1)) in contrast to interlights (240 µmol/m^2/s Hybrid lighting (HPS:LED, 1:1) together with 120 µmol/m^2/s LED interlighting) (*Stadler*, 2021b).

The Icelandic greenhouse growers are still using a high light intensity with HPS lights. Therefore, it is important to test if the growers should replace some HPS lights by LEDs or if it would be better to use only HPS lights in tomato production. In the past, experiments with HPS lights were conducted with 750 W bulbs. However, with the use of 1000 W bulbs it would be possible to reduce lighting costs as investment costs could be lowered. Furthermore, a better PAR value could be reached by adjusting the height of lamps in depence to the plant canopy.

In addition to the yield, the quality of the harvest is also important. Research in the Netherlands has shown that with LED lights it was possible to increase the taste of strawberries (*Hanenberg* et al., 2016). Experience of the effect of the light source in growing tomatoes under Hybrid top lighting compared to HPS top lighting and with different heights of the lamps is not available in Iceland. Therefore, the effect of the light on yield over the high winter (with low levels of natural light) needs to be tested under Icelandic conditons. Incorporating lighting into a production strategy is an economic decision involving added costs versus potential returns. Therefore, the question arises whether these factors are leading to an appropriate yield of tomatoes.

The objective of this study was to test if (1) the light source and their mounting height 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 choice of the light source and by the height of the lights. This study should enable to strengthen the knowledge on the best method of growing tomatoes and give vegetable growers advice of 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 2021/2022.

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 30.09.2021 seeds of tomatoes were sown in rockwool plugs. On 09.11.2021 four plants with one top/plant were planted into rockwool slabs (50 cm x 24 cm x 10 cm). On each bed were six slabs placed in three chambers. Tomatoes were transplanted in rows in three 65 cm high beds (Fig. 1) with 2,5 plants/m^2. Beds were equipped with six slabs respectively 24 tops. Three replicates, one replicate in each bed consisting of two slabs (8 plants) acted as subplots for measurements. Other slabs were not measured. Due to the weekly hanging down all plants were once at the end of the bed.

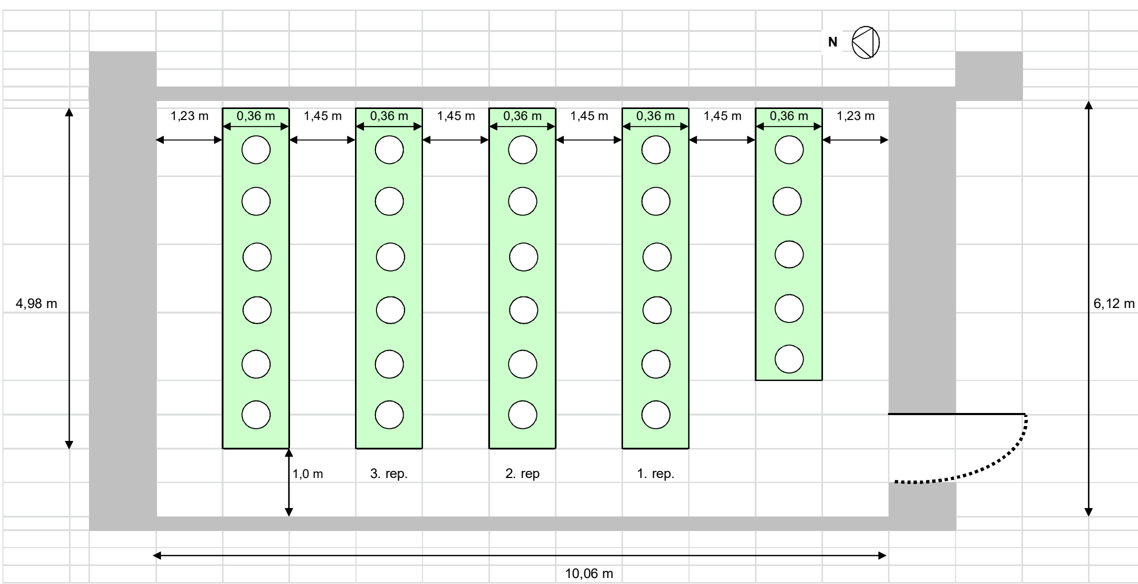


Fig. 1: Experimental design of cabinets.

Shoots were regularly taken 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 two leaves were taken of the bottom and one top leaf was taken at the upper flowering cluster to create a more open and generative plant habit. That improves light penetration and air circulation and prevents fungal diseases and aphids. The removal of young leaves reduces the total vegetative sink-strength and favours assimilate partitioning into the fruit (*Heuvelink* et al., 2005). Double clusters were removed. Fruits on each cluster were not pruned to be able to enable a high yield potential. Plants were not topped during the experiment to be able to have a “normal” growth until the end of the experiment and to conduct measurements. Wires were placed in 3,5 m height from the floor. Handpollination was used instead of bumblebees to guarantee an even pollination among chambers.

Until the 07.01.2022 was the temperature set on 20°C and after that on 20°C / 16-17°C (day / night). The aim was to reach 20°C at one hour after day starts. At the end of the day the temperature was dropped immediately. Ventilation started at 24°C. It was heated up with 1,5-2,0°C per hour. The underheat was set to 35°C in the beginning, increased to 50°C on 07.12.2021 and to 55°C on 24.02.2022. On 10.01.2022 the heating pipes were set on 45°C. Carbon dioxide was provided (800 ppm CO_2 with no ventilation and 600 ppm CO_2 with ventilation). A misting system was installed. Humidity was set to 75%. Plant protection was managed by beneficial organisms: En-Strip (Parasitic wasp, *Encarsia Formosa*) was used to prevent whitefly (see details in appendix).

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

Tab. 1: Fertilizer mixture.

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

Plants were irrigated through drip irrigation (4 tubes per slab). The watering was set up that the plants could root well down, which means a low amount of runoff in the first 2-3 weeks. The slabs were watered with an E.C. of 5. The irrigation (100 ml/drip) was arranged to 30% runoff with an E.C. in the drip of 4-6. The first watering was at 5:00 and the last watering was at 18:00. The irrigation interval was variable in accordance to the runoff.

3.2 Treatments

Tomatoes were grown from 09.11.2021 until 16.03.2022 under different lighting regimes in three cabinets at the Agricultural University of Iceland at Reykir:

1. HPS top lighting (1000 W bulbs), HPS lamps in 4,5 m height from the floor
   HPS
2. Hybrid top lighting (2:1, HPS:LED, 750 W HPS bulbs), HPS lights in 4,9 m and LEDs in 4,5 m height from the floor
   Hybrid high
3. Hybrid top lighting (2:1, HPS:LED, 750 W HPS bulbs), HPS lamps and LEDs in 4,5 m height from the floor
   Hybrid

To test if the light source had an influence on the yield of tomatoes plants that got HPS lights were compared to plants that got Hybrid lights (compare 1 and 3). In addition, it was tested if the height of the light source can be used to increase yield and profit margin (compare 2 and 3).

HPS lights were used with an electronic ballast and 750 W bulbs (Philips) in the Hybrid treatments, but 1000 W bulbs in the HPS treatment to reduce lighting costs. 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 LEDs and of Agrolux for the HPS lights (Tab. 2). HPS lamps were mounted horizontally in 1,4 / 1,0 m ("Hybrid high" / "Hybrid" and "HPS") distance over the canopy, which corresponds to a height of 4,9 m from the floor in "Hybrid, high", but in 4,5 m in "Hybrid". LEDs for top lighting were mounted 4,5 m from the floor, which was equivalent to 1,0 m over the canopy. However, due to the roof of the greenhouse the LEDs over the shelter beds were mounted 4,15 m from the floor.

White plastic on the surrounding walls helped to get a higher light level at the edges of the growing area. The µmol level of the lights in "HPS" (472 µmol/m^2/s) and "Hybrid" (454 µmol/m^2/s) was comparable, while the µmol level of "Hybrid high" was much lower (373 µmol/m^2/s) (Tab. 3). The setup of the HPS lights was corresponding to 300 W/m^2 (HPS) and to 210 W/m^2 ("Hybrid", "Hybrid high"). Light was provided from 03:00-19:00 after planting.

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

Light treatment	Lights	Lights/chamber (no)	Distance between lights
HPS	HPS top lighting	16	3 C profiles with 4 / 6 HPS, 1,75 m for HPS distance centre centre and 2 m for HPS centre centre
Hybrid and **Hybrid high**	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 top lighting	24	8 C profiles with 3 modules, 1,3 m for C profile distance and 1,9 m for modules centre centre

Tab. 3: Light distribution in the chambers.

Measurement points	HPS	Hybrid high	Hybrid
	(µmol/m^2/s)		
1,5 m (floor to top lights)	374	321	372
2,0 m (floor to top lights)	420	352	426
2,5 m (floor to top lights)	474	381	498
3,0 m (floor to top lights)	620	437	520
Top lighting (average)	**472**	**373**	**454**

3.3 Measurements, sampling and analyses

Substrate temperature was measured in 1-2 cm depth by a portable thermometer (TP1110-HD2307.0 Temperature meter, Nieuwkoop, Aalsmeer, The Netherlands) and leaf temperature by a portable infrared contact thermometer (BEAM infrared thermometer, TFA Dostmann GmbH & Co. KG, Wertheim-Reicholzheim, Germany) by hand. The amount of fertilization water (input, 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 and the diameter of the cluster 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 fruits were 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 on each plant from the subplots the number of immature fruits (green) were counted by harvesting five clusters with only green fruits above the last harvested cluster with mature fruits. The marketable yield of the whole chamber was also measured. LED glasses were used for picking to be able to distinguish if fruits were ready for harvesting or not.

The interior quality of the fruits was determined. A brix meter (Pocket Refractometer PAL-1, ATAGO, Tokyo, Japan) was used to measure sugar content in the fruits at the beginning and in the middle of the growth period. Sugar content at the end of the growth period was not measured, because harvested fruits were stored, due to closed roads, temporary in a cooler before sugar measurements would have been possible.

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

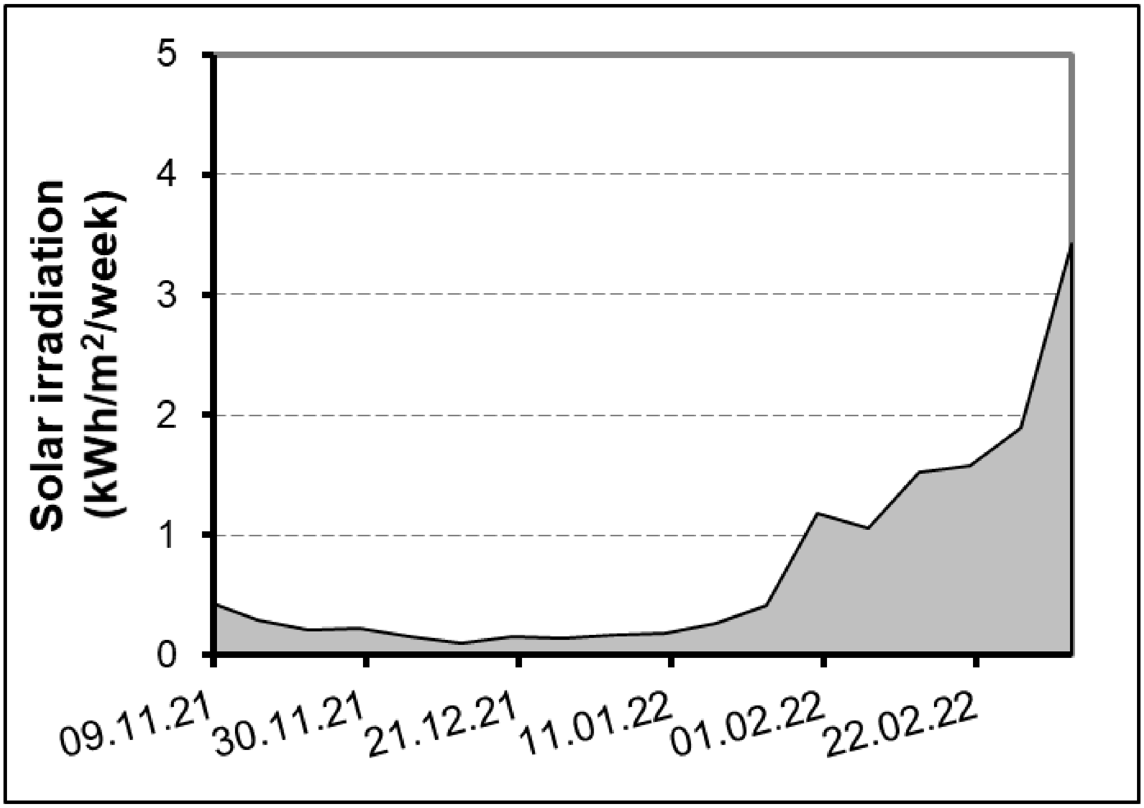


Fig. 2: Time course of solar irradiation.
Solar irradiation was measured every day and values for one week were cumulated.

4.1.2 Chamber settings

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

The average air temperature amounted around 21°C and was very similar between the light treatments. The average air temperature during the day was about 0,5°C lower in the treatment “HPS” compared to the other light treatments. However, the average night temperature was similar between light treatments.

The floor temperature during the day was comparable between the light treatments. The floor temperature during the night was less than 3°C lower in the treatment “HPS” compared to the other treatments.

The mean CO_2 amount was very similar between treatments. Windows were in all light treatments most of the time closed. Humidity amounted 61-68%.

Tab. 4: Chamber settings according to greenhouse computer.

Greenhouse computer data (Average over the experimental period)	HPS	Hybrid high	Hybrid
Air temperature (°C)	21,1	21,3	21,5
day (°C)	22,4	22,8	23,0
night (°C)	18,6	18,6	18,7
Floor temperature day (°C)	42,4	42,2	41,6
Floor temperature night (°C)	34,4	36,9	37,2
CO_2 (ppm)	740	747	761
Windows opening 1 (%)	1,8	2,0	3,6
Windows opening 2 (%)	1,6	2,3	2,1
Humidity (%)	66	61	68

4.1.3 Substrate temperature

Substrate temperature was measured weekly at low solar radiation at around noon and fluctuated between 18-23°C. Substrate temperature was on average significantly lower in “Hybrid high” compared to the other light treatments. On average amounted this difference 0,6°C (Fig. 3).

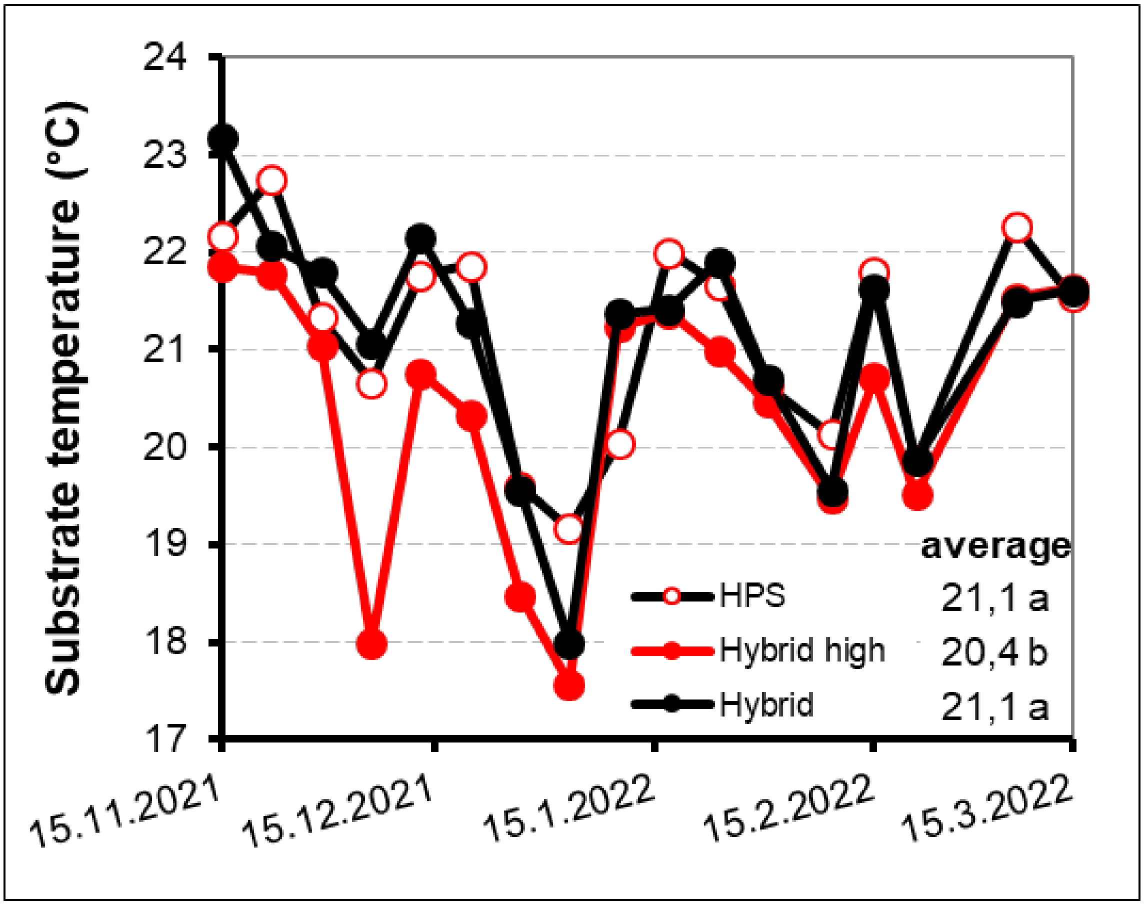


Fig. 3: Substrate temperature.

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 17-24°C. On average the leaf temperature was significantly higher in “HPS” compared to plants that got Hybrid lights (Fig. 4).

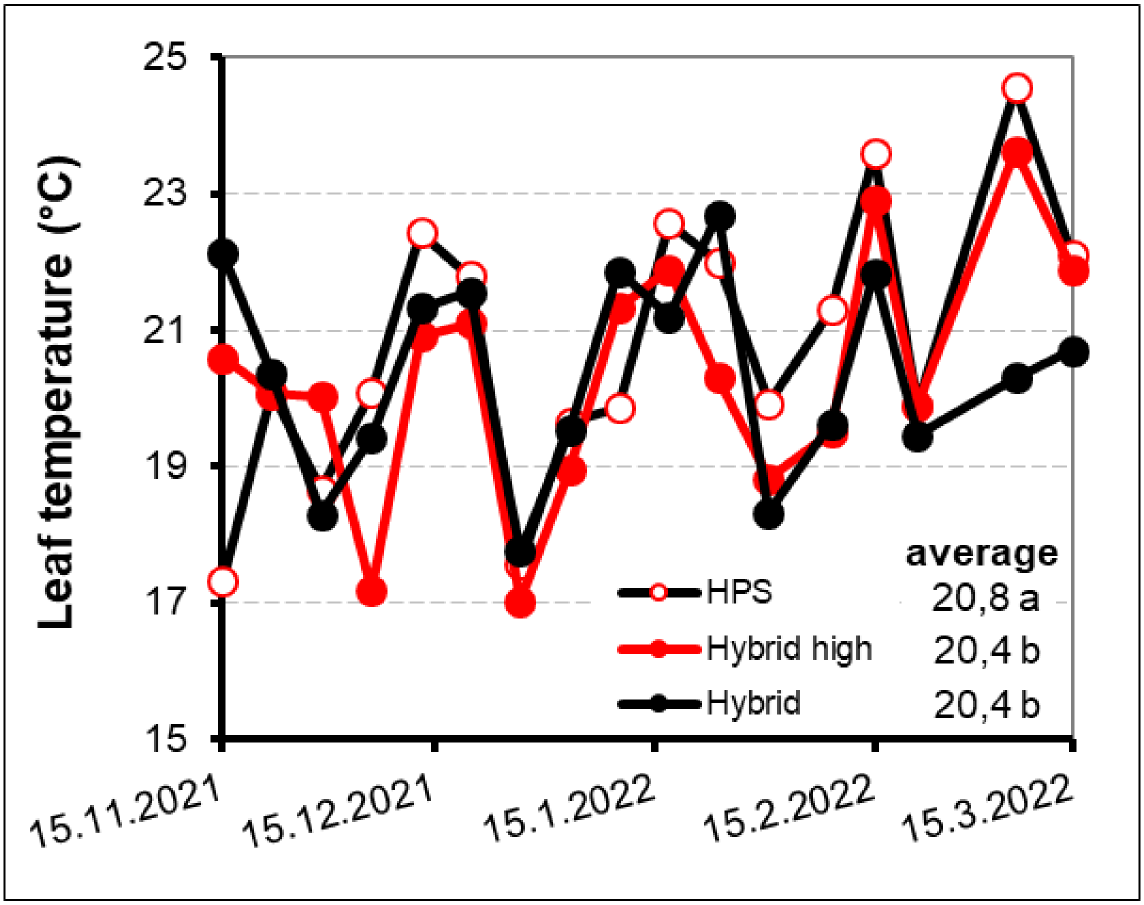


Fig. 4: Leaf temperature.

