Young tomato plants with LED lighting (temporarily positioned overhead) (experiment 2009/2010 at WUR).

LEDs toplights are being installed for experiment at WUR in Bleiswijk (October 2009).

HPS and LED lighting are installed overhead shortly after planting (experiment 2009/2010 at WUR).

LEDs for greenhouse lighting

Light Emitting Diodes (LEDs) are a promising technology for greenhouse lighting with their efficiency to activate plant photosynthesis potentially higher in red LEDs than in HPS lamps. Due to their particular light colour, LEDs can initiate special effects in plants or steer plant processes and plant balance.

By ELLY NEDERHOFF

Introduction

Growers in North-West Europe have to deal with very low light levels in winter. Days are short and dark from November until January, especially on dull days. Light sums in winter can be less than one-tenth of the average in summer. Crops like tomatoes and roses could not be grown in winter time in this part of the world, until the introduction of artificial lighting in the 1980s/1990s. In the Netherlands alone, an estimated 2,000ha out of 10,000ha of greenhouses have lighting. Also in Scandinavia and northern Canada, where winters are very dark, greenhouses are lighted.

The normal way of lighting is with high-pressure sodium (HPS) lamps also known as SON-T. These lamps are very effective, but also very expensive to install and to run, as they use a lot of electricity. So growers are eager to find a cheaper way of lighting. In 2007 new LED systems (Light Emitting Diodes) that were especially adapted for application in greenhouses came on the market. With the prospect of highlighting efficiency, LEDs were embraced by growers and scientists in the Netherlands and various tests were started immediately.

The test results in the first winter season were mixed. In the second season, LEDs proved to perform as well as HPS lamps and in some tests clearly better. Now in the third season the specs for efficiency of LEDs look better than those of HPS lamps and more is known about how to use LEDs.

Currently, there are several blocks of several hundreds to several thousand square metres with LED lighting in the Netherlands. Whether this will expand next year depends largely on what will happen in this 2009/2010 season, and on the price of the systems. At the moment LEDs cost multiple times more than HPS lighting and the hope is that the price will come down. LEDs are regarded as a promising technique for year-round production of greenhouse-grown crops, including fruit-vegetables, salads, herbs, cut flowers and ornamental plants.

History of greenhouse lighting

Large-scale application of lighting in greenhouses in the Netherlands started in the early 1980s. Plant propagators started using high-pressure sodium (HPS) lamps to get young tomato and cucumber plants ready for planting in winter (December). Lighting significantly increases the quality of the young plants and also shortens the propagation time. In the late 1980s some rose growers in the Netherlands started experimenting with lighting to keep rose crops going through the winter. It was successful and became a feasible technique thanks to the high produce prices in winter. In the 1990s some tomato growers trialled the use of HPS lighting on tomato crops planted in autumn (October or earlier). After a learning period of some years, these growers achieved the perfect control of plant growth and production in winter with the use of lighting.

Lighting with HPS lamps is now common practice for the majority of the large rose growers, and is also applied by a number of tomato growers who specialise in winter production. The use of lighting is practically and technically feasible. Whether it is economical depends on the produce prices and also on the price of electricity. Growers with lighting generate their own electricity (see further), and often sell electricity when they don't need it. At the moment produce prices have sunk and costs are on the rise, so the economics are uncertain.

HPS (SON-T) lamps

Until very recently nearly all lighting in greenhouses was with high-pressure sodium (HPS or SON-T) lamps, mounted in a special reflector to create an even spread of light. While the first SON-T lamps were 400 Watt, later 600 and 1000 Watt became the norm. Lamps of 1000 Watt are preferred because fewer lamps are needed to get the required light level. Fewer lamps are better, for the reflectors of the HPS lamps block some of the natural light. Every little bit of light counts, as the rule of thumb is that 1% light equals 1% production.

These SON-T lamps are relatively efficient, namely about 30% of incoming electricity is converted to light. This is excellent in comparison to incandescent lamps that convert only 6% to light. The remaining 70% of the electricity used by HPS lamps is converted to heat.

The heat from the lamps increases the air and plant temperature. This is good, but on the other hand, heating with electricity is very uneconomic. Also the heat produced by HPS lamps is sometimes counter-productive. On mild days the temperature can become excessive, and therefore vents and screens ('curtains') have to be opened. This wastes energy and causes 'light pollution' (more about this later).

