Growth of Tomatoes under Hybrid LED and HPS Lighting

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Abstract

The use of LEDs can be promising for greenhouse horticulture, but before it can be put into practice on a large scale more knowledge must be acquired on effects of LED lighting on crops. Furthermore, the growers will have to learn to grow their crops under LEDs and the efficiency of LEDs must increase even more. In order to gain more insight into the influence of LEDs on crop growth and production, an experiment was performed in the Wageningen UR greenhouses with a small Santa type tomato ('Sunstream') from October 2009 to June 2010. Four lighting treatments were applied, with each treatment in a separate greenhouse compartment: top lighting with HPS (1) or LED (2), and hybrid lighting with HPS above the crop in combination with LED lighting above the crop (3) or in between the canopy (interlighting) (4). The light intensity from the lamps in all treatments was maintained at 170 µmol m^{-2} s^{-1}. The light was 50/50 divided between HPS and LED in the hybrid treatments. The climate in each treatment was adapted to the needs of the crop in each lighting system. The various lighting systems resulted in different greenhouse climates, in which more heating was required in the LED treatment and the least heating in the hybrid with interlighting. A strong crop developed under LED alone, and to maintain a proper crop balance the fruit load was altered by maintaining an extra tomato fruit per truss and increasing the stem density relative to that under HPS. The leaves of tomato grown under HPS were thinner and aged more rapidly in the winter than in the other treatments. Leaves lower in the canopy under LED alone or hybrid treatments had a higher photosynthesis capacity in the winter than leaves developed under HPS lighting. Differences in production were small, although the production under all LEDs was lower. There were only small differences in fruit quality. The amount of energy required per kilogram tomato was highest in the LED treatment and hybrid with top LED lighting. This was primarily due to the fact that a higher air temperature was necessary and these LEDs were cooled and the cost of cooling added to the use of energy. The consequences and future perspectives of the different types of supplementary lighting for crop growth and production as well as for crop management practices will be discussed.

INTRODUCTION

The use of LED assimilation lighting can become an important player in greenhouse horticulture if energy efficient LEDs can increase production in the winter. However, before LEDs can be broadly applied in horticulture, more knowledge is necessary on the effects of LEDs on crops, how to manage crops growing under LEDs and how efficient they really are, not only in terms of light output, but also in relation to crop production. While the energy efficiency of LEDs is the result of technical improvement, knowledge on the effects of various lighting systems with LEDs on greenhouse crops and crop management as well as the efficiency of LED lighting per unit production must result from experimental research. To date, in experiments with LED lighting systems in greenhouses problems with crop growth and physiology have been encountered and are thought to be due to insufficient tuning of crop cultivation to assimilation lighting with LEDs (Nederhoff et al., 2010). These problems seem to focus on plant temperature, plant load and the influence of LED lighting on plant morphology

(Hogewoning et al., 2010a). In order to investigate the consequences of growing greenhouse crops under LED lighting, an experiment was designed with lighting systems with and without LEDs. The experiment focussed on crop growth, physiology, and the energy efficiency of LED lighting systems.

MATERIALS AND METHODS

Tomato plants were planted on October 15th 2009 in four greenhouse compartments of 144 m^2 at the Wageningen UR Glasshouses in Bleiswijk (52°N), The Netherlands. The tomato cultivar was 'Sunstream', a small Santa type tomato, grafted on Maxifort. The experiment ended July 1st 2010.

Four different lighting systems were compared. Two hybrid lighting systems with HPS lamps above the crop in combination with LEDs either above (toplighting) or in between the crop (interlighting) were compared to only HPS or LED lighting above the crop. The toplighting systems with LEDs (from Lemnis Lighting, the Netherlands), 100% or 50% LEDs, were water-cooled to improve their efficiency, removing the heat generated by conversion of electrical energy to light from the greenhouse. The interlighting LEDs (from Philips Lighting, the Netherlands) were (passively) air-cooled and the resulting heat warmed the air and crop around this lighting system. The light intensity was 170 µmol m^{-2} s^{-1} in total and was equally divided between HPS and LED in the hybrid lighting systems. The LED lighting was composed of 12% blue LEDs (around 450 nm) and 88% red LEDs (around 660 nm). The lamps at the top were placed 1.5 m above the top of the canopy. The rows of interlighting LEDs were placed approximately 1.5 m below the top of the canopy in order to contain and utilize all the available light in canopy itself. The maximum day length was 18 hours and lamps were always switched off one hour before sunset. In March and April the use of the assimilation lighting depended on solar radiation. The lamps were not used after mid May.