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

4.1.5 Irrigation of tomatoes

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

E.C. and pH of irrigation water was fluctuating much (Fig. 7). The E.C. of applied water ranged most of the time between 3,5-5,0 and the pH between 5,5-6,5. The E.C. of runoff stayed most of the time between 4,0-7,0 and the pH between 5,5-8,0. The E.C. of the runoff seem to be lowest for “Hybrid high”.

The amount of runoff from applied irrigation fluctuated very much and varied most of the time between 20-60% runoff. It seems to be on average highest in “Hybrid high” (Fig. 8).

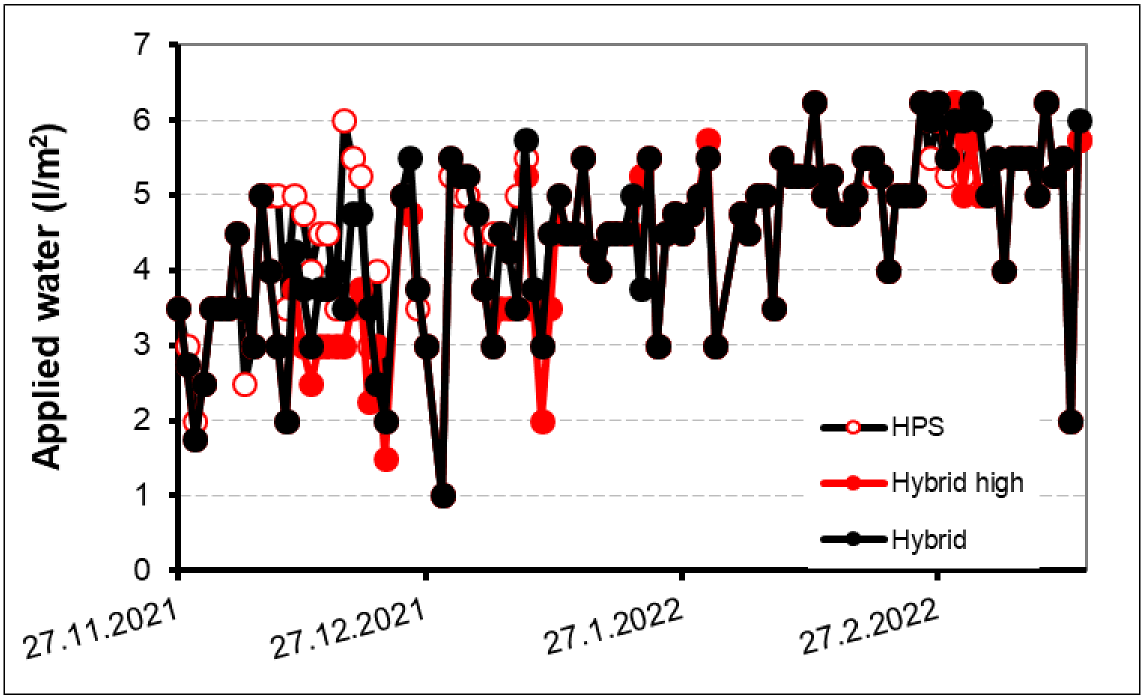


Fig. 5: Daily applied water.

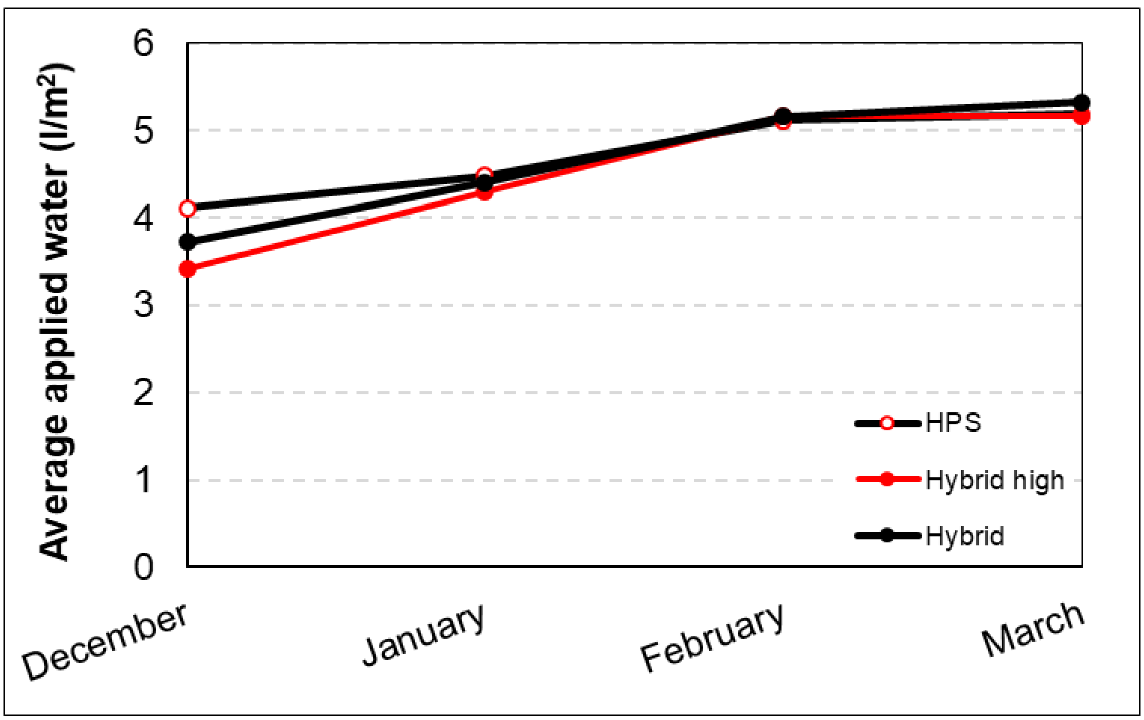


Fig. 6: Average daily applied water in each month.

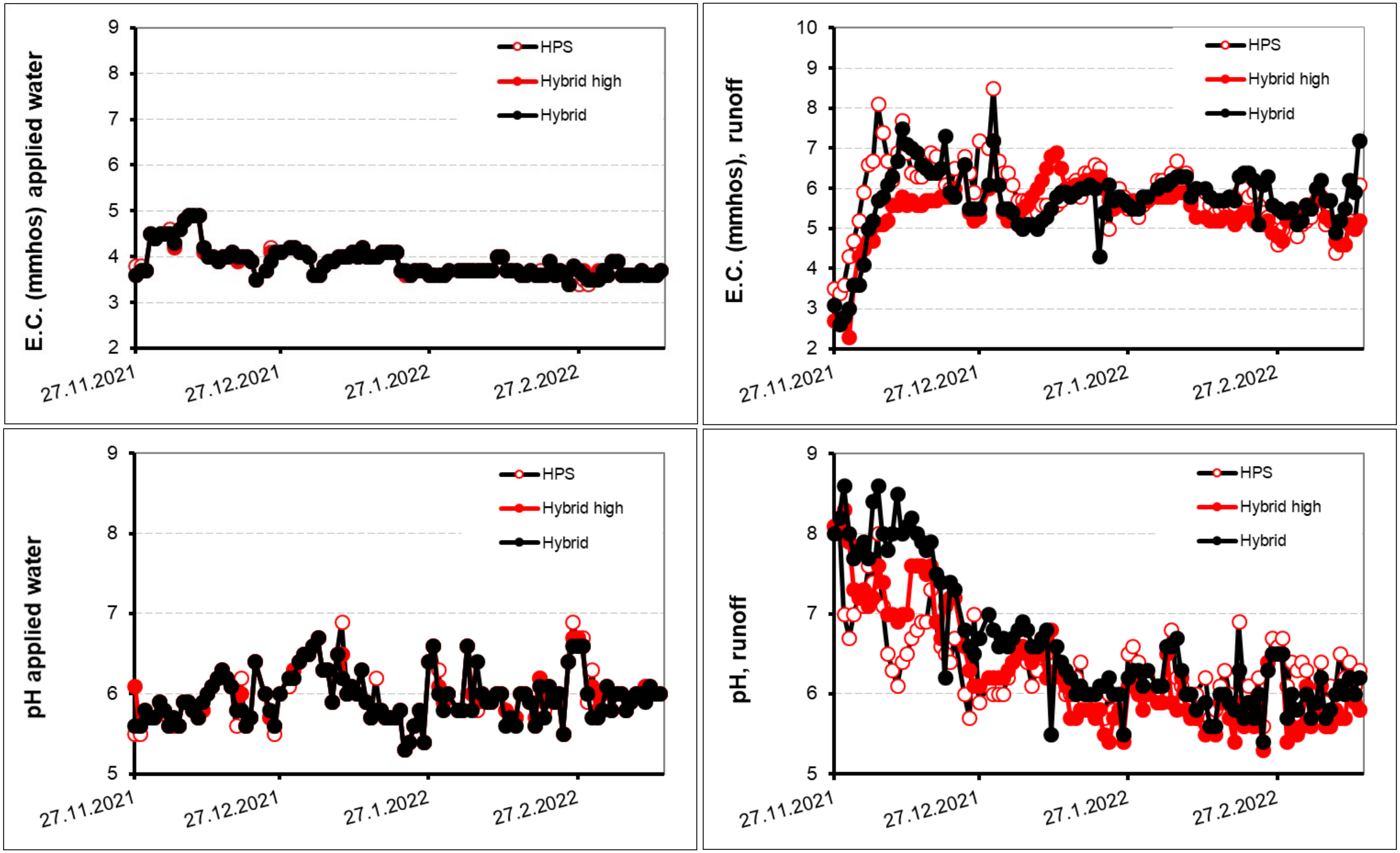


Fig. 7: **E.C. and pH of irrigation water and runoff.**

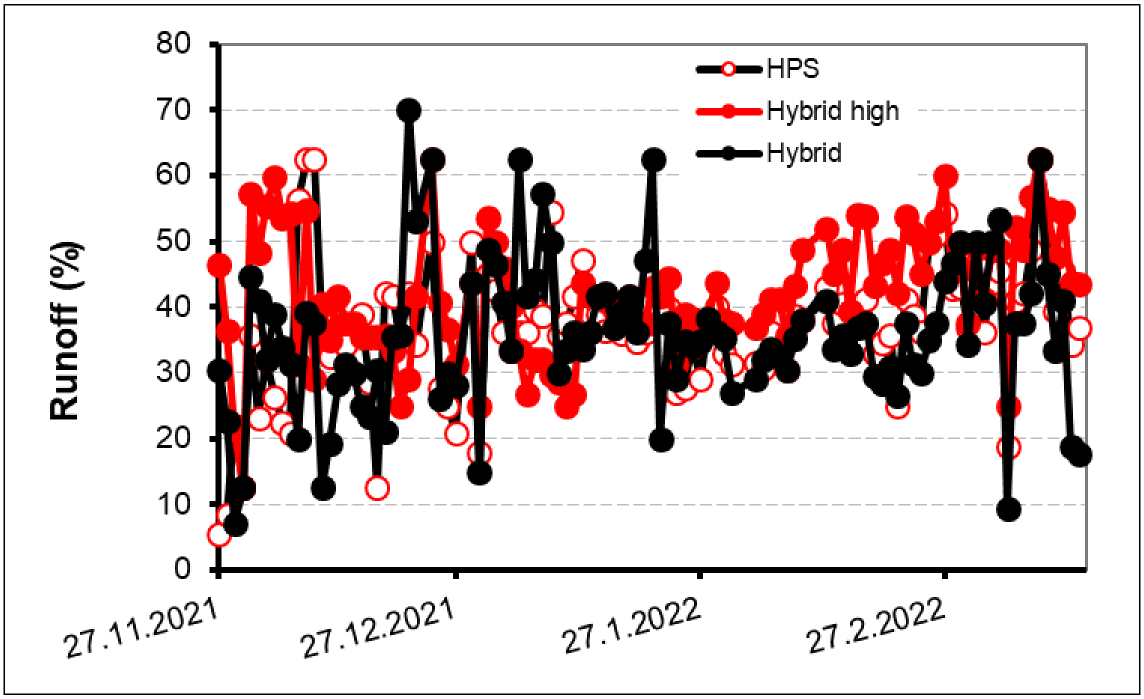


Fig. 8: **Proportion of amount of runoff from applied irrigation water.**

Plants took up to 1,5-4,0 l/m². It seems that plants took up less water in the treatment "Hybrid high" (Fig. 9).

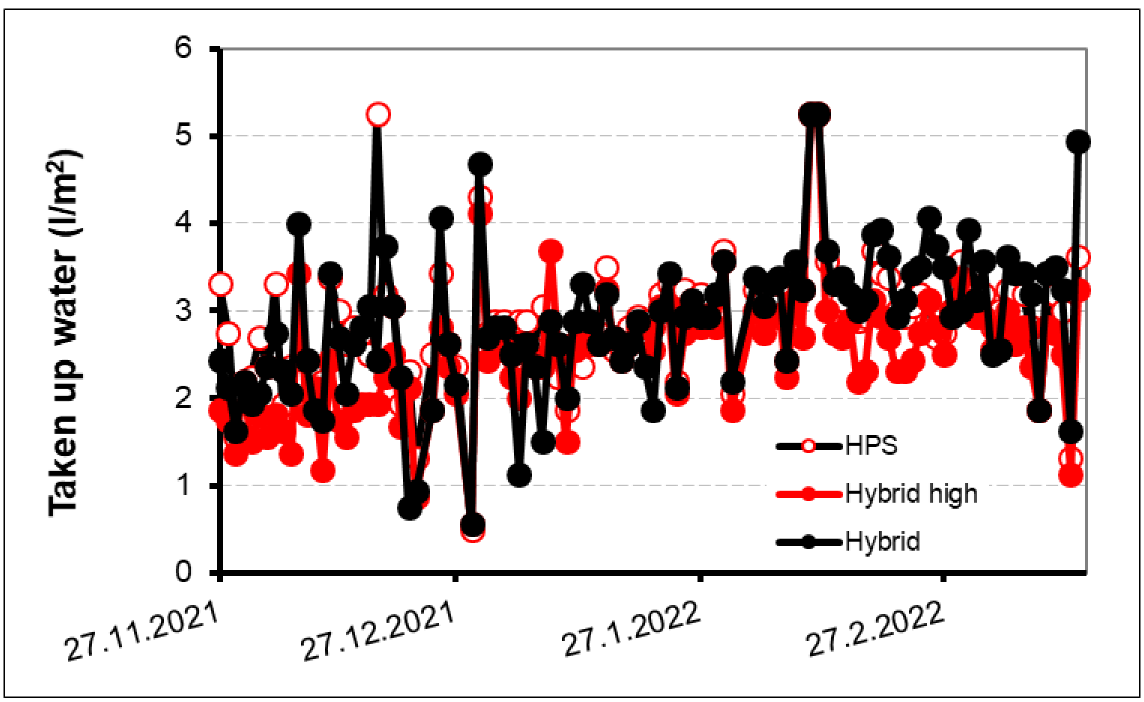


Fig. 9: **Water uptake.**

4.2 Development of tomatoes

4.2.1 Plant diseases and pests

Neither plant diseases nor pests were observed.

4.2.2 Height

Tomato plants were growing about 2-4 cm per day and reached at the end of the experiment more than 4 m (Fig. 10). Plants were significantly taller when grown under HPS lights.

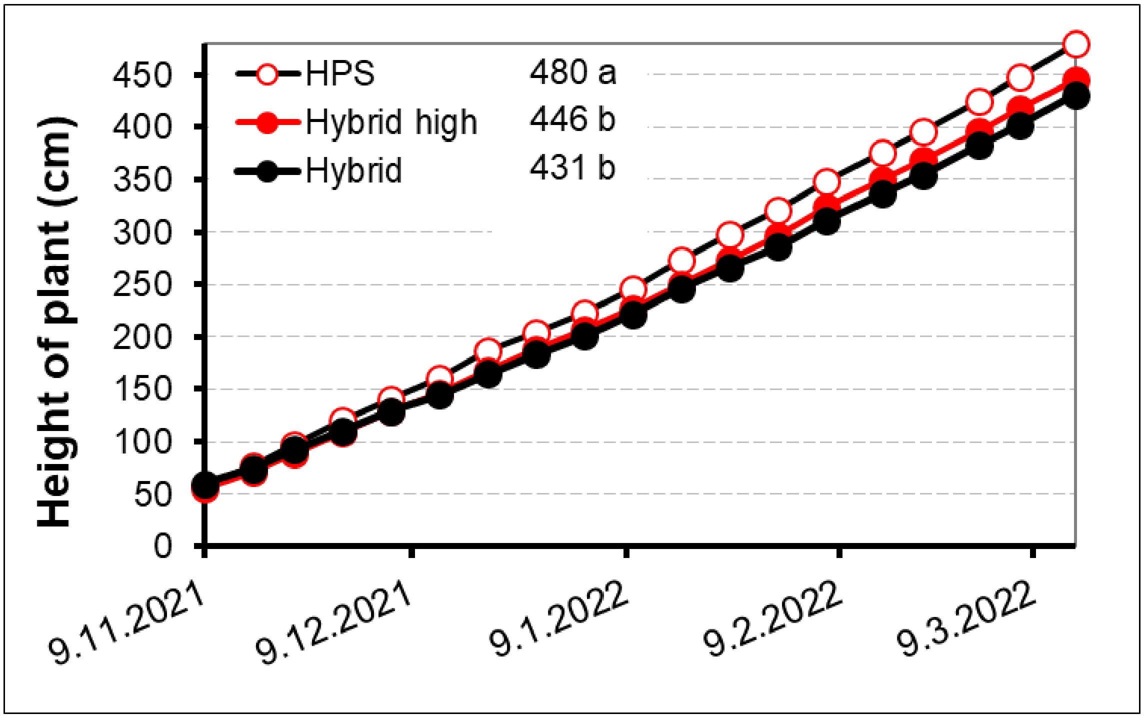


Fig. 10: Height of tomatoes.

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

4.2.3 Weekly growth

The weekly growth amounted 15-30 cm. Plants under HPS lights grow on average significantly more compared to the two Hybrid treatments (Fig. 11).

4.2.4 Number of leaves

Plants had on average 15-17 leaves. However, “Hybrid high” had on average a significantly lower amount of leaves compared to the other light treatments (Fig. 12).

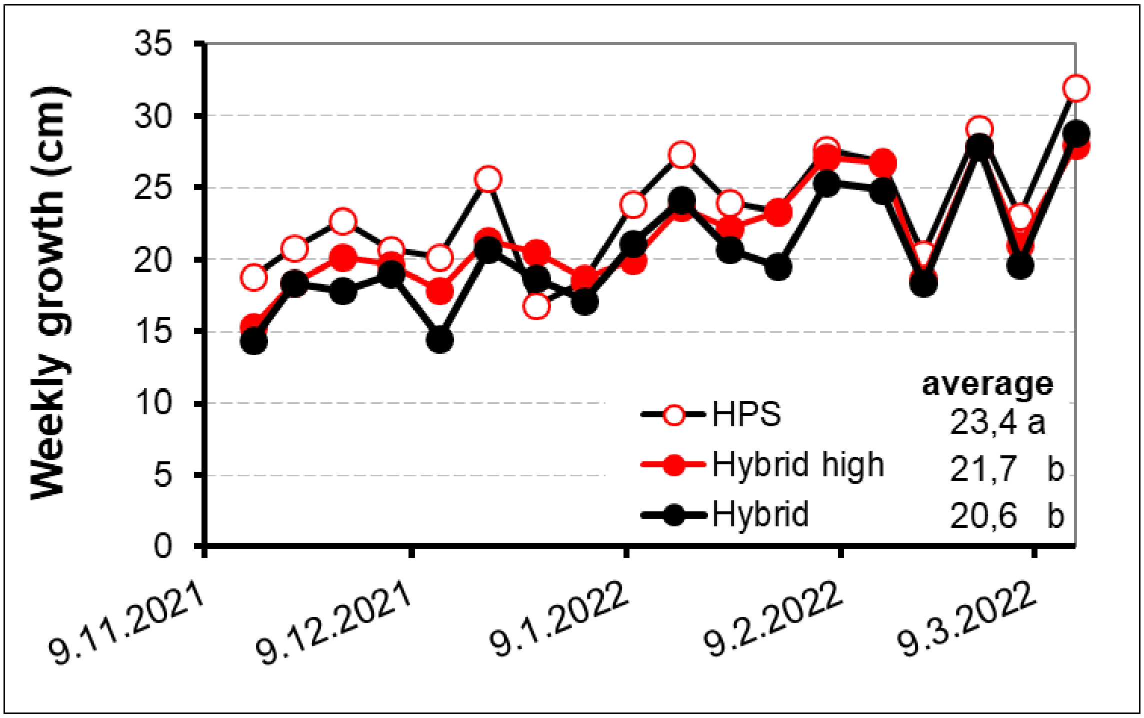


Fig. 11: Weekly growth.