LEDs introduced to horticulture

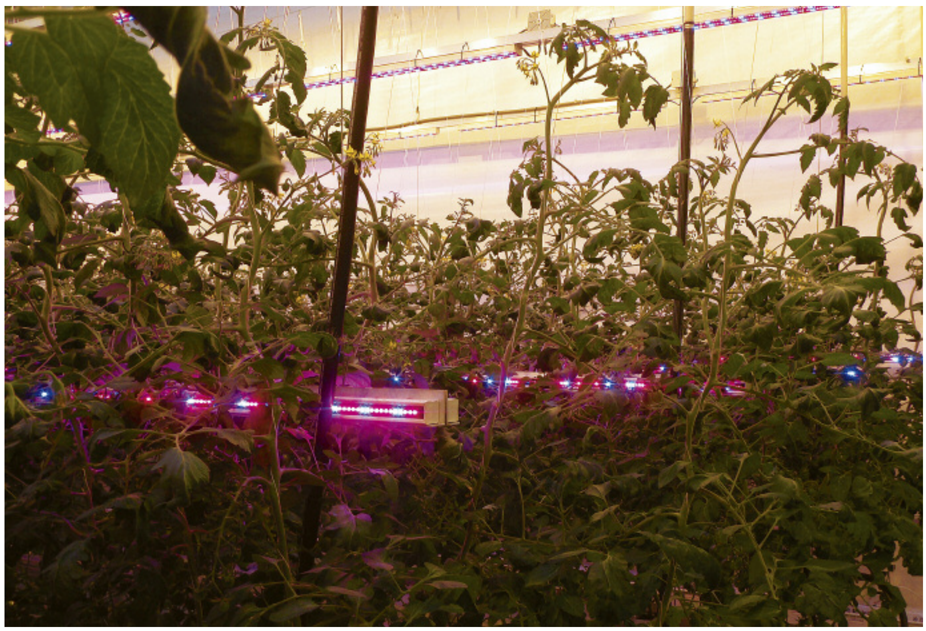
At the Hortifair in Amsterdam of 2007 some companies introduced special LED modules for the greenhouse industry. This raised expectations of lower electricity costs thanks to high efficiency, and also expectations of higher yields thanks to special light colours.

Growers were very interested and despite the high price, some leading growers decided to trial the new lighting systems. The results were moderate, as it was still unknown how to make the best use of these lights. In the winter of 2008/2009 some large-scale experiments were carried out with LED lighting on roses, tomatoes, sweet pepper, cucumber, herbs and more, partly funded by the industry and some with research funding from the Ministry of Agriculture and the Product Board. Although the results at the end of the lighting season were not always as positive as the growers had hoped, the LEDs came out to be at least as good as or better than the standard HPS lamps. The knowledge increased and at the same time new questions arose about the finer art of growing under LEDs. New research that is underway now will provide answers to these questions.

Light intensity for growth (photosynthesis)

Lighting in greenhouses is applied to increase the photosynthesis, which is the uptake of CO_2 to generate plant growth. Photosynthesis is also known as assimilation, therefore lighting for this purpose is known as assimilation lighting. Photosynthesis is stimulated by light of any colour with wavelengths between 400 and 700 nanometers (nm). The most effective colour for photosynthesis is red light (especially a wavelength around 600 nm), while blue light (400-500 nm) is least effective for photosynthesis. The light spectrum of HPS lamps contains a mix of yellow/orange/red light that is towards the most effective wavelength, plus a bit of blue.

LEDs come in any colour, so LED modules are often made of mainly red light to get the highest photosynthesis.



Left to right - Top to bottom:

- *LED interlighting with one streng positioned overhead and one between the plants and HPS lighting overtop (experiment 2009/2010 at WUR).*
- *HPS lighting as one of the four treatments in the experiment in 2009/2010 at WUR.*
- *Tomatoes (cv Sunstream) under LED toplighting and HPS light (experiment 2009/2010 at WUR)*
- *One streng of LED interlighting is already between the plants and the other is steil overhead.*
- *Combined HPS + LED toplighting (experiment 2009/2010 at WUR)*

Light colour for shape (morphogenesis)

Additional light in winter raises the light intensity to spring levels. Plant density has to be increased and plant management adjusted to the new light conditions. Failing that, the plants will grow completely out of shape.

Apart from the quantity of light, also the quality of light is important for plant shape. This has to do with processes such as flower initiation, fruit set, plant balance, stomata control and more. These processes shape the plant, known as 'morphogenesis'.

