Effects of supplemental light and temperature on summer production of tomato in Norway

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Abstract

Addition of artificial light to the natural light conditions in greenhouse vegetables production along the coastline of Norway have shown to result in highest yields of greenhouse vegetables worldwide. Even during summertime, cloudy days require the use of supplemental light to reach optimal light levels. Hydroelectric energy is used to provide energy for high pressure sodium (HPS) lamps. High levels of installed power of HPS lamps contribute significantly with heat radiation energy, causing effects on evaporation and plant performance and requiring increased ventilation with subsequent loss of energy and CO_2. Alternatively, light emitting diodes (LED) can be used, that produce less radiation energy.

The present experiment was designed to quantify effects of high light intensities of additional HPS and LED light on production and energy use in greenhouse tomato production in Norway. The higher light intensity increases the optimal temperature for plant growth, raising the question of optimal regulation of ventilation temperature in the greenhouse. To address this question, three different production strategies were tested: (1) a control with HPS light and a ventilation temperature of 22/18°C (day/night), (2) a strategy with HPS light and additional LED inter-lighting with the same ventilation temperatures as (1), and (3) a strategy as (2) but with a ventilation temperature of 27/20°C (day/night).

Results showed that additional inter-lighting with LED increased the need for ventilation compared to the control. A higher ventilation temperature resulted in a higher temperature, but not in a higher development rate. For production strategy 3, dry matter distribution to the fruits was considerably lower compared to the other strategies, indicating sink limitation. In order to profit from additional LED interlighting with respect to yield and energy saving, an increase in ventilation temperature of 1-2 °C is suggested.

Keywords: Greenhouse production, tomato, artificial light, CO_2, dry matter accumulation, yield, photosynthesis, dry matter distribution, greenhouse climate, energy consumption

INTRODUCTION

Along the coastline of Norway, natural light is the limiting factor for plant production in greenhouses. Precipitation of 1200 – 3500 mm y^{-1} provides the availability of hydroelectric energy. To prevent adverse effects of low light conditions in a cloudy summer, hydroelectric energy is used to provide supplemental light in greenhouse production of tomatoes. Both high pressure sodium lamps (HPS) and light emitting diodes (LED) can be used. Earlier experiments using additional artificial light with HPS lamps in year-round greenhouse tomato production showed a yield potential of 125-140 kg $m^{-2}y^{-1}$ (Verheul et al., 2012). Based on this

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experimental work, yields of 120 kg $m^{-2}y^{-1}$ have been registered in commercial production in Norway.

Tomato is recognized as a crop with a high light requirement that will need a daily light integral of at least 30 mol PAR to achieve high production (Moe et al., 2005). This means that natural light conditions are limited for tomato production in Norway, even in summertime.

Little is known about the use of high levels of artificial light, i.e. 220 µmol $m^{-2}s^{-1}$ or higher, on plant production. There is evidence that suggest that every increase in photosynthetically active light (PAR) results in a comparable increase in production (Marcelis et al., 2006). However, HPS lamps provide also additional near infrared radiation energy. High levels of installed power of HPS lamps in the top of the greenhouse might stress plants and will influence crop evaporation. Excessive input of heat energy increases the need for ventilation and might thus contribute to loss of energy and CO_2. Alternatively, LED lamps can be used, that are more efficient in converting electricity into light, have an adjustable spectrum that can be optimized for PAR, and have low radiative heat emission that makes it possible to place them close to the plants (e.g. interlighting).

CO_2 is usually added to the greenhouse air to a level of 800- 1000 µmol mol^{-1}, which increases production with 30% compared to the CO_2 level of the outside air of 400 µmol mol^{-1} (Nederhoff, 1994). Elevated CO_2 concentrations causes higher production of assimilates and better fruit set. Relative humidity in the greenhouse should not be too high (above 94% at 25°C) or too low (below 75% at 25°C). High relative humidity will reduce transpiration, while low relative humidity will increase stomatal resistance and thus reduce photosynthesis (Stanghellini et al., 2019).