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

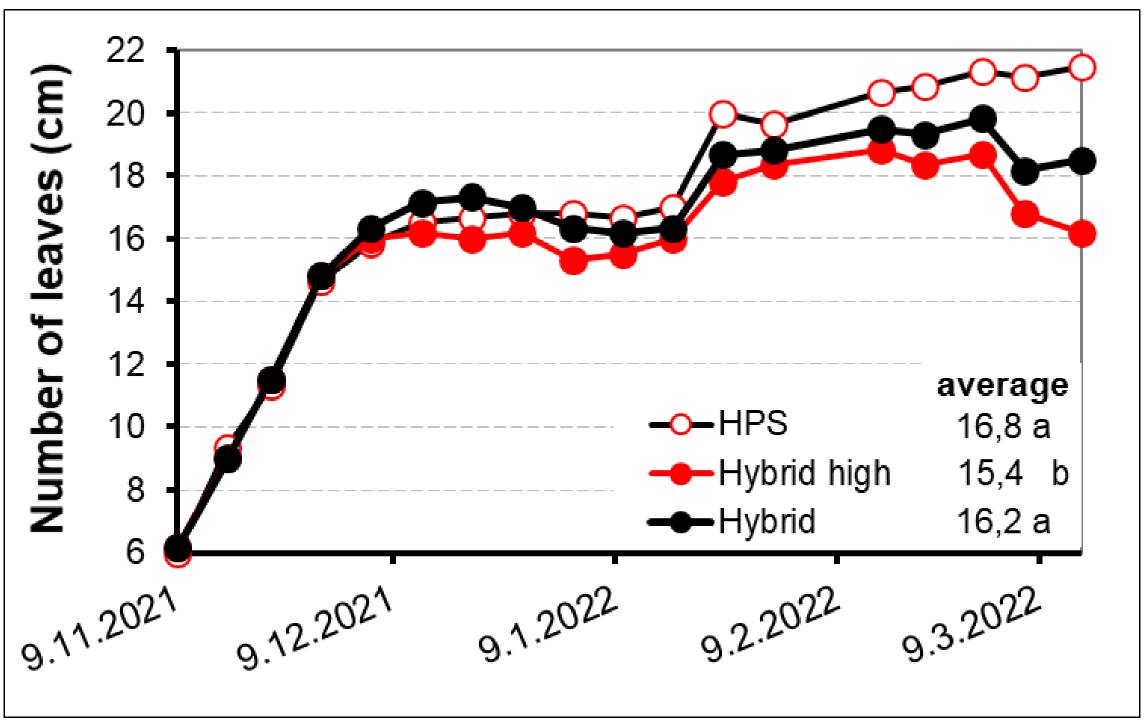


Fig. 12: Number of leaves on the tomato plant.

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

4.2.5 Length of leaves

Length of leaves during the experiment remained at 36-48 cm (Fig. 13). The light treatment had no influence on the length of the leaves.

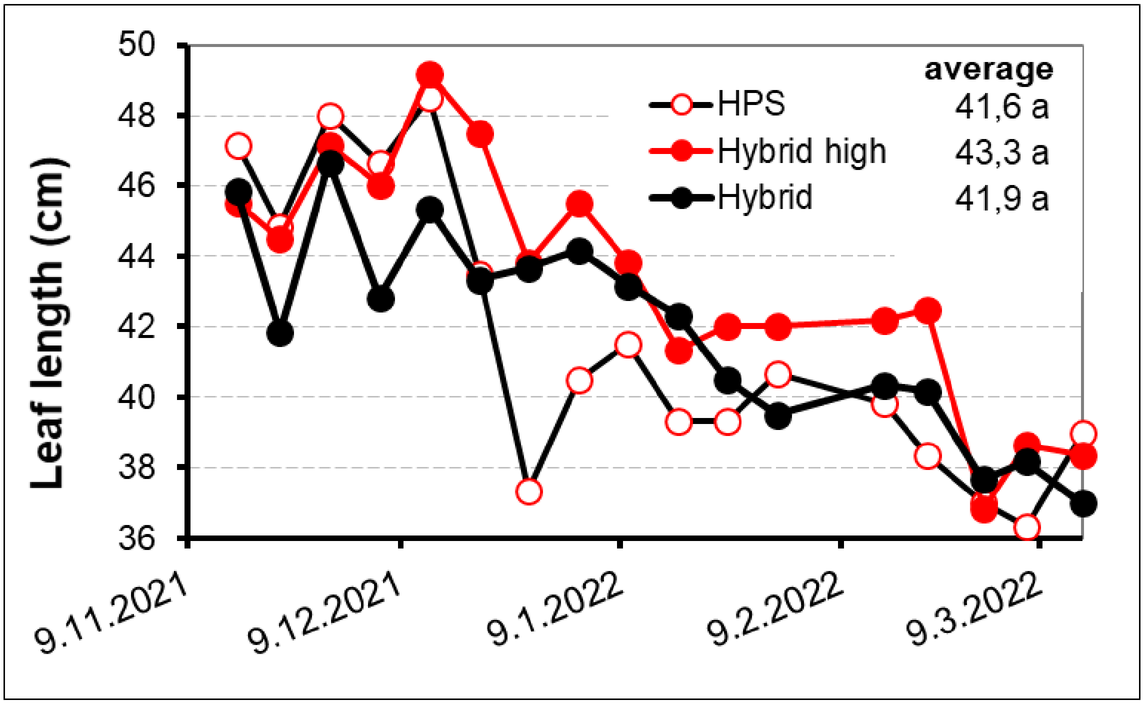


Fig. 13: Length of leaves.

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

4.2.6 Number of clusters

The number of clusters increased with approximately one additional cluster per week. The treatment "Hybrid high" had a significantly lower amount of clusters compared to "HPS", whereas no differences in the number of clusters were observed for "HPS" and "Hybrid" as well as for "Hybrid" and "Hybrid high" (Fig. 14).

4.2.7 Length of clusters to top

The length from the uppermost flowering cluster to the top of the plant amounted on average 18-20 cm with no significant differences between light treatments (Fig. 15).

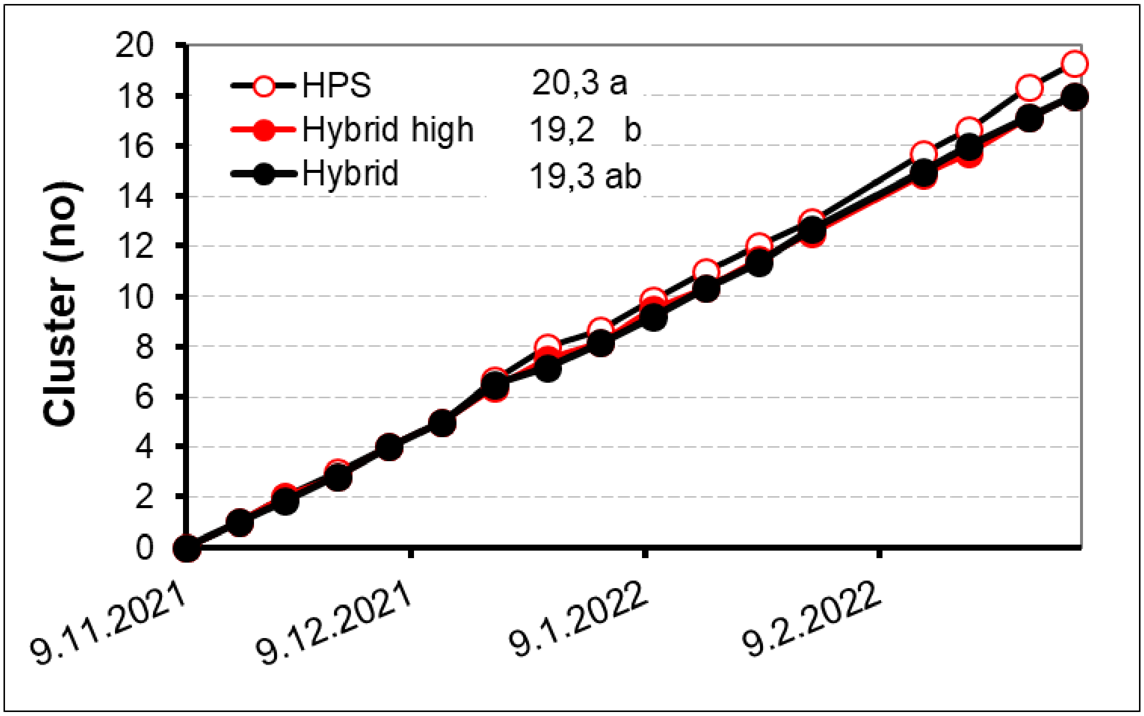


Fig. 14: Number of clusters.

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

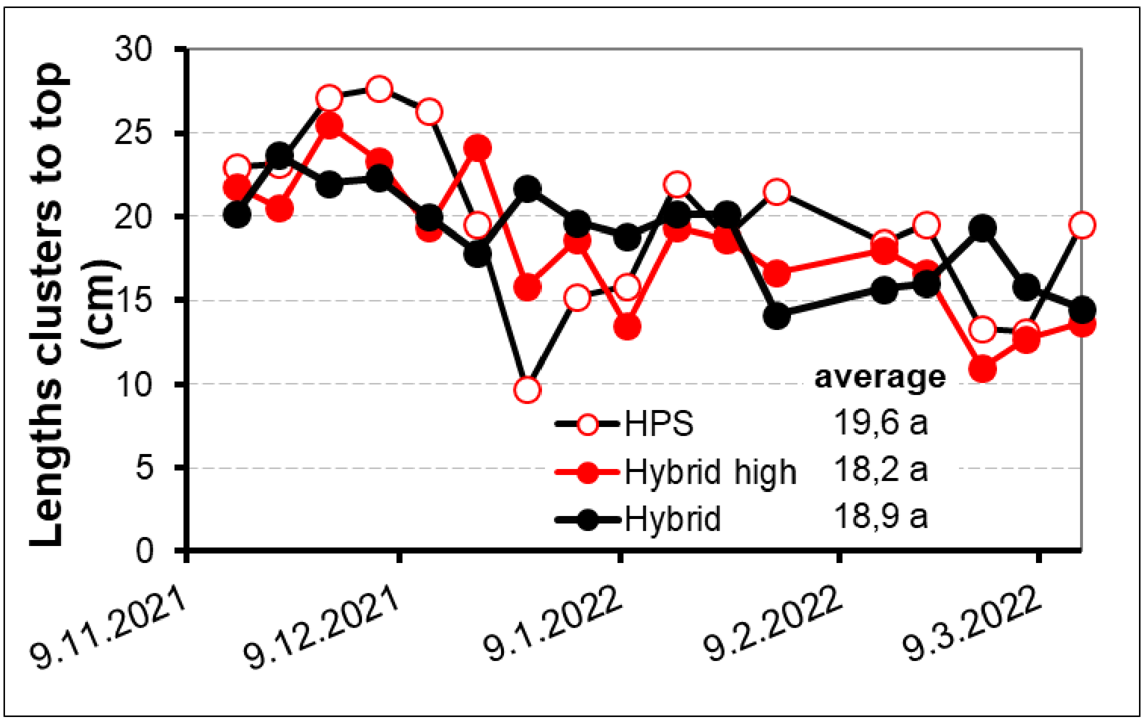


Fig. 15: Length of uppermost flowering cluster to plant top.

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

4.2.8 Distance between clusters

The distance between clusters was fluctuating between 18-24 cm during the growth period. On average amounted the distance 21-22 cm and was significantly higher for "HPS" than for "Hybrid", whereas no significant differences were found between "Hybrid" and "Hybrid high" as well as between "HPS" and "Hybrid high" (Fig. 16).

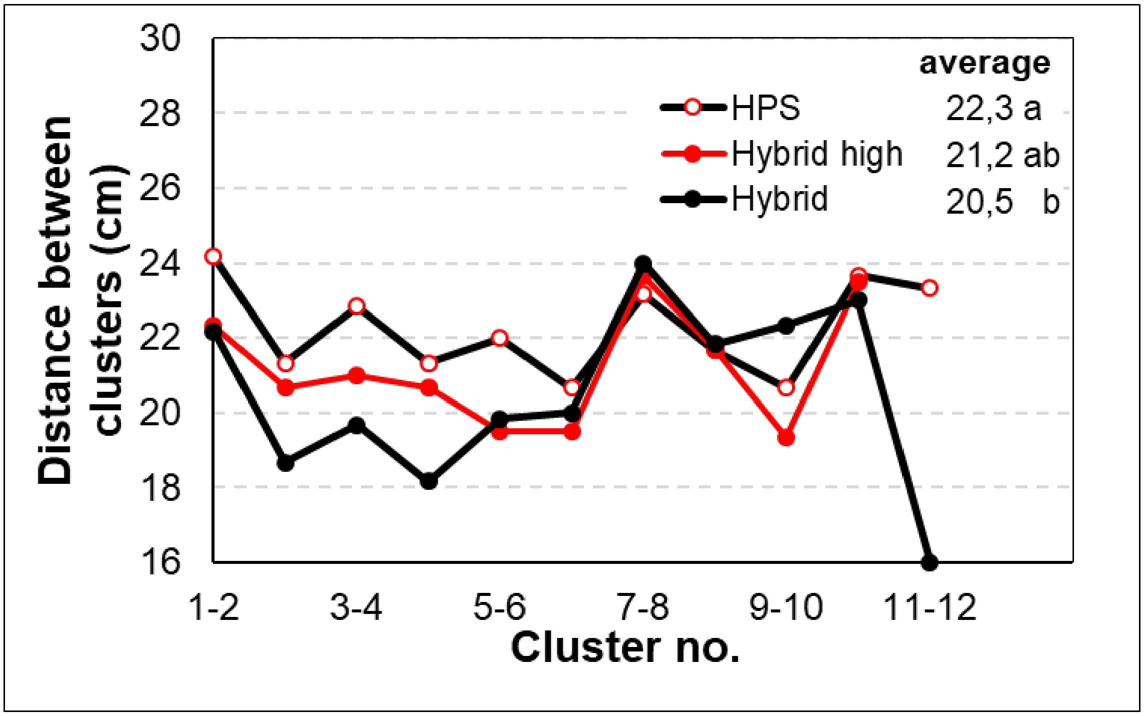


Fig. 16: Distance between clusters.

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

4.2.9 Length of clusters

The length of clusters decreased from about 30 cm to about 20 cm at the end of the experiment (Fig. 17). On average no significant differences between light treatments in the length of clusters were measured.

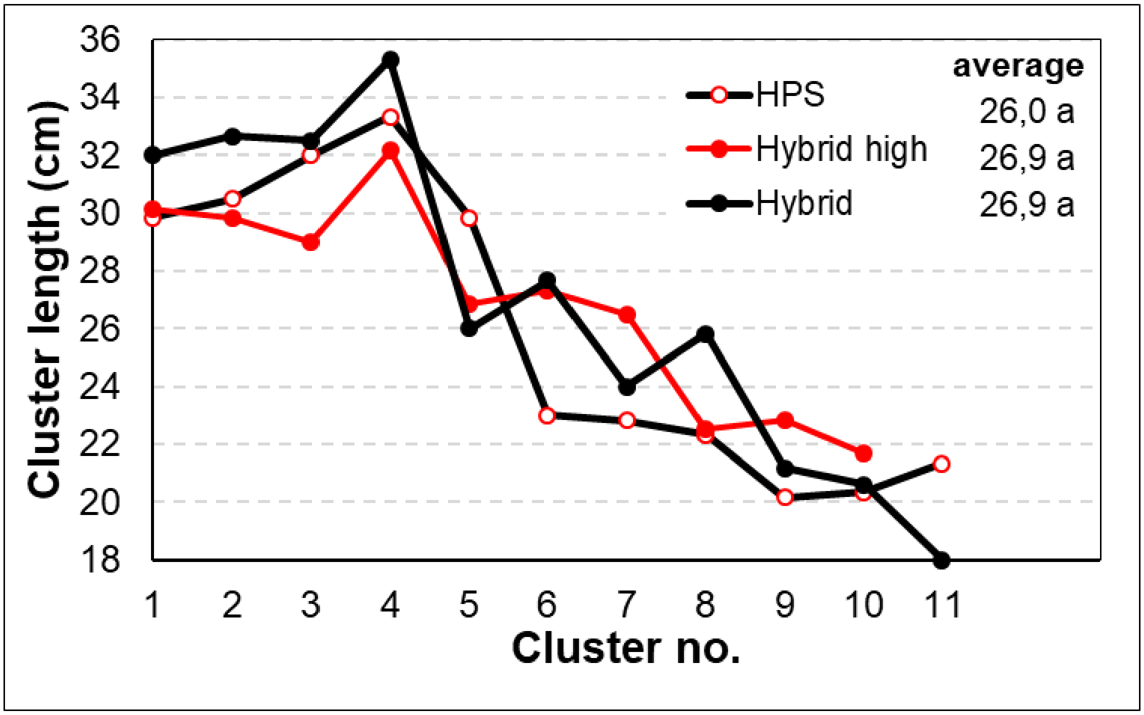


Fig. 17: Length of clusters.

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

4.2.10 Fruits per cluster

Clusters were not pruned. Consequently the number of fruits per cluster fluctuated (Fig. 18). The number of fruits per cluster decreased during the harvest period from around 12 at the beginning of the harvest period to about 9 at the end of the harvest period. The average number of fruits per cluster amounted around 11 and was independent of the light treatment.

The number of not pollinated fruits per cluster was fluctuating between 0-2, however, with a peak of 3 on the third cluster. The average number of not pollinated fruits amounted around 1 and was independent of the light treatment (Fig. 19).

4.2.11 Number of open flowers

On the uppermost cluster was the number of open flowers counted. The number of open clusters fluctuated during the growth period between 2-5 per cluster. On average were significant more open flowers under “HPS” than under “Hybrid high” observed, whereas the number was independent between “HPS” and “Hybrid” as well as between “Hybrid” and “Hybrid high” (Fig. 20).

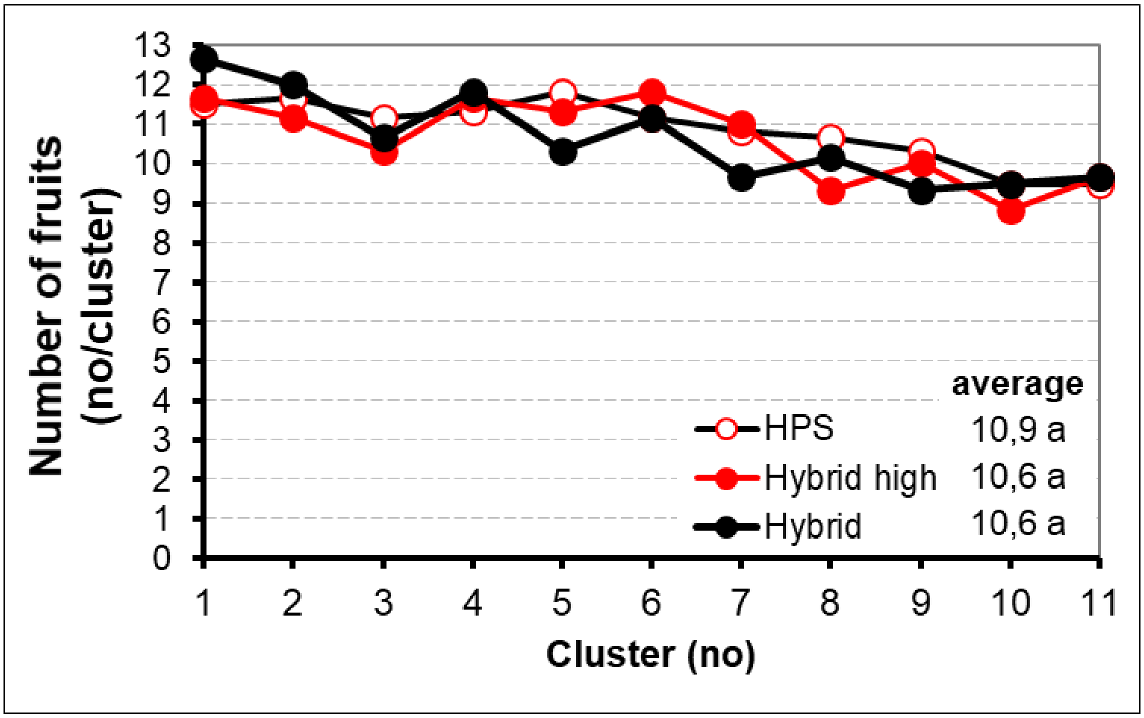


Fig. 18: Number of fruits per cluster.