Plants need a minimal amount of blue light (in the order of 6 - 10%) to allow normal plant development and plant shape. Also important for morphogenesis is far-red light, as well as the ratio between blue, far-red and red light. The light colour ratio can make or break the plant-shaping processes. Also the timing is important, as it makes a difference whether certain light colours are given in the morning or evening.

Light from HPS lamps not only contains yellow/orange/red that is good for photosynthesis, but also a bit of blue, which is essential for normal plant shape.

Each LED radiates one particular light colour, so modules can be made of selected LEDs to get the required mix of light colours. When morphogenetic effects of the light spectrum are fully understood, growers will be able to use LEDs of particular colours for accurate control of how plants in greenhouses grow and produce.

Electric efficiency

The so-called wall-plug efficiency is the amount of light produced (in Watts, called optical Watts) as a percentage of the amount of electricity used (also in Watts). As described earlier, the wall-plug efficiency of HPS lamps is about 30%. The wall-plug efficiency of LEDs is increasing and now exceeds that of SON-T lamps. Apparently some LEDs used for horticulture are approaching 40%. Obviously, the portion of electricity not converted to light is converted to heat (see further). It is expected that new developments will make LEDs even more efficient, which contributes to energy saving.

Other advantages of LEDs are that they run on low voltage, and that (in principle) LEDs can be dimmed.

Electricity and economy of scale

Clearly, the electricity use of lighting is very high, no matter if it is with HPS or LED lamps. In most places in Scandinavia and northern Canada where intensive greenhouse lighting is applied, the electricity is very cheap. In contrast, the Netherlands have a very high electricity price. Hence Dutch growers with lighting generate their own electricity in a co-generator. These are heavy engines, fired on natural gas, that produce electricity, heat and CO_2 gas. A flue-gas purification system is needed to clean the flue gases to make them suitable for CO_2 enrichment. The co-generator and gas purifier requires large investments, which means lighting is only economical on a large scale. Dutch greenhouses with lighting are often large, over many hectares. It must be added that many growers sell electricity to the grid in periods when they are not using lighting. The sale of electricity is in most situations important for profitability.

Different LED systems

There are many manufacturers of LED lights and LED systems. Only some focus on greenhouse horticulture, which is a very demanding market. LED modules need to give selected light colours, be water-proof, robust and compact. Ideally, the modules and supporting structures are small in order to cause only minimal obstruction of natural light.

Generally, one LED has an electric power in the order of 0.5 to 2 Watt. A number of LEDs are combined to form a module, and many modules in a series form a line or 'streng'. Modules come in various shapes, e.g. current Philips LED modules measure 1500 x 40 x 60 mm, and Lemnis modules are 120 x 25 x 30 mm. New and other modules are being produced too.

The light intensity achieved in a greenhouse depends on the number of modules installed per m^2.

Water-cooled LEDs

HPS lamps and LED systems both produce a lot a heat. Roughly 60 to 70 Watts from every 100 Watts comes out as heat. There are differences though. LEDs release convective heat from the back. This heat has to be removed by cooling, because LEDs are more efficient when operating at a lower temperature.

Some LED systems (e.g. from Lemnis Lighting) contain a water-based cooling system. Each LED backs on to a tube with cold water pumped through it, and lukewarm water comes out at the other end of the tube. The boost in water temperature depends on the temperature of the incoming water and the flow rate. The warm water is put into the return of the heating system. Thus, water-cooled LED systems don't release heat at all.

Air-cooled LEDs

Other systems, for instance Philips LED systems, release the heat passively. The heat is absorbed by the surrounding air and plants. Air movement would help remove the heat faster, but there is no fan or so involved.

The difference between air-cooled LEDs and HPS systems lies in the heat distribution. The huge HPS lamp (1000 Watt) produces a lot of heat on one spot (700 Watt), while the tiny LEDs (0.5 – 1 Watt) produce a tiny amount of heat locally. Because the LEDs are spread out over a wider space, the heat is evenly distributed. This is beneficial for climate control and for keeping the crop warm and dry. LEDs don't cause an excessive heat load, and a screen (curtain) can be closed if desired.

Top lighting, interlighting and multi-layer systems

In conventional lighting systems, the (HPS) lamps are situated above the crop, often at least 1.5 metres above the plant heads. Because LEDs don't produce any radiant heat, they can be placed closer to the plants.