The plant density at planting was 3.12 m^{-2}. Additional auxillary stems were retained on Dec. 14th and Jan. 27th, resulting in a stem density of 4.7 m^{-2}. In the LED-top and LED interlighting treatments the stem density was further increased to 5.2 m^{-2} on March 10th.

The CO_2 concentration was maintained at about 1000 ppm (max. dosing capacity 180 kg ha^{-1} h^{-1}). Watering, leaf pruning and temperature set points were adjusted to the needs of the crop in each individual treatment in order to realize optimal growth and production. Crop growth and production was measured and monitored on a regular basis. Leaf photosynthesis was measured by a LI-6400XT (LiCor, VS) in January and March. Leaves from two positions in the canopy were used: upper fully-grown leaves and leaves in the lowest part of the canopy. Canopy temperature was measured by infrared cameras pointing at the top of the canopy. The amount of electrical energy used by each of the four lighting systems and the thermic energy of all heating pipes and cooling systems were measured throughout the experiment.

RESULTS AND DISCUSSION

Climate

The amount of PAR light received by the canopy from the lighting systems was almost at the same, approximately 87% as much as from the sun (Table 1). The weekly climate set points were based on the crop response to the greenhouse climate in order to create a crop that could optimally grow and produce. On average, the daily mean climate realized was similar between the treatments (Table 1). During the winter from October to May the greenhouse air temperature in the treatment with the water-cooled top LED-lighting did not increase sufficiently in the morning hours for optimal plant temperature and growth. Crop growth and development remained lower than desired, and more thermal heat had to be applied in that treatment. In addition to the input of more thermal energy into the greenhouse, the use of screens at night was increased too in order to contain heat in the greenhouse and maintain the plant temperature in the top of the canopy. Due to the fact that the interlighting system with LEDs is air-cooled and thus acts as a heating tube in the crop, less thermal heat was necessary from the heating pipes in that treatment. Although the temperature set points were determined to realize optimal growth in each compartment, the average air temperatures were rather similar in the treatments (Table 1). The greenhouse air temperature in the interlight-LED treatment however, was about 0.3°C higher on average than in the other treatments. The treatments with 50 or 100% LEDs above the canopy (top LED and hybrid) had water-cooled LEDs. Consequently, these treatments needed less ventilation to cool the greenhouse air, which in turn resulted in a higher vapour deficit of the air (Table 1) and reduced the CO_2 requirement.

The difference between LED and HPS light had a direct influence on the canopy temperature (Fig. 1). Radiative heat from HPS lamps warmed the plant to a temperature similar to that of the air temperature (Fig. 1B). LEDs receiving no NIR radiation did not sufficiently warm the canopy or greenhouse air, so that the set points of the heating tubes were increased. This increased the air temperature (Fig. 1A), but left the plant temperature ca. 1.5°C lower than the air temperature. It appears that each lighting system requires its own climate set points for optimum crop growth and production.

Crop Responses

In winter time under HPS, specific leaf area (SLA) was higher than in the other LED treatments (ca. 17 vs. 15 $cm^2\ g^{-1}$ fresh weight), which means a relatively larger, thinner leaf in comparison to leaves grown under the LED lighting systems. Leaves developed under LEDs were thus relatively thicker (lower SLA) in the winter, but the SLA increased with increasing sunlight in the spring so that leaves in all treatments had an SLA of ca. 17 $cm^2\ g^{-1}$ fresh weight. The crop under HPS lighting also used more water (for growth + transpiration) than under LED lighting in the early winter (2 vs. 1.6 $L\ m^{-2}\ day^{-1}$), possibly due to an increase in transpiration caused by more radiative heat from the HPS lamps. Later, as the crops under LED lighting caught up in their growth, more water was taken up by the crops under LEDs than under HPS, especially under the top-LED lighting system (3.5 vs 3 $L\ m^{-2}\ day^{-1}$), with both hybrid systems taking in an intermediate position.