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

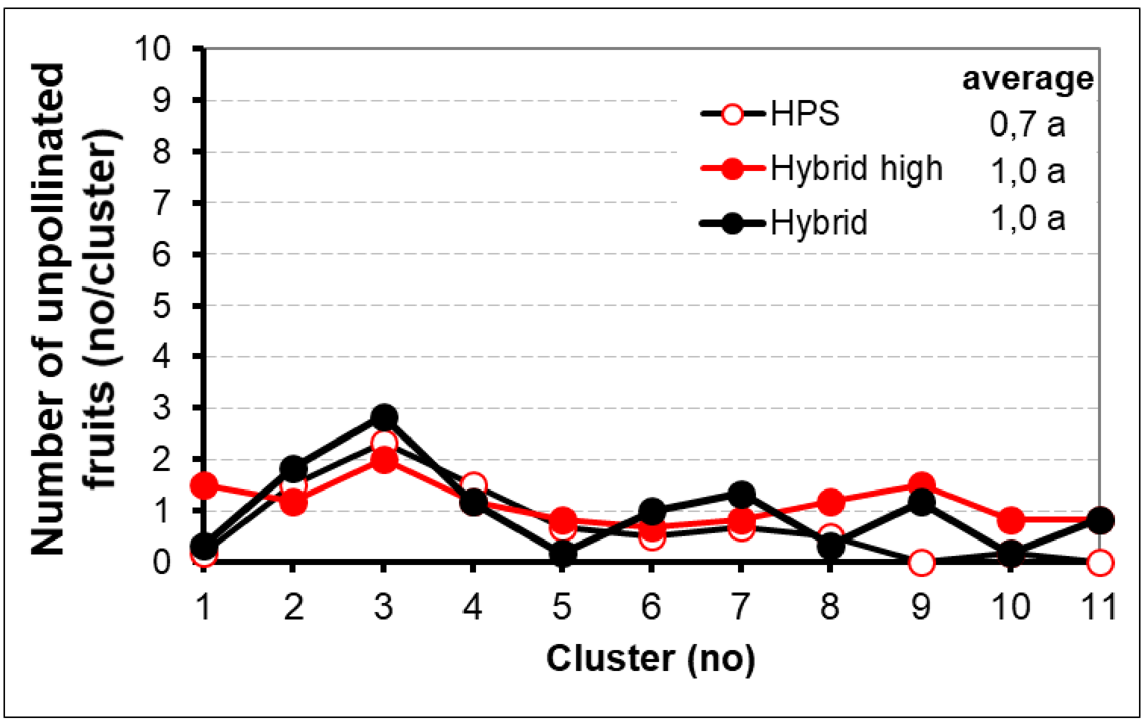


Fig. 19: Number of unpollinated fruits per cluster.

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

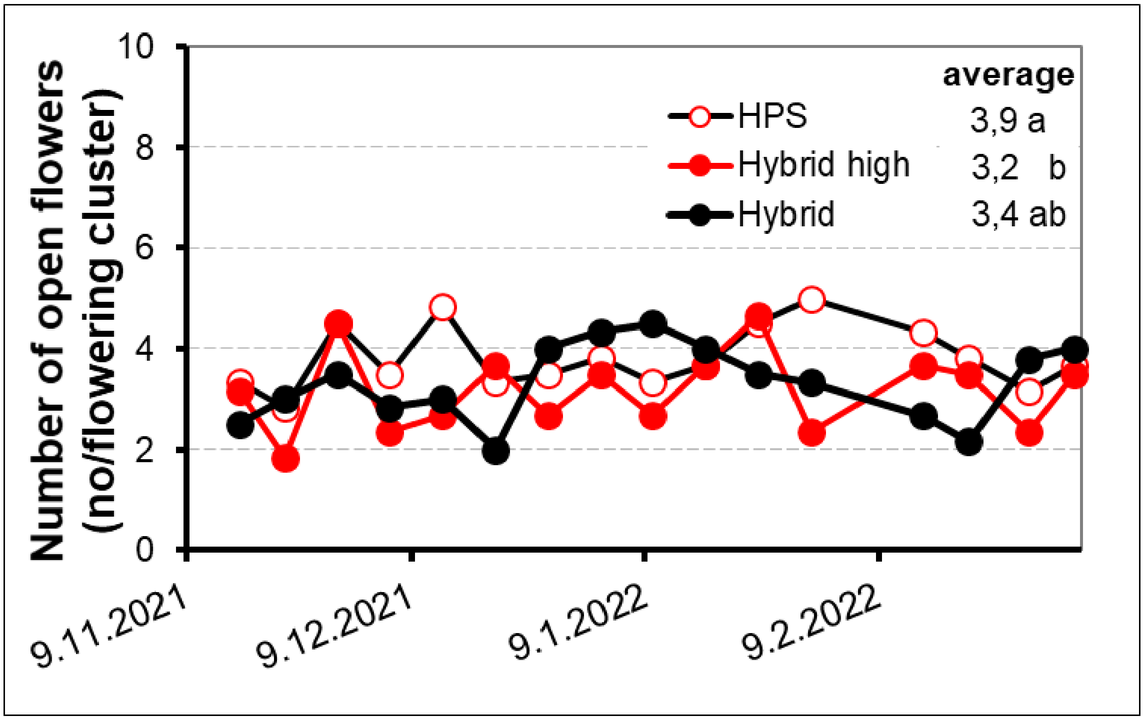


Fig. 20: Number of flowers.

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

4.2.12 Stem diameter

Stem diameter was varying from 0,7 to 1,5 cm (Fig. 21). On average amounted the diameter of the stem 0,92-1,01 cm and was independent of the light treatment. Plants were most of the time of the growth period weak vegetative, respectively very vegetative.

4.2.13 Diameter of the uppermost flowering cluster

The diameter of the uppermost flowering cluster decreased from about 1,0 mm to about 0,7 mm during the growth period. No significant differences between the light treatments were measured.

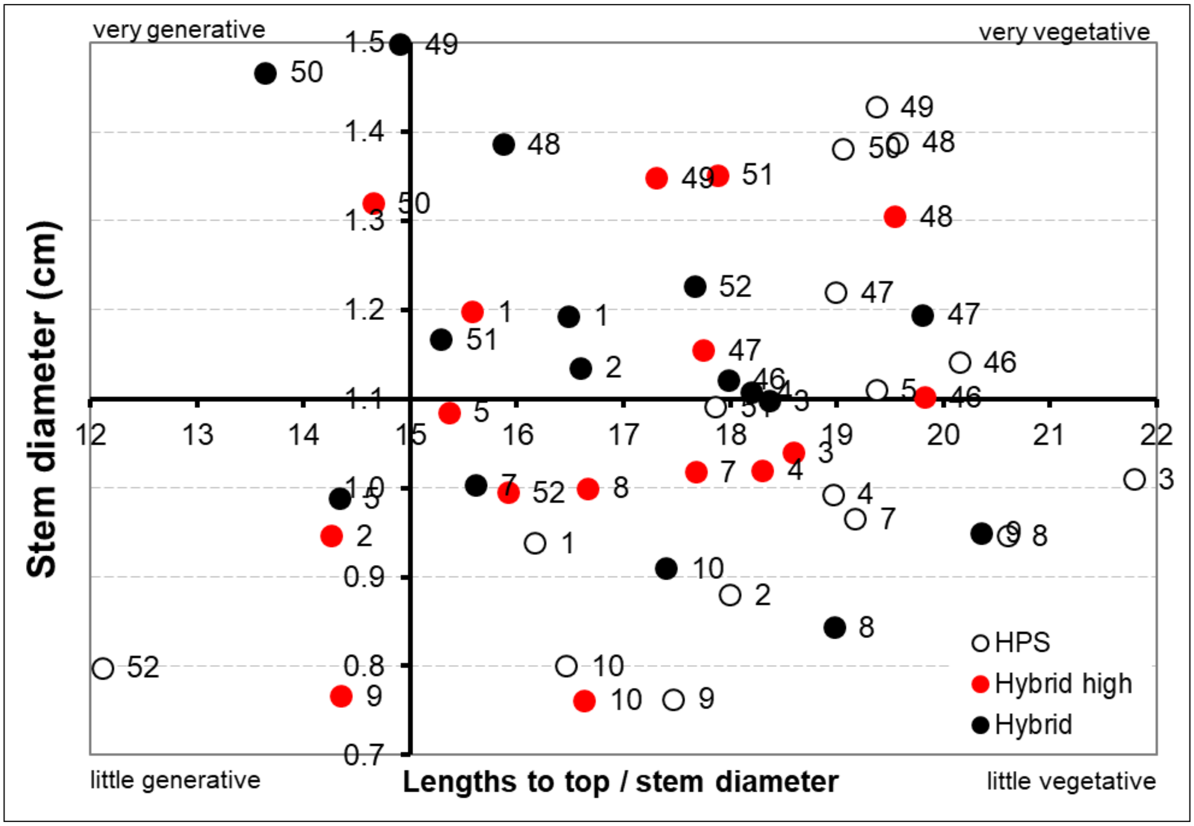


Fig. 21: Stem diameter and quotient lengths to top and stem diameter.
Numbers are representing the week number.

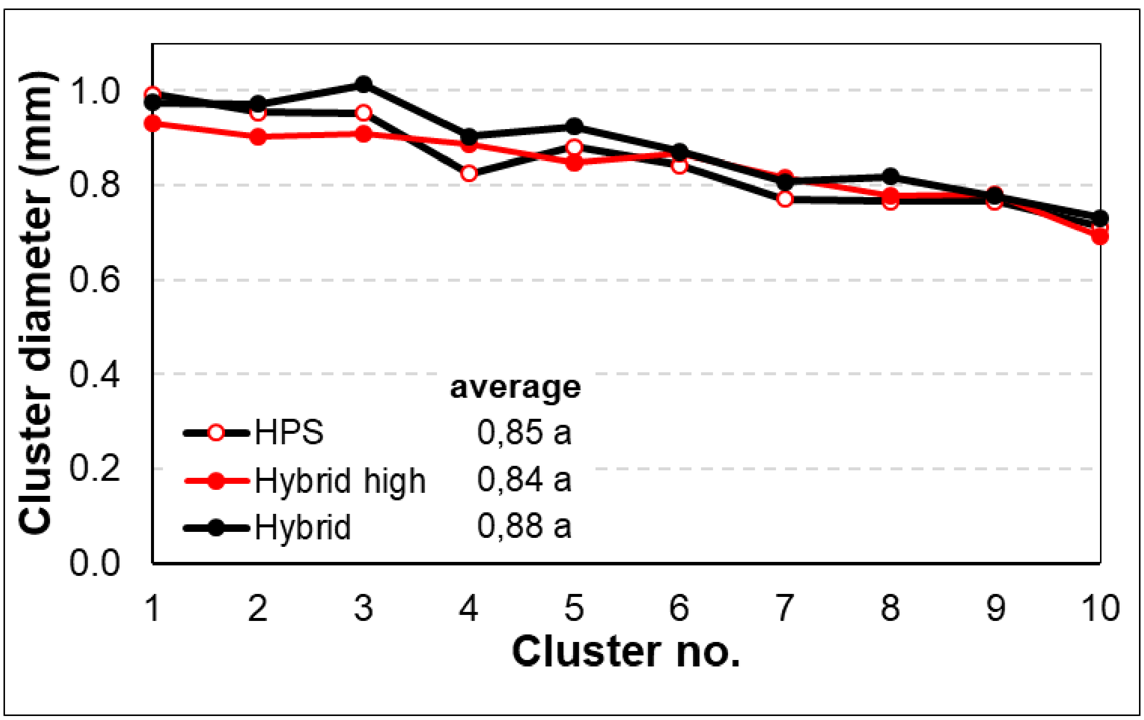


Fig. 22: Diameter of the uppermost flowering cluster.

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

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 27-32 kg/m^2 (Fig. 23). In total the cumulative total yield of tomatoes was independent of the light treatment ("HPS" versus "Hybrid"), but significantly lower when lights were mounted higher. However, the 1. class yield and the 2. class yield was affected by the light treatment. Under "Hybrid high" significantly lower 1. class yield was measured than under "Hybrid", whereas the 2. class yield was independent of the height of the lights. A significantly higher 2. class yield was measured under "HPS" compared to "Hybrid". In contrast, the too little fruits as well as the green fruits were neither affected by the light source nor by the height of the lights.

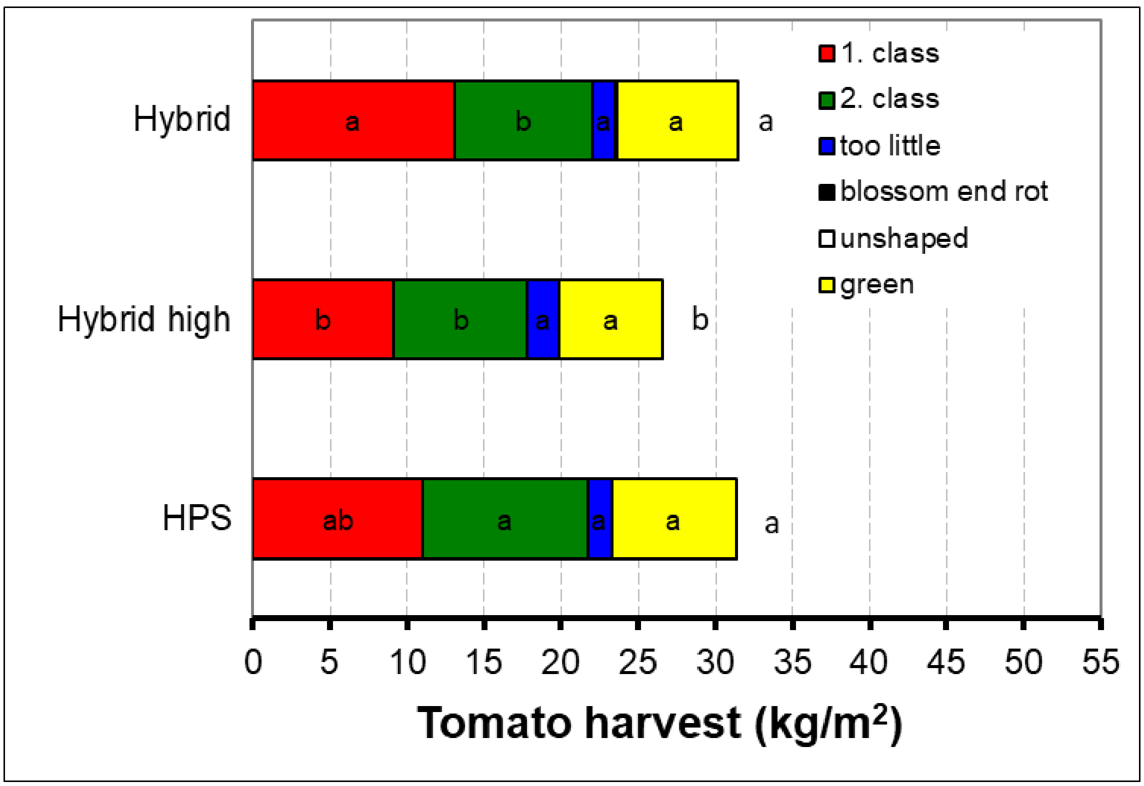


Fig. 23: Cumulative total yield of tomatoes in kg.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

The total amount of fruits harvested was independent of the light source and the height of the lights. While the number of 1. class fruits, too little fruits and green fruits was independent of the light treatment, was the amount of 2. class fruits significantly higher under “HPS” compared to “Hybrid”, whereas the number was not influenced by the height of the lights (Fig. 24).

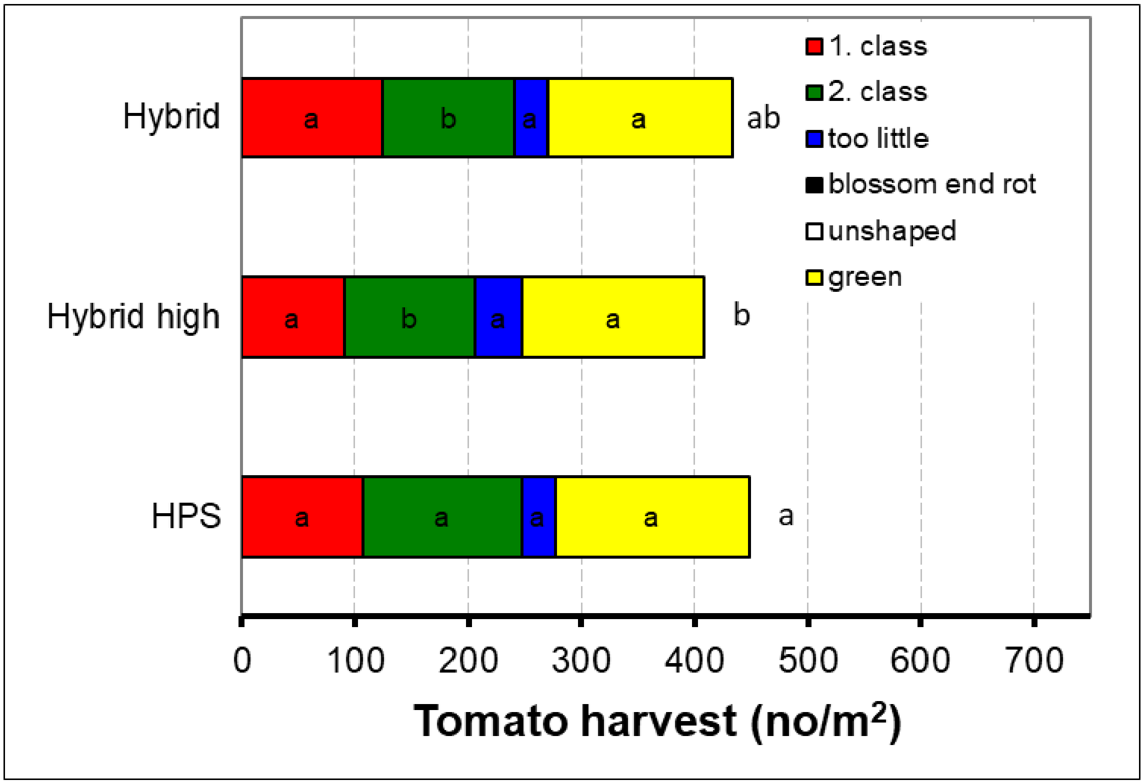


Fig. 24: Cumulative total yield of tomatoes in number.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

4.3.2 Marketable yield of tomatoes

Plants that received HPS or Hybrid lights, where the distance between light and plants was reduced, started to give red fruits about half a week earlier than plants where Hybrid lights were mounted higher. At the end of the harvest period amounted marketable yield of tomatoes 18-22 kg/m^2 (Fig. 25). No significant differences between light sources (“HPS” versus “Hybrid”) were observed, whereas a significantly lower marketable yield was measured when the lights were mounted higher. This difference amounted about 20% less marketable yield at “Hybrid high” compared to “Hybrid”.

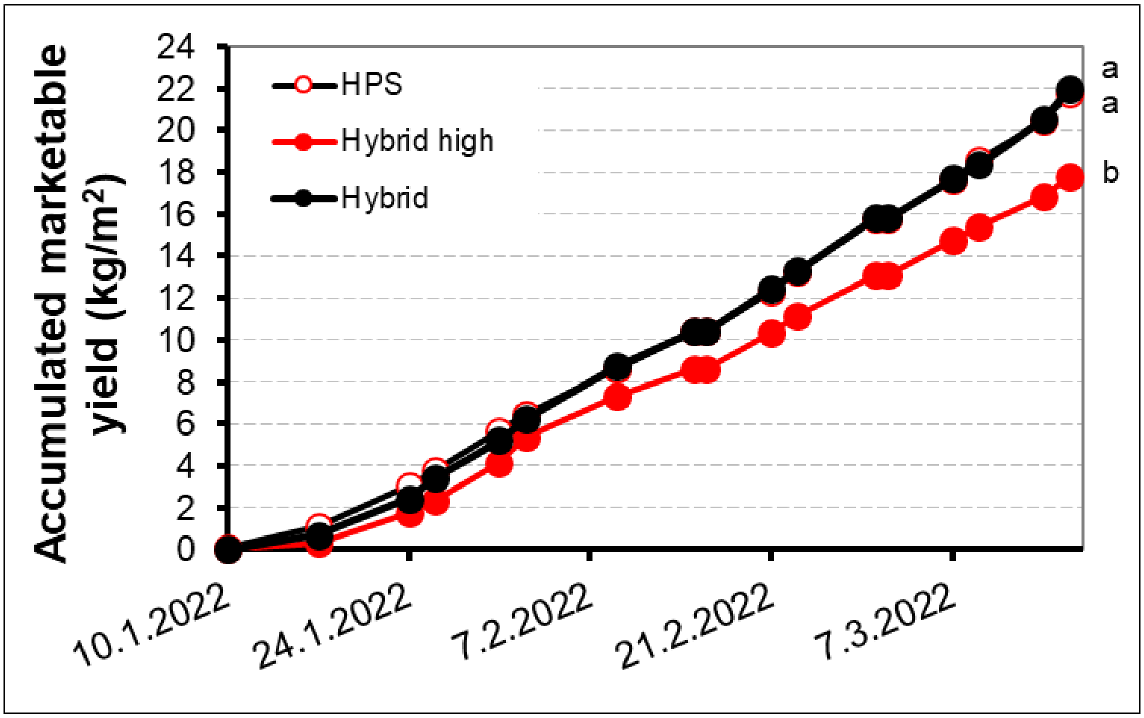


Fig. 25: Time course of marketable yield (1. and 2. class tomatoes).
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0{,}05$).