In the so-called interlighting system, LED modules are placed between plants (in or between rows or beds), at a height of the leaf package. Interlighting has existed in Scandinavia for many years already, but in the Netherlands it has been practised only since LED lights were introduced. The expected advantage is that the lights are closer to the leaves and therefore more effective. Leaves lower in the crop may remain active for longer when they receive light.

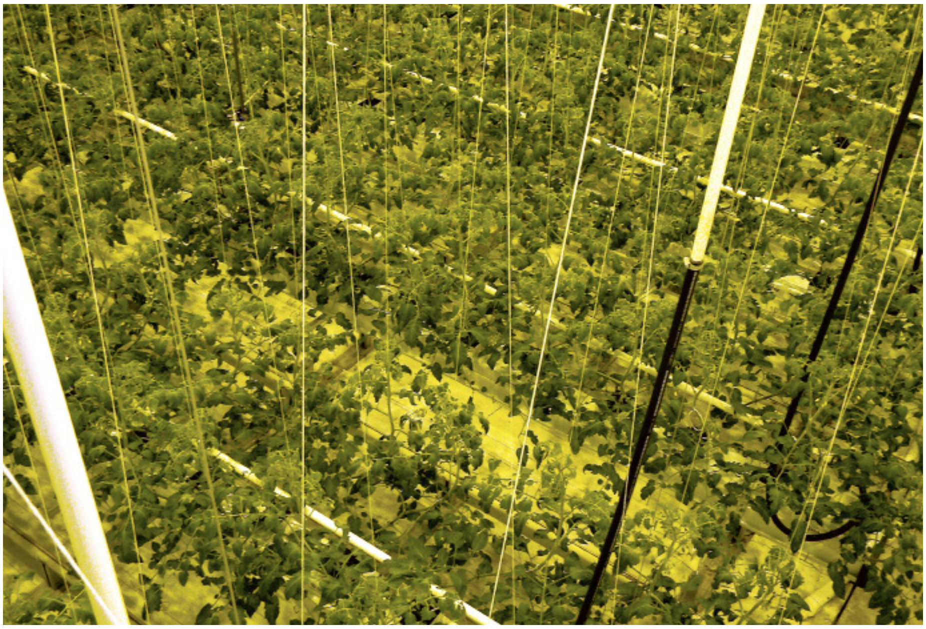
With air-cooled LEDs situated between the plants, the heat is released right where it is needed. This helps to keep the

Left to right - Top to bottom:

- *Large-scale tests with a combination of blue and red LEDs (at Redstar Trading, photo Mary Warmenhoven)*
- *Some large-scale tests with LED lighting were completed last season (at Redstar Trading, photo D. Uenck)*
- *Large-scale tests with a combination of blue and red LEDs (at Redstar Trading, photo Mary Warmenhoven)*
- *Combined HPS and LED toplighting, with only the LEDs lighted (experiment 2009/2010 at WUR)*
- *A scale is used to measure the dry-back overnight as a measure of transpiration (WUR, 2009/2010)*

Left to right - Top to bottom:

- *LED interlighting at night positioned overhead shortly after planting (experiment 2009/2010 at WUR).*
- *LED top lighting (experiment 2009/2010 at WUR)*
- *To avoid light pollution, greenhouses should be closed off by screens on all sides including the top.*
- *Tomatoes under LED toplighting (experiment 2009/2010 at WUR*
- *Young tomato plants (cv Sunstream) shortly after planting in October 2009 in the lighting experiment at WUR in Bleiswijk*



Left to right - Top to bottom:

- *HPS lighting as a reference for testing LED lighting (experiment 2009/2010 at WUR).*
- *Lighting with HPS lamps is applied by some tomato growers supplying a niche market in winter (at Redstar Trading)*
- *The light intensity of the LEDs looks relatively low compared to day light (at Redstar Trading).*
- *The rail with HPS lamps runs under the truss to minimize the obstruction of the natural light (at Redstar Trading)*
- *Lighting with high pressure sodium (HPS) lamps is common practice for large rose growers*

plants warm and dry, thus avoiding fungal diseases. The well-distributed heat release is then an advantage.

A special application is the multi-layer system, where plants are grown in different layers in growth rooms. Because there is no natural light, all required colours have to be supplied by the light systems, including enough blue.

Plant temperature and transpiration

HPS lamps produce radiant heat and a distinctive chunk of convective heat. This warms up the plants and stimulates transpiration. Transpiration in turn cools the leaves. As a result, leaf temperature under HPS lamps can be lower, equal or higher than the temperature of the surrounding air.