A remarkable observation was the occurrence of small plantlets growing on the leaf stems of plants under LED-lighting, but never under HPS lighting. They occurred in short rows of 1-5 plantlets close to the tomato stem. Another observation was that leaves in the canopy curled under the LED-lighting systems, both under top-LED as under hybrid lighting systems. From earlier observations, this is a response by both tomatoes as cucumbers due to the red light from LEDs (Meinen et al., 2009; Trouwborst et al., 2010).

During the winter measurements of the photosynthetic light response curves were performed on leaves in the top of the crop and low in the canopy. There was very little difference in photosynthetic light response of leaves at the top of the crop between the various light treatments, but deeper in the canopy some differences were observed (Fig. 2).

The lower leaves under HPS lighting had the lowest response curve, ca. 4-5 µmol $CO_2\ m^{-2}\ s^{-1}$ lower than both hybrid lighting systems, which in turn were ca. 4-5 µmol $CO_2\ m^{-2}\ s^{-1}$ lower than the top LED-lighting system. The higher photosynthesis under LEDs in the winter correlated with the lower SLA (thicker leaves) measured during this period. This means that under top LED-lighting in the winter, a time in which light is at a premium, any light reaching the lower parts of the canopy will be better utilized under top LED-lighting. The difference in photosynthesis of lower leaves found in January had disappeared in March (data not shown).

The tomato crop under HPS lighting developed more rapidly in the beginning of the experiment so that more fruits were allowed to develop per truss (less fruit pruning), resulting in a higher fruit load. This means that more fruits per truss were carried on plants under HPS lighting. However, later on the crops under LED-lighting developed so well that especially under top LED-lighting the stem density was increased even more than that of the HPS crop. Thus, not only were more fruits carried per truss, but more trusses developed as a result of the increased stem density. In the end, the total number of flowering and set trusses under HPS lighting was only slightly higher than under top LED or hybrid lighting (Table 2). The logical result was that under HPS lighting, the production (25.9 kg m^{-2}) was also higher than under the other lighting systems, varying from 3 to 6% higher under HPS lighting (Table 2).

Energy

The two types of LED lighting systems used in this experiment differed in their manner of dealing with surplus heat production. The top LED-lighting systems were water-cooled, thus requiring electricity not only for the light itself, but also for the water pump to remove the warm water from the lighting system. In addition to the heat (energy) removed from the greenhouse in this manner, additional energy was used by the energy exchanger to cool the water before it was again pumped through the lighting system. The air-cooled interlighting LED-system operated differently, in that the surplus heat was transferred directly into the greenhouse as convective and radiative heat.

The consequences of the four lighting systems for the amount of energy used in each crop can be seen in Figure 3. The amount of electrical energy (left) used by the top lighting systems with LEDs, whether solely LEDs or hybrid LED and HPS, was slightly higher than that of the hybrid LED-interlighting and HPS systems. However, the extra energy used by the top LED-lighting is also apparent in the lower part of Figure 3A, where the red broken line denotes the energy used to cool the water (and run the pump). The thermal energy input used in each treatment is given in Figure 3B. Here the higher heat requirement in the morning hours of the crop under top LED-lighting is made clear, followed by the hybrid treatment with top LEDs. The HPS treatment required less thermal energy, with the LED interlighting system using the least amount of thermal energy, the latter as a result of the air-cooled system, giving off its heat into the greenhouse air. In itself, the amount of electrical energy for light from LED lighting do not differ greatly between air-cooled and water-cooled systems, but the amount of energy for cooling the LEDs (energy and equipment) makes a large difference between the two systems.

The efficiency of the LEDs used in this experiment was ca. 1.6 µmol W^{-1} compared to ca. 1.8 µmol W^{-1} for the HPS lamps, but the efficiency of LEDs will certainly increase in the next few years. However, the energy efficiency should also be viewed in relation to the amount of tomatoes produced. In order to be able to do this, both forms of energy, electrical (measured in kWh) and thermal (measured in MJ), have to come under a common denominator, in this case the natural gas equivalent (g.e.). The energy efficiency (g.e./kg tomato) calculated for all four treatments show that the most efficient lighting system under these experimental conditions was the hybrid LED interlighting system (281 g per g.e.), followed by the HPS-lighting system with 276 g per g.e., the hybrid LED toplighting system (258 g per g.e.) and finally the LED toplighting system (235 g per g.e.). Thus, the most tomatoes were produced under HPS lamps, and used almost the least amount of energy per gram produced.