The main challenge of optimization environmental conditions is related to the fact that there is interaction among different environmental and plant factors so that the optimum level of one factor depends on the levels of other factors. Changing environmental conditions will influence the balance between the source, the production of assimilates, and the sink, the capacity of plants to use assimilates. Optimizing greenhouse tomato production includes not only light, but also optimization of temperature, CO_2 concentration and relative humidity in the greenhouse air. Leaf and fruit development rates in tomato increase with increasing daily average air temperatures (de Koning, 1994.). Crop photosynthesis is a function of intercepted radiation and thus strongly related to the partitioning of dry matter to the leaves, total leaf area, the leaf area index (LAI) and the specific leaf area (SLA), all affected by temperature, light, CO_2 and air humidity (Stanghellini et al., 2019). In addition, the optimum temperature for leaf photosynthesis is higher at high light levels compared to low light levels (Körner et al., 2009) and at elevated CO_2 levels compared to ambient level (Taiz and Zeiger, 2010). All these interactions makes it challenging to adjust temperature to optimize tomato production.

A commercial greenhouse has the highest demand for energy as compared to all other agricultural industry sectors. Here, energy management is important from a broad sustainability perspective (Vadiee and Martin, 2012). The closed greenhouse concept can reduce the use of fossil fuel-derived energy by 25 – 35%, compared with open greenhouses in temperature climates, but changes also environmental conditions drastically (De Gelder et al., 2012). Aspects like energy efficiency, environmental benefits and economics must be further examined since this is seldom presented in the literature (Vadiee and Martin, 2012). These aspects are closely related to yield. Little is known about how to adjust temperature and light conditions to optimize tomato production and energy use at northern latitudes.

We hypothesize that an increase in light, and thus an increase in assimilate production, will allow a higher air temperature, and thus a higher development rate and sink capacity. Allowing a higher air temperature will reduce the need for ventilation and thus reduce loss of energy and CO_2 to the outside air. In addition, less ventilation will contribute to a higher CO_2 concentration in the greenhouse and thus to a higher assimilate production.

MATERIALS AND METHODS

Tomato plants (Lycopersicon esculentum Mill.) variety 'Dometica' were raised in 0.5 L rockwool cubes and planted with a plant density of 4.4 plants per m^{-2} on the 2nd of May 2017 on standard rockwool slabs (90 cm x 10 cm x 15 cm) in three identical and adjacent glasshouse compartments in the research greenhouse at NIBIO Særheim (58°47'N, 5°41'E) at the time that the 2nd truss reached anthesis. Plants were grown at 0.80 cm between row distance and subjected to high pressure sodium lamps (SON-T 600 W, 210 W m^{-2} installed) when outside global radiation was less than 250 W m^{-2}. LED tubes (Union Power Star 160 W, 80% red, 20% blue, 70 W m^{-2} installed) were installed in between every other plant row at two heights, 1.35 and 1.75m from slab height. LED light was switched on 18h a day after plants reached a height of 1.75m at 30.05.17. Global radiation was measured with a Kipp solarimeter. The light transmission factor through the greenhouse cover was measured to be 0.63. A temperature set point of 21°C day and 17°C (night) was used in all compartments. Pure CO_2 was provided with a set point of 900 ppm, when the windows were closed, from the start of the experiment until 29.06.17. Thereafter, the set point was raised to 1200 ppm. CO_2 set point when ventilating was reduced depended on window opening to 600 ppm. Only lee-side ventilation was used. CO_2 of greenhouse air was measured at 5 minutes interval with a gas analyser (Priva CO_2 monitor Guardian +). Air temperature and relative humidity were measured by dry- and wet-bulb thermocouples placed in ventilated boxes that shielded against direct solar radiation and placed in the middle of the canopy at a height of 1.5 meter. Ventilation tubes were placed beneath the plants to ensure optimal stirring of the greenhouse air. Thermocouples were calibrated before the start, and controlled at the end of the experiment. Temperature (°C), relative humidity (%), CO_2 concentration (ppm) and window opening (%) were registered every 5 minutes. Heat energy consumption was measured with an energy flow meter (Kamstrup Multical 602).

Plants were irrigated with a standard complete nutrient solution for tomatoes in an open system (de Kreij et al., 1999), an electrical conductivity of 3.5 and a drainage percentage of 50. Flowers were pollinated with bumblebees and trusses were pruned to six fruits just after fruit set of each truss. Shoots were trained according to the high-wire system, side shoots and mature leaves below the harvest-ripe fruits were removed once a week. Harvesting started 19.06.17 and the experiment ended at August 10th 2017.

During the experiment, three production strategies were used: (1: Control) a standard production with a ventilation temperature of 22°C (day) and 18°C (night), (2: +LED) a production with additional LED interlighting and a ventilation temperature of 22°C (day) and 18°C (night), and (3: +LED+VT) a production with additional LED interlighting and a ventilation temperature of 27°C day and 20°C night.