The 1. class yield amounted 9-13 kg/m^2 (Fig. 26) and the 2. class yield 9-11 kg/m^2 at the end of the harvest period (Fig. 27). The 1. class yield was not affected by the light source ("HPS" versus "Hybrid"). However, when Hybrid lights were mounted lower ("Hybrid") a significantly higher 1. class yield was reached compared to when Hybrid lights were mounted higher ("Hybrid high"). This difference amounted about 30%. In contrast, the 2. class yield was independent of the height of the lights. However, the 2. class yield was significantly higher when plants received HPS lights compared to Hybrid lights (Fig. 27).

Also, the marketable yield of the whole chamber was measured (Fig. 28). A higher marketable yield was reached with "HPS" (5,5 kg/plant) and "Hybrid" (5,7 kg/plant) compared to "Hybrid high" (4,8 kg/plant).

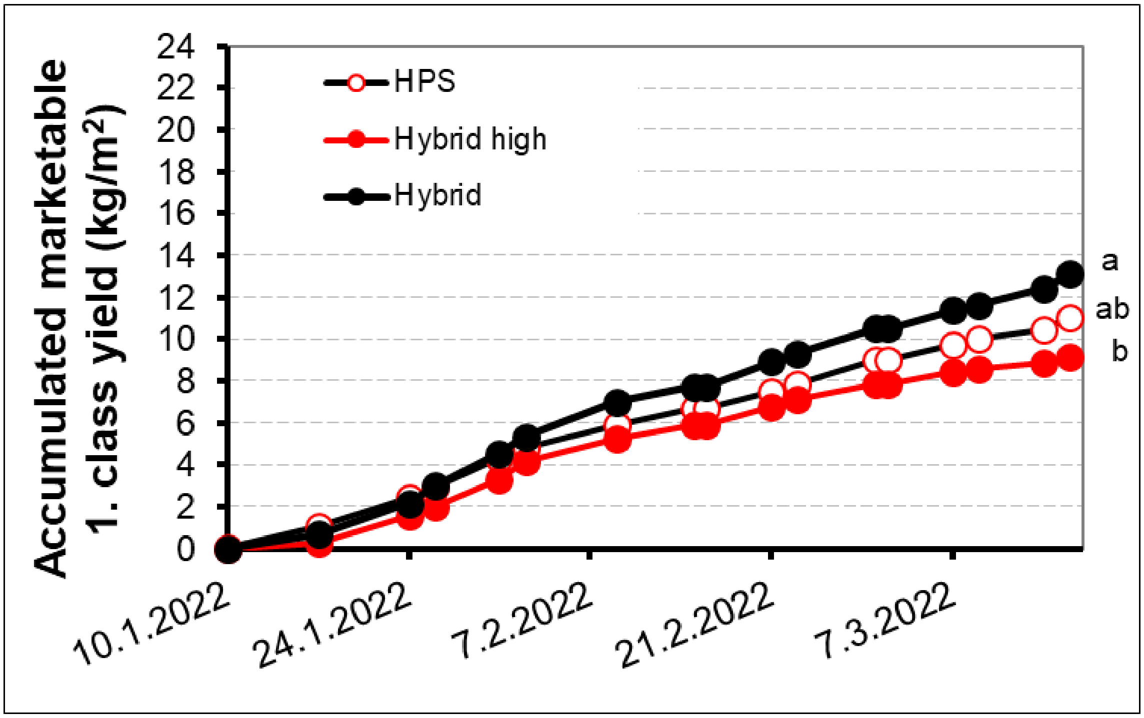


Fig. 26: Time course of marketable 1. class yield.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

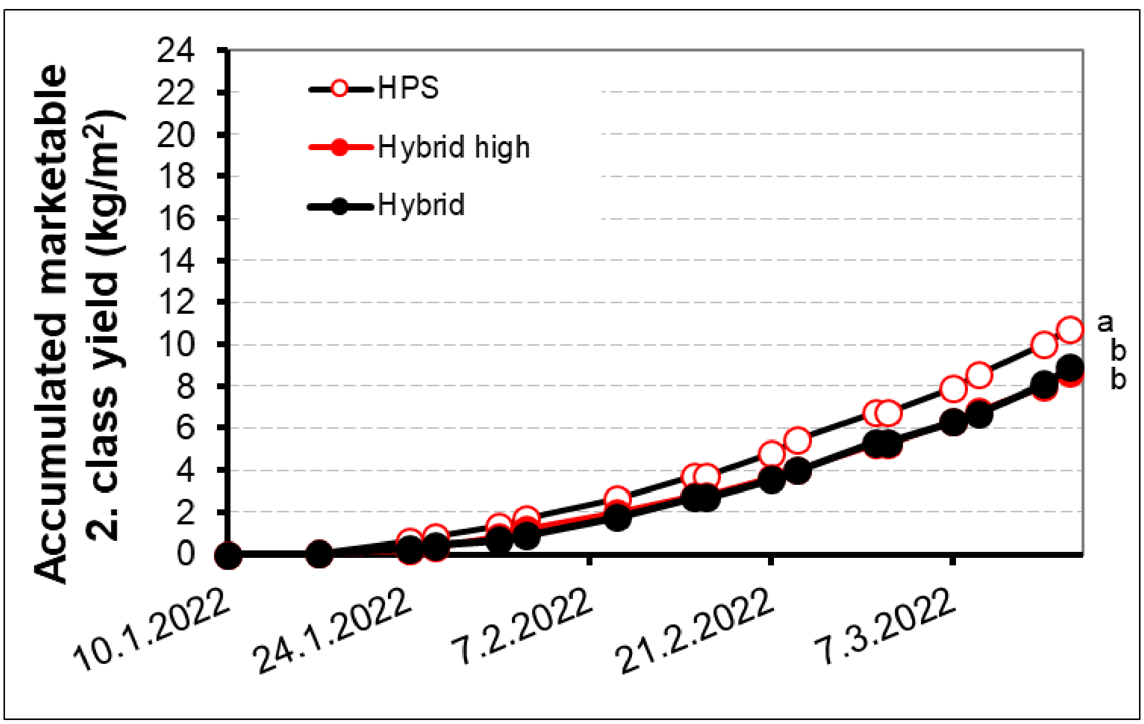


Fig. 27: Time course of marketable 2. class yield.
Letters indicate significant differences at the end of the experiment (HSD, $p \leq 0,05$).

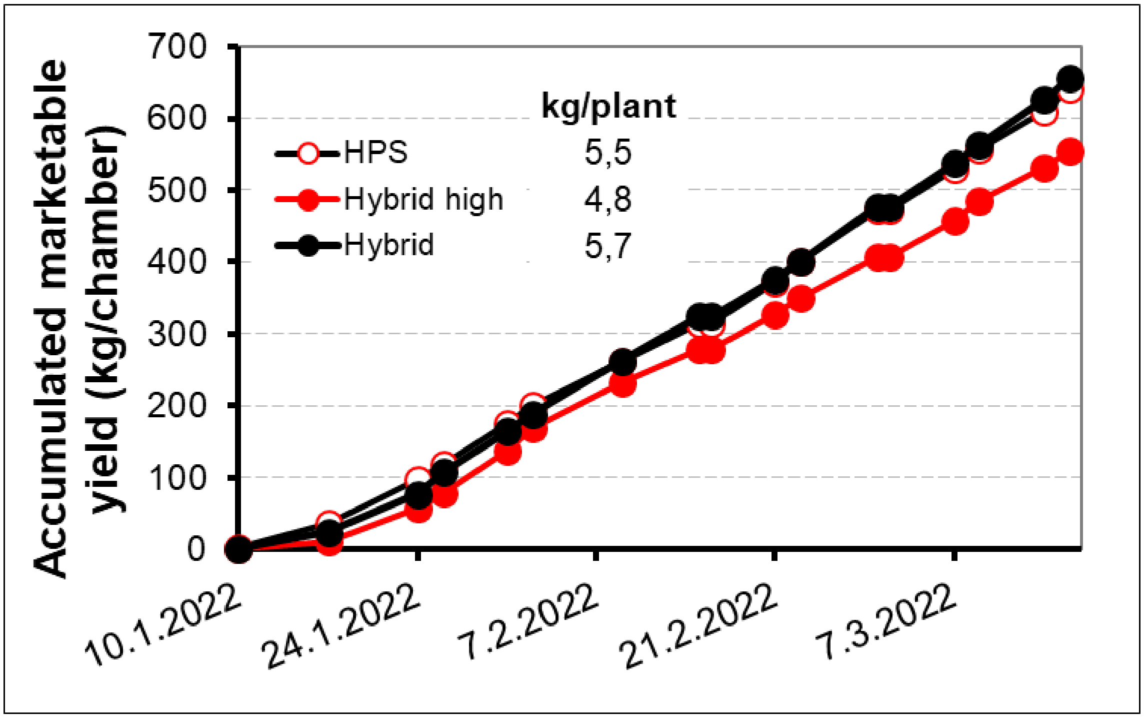


Fig. 28: Time course of marketable yield of tomatoes in the whole chamber.

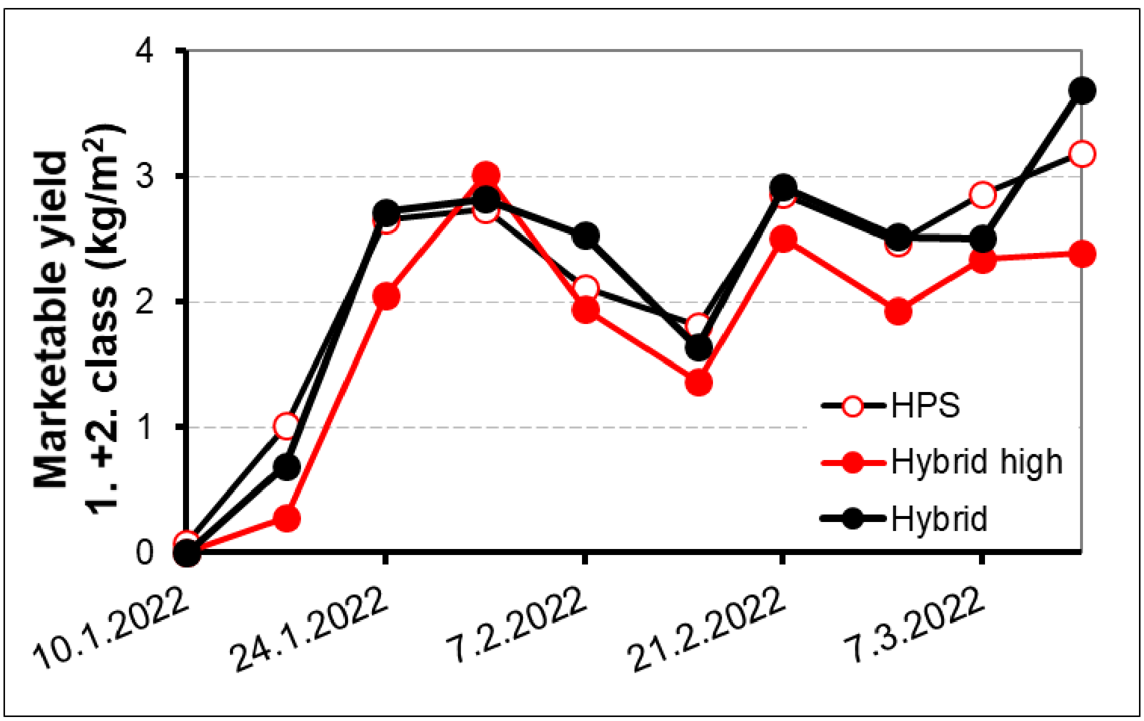


Fig. 29: Time course of marketable yield.

The weekly harvest of 1. class and 2. class fruits amounted 1,0-3,5 kg/m^2, but was most of the time 2,0-3,0 kg/m^2 (Fig. 29).

The number of 1. class fruits was independent of the light treatment (Tab. 5). The number of 1. class fruits was neither influenced by the light source nor by the height of the lights. The number of 2. class fruits was significantly higher in "HPS" than in the other light treatments. The total number of marketable fruits was neither significantly different between light sources ("HPS" versus "Hybrid") nor between different heights of the lights.

Tab. 5: Cumulative total number of marketable fruits.

Treatment	Number of marketable fruits		
	1. class (no/m^2)	2. class (no/m^2)	total (1. class + 2. class) (no/m^2)
HPS	107 a	140 a	247 a
Hybrid high	90 a	115 b	205 b
Hybrid	124 a	116 b	240 ab

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

Average fruit size of 1. class tomatoes varyied between 95-110 g / fruit and decreased slightly from 100-110 g / fruit to 95-100 g / fruit during the harvest period (Fig. 30). On average the weight of 1. class tomatoes was independent of the light source. However, when the lights were mounted higher, a significantly lower average size was measured.

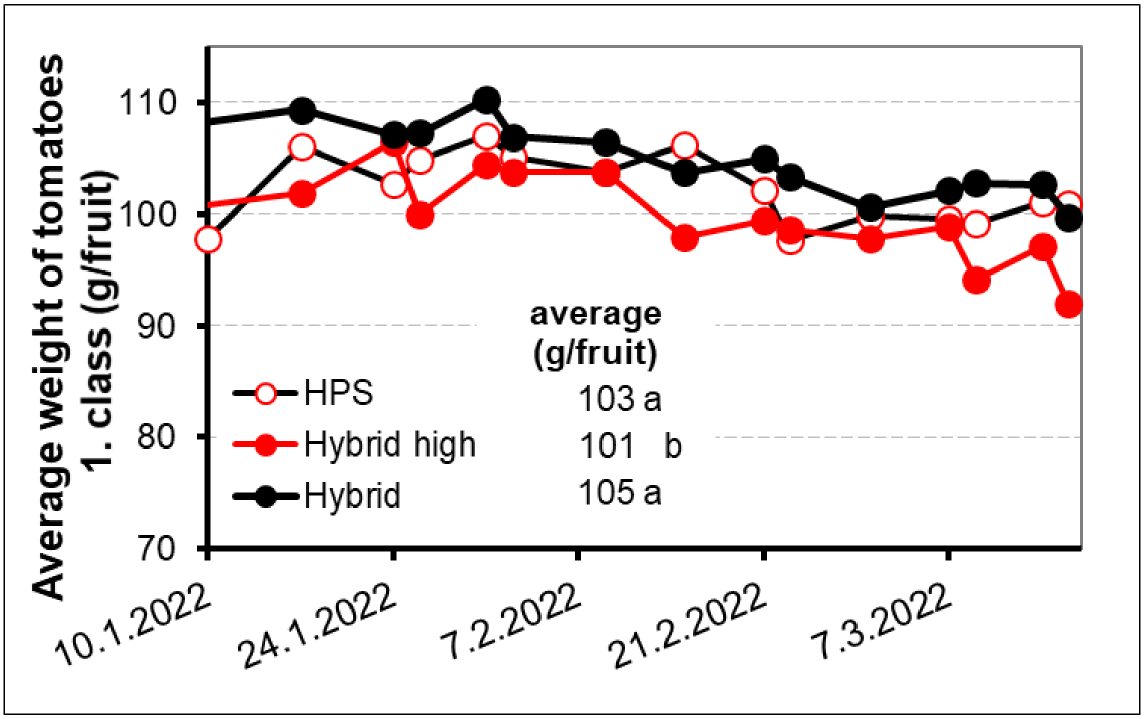


Fig. 30: Average weight of tomatoes (1. class fruits).

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

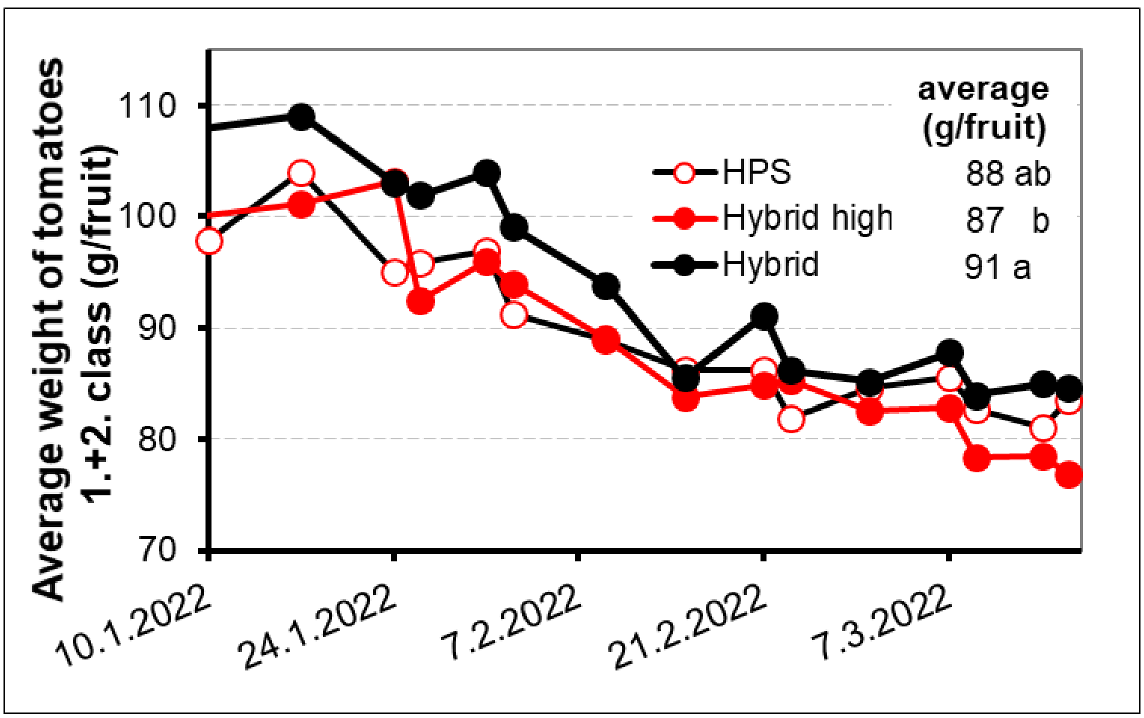


Fig. 31: Average weight of tomatoes (1. and 2. class fruits).

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

Average fruit size of 1. and 2. class tomatoes was varying between 80-110 g / fruit (Fig. 31). The fruit size decreased at proceeded harvest period from 100-110 g / fruit to 80-85 g / fruit. The light source did not affect average fruit size, even though a slightly higher average size of 3 g was found under Hybrid lights compared to HPS lights. In contrast, when lights were mounted higher, were significantly lighter fruits measured. This difference amounted 14 g.

4.3.3 Outer quality of yield

Marketable yield was around 70% of total yield for all light treatments (Tab. 6). The percentage of 1. class fruits, 2. class fruits and too little fruits was both independent of the light source as well as of the height of the lights. However, while "HPS" and "Hybrid high" had a comparable proportion of 1. and 2. class fruits, for "Hybrid" the proportion of 1. class fruits was higher than of 2. class fruits. Blossom end rot fruits as well as unshaped fruits had a proportion of zero on total yield. The proportion of green fruits on total yield was in all light treatments very high due to the fact that tomato plants were not topped and allowed to grow "naturally" until the end of the experiment. Therefore, the amount of green fruits was high as new clusters developed until the end of the experiment, which were then harvested as green fruits. The proportion of green fruits was comparable in all light treatments.

Tab. 6: Proportion of marketable and unmarketable yield.

Treatment	Marketable yield (%)		Unmarketable yield (%)			
	1. class > 55 mm	2. class > 45-55 mm	too little weight	blossom end rot	not well shaped	green
HPS	35 a	34 a	5 a	0 a	0 a	26 a
Hybrid high	34 a	33 a	8 a	0 a	0 a	25 a
Hybrid	42 a	28 a	5 a	0 a	0 a	25 a

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

4.3.4 Interior quality of yield – sugar content

Sugar content of tomatoes was measured two times during the harvest period. Completo had a sugar content of 3,2-3,6°BRIX. The sugar content was independent of the light treatment. However, the sugar content seems to be tendentially higher under HPS lights than under Hybrid lights (Fig. 32).