Lighting Systems

The results of this experiment were influenced by the lighting systems used. The light intensity used are conform those in Dutch horticulture, thus comparison of the assimilation lighting with HPS and LED have a sound basis. However, the ratio of HPS to LED in the hybrid treatments was chosen prior to the experiment, based on current knowledge. All cultivation practices and climate set points were continuously discussed and updated by tomato growers. These growers have many years of experience with tomato production under HPS lamps while no experience with LEDs. This might have resulted in maximum yield compared to what is possible under HPS, while under LED due to lack of practical experience not yet the maximum production was attained.

In this experiment less production was realized than was expected, but much has been learned. Aspects like vertical light distribution in hybrid systems and choice of light spectrum might be subjects of future research. Given the crop responses to light and temperature in each treatment, a higher light intensity from HPS toplighting relative to LED in the hybrid treatments might have had a more positive effect on the physiology and growth of the crops. There are more possibilities in the positioning of greenhouse lighting which affects the horizontal and vertical light distribution in the canopy and ratio's of types of lamps (HPS and LED) by hybrid lighting systems. Furthermore, when using LED as supplemental lighting, choices may have to be made with respect to spectrum. Red light can be efficient for instantaneous rates of leaf photosynthesis (Paradiso et al., 2011), but morphological effects of spectrum can have profound effects on plant growth (Hogewoning et al., 2010b).

CONCLUSIONS

1. Each lighting system requires its own climate set points for optimum crop growth and production.
2. Crops under LEDs above the canopy miss radiative heat, and thus require more thermal energy to maintain the desired greenhouse climate and crop temperature.
3. In order to maintain a sufficiently high plant temperature in the top of the canopy under interlighting with LEDs, more light and heat is required from above than received (85 µmol m^{-2} s^{-1} HPS) here, or the ratio top light to interlight (50%) may be too low.
4. The crop under toplighting with only LEDs is able to carry a higher fruit load (more fruits per m^2 by more trusses due to higher stem density and by more fruits per truss).
5. The energy costs of LED lighting for the light do not differ greatly between air-cooled and water-cooled systems, but the costs of cooling the LED systems (energy and equipment) make the large difference between the two systems.
6. The energy efficiency of top LED-lighting (gram tomato per unit energy input) relative to the amount of tomatoes produced was highest under LED-interlighting and lowest in top-LED lighting. However, with an increase in technical efficiency of new LEDs and more knowledge on growth of tomato under LEDs, the efficiency of LEDs will increase even more.

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Tables

Table 1. Mean air temperature (°C), vapour deficit (g m^{-3}) and CO_2 concentration (ppm) in each treatment as well as the cumulative incident light (mol m^{-2}) from the HPS and LED lighting systems and the sun during the lighting season (October 15th – May 20th).

	Temperature (°C)	Vapour deficit (g m^{-3})	CO_2 (ppm)	Sunlight (mol m^{-2})	Assimilation light (mol m^{-2})
Hybrid-top	20.3	4.0	1016	2065	1708
Interlight	20.6	3.4	1045	1974	1796
LED-top	20.2	4.0	1043	2004	1747
HPS	20.3	3.5	1008	1974	1733

Table 2. Total number of flowering trusses, trusses set and production (kg m^{-2}) of tomatoes under HPS and LED toplighting, and under hybrid lighting with LEDs as toplighting or interlighting from November 2009 to June 2010.

	Flowering truss	Total set trusses	Production (kg m^{-2})	Production (%)
Hybrid-top	35.4	1466	25.2	-3%
Interlight	35.3	1433	24.3	-6%
LED-top	34.9	1472	25.5	-5%
HPS	36.1	1498	25.9	-