Plant vigour (increase in plant length, thickness of the stem, leaf length of the last fully developed leave, number of leaves on the plant) and fruit development (flowering rate, truss development rate, number of trusses and fruits on the plant) was measured once a week on two replications of each six plants in each compartment.

Fruits were harvested twice a week. Yield registrations were based on eight replications of each seven plants in each compartment.

Dry matter accumulation was assessed based on weekly measurements of plant length, number of leaves and number of fruits. Three times during the experiment, on 10.07.17, 20.07.17 and 03.08.17, ripened fruits and leaves were harvested for determination of fresh and dry weight and leaf area. At final harvest date, August 10th 2017, all remaining fruits, leaves and stem were harvested for determination of fresh and dry weight and leaf area. Leaf area was determined using a leaf area meter (LiCor LI 3000). Dry weight was determined after 96h oven drying at 70°C. Six replications of each two plants were harvested in each compartment.

Simple statistics (ANOVA, GLM, Tukey pairwise comparisons and 95% confidence) were used to compare the three production strategies.

RESULTS

Results in Figure 1 (left) show that the average outside global radiation varied from day to day between 50 and 330 W m^{-2}. Inside the greenhouse, addition of HPS lamps provided a much more stable light environment (Figure 1, right). The use of LED inter-lighting increased the radiation level with 53 W m^{-2} on a daily basis. As expected, the higher ventilation temperature in production strategy 3 (+LED+VT), resulted in less ventilation opening, a higher average daily temperature and a higher CO_2 concentration in the greenhouse (Figure 2). Results show that addition of LED also increases air temperature in the greenhouse. In case the ventilation temperature was equal to the treatment without LED, this resulted in a higher ventilation opening and a lower CO_2 concentration in the greenhouse (Figure 2).

Addition of LED light tended to increase specific leaf area of leaves, truss development rate and number of fruits on the plant, but not significant compared to the control (Table 1). The production strategy with a higher ventilation temperature resulted in shorter plants, shorter and thicker leaves, lower leaf area index and less fruits on the plant, while truss development rate was not affected compared to the two other production strategies (Table 1). No significant differences in yield were found between the different treatments. However, dry matter accumulation in leaves and stem were significantly higher, while dry matter distribution to the fruits was significantly lower in the production strategy with a higher ventilation temperature (Table 2).

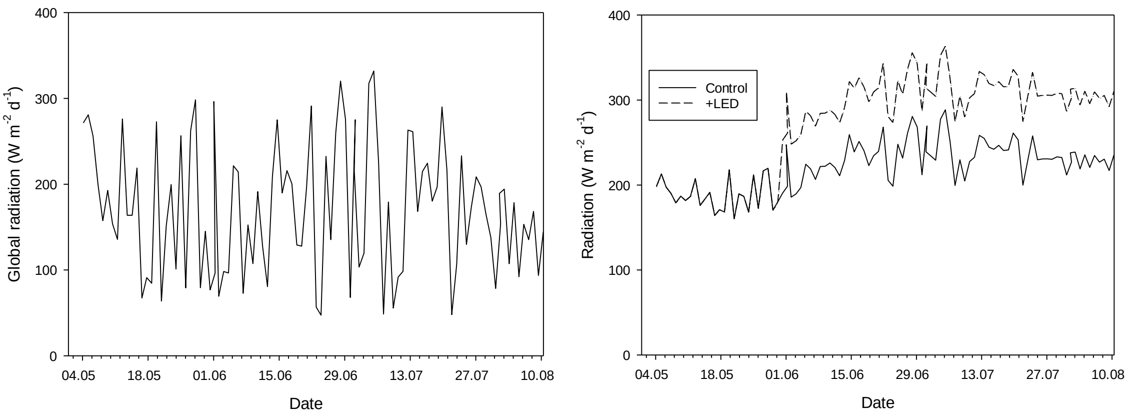

Figure 1: Outside global radiation (left) and total light radiation at plant level (right, with (+LED) and without (control) additional LED light).