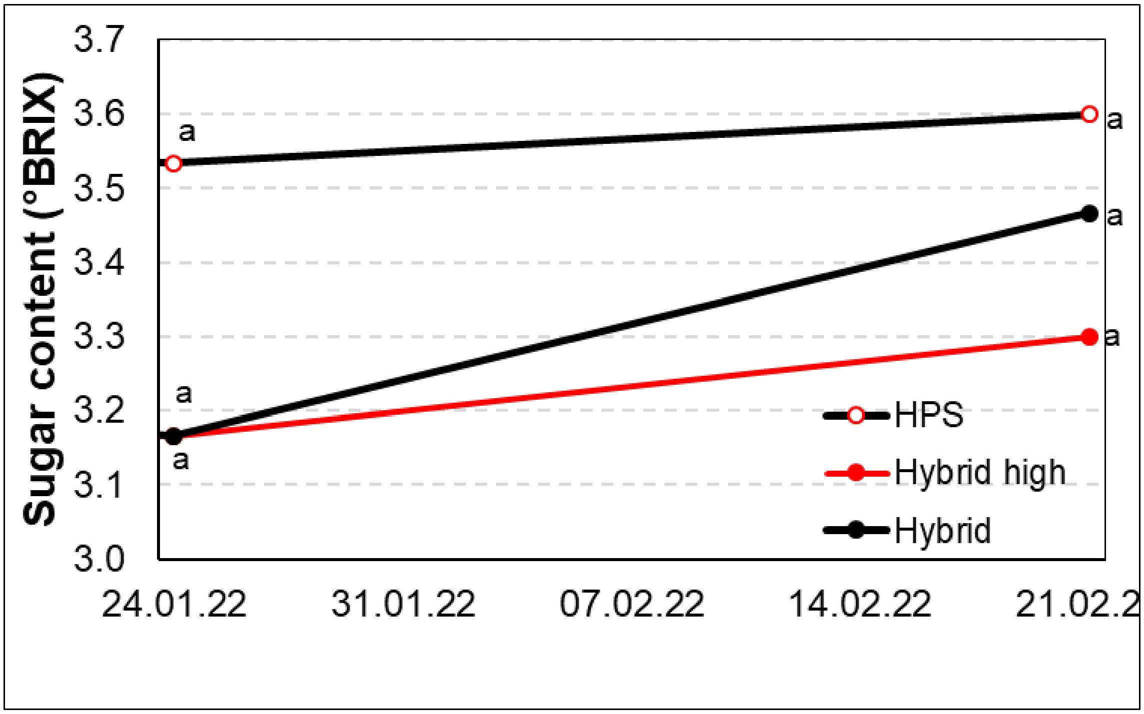


Fig. 32: Sugar content of tomatoes.

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

4.4 Economics

4.4.1 Used energy

The number of lighting hours is contributing to high annual costs and needs therefore special consideration to consider decreasing lighting costs per kg "yield". The total hours of lighting and the used kWh's during the growth period after transplanting were measured with dataloggers.

Production of tomatoes resulted in the "HPS" chamber in a daily usage of 235,9 kWh, in the "Hybrid high" chamber in a daily usage of 237,8 kWh and in the "Hybrid" chamber in a daily usage of 241,1 kWh (Tab. 7). This means that the costs for growing tomatoes were in all the light treatments comparable (Tab. 7).

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

Treatment	HPS	Hybrid high	Hybrid
Energy (kWh/day)	235,9	237,8	241,1
Energy (kWh/growth period)	29.959	29.961	29.965
Energy/m² (kWh/m²)	**571**	**571**	**571**

4.4.2 Energy use efficiency

When tomatoes were lightened with Hybrid lights that were placed high, were kWh's transferred less good into yield compared to Hybrid lights that were placed closer to the plants (Fig. 33). This difference amounted 20%. In contrast, the light source, HPS or Hybrid lights, had no influence on the energy use efficiency.

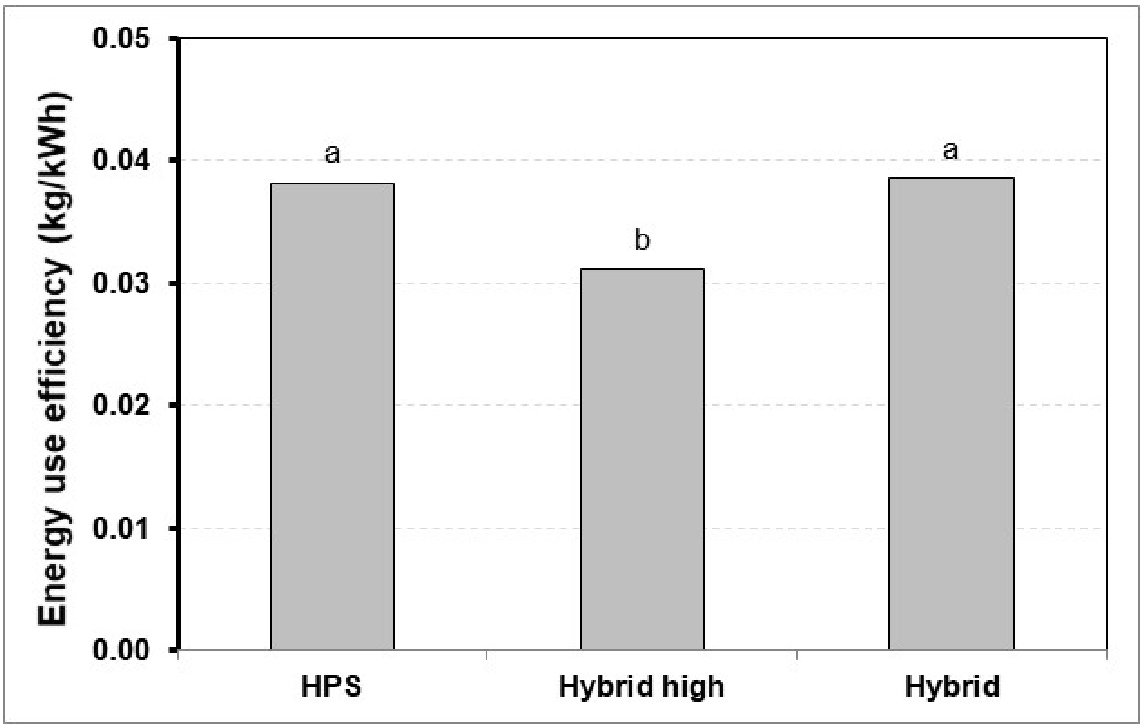


Fig. 33: Energy use efficiency (= marketable yield per used energy) for tomatoes under different light treatments.

4.4.3 Light related costs

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

The government subsidises the distribution cost of growers that comply to certain criterias. In recent years, the subsidies fluctuated quite much. After substitution / direct payment from the state of variable cost of distribution (95%) resulted in costs of about 1 ISK/kWh for distribution, while for the sale values amounted 5,89-7,49 ISK/kWh. However, it has to be taken into account that big vegetable growers can get at least 50% discount on the tariff values. Based on this information, were energy costs for tomato production calculated (Tab. 8). The electricity costs did not differ much between light treatments. In contrast, investments into lights were much lower for “HPS” than for “Hybrid high” and for “Hybrid”. The investment costs into lights more than doubled when Hybrid lights were used compared to only HPS lights (Fig. 34).

Tab. 8: Energy costs and investment into lights for one growing circle of tomatoes under different light treatments.

Costs (ISK/m^2)	HPS	Hybrid high	Hybrid
Electricity distribution [1]	571	571	571
Electricity sale [2]	3.363-4.277	3.363-4.277	3.363-4.277
∑ **Electricity costs**	3.934-4.848	3.934-4.848	3.934-4.848
Lamps [3]	944	2.738	2.738
Bulbs [4]	604	549	549
∑ **Investment lights**	1.548	3.287	3.287
Total light related costs	**5.482-6.396**	**7.221-8.135**	**7.221-8.135**

[1] Assumption: On average around 1 ISK/kWh after substitution / direct payment from the state

[2] Assumption: Around 5,89-7,49 ISK/kWh (according to data from Rarik in the year 2022)

[3] HPS lights: 25.760 ISK / 750 W lamp, 26.565 ISK / 1000 W lamp, lifetime: 8 years, LEDs: 50.000 ISK/lamp, lifetime: 11 years

[4] HPS bulbs: 5.474 ISK / 750 W bulb / 5.275 ISK / 1000 W bulb, lifetime: 2 years

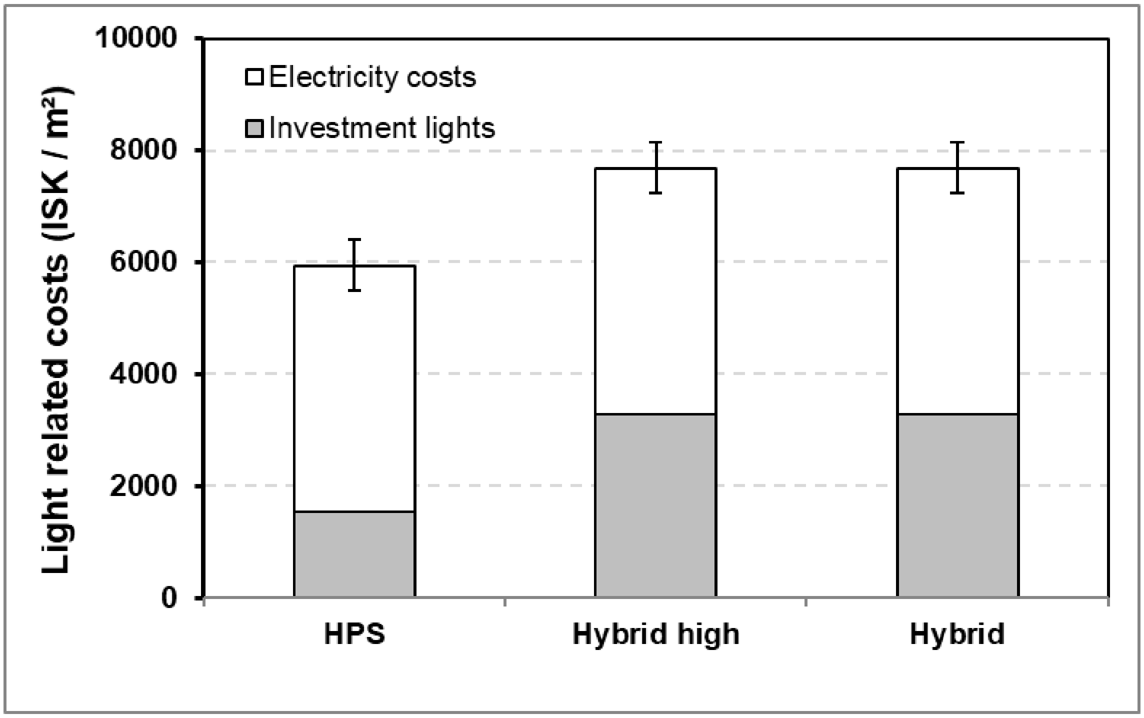


Fig. 34: Light related costs in tomato production under different light treatments.

4.4.4 Costs of electricity in relation to yield

Costs of electricity in relation to yield for wintergrown tomatoes were calculated (Tab. 9). The costs of electricity per kg yield increased by 22% when Hybrid lights were mounted high. In contrast, the light source had no influence on the costs of electricity in relation to yield.

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

Treatment	HPS	Hybrid high	Hybrid
Yield (kg/m^2)	21,8	17,8	22,0
Electricity costs (ISK/kg yield)	188-222	221-272	179-220

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 590 ISK from Sölufélag garðyrkjumanna (SFG, The Horticulturists' Sales Company) and in addition about 113 ISK from the government.

Therefore, the revenues increased with more yield (Fig. 35). The light source had no influence on the revenue, whereas a higher profit margin was reached by having the lights closer to the plants.

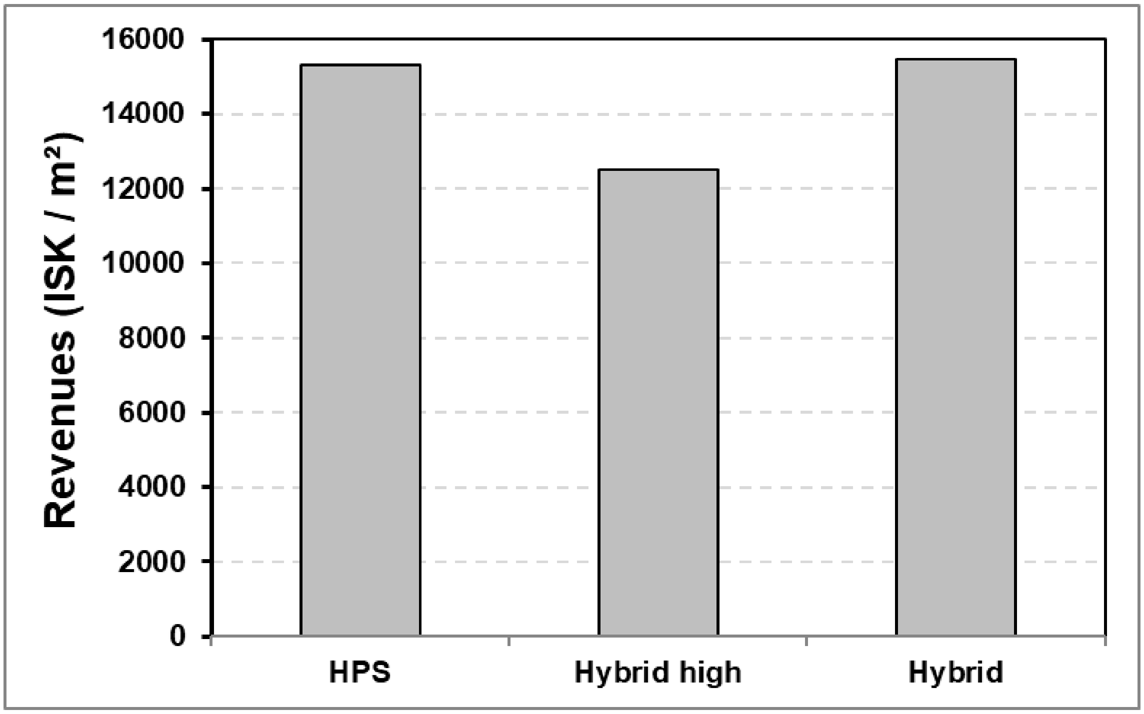


Fig. 35: Revenues at different light treatments.

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, those are e.g. the costs for seeds and seedling production (≈ 350 ISK/m^2) and transplanting (≈ 480 ISK/m^2), costs for gutters (≈ 100 ISK/m^2), and watering system (≈ 350 ISK/m^2), costs for plant nutrition (≈ 370 ISK/m^2), costs for plant protection (≈ 30 ISK/m^2), truss support (≈ 70 ISK/m^2), CO_2 transport (≈ 260 ISK/m^2), liquid CO_2 (≈ 2.600 ISK/m^2), the rent of the tank (≈ 440 ISK/m^2), the rent of the green box (≈ 170 ISK/m^2), material for packing (≈ 800 ISK/m^2), packing costs with the machine from SFG (≈ 330 ISK/m^2) and transport costs from SFG (≈ 260 ISK/m^2) (Fig. 36).

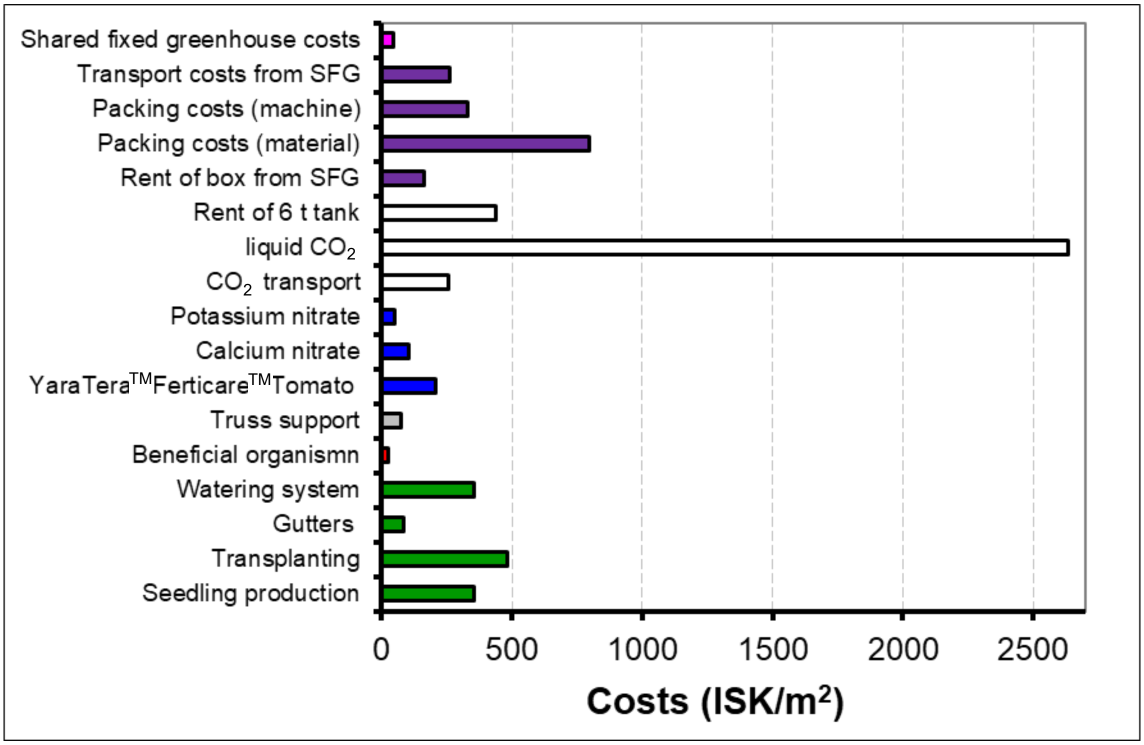


Fig. 36: Variable and fixed costs (without lighting and labour costs).

However, in Fig. 36 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. 37 and it is obvious, that especially the electricity and the investment in lamps and bulbs as well as the CO_2 and labour costs are contributing much to the variable and fixed costs beside the costs for seedling production, transplanting and cultivation and the costs for packing and marketing. The proportion of the variable and fixed costs is mainly the same for all light treatments. Attention has to be paid on the big proportion of 40-47% of light related costs (electricity + investment into lamps and bulbs) on total production costs. With a use of HPS lights instead of Hybrid lights decreased the costs of investment into lamps and bulbs from 20% to 10%. The proportion of the other costs is comparable for all light treatments.

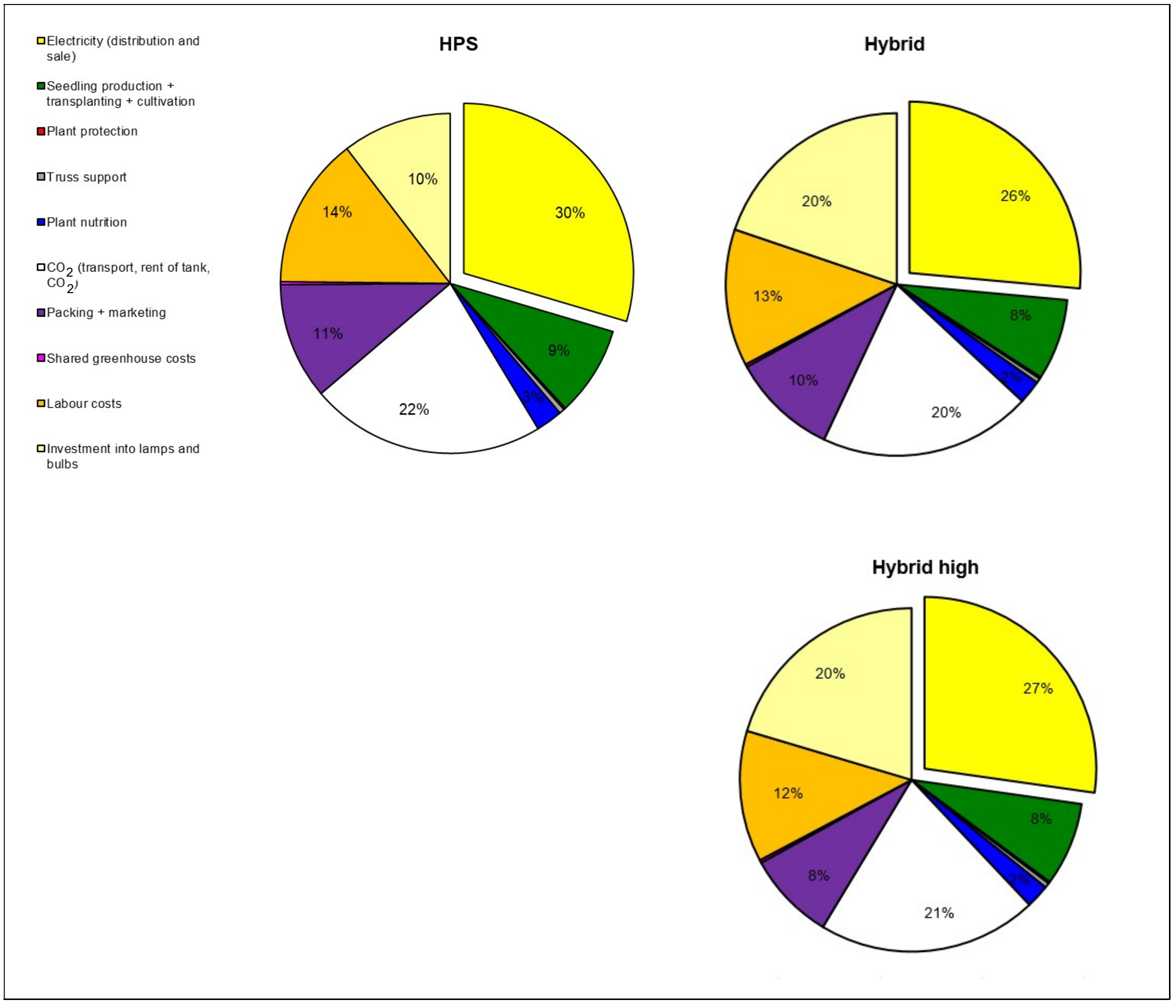


Fig. 37: Division of variable and fixed costs.