Figures

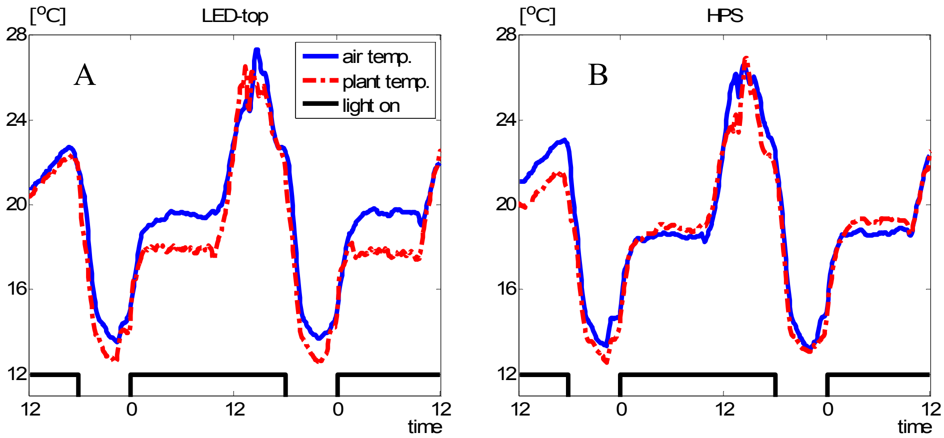

Fig. 1. Typical daily time course of canopy and greenhouse air temperature (°C) under LED top and HPS lighting during a 48 h period in February 2010. The black bar denotes the periods of artificial lighting.

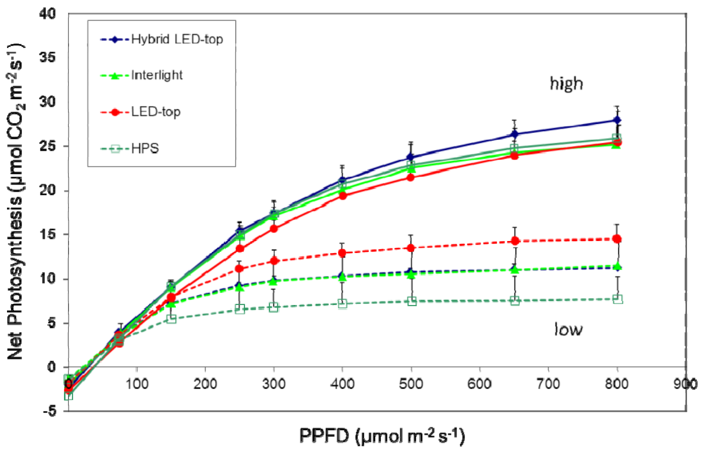

Fig. 2. Light response curves of photosynthesis of leaves high (solid lines) and low (broken lines) in the canopy of four tomato crops grown under HPS and LED toplighting, and under hybrid lighting with LEDs as toplighting or interlighting. Measurements were performed at 21°C, 85% RH and 700 ppm CO_2. n=3.

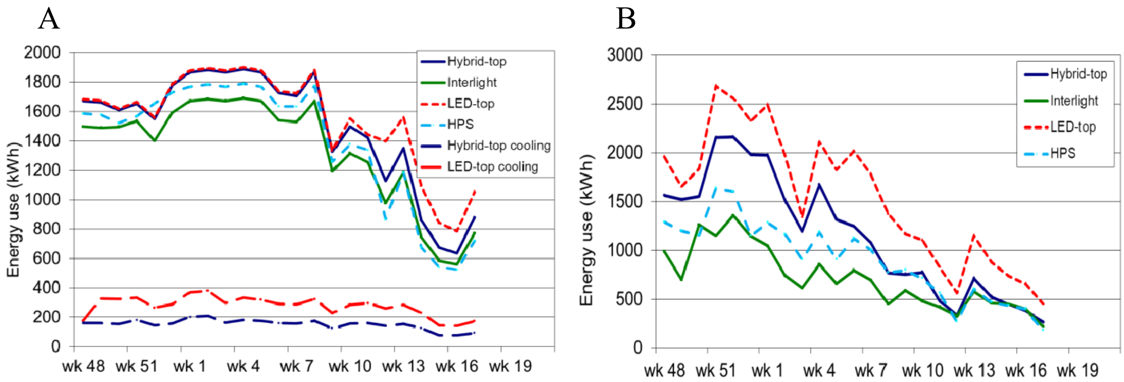

Fig. 3. Electrical energy input (A) and thermal energy (B) in kWh from November 2009 to May 2010 in 4 tomato crops, 2 crops grown under HPS and LED toplighting, and 2 crops under hybrid HPS and LED with LEDs as toplighting or interlighting.