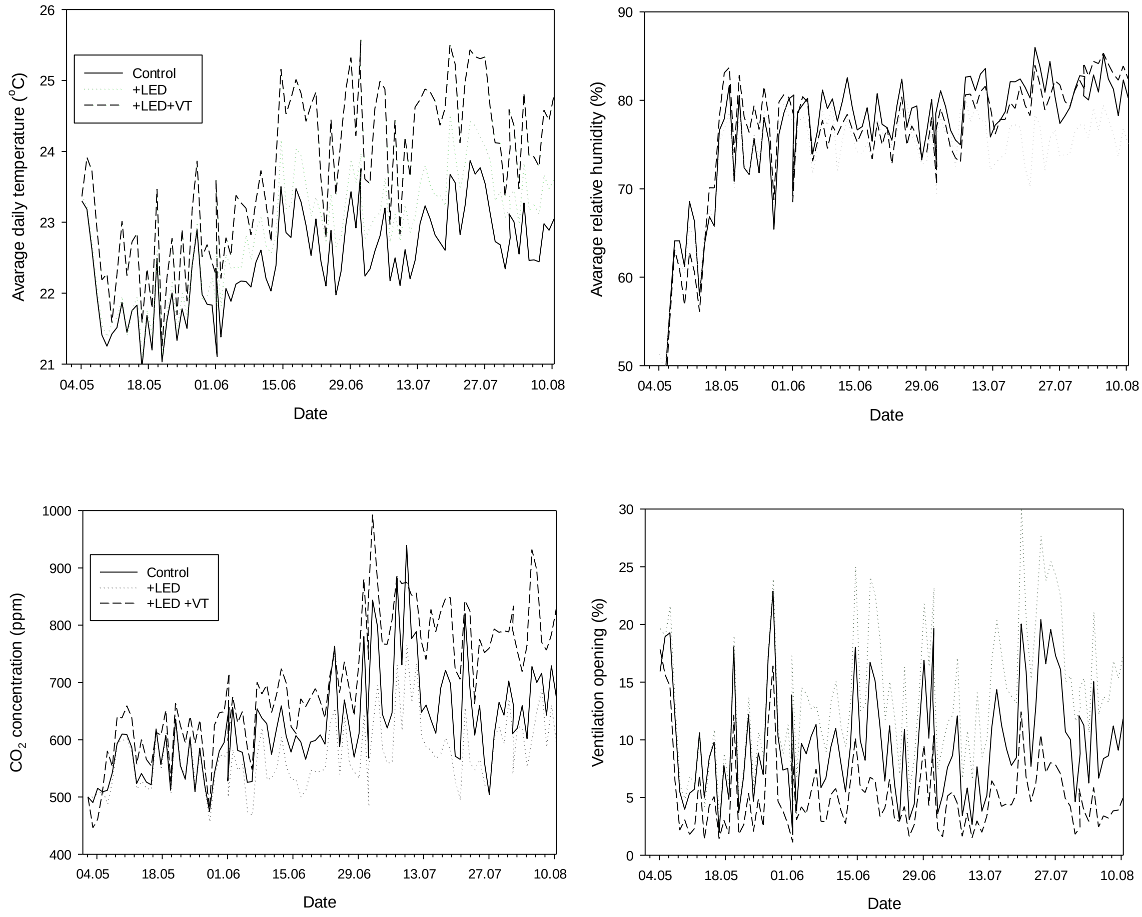

Figure 2. Average daily temperature (°C), relative humidity (%), CO_2 concentration (ppm) and ventilation opening for three production strategies: (1: Control)) standard production, (2: +LED) standard production + LED inter-lighting, (3: +LED+VT) production with LED inter-lighting and higher ventilation temperature.

Table 1. Plant vigour and generative development of plants for three production strategies from planting to final harvest: (1: Control) standard production, (2: +LED) standard production + LED inter-lighting, (3: +LED +VT) production with LED inter-lighting and higher ventilation temperature.

Plant characteristics	Control	+LED	+LED+VT
Plant vigour:			
Plant length increase (cm week^{-1})	30 (a)*	29 (ab)	27 (b)
Stem thickness (mm)	12 (a)	12 (a)	12 (a)
Leaf length (cm)	45 (a)	45 (a)	41 (b)
Number of leaves (plant^{-1})	21 (b)	22 (ab)	24 (a)
Specific leaf area (cm g^{-1}) upper leaves	272 (ab)	334 (a)	202 (b)
Specific leaf area (cm g^{-1}) lower leaves	347 (a)	316 (ab)	232 (b)
Leaf area index (m^2 m^{-2})	3.73 (a)	3.75 (a)	2.89 (b)
Generative development:			
Truss development rate (week^{-1})	1.02 (a)	1.10 (a)	1.04 (a)
Number of fruits on plant	46 (ab)	48 (a)	43 (b)

*Mean values that do not share a letter between production strategies are significantly different.