Air-cooled LEDs give a nicely distributed heat output. In an interlighting system these LEDs deliver the heat at plant height. This may slightly stimulate the transpiration. Top lighting LED systems, especially water-cooled systems, have little effect on plant temperature and transpiration.

Overall, the leaf temperature is usually not a lot different between plants in the three lighting systems (HPS, air-cooled LEDs, water-cooled LEDs), but the transpiration is likely to be highest under HPS lamps and lowest under water-cooled top-lighting LEDs.

Screening and climate control

Greenhouses with lighting are visible from a distance. Light escaping from a greenhouse is reflected against clouds, lighting a large area. In the Netherlands, this 'light pollution' is controlled by regulations that order screens (curtains) to be closed during parts of the night. Screening has an effect on the conditions in the greenhouse though, namely increased temperature and humidity. This is a real problem with HPS lighting.

HPS lamps are often located 1.5 metres or more above the plants. So the heat is released far above plant heads, where it is least useful. Heating is needed near the root-zone and in the middle of the plants, where the heating pipes are purposely situated. From here heat rises. Under a closed screen there is normally a build-up of heat, and HPS lamps just aggravate the heat build-up. HPS lamps also stimulate transpiration and cause the humidity to rise. In addition, with a screen closed, the greenhouse air is not in contact with the roof, so no moisture is removed by condensation against the cold glass. The consequence of using HPS lighting is that on mild days the thermal screens and even the vents have to be opened to get rid of excessive heat and moisture. This is a dire waste of energy. In addition, opening screens after dark is not permitted for reasons of light pollution.

With LEDs, there is hardly a problem with climate control or with complying with the regulations for night screening, thanks to the more even heat distribution, as described earlier.

Light units

Light can be measured in various units, for instance Watt and Mol, but should not be expressed in Lux. This requires some explanation.

Lux is an old unit for light that says something about how the human eye sees light. Lux has no relation to how plants experience light. Lux is really not a suitable unit, and should not be used in horticulture.

Watt is the unit for energy: one Watt equals one Joule per second. Watt is based on the theory that a light beam is a stream of energy. The amount of light in Watts can be easily calculated from the electricity use. Light intensity is expressed in Watt/m^2, and light sum is expressed in Joules/cm^2/day.

Mol is the modern unit for light. Light intensity is expressed in micromol/m^2/seconds, and light sum is mol/m^2/day. This unit is based on the theory of Einstein, that a light beam is a stream of light particles (instead of a stream of energy).

A 'standard lighting' installation in the Netherlands has an intensity in the order of 80-120 micromol/m^2/seconds. An extremely high level can be 200 micromol/m^2/seconds.

Further research

Now in the 2009/2010 winter season, further experiments are being carried out to answer a range of questions, and to see how LEDs compare with HPS lamps. A large experiment is set up with four greenhouse compartments with tomatoes. Four light treatments will be compared: SON-T, LED (as top light), SON-T + LED (as top light), and the last one is SON-T + LED (as interlight). All four treatments will get the same total amount of light, namely 160 micromol/m^2/s. The aim is to investigate the production, plant growth and all underlying processes, such light distribution, photosynthesis per leaf layer, temperature effects, transpiration, morphogenetic effects, and plant balance. Also several trials, on a total area of several hectares, are underway in commercial greenhouses with a range of crops including tomatoes, capsicum and roses.

Conclusions

Light Emitting Diodes (LEDs) are a promising technique for greenhouse lighting. When the development continues, LEDs will become far more efficient and effective than the current standard lamp used for greenhouse lighting (high-pressure sodium lamps [HPS] or SON-T). The efficiency for conversion of electricity to light is already more superior in some LEDs than in HPS lamps, and is on the rise. The efficiency to activate plant photosynthesis is potentially higher in red LEDs than in HPS lamps. Due to their particular light colour, LEDs can initiate special effects in plants or steer plant processes and plant balance (morphogenetic effects).

In the Netherlands, several trials and experiments were carried out over the last two winters, and several more are currently being performed, some on a very large scale of thousands of square metres. The results of new experiments and practical tests are eagerly awaited. Successful application of LED lighting will significantly improve energy efficiency, and will overcome light pollution. LEDs are applicable to winter production of fruit-vegetables, salads, herbs, cut flowers and ornamental plants in greenhouses.

Acknowledgements

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