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

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

Treatment	HPS	Hybrid high	Hybrid
Marketable yield (kg/m^2)	21,8	17,8	22,0
Sales			
SFG (ISK/kg) [1]	590	590	590
Government (ISK/kg) [2]	112,84	112,84	112,84
Revenues (ISK/m^2)	**15.322**	**12.511**	**15.462**
Variable and fixed costs (ISK/m^2)			
Electricity distribution [3]	571	571	571
Electricity sale [4]	3.363-4.277	3.363-4.277	3.363-4.277
Seeds [5]	192	192	192
Grodan small [6]	13	13	13
Grodan big [7]	149	149	149
Slab [8]	397	397	397
Strings [9]	84	84	84
Gutters [10]	85	85	85
Watering system	353	353	353
Beneficial organismn [11]	26	26	26
Truss support [12]	74	74	74
YaraTera™Ferticare™ Tomato[13]	214	202	209
Potassium nitrate [14]	109	103	106
Calcium nitrate [15]	53	51	53
CO_2 transport [16]	256	256	256
Liquid CO_2 [17]	2.636	2.636	2.636
Rent of CO_2 tank [18]	440	440	440
Rent of box from SFG [19]	176	143	177
Packing material [20]	847	692	855
Packing (labour + machine) [21]	349	285	352
Transport from SFG [22]	276	225	278
Shared fixed costs [23]	43	43	43
Lamps [24]	944	2.738	2.738
Bulbs [25]	604	549	549
∑ variable costs	**12.252-13.166**	**13.670-14.594**	**13.958-14.912**
Revenues -∑ variable costs	**3.070-2.156**	**-1.159- -2.073**	**1.464-550**
Working hours (h/m^2)	0,96	0,90	0,97
Salary (ISK/h)	2.221	2.221	2.221
Labour costs (ISK/m^2)	2.140	1.991	2.147
Profit margin (ISK/m^2)	**930-16**	**-3.151- -4.065**	**-683- -1.597**

[1] Price winter 2021/2022: 590 ISK/kg

[2] Price for 2021: 112,84 ISK/kg

[3] Assumption: On average around 1 ISK/kWh after substitution / direct payment from the state

[4] Assumption: Around 5,89-7,49 ISK/kWh (according to data from Rarik in the year 2022)

[5] 76.880 ISK / 1.000 Completo seeds

[6] 36x36x40mm, 1.100 ISK / 220 Grodan small

[7] 27/35, 48 ISK / 1 Grodan big

[8] 50x24x10cm, 512 ISK/slab
[9] 27 ISK / string
[10] 4.388 ISK / m gutter; assumption: 10 years lifetime, 1,33 circles / year
[11] 3.956 ISK / unit parasitic wasps (*Encarsia formosa*), twice
[11] 2 ISK / truss support
[13] 7.275 ISK / 25 kg YaraTera™ Ferticare™ Tomato
[14] 5.225 ISK / 25 kg Potassium nitrate
[15] 3.050 ISK / 25 kg Calcium nitrate
[16] CO_2 transport from Rvk to Hveragerði / Flúðir: 9,34 ISK/kg CO_2
[17] Liquid CO_2: 77,39 ISK/kg CO_2
[18] Rent for 6 t tank: 80.000 ISK/mon, assumption: rent in relation to 1.000 m^2 lightened area
[19] 104 ISK / box
[20] Packing costs (material):
Costs for packing of tomatoes (1,00 kg): Platter: 21 ISK / kg,
plastic film: 11 ISK / kg,
label: 2 ISK / kg
[21] Packing costs (labour + machine): 16 ISK / kg
[22] Transport costs from SFG: 10,2 ISK / kg
[23] 94 ISK/m^2/year for common electricity, real property and maintenance
[24] HPS lights 750 W: 25.760 ISK/lamp, lifetime: 8 years
HPS lights 1000 W: 26.565 ISK/lamp, lifetime: 8 years
LED top lights: 50.000 ISK/lamp, lifetime: 11 years
[25] HPS bulbs: 5.474 ISK / 750 W bulb, 5.275 ISK / 1000 W bulb, lifetime: 2 years

The profit margin was dependent on the light treatment and was varying between 900 to -4.100 ISK/m^2 (Fig. 38). The profit margin was lower under the treatment where the Hybrid lights were mounted higher (-3.200 to -4.100 ISK/m^2) than under treatments where Hybrid lights were mounted lower (-700 to -1.600 ISK/m^2). That means by lowering the lights closer to the plants profit margin increased by 2.500 ISK/m^2. When some of the HPS lights were replaced by LED top lights profit margin decreased by 1.600 ISK/m^2 and reached -700 ISK/m^2 instead of 900 ISK/m^2, respectively -1.600 ISK/m^2 instead of 0 ISK/m^2. However, it must be taken into account that the profit margin depends much on the actual price of the LEDs in the Hybrid treatments.

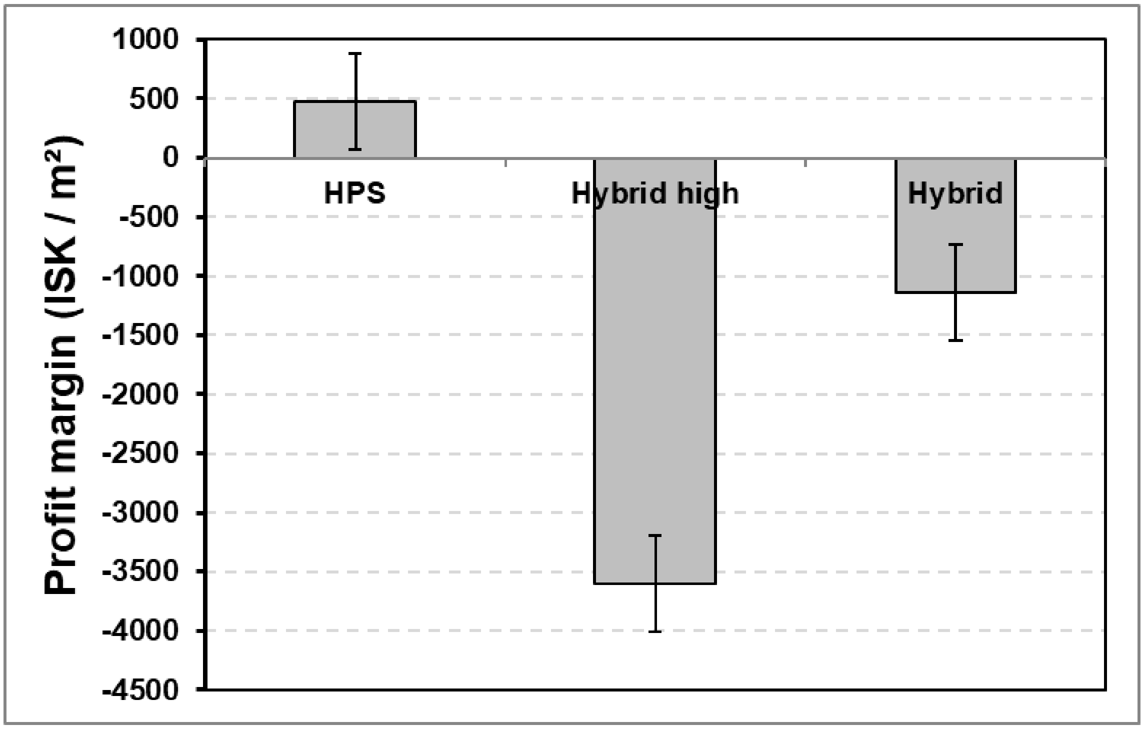


Fig. 38: Profit margin in relation to the light treatment.

5 DISCUSSION

In winter production, the success of vegetable growing strongly depends on supplemental lighting. In this experiment, the effect of two light sources and the effect of the height of the lights over the plant canopy was tested on tomatoes.

5.1 Yield in dependence of the light source

When tomatoes were lighted, either with HPS or Hybrid top lights with a distance of one meter between lights and plant canopy, a comparable µmol level between light sources was reached. Then, the beginning of harvest, the total and marketable yield of tomatoes and their number was independent of the light source. However, previous experiments have shown that the harvest was delayed when plants were grown under HPS lights compared to LEDs: The harvest started half a week earlier when tomatoes received LEDs in young plant production, but this advantage was not reflected in a higher marketable yield (*Stadler*, 2021b). Also, strawberry plants under HPS lights showed a delayed growth that was one week behind the development of strawberries treated with LEDs and increased temperature (*Stadler*, 2019), while strawberries in the LED treatment were delayed when temperature settings were the same, however with no yield differences between HPS and LEDs (*Stadler*, 2018). In contrast, 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 *Dysko* & *Kaniszewski* (2021) reported that tomato plants that got LEDs fruited earlier than plants that got HPS lights, thus increasing the early yield. In contrast, the authors did not observe an effect of the light source on yield of cucumbers. However, as in the presented experiment LED lights were used in combination with HPS lights, the effect of only LEDs on earliness might have been overshadowed.

While the temperature in the substrate was the same between the light sources, the leaf temperature was significantly lower under "Hybrid" compared to "HPS". *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 were increased compared to full HPS (HPS top and HPS interlights) and Hybrid (HPS top and LED interlights) lighting. The lower temperature might have decreased fruit growth of cucumbers in the LED treatment through reduced cell growth and indirectly through sink strength. Also, *Hernández* & *Kubota* (2015) attributed the 28% greater shoot dry mass of cucumber transplants, the 28-32% higher shoot fresh weight and the 9-12% higher leaf number under HPS lights compared to the LED treatments (blue LED, red LED) to the higher canopy air temperature. Indeed, *Davis* & *Burns* (2016) reported that in all experiments that compare HPS and LED light there is a need to assess the differences in plant temperature to ensure that any effect of temperature can be seperated from the effects of light on plants responses. The authors concluded that the switch from HPS to LED lighting would require a period of learning to develop protocols for correct management of plant irrigation and growth. For example, *Kowalczyk* et al. (2018) draw the conclusion to increase the density of cucumbers when providing LED lighting. However, as in the present experiment were LED in combination with HPS lights used and therefore, the influence of only LEDs was overshadowed. In addition, it seems to be not necessary in a Hybrid lighting system to increase the floor temperature or day temperature to compensate for additional radiation heat of the HPS lights as it has been recommended earlier for the only use of LEDs. However, this kind of operation was necessary to prevent a harvest delay under only LED lights (*Stadler*, 2018). Indeed, *van Delm* et al. (2016) concluded that the regulation of temperature and lighting strategy seems to be important for plant balance between earliness and total yield.

While light quality did not affect yield, it had an influence on the appearance of the plant. The weekly growth and with that the total height of the tomato plant and the distance between clusters was significantly increased when plants received HPS lights compared to Hybrid lights. This is in accordance with *Stadler* (2020) who reported that the distance between tomato clusters and the length of clusters was significantly higher under HPS top lighting. Tomato plants were growing significantly more each week and showed consequently significantly tallest plants compared to LED top lighting. Also, *Trouwborst* et al. (2010) measured a lower plant length of cucumbers under LEDs. Tomatoes that received LEDs in young plant production were more compact than tomatoes that received HPS lights in young plant production (*Stadler*, 2021a; *Stadler*, 2021b).

With LED lighting LED glasses were needed to distinguish between ripe and not ripe fruits. For strawberries the maintenance of the crop and the harvest were 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 as well as under Hybrid lights compared to only LED lights.

The BRIX content of the tomatoes was not influenced by the light treatment, which was in accordance with *Stadler* (2021b). *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 *Hanenberg* et al. (2016) also mentioned that it was possible to increase the taste of strawberries by using LED lights.

The use of HPS lights resulted in a 1.600 ISK/m^2 higher profit margin than the use of Hybrid lights (Fig. 39). The yield was reduced by 0,2 kg/m^2. When the yield of the

Hybrid treatment would have been nearly 3 kg/m^2 higher, would the profit margin have been comparable to the treatments that received HPS lights. However, the profit margin was negative for the Hybrid treatment. To be able to get a positive profit margin would a yield increase be necessary: Yield must reach nearly 24 kg/m^2.

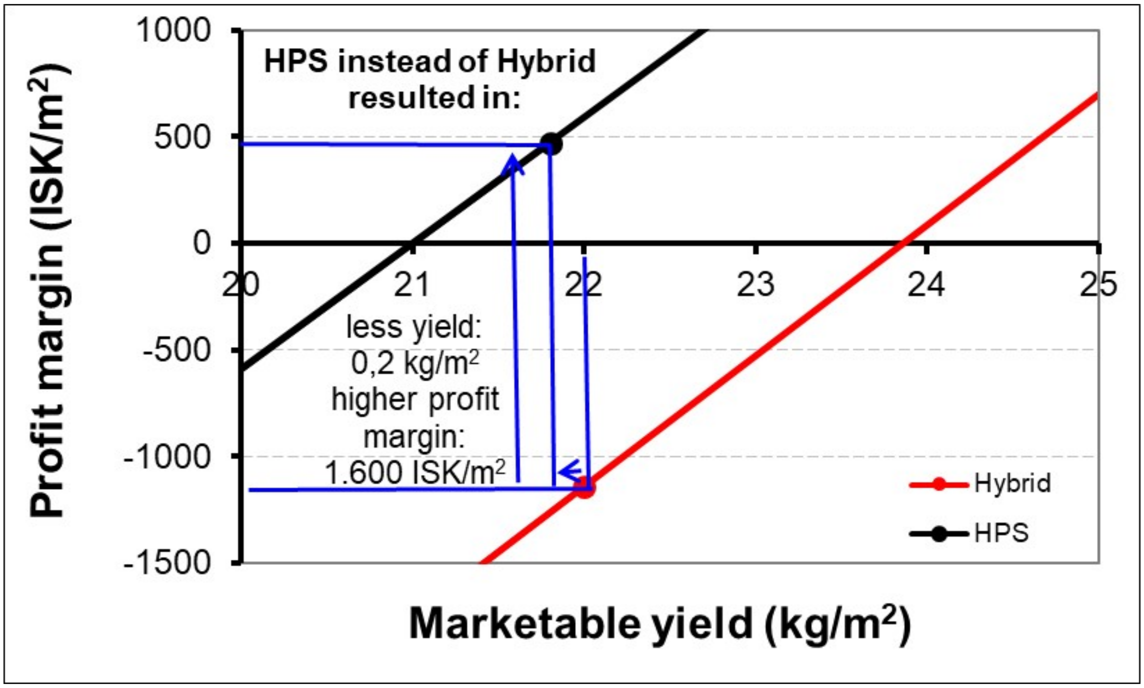


Fig. 39: Profit margin in relation to yield with different light sources in tomato production – calculation scenarios.

Dueck et al. (2012b) reported that the production under LEDs was lower than under HPS, but LEDs saved 30% of dehumidification and heat energy and 27% of electricity relative to the crop grown with HPS lights. *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 the light use efficiency (g fruit FW mol^{-1} PAR) was 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. The high investment costs for LEDs are one reason why it is more economic to invest rather in HPS lights with an electronic ballast and 1000 W bulbs instead of 750 W bulbs. *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 (*Appolloni* et al., 2021). 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. Despite of the fact that in a Hybrid system the effect of LEDs is less pronounced compared to the only use of LEDs, even less information is available regarding the effect of a mixed HPS + LED top lighting system (*Rakutko* et al., 2020). Therefore, the above stated conclusion is also valid for Hybrid lighting.

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. This is in accordance with *Dueck* et al. (2012a) who suggested that a combination of HPS and LEDs as top lighting is the most promising alternative for greenhouse grown tomatoes in the Netherlands when taking into consideration different production parameters and costs for lighting and heating. *Rakutko* et al. (2020) stated that the use of a Hybrid lighting system is the best available technique as it significantly increased the efficiency of light energy use by cultivated plants leading to shorter pre-fruiting period, higher plant productivity, improved commercial quality of fruits and higher sugar and vitamin content in them. *Verheul* et al. (2022) concluded that artificial HPS top lighting is more efficient for tomato production than LED interlighting. This was in accordance with recent experiments (*Stadler*, 2021b) as well as to the present experiment, where it is recommended to use rather LED lights as top lightings and no LED interlights. However, taking the investment costs into account, HPS top lights (1000 W) are rather recommended than a combination of HPS top lights (750 W) and LED top lights.

5.2 Yield in dependence of the height of the light source

By lowering the HPS lights in the Hybrid lighting treatment from 1,4 m distance between lights and plant canopy to 1,0 m it was possible to increase the photosynthetic photon flux density from 373 µmol/m^2/s to 454 µmol/m^2/s by nearly 100 µmol/m^2/s. With that was the substrate temperature significantly increased and a positive effect on yield was observed: Total yield, total number of fruits and marketable yield increased significantly. The yield increase was related to a higher first class yield due to a significantly higher average weight of the fruits. However, the number of marketable fruits was independent of the height of the light source, despite of a tendentially higher number of 1. class fruits when lights were lowered. The marketable yield was increased by more than 20% when Hybrid lights were mounted more closer to the plants. Indeed, also *Verheul* et al. (2022) observed a yield increase with a higher light intensity of HPS top lights or a combination of HPS top lights and LED interlights. However, in contrast to the presented results was the yield increase related to an increase in the number of harvested fruits, whereas the fruit weight was much less affected by a higher light intensity.

Moving the Hybrid lights closer to the plants resulted in a 2.500 ISK/m^2 higher profit margin (Fig. 40). The yield was increased by 4,2 kg/m^2. Therefore, it is highly recommended to move the lights closer to the lamps, as the µmol level increased and this resulted in an increase in yield and profit margin.

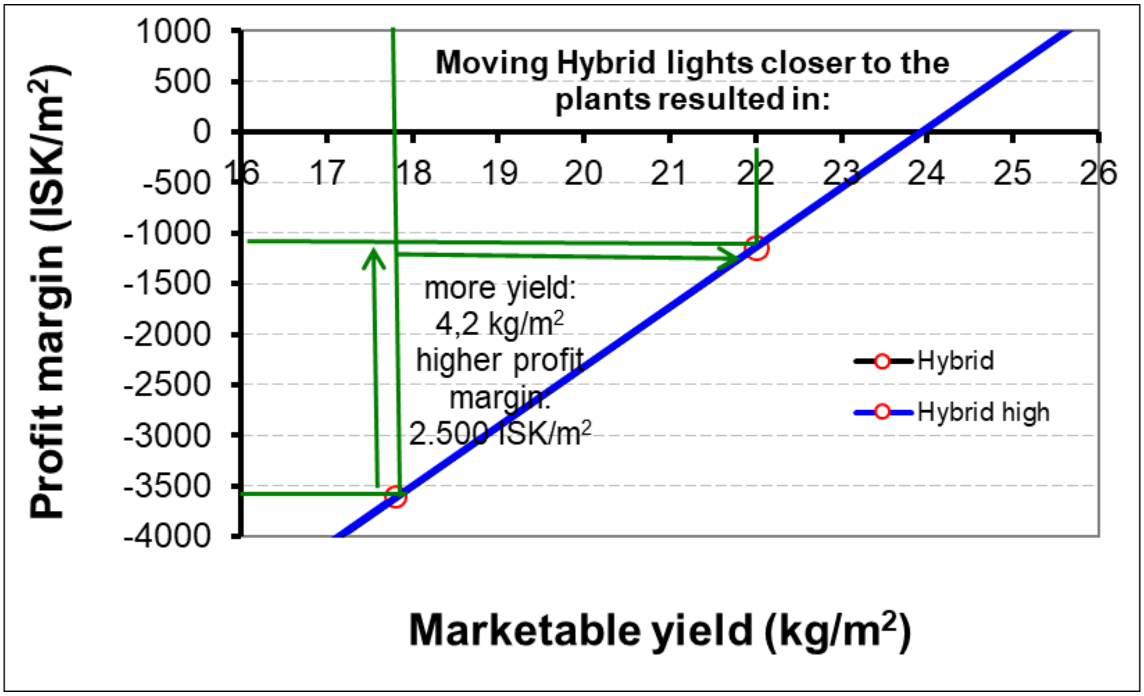


Fig. 40: Profit margin in relation to yield with different heights of the lights in tomato production – calculation scenarios.

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 "Hybrid high" with "Hybrid") 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*, 2013).

When the marketable yield per cluster was set into relation to the number of harvested clusters (Tab. 11), the marketable yield per cluster was not influenced by the light source, but by the height of the light source over the canopy, indicating that with a higher light level also a higher yield can be gained.