Table 2. Yield and plant characteristics at final harvest.

	Control	+LED	+LED+VT
Plant characteristics:			
Plant length (cm)	482 (a)	460 (a)	410 (b)
Number of trusses	17,1 (a)	17,5 (a)	17,0 (a)
Total yield:			
Number of fruits ($plant^{-1}$)	60 (a)	57 (a)	55 (a)
Average fruit weight (g)	77 (a)	80 (a)	75 (a)
Yield per plant (g)	4595 (a)	4542 (a)	4194 (a)
Total dry matter production:			
Fruits (g $plant^{-1}$)	375 (a)	403 (a)	330 (a)
Leaves (g $plant^{-1}$)	124 (b)	143 (b)	184 (a)
Stem (g $plant^{-1}$)	100 (b)	101 (b)	147 (a)
Dry matter distribution:			
To fruits (%)	62 (a)	62 (a)	50 (b)
To leaves (%)	21 (b)	22 (b)	28 (a)
To stem (%)	17 (b)	16 (b)	22 (a)

*Mean values that do not share a letter between production strategies are significantly different.

DISCUSSION

Photosynthesis, dry matter accumulation and tomato production are positively affected by light intensity (Heuvelink, 2018) and CO_2 concentration of the ambient air (Nederhoff, 1994). Earlier experiments showed that a hybrid system of HPS and LED resulted in a 20% higher yield, due to a higher number of fruits and a higher average fruit weight (Moerkens et al., 2016), and a higher photosynthetic light use efficiency of low-positioned leaves (Paponov et al., 2018). In the present experiment, addition of LED inter-lighting did not result in a significant increase in yield, average fruit weight or number of fruits. This might be explained by the chosen production strategy. Addition of LED increases the input of energy in the greenhouse. When ventilation temperature is not altered compared to a standard production, this resulted in a higher ventilation opening and a lower CO_2 concentration in the greenhouse. The lower CO_2 concentration in the greenhouse air for production strategy 2 can be the result of ventilation losses, a lower amount of CO_2 provided, due to the CO_2 set point that reduces depended on window opening, and/or a higher amount of CO_2 used by the plants due to assimilation at higher light intensity.

Plant development is reported to be depended on temperature. Usually, truss development rate increases with increasing air temperature in the range between 18 and 24^{o}C (de Koning, 1994). In the present experiment, truss development was not affected by temperature. The number of fruits on the plant was even reduced when a higher ventilation temperature was used. The average greenhouse air temperature during harvesting using the three production strategies was measured to be 22.8 (control), 23.4 (+LED) or 24.4 ^{o}C (+LED+VT). Results might indicate that the temperature for the last mentioned strategy was beyond optimum for truss and flower development. Earlier research has shown that high day and night temperatures drastically impede tomato flowering (Dane et al., 1991), pollination (Adams et al., 2001) and fruit set (Peet et al., 1997).

The effect of supplementary lighting on plant growth and production is determined by the balance between assimilate production in the source leaves and the overall capacity of plants to use assimilates (sink demand) (Li et al., 2015). In the present experiment, the combination of addition of LED light and a higher ventilation temperature resulted in significantly shorter plants, shorter and thicker leaves and a higher allocation of dry matter to the leaves and stem compared to the control. In addition to the observation that flowering and fruit development did not increase, this indicates that plants were sink limited. This explains why supplementary light did not have the positive effect as might be expected.

Heat energy used from the start to the end of the experiment was registered to be 56 (control), 63 (+LED) or 50 (+LED+VT) kWh per m^{-2}. This means that energy saving due to a higher ventilation temperature was limited. In addition to the effects on fruit set, a less high ventilation temperature is recommended in commercial production. In order to be able to achieve an increase in yield when adding LED inter-lighting and in addition save energy, it seems necessary to increase ventilation temperature with 1-2 ^{o}C.

CONCLUSIONS

The following conclusions can be drawn from the study:

- Additional inter-lighting with LED light increases the need for ventilation compared to no inter-lighting.
- An increase in ventilation temperature increases temperature and CO_2 concentration in the greenhouse as well as crop dry matter production. However, a too high temperature level of 24.4 ^{o}C reduces partitioning of dry matter to the fruits.
- Energy saving due to a higher ventilation temperature during summer is limited.

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