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

Treatment	HPS	Hybrid high	Hybrid
Yield (kg/m^2)	21,8	17,8	22,0
Harvested clusters (no/m^2)	26	25	26
Yield (kg/cluster)	0,84	0,71	0,85

BRIX content did not increase, when Hybrid lights were lowered and with that the µmol level increased. Indeed, also *Kowalczyk* et al. (2018) found that the taste desirability was similarly high for cucumbers irrespectively of HPS top lighting, HPS top lighting + LED interlighting or LED top lighting + LED interlighting. But *Verheul* et al. (2022) observed that with a higher amount of HPS top lights and LED interlights increased BRIX content in the fruits. This increase was related to an increase in dry matter content of the fruits.

It can be expected that a higher µmol level will cause a higher transpiration from the plants. The presented results show a higher humidity in the Hybrid treatment where a higher µmol level was reached by lowering the lamps.

As “Hybrid” and “Hybrid high” used the same energy, the energy use efficiency could be significantly increased by 20% by lowering the lamps and with that increasing the photosynthetic photon flux density. This was in accordance to results from *Verheul* et al., (2022) where a higher light intensity (242 W/m^2, HPS top lighting) used less energy per kg tomato produced compared to a lower light intensity (161 W/m^2, HPS top lighting). *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. In cucumbers, LED interlighting increased light use efficiency, mainly by increasing light reaching the inter canopy, compared with HPS top lights (*Hao* et al., 2014). Moreover, the response of cucumbers to LED interlighting could be optimized by using proper crop management (e.g. plant density) and ratio of top light / interlight. In contrast, in the presented experiment was the electricity per yield only dependend on the height of the lights and decreased with less distance between lights and plant canopy. Also, “Hybrid” transferred the used kWh’s better into yield than “Hybrid high”.

5.3 Future speculations concerning energy prices

When tomatoes were grown under HPS lights in young plant production, the energy costs were as high as under Hybrid lights. In contrast, *Stadler* (2020) reported higher savings with LED top lighting without compromising yield of tomatoes: Using LEDs was associated with about 40% lower daily usage of kWh's, resulting in lower expenses for the electricity compared to the use of HPS top lights. With the use of LED top lights were energy costs (distribution + sale) per kg yield lowered by 45% compared to the use of HPS lights. However, the investment into LEDs was nearly double the price as for HPS lights. Meaning the higher price of the LEDs compensated their lower use of electricity (*Stadler*, 2020). In contrast, in the presented experiment where the investment costs into Hybrid lights double the price as the treatment that received only HPS lights. The lower costs in HPS lights were reached by investing in 1000 W bulbs instead of 750 W bulbs as it was the case in the Hybrid light treatment. With that, a fewer number of lamps was needed to reach the same light level and with that could investment costs be lowered. This resulted in total light related costs that were more than 50% higher for “Hybrid” compared to “HPS”.

In terms of the economy of lighting it is also worth to make some future speculations about possible developments also regarding the fluctuation of the subsidy. So far, the lighting costs (electricity + bulbs) are contributing to a big part of the production costs of tomatoes. In the past and present, there have been and there are still a lot of discussions (for example in Bændablaðið, 11. tölublað 2022, blað nr. 612) concerning the energy prices. Therefore, it is necessary to highlight possible changes in the energy prices (Fig. 41). So far, the lighting costs are contributing to about 1/3 of the production costs.

The white columns are representing the profit margin according to Fig. 38. 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 -10.400 to -14.500 ISK/m^2 (black columns, Fig. 41). Without the subsidy of the state, probably less Icelandic growers would produce tomatoes over the winter months. When it is assumed that the energy costs, both in distribution and sale, would increase by 25%, but growers would still get the subsidy, then the profit margin would range between -770 to -4.800 ISK/m^2 (dotted columns). When it is assumed that growers must pay 25% less for the energy, the profit margin would increase to -2.400 to 1.700 ISK/m² (gray columns). From these scenarios, it can be concluded that from the grower's side it would be preferable to get subsidy to be able to get a higher profit margin and grow tomatoes over the winter. It is obvious that actions must be taken, that growers are also producing during the winter at low solar irradiation.

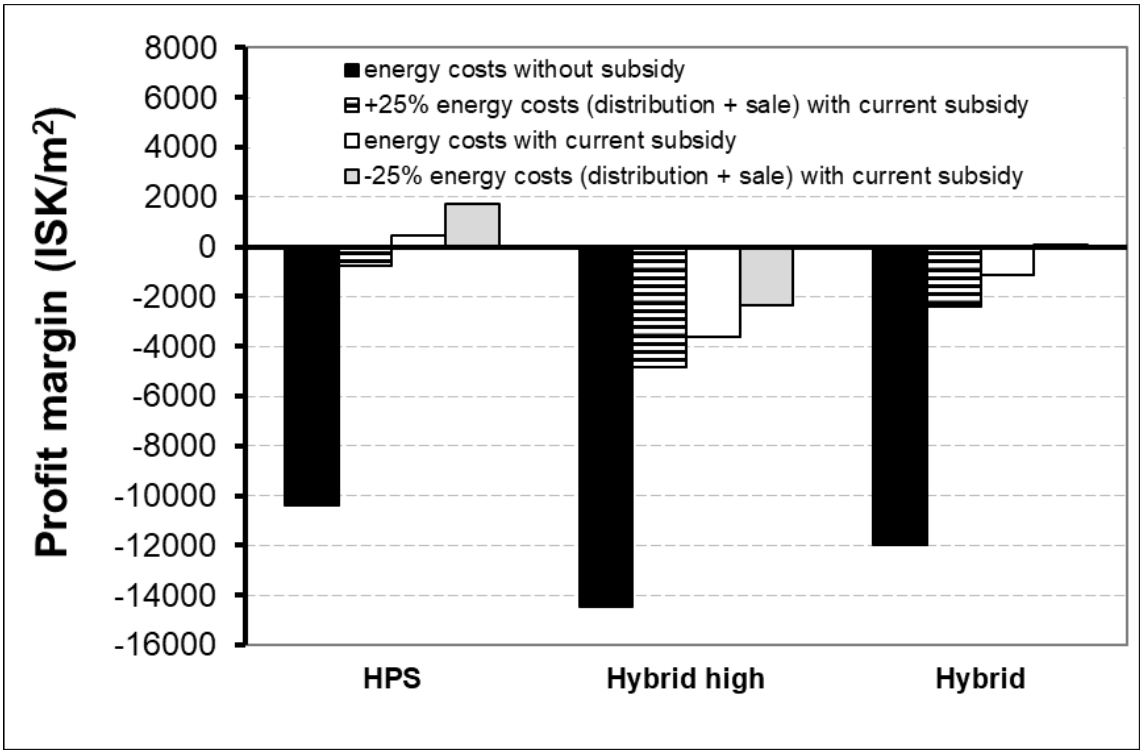


Fig. 41: Profit margin in relation to the light treatment – calculation scenarios.

5.4 Recommendations for increasing profit margin

The current economic situation for growing tomatoes necessitate for reducing production costs to be able to heighten profit margin for tomato production. On the other hand, growers need to decide, 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 through SFG).

2. Decrease plant nutrition costs

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

3. Lower CO_2 costs

   The costs of CO_2 are rather 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 position in the market 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 boxes are high. Costs could be decreased by using cheaper packing materials. Also, packing costs could be decreased when growers would do the packing on site.

5. Efficient employees

   The efficiency of each employee needs 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. It is often possible to optimize by not letting each employee doing each task, but to distribute tasks among employees by creating a flow line where employees become more specialized and thus achieve better productivity. 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 need to make sure that 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 best possible 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 at the most expensive time but have a high use during cheap times.
- Growers can save up to 8% of total energy costs by dividing the winter lighting over all day. That means growers should not let all lamps be turned on at the same time. This would be practicable, when they are growing in different independent greenhouses. Of course, this is not so easy to implement, when greenhouses are connected 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 day would pay off. However, a tomato experiment showed that the yield 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 hour's light. Also at high natural light, lamps would be turned off. In doing so, compared to the

traditional lighting system, profit margin could be increased by about 10% (assuming similar yield).

- For large growers, that are using a minimum of 2 GWh it could be recommended to change to “stórnotendataxti” in RARIK and save up to 35% of distribution costs.
- It is expected that growers are cleaning their lamps to make it possible, that all the lights are used effectively and that they are replacing their bulbs before the expensive season is starting.
- *Aikman* (1989) suggests using 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.
- By moving lights closer to the plants the µmol level is increasing. This is positively influencing yield and with that profit margin.
- By replacing 750 W bulbs by 1000 W bulbs less lights are necessary. With that the investment costs of lights can be reduced and a positive effect on profit margin was reached.
- The use of a high light level is required for getting a high yield and with that a positive profit margin.

6 CONCLUSIONS

The development of tomato plants was affected by the height of the lights over the plant canopy. When Hybrid lights were placed more further away from the plant, the photosynthetic photon flux density was naturally lowered, and the tomato harvest was delayed and a lower marketable yield was reached. In contrast, the yield was not affected by the light source, HPS or Hybrid.

The high capital costs into LEDs have been one important aspect delaying the LED technology in horticultural lighting as well as lack of knowledge on this light source to different plant species. This has been one of the reasons why a replacement of the HPS lamps by LEDs has not been recommended. As the combined light treatment ("Hybrid") resulted in a lower profit margin than "HPS", the results are not justifying replacing part of the HPS top lights by LED toplights as energy costs could also not be lowered. Therefore, from the economic side it can be recommended to rather invest in HPS lights with 1000 W bulbs instead of 750 W bulbs to reduce investment costs and place the lamps one meter over the plant canopy to be able to get a higher photosynthetic photon flux density and have a positive influence on yield and profit margin. 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.

APPOLLONI E, ORSINI F, PENNISI G, DURANY XG, PAUCEK I, GIANQUINTO G, 2021: Supplemental LED lighting effectively enhances the yield and quality of greenhouse truss tomato production: Results of a mata-analysis. Frontiers in Plant Science 12, 596927.

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.

DYSKO J, KANISZEWSKI S, 2021: Effects of LED and HPS lighting on the growth, seedling morphology and yield of greenhouse tomatoes and cucumbers. Horticultural Science 48, 22-29.

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.

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 CO_2 enrichment in model ecosystems. Adv. Space Res. 24, 281-291.

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.

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.

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.

PHILIPS, 2015: The ideal replacement for the incandescent lamp. http://www.lighting.philips.com/b-dam/b2b-li/en_AA/Experience/cases/Brook-berries/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.

RAKUTKO S, AVOTINS A, GRUDULS J, RAKUTKO E, 2020: Hybride irradiation as best available practice in artificial plant lighting. Engineering for rural development, 1076-1081.

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

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

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

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

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

STADLER C, 2021a: Áhrif LED topplýsingar á forræktun tómata, agúrku og papriku. Final report, Rit LbhÍ nr. 135.

STADLER, C., 2021b: Áhrif ljósmeðferðar í forræktun og lýsingarmeðferð í áframhaldandi ræktun á vöxt, uppskeru og gæði gróðurhúsatómata. Final report, Rit LbhÍ nr. 143.

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.

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.

VERHEUL MJ, MAESSEN HFR, PAPONIV M, PANOSYAN An, KECHASOV D, NASEER M, PAPONOV IA, 2022: Artificial top-light is more efficient for tomato production than inter-light. Scientia Horticulturae 291, 110537.

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

	HPS		Hybrid high		Hybrid	
Date	tasks	observations	tasks	observations	tasks	observations
09.11	transplanting, light from 3-19, 20°C/20°C (day/night), ventilation 24°C, underheat 35°C, 800 ppm CO_2 (600 ppm CO_2 with ventilation), humidity 75% (06-18, humification 1:30 min, 0,5-0,3 min in between) 300 ml H_2O/plant per day (watering from 05-18, 100 ml watering with 3 h in between)		transplanting, light from 3-19, 20°C/20°C (day/night), ventilation 24°C, underheat 35°C, 800 ppm CO_2 (600 ppm CO_2 with ventilation), humidity 75% (06-18, humification 1:30 min, 0,5-0,3 min in between) 300 ml H_2O/plant per day (watering from 05-18, 100 ml watering with 3 h in between)		transplanting, light from 3-19, 20°C/20°C (day/night), ventilation 24°C, underheat 35°C, 800 ppm CO_2 (600 ppm CO_2 with ventilation), humidity 75% (06-18, humification 1:30 min, 0,5-0,3 min in between) 300 ml H_2O/plant per day (watering from 05-18, 100 ml watering with 3 h in between)	
10.11						
11.11						
12.11						
13.11	handpollination	first flowers open	handpollination	first flowers open	handpollination	first flowers open
14.11	handpollination		handpollination		handpollination	
15.11	weekly measurement, measured leaf + soil temperature, handpollination		weekly measurements, measured leaf + soil temperature, handpollination		weekly measurements, measured leaf + soil temperature, handpollination	
16.11						
17.11						
18.11						
19.11						
20.11						
21.11						
22.11	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
23.11	watering for 2 min, interval 1 h		watering for 2 min, interval 1 h		watering for 2 min, interval 1 h	
24.11						

	HPS		Hybrid high		Hybrid	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
25.11						
26.11						
27.11						
28.11						
29.11	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
30.11	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
01.12						
02.12						
03.12						
04.12						
05.12						
06.12	weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom, removed leaf behind the cluster		weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom, removed leaf behind the cluster		weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom, removed leaf behind the cluster	
07.12	floortemperature 50°C, watering for 2 min, intervall 1 h		floortemperature 50°C, watering for 2 min, intervall 2 h		floortemperature 50°C, watering for 2 min, intervall 2 h	
08.12						
09.12						
10.12						
11.12						
12.12						
13.12	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
14.12						
15.12						
16.12						
17.12						

	HPS		Hybrid high		Hybrid	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
18.12						
19.12						
20.12	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
21.12	handpollination		handpollination		handpollination	
22.12	deleafed 2 leaves from the bottom	fertilizer mixture tank was not working (50% less watered)	deleafed 2 leaves from the bottom	fertilizer mixture tank was not working (50% less watered)	deleafed 2 leaves from the bottom	fertilizer mixture tank was not working (50% less watered)
23.12	removed leaf behind the cluster, handpollination	watering pump did not work (no watering): plant tops are flabby	removed leaf behind the cluster, handpollination	watering pump did not work (no watering): plant tops are less flabby than in “HPS”	removed leaf behind the cluster, handpollination	watering pump did not work (no watering): plant tops are less flabby than in “HPS”
24.12	handpollination, watering for 6 min, intervall 1 h		handpollination, watering for 6 min, intervall 1 h		handpollination, watering for 6 min, intervall 1 h	
25.12	fertilizer mixture changed, handpollination		fertilizer mixture changed, handpollination		fertilizer mixture changed, handpollination	
26.12	handpollination		handpollination		handpollination	
27.12	weekly measurements, measured leaf + soil temperature, handpollination, watering for 6 min, intervall 2 h	little development due to the event on 23.12	weekly measurements, measured leaf + soil temperature, handpollination, watering for 6 min, intervall 2 h	the event on the 23.12 seems to have no negative effect on the growth	weekly measurements, measured leaf + soil temperature, handpollination, watering for 6 min, intervall 2 h	the event on the 23.12 seems to have no negative effect on the growth
28.12	deleafed 2 leaves from the bottom, handpollination, watering for 6 min, intervall 1,5 h		deleafed 2 leaves from the bottom, handpollination, watering for 6 min, intervall 1,5 h		deleafed 2 leaves from the bottom, handpollination, watering for 6 min, intervall 1,5 h	
29.12		watering pump did not work		watering pump did not work		watering pump did not work
30.12	deleafed 1 leaf from the middle		deleafed 1 leaf from the middle		deleafed 1 leaf from the middle	
31.12	handpollination		handpollination		handpollination	

	HPS		Hybrid high		Hybrid	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
01.01						
02.01	handpollination		handpollination		handpollination	
03.01	weekly measurements, measured leaf + soil temperature, handpollination		weekly measurements, measured leaf + soil temperature, handpollination		weekly measurements, measured leaf + soil temperature, handpollination	
04.01	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
05.01	handpollination, En-Strip put out		handpollination, En-Strip put out		handpollination, En-Strip put out	
06.01	deleafed 1 leaf from the middle		deleafed 1 leaf from the middle		deleafed 1 leaf from the middle	
07.01	handpollination, night temperature 16-17°C (-2°C)		handpollination, night temperature 16-17°C (-2°C)		handpollination, night temperature 16-17°C (-2°C)	
08.01	handpollination		handpollination		handpollination	
09.01						
10.01	1. harvest, weekly measure-ments, measured leaf + soil temperature, 45°C heating pipes, handpollination		weekly measurements, measured leaf + soil temperature, 45°C heating pipes, handpollination		1. harvest, weekly measure-ments, measured leaf + soil temperature, 45°C heating pipes, handpollination	
11.01	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
12.01	handpollination, watering for 6 min, intervall 1,3 h		handpollination, watering for 6 min, intervall 1,3 h		handpollination, watering for 6 min, intervall 1,3 h	
13.01	handpollination, deleafed 1 leaf from the bottom		handpollination, deleafed 1 leaf from the bottom		handpollination, deleafed 1 leaf from the bottom	
14.01	handpollination		handpollination		handpollination	
15.01						
16.01						
17.01	harvest, weekly measure-ments, measured leaf + soil temperature		harvest, weekly measure-ments, measured leaf + soil temperature	more additional growth than in „HPS“	harvest, weekly measure-ments, measured leaf + soil temperature	more additional growth than in „HPS“
18.01	En-Strip put out, handpollination		En-Strip put out, handpollination		En-Strip put out, handpollination	
19.01	handpollination		handpollination		handpollination	

	HPS		Hybrid high		Hybrid	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
20.01	handpollination, removed leaf behind the cluster		handpollination, removed leaf behind the cluster,		handpollination, removed leaf behind the cluster,	
21.01	handpollination		handpollination		handpollination	
22.01						
23.01						
24.01	harvest, BRIX, weekly measurements, measured leaf + soil temperature, handpollination		harvest, BRIX, weekly measurements, measured leaf + soil temperature, handpollination		harvest, BRIX, weekly measurements, measured leaf + soil temperature, handpollination	
25.01	deleafed 2 leaves from the bottom, handpollination		deleafed 2 leaves from the bottom, handpollination		deleafed 2 leaves from the bottom, handpollination	
26.01	harvest, handpollination		harvest, handpollination		harvest, handpollination	
27.01	handpollination, removed leaf behind the cluster		handpollination, removed leaf behind the cluster		handpollination, removed leaf behind the cluster	
28.01						
29.01						
30.01						
31.01	harvest, weekly measure-ments, measured leaf + soil temperature		harvest, weekly measure-ments, measured leaf + soil temperature		harvest, weekly measure-ments, measured leaf + soil temperature	
01.02	handpollination		handpollination		handpollination	
02.02	harvest		harvest		harvest	
03.02	removed leaf behind the cluster		removed leaf behind the cluster		removed leaf behind the cluster	
04.02						
05.02						
06.02						
07.02	watering for 7 min, intervall 1,3 h		watering for 7 min, intervall 1,3 h		watering for 7 min, intervall 1,3 h	
08.02	harvest, weekly measure-ments, measured leaf + soil temperature		harvest, weekly measure-ments, measured leaf + soil temperature		harvest, weekly measure-ments, measured leaf + soil temperature	
09.02	harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom	
10.02						

	HPS		Hybrid high		Hybrid	
Date	tasks	observations	tasks	observations	tasks	observations
11.02	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
12.02						
13.02						
14.02						
15.02	harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom	
16.02						
17.02						
18.02	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
19.02						
20.02						
21.02	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
22.02						
23.02	harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom		harvest, deleafed 2 leaves from the bottom	
24.02	55°C heating pipes, additional watering (0,5 h before light is turned on and at 23)		55°C heating pipes, additional watering (0,5 h before light is turned on and at 23)		55°C heating pipes, additional watering (0,5 h before light is turned on and at 23)	
25.02						
26.02						
27.02						
28.02						
01.03	harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature		harvest, weekly measurements, measured leaf + soil temperature	
02.03	deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom		deleafed 2 leaves from the bottom	
03.03						
04.03	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	

	HPS		Hybrid high		Hybrid	
Date	**tasks**	**observations**	**tasks**	**observations**	**tasks**	**observations**
05.03						
06.03						
07.03	harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom, watering for 6 min, intervall 2 h		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom, watering for 6 min, intervall 2 h		harvest, weekly measurements, measured leaf + soil temperature, deleafed 2 leaves from the bottom, watering for 6 min, intervall 2 h	
08.03	watering for 7 min, intervall 1,5 h		watering for 7 min, intervall 1,5 h		watering for 7 min, intervall 1,5 h	
09.03	harvest		harvest		harvest	
10.03	deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom		deleafed 1 leaf from the bottom	
11.03						
12.03						
13.03						
14.03	harvest, watering for 6 min, intervall 1,5 h		harvest, watering for 6 min, intervall 1,5 h		harvest, watering for 6 min, intervall 1,5 h	
15.03	weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature		weekly measurements, measured leaf + soil temperature	
16.03	final harvest		final harvest		final harvest	