Use of Natural and Artificial Light in Horticulture - Interaction of Plant and Technology

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Abstract

In intensive horticultural cultivation natural light levels often limit crop production during several periods. For an optimum plant production and product quality light intensity, spectrum and photoperiod have to be adapted to the needs of the crops at every moment. Light has to be optimised together with all other growth factors like temperature, humidity and CO_2. For a sustainable greenhouse production the use of freely available sunlight has to be preferred. New transparent greenhouse covering materials, like ETFE, glass with new anti-reflection coatings or materials with micro-surface structures, transmit a very high amount of light into the greenhouse. Other new materials are able to scatter the incoming light and make it diffuse. Diffuse light penetrates deeper into the canopy, increases light interception by the crop, influences micro-climate and increases crop production by 6.5-9.2% in The Netherlands, the potential in lower latitudes is even higher. Other materials manipulate light spectrum. Photoselective nettings have been developed in different colours influencing morphogenesis and crop production. Fluorescent plastic films combine effects on morphogenesis with high light transmission, especially important for higher latitudes. When sunlight is optimized it can still be necessary to add artificial light to ensure a year-round supply of horticultural products. There is still room for improving the crop energy efficiency under artificial lighting by changing duration and intensity of lighting, different growing systems and plant densities. Since artificial lighting requires a high amount of energy, new artificial lighting systems have been developed, such as interlighting and light emitting diodes (LED). LED give the possibility for true light spectrum control in the future. The (partial) replacement of HPS lamps by LED systems is currently under investigation in Dutch greenhouses. Integration in current growing systems has full attention. In order to reach a high sustainable and economic beneficial production the factor light has to be integrated and optimized within the total horticultural system.

INTRODUCTION

In intensive horticultural cultivation natural light levels often limit crop production during several periods. The light level can either be too low, due to insufficient sun light or sub-optimal growing systems or it can be too high. For an optimum plant production and product quality light intensity, light spectrum and photoperiod have to be adapted to the needs of the plants at every moment. For that the requirements of the crops are important. Light has to be optimized together with all other growth factors like temperature, humidity and CO_2. Interactions between different growth factors have to be considered while optimizing light. In order to optimize light, as well light intensity, daily light integral, light spectrum and the desired photoperiod have to be considered. Since natural sun light and energy is available without any costs, it has to be preferred above artificial light. So first all possibilities to optimize natural sun light penetration into the greenhouse have to be investigated by adapting greenhouse coverings, screens and screening strategy, using (photoselective) plastic films, coatings or nettings and optimizing the light use efficiency of crops by manipulating the crop itself or adapting the growing system. If a shortage of light during certain periods remains, the addition of artificial lighting should be considered. Technical, plant physiological and economical aspects need to be optimized. Since artificial lighting increases the energy consumption of the greenhouse, energy efficient lighting strategies are important. Next to that new lighting sources have to be developed in order to consume less energy in the future and to increase production under such light sources as much as possible. While optimizing the use of light crop requirements are of highest importance, technology used should be fitted into the total greenhouse system in order to make a sustainable and economic beneficial greenhouse production possible.

OPTIMISE USE OF NATURAL LIGHT

Light Intensity

Light intensity is a limiting factor in higher latitudes during the winter period. In such regions, there is a rule, that 1% more light equals 0.5-1% more production (Marcelis et al., 2006). The exact production increase due to more light is depending on crop, cultivar, season and other growth factors. Modern Venlo-type glass covered greenhouse systems designed for fruit vegetable production in The Netherlands have a total light transmission on crop level of 75-80%. That means that under Dutch circumstances about 2700-2800 MJ m^{-2} $year^{-1}$ solar radiation is entering the greenhouse. Since half of that radiation is PAR light, about 6200-6500 mol m^{-2} $year^{-1}$ are entering the greenhouse, while the daily light integral in summer is ten times higher than in winter. In greenhouses designed for potplant production in general the light transmission is lower, mainly due to a different construction and due to more installation on top of the crop.

In order to get more light into the greenhouse advanced covering materials could be used, such as white, low-iron glass (light transmission increase +1-2%), modern anti-reflection coatings on glass (+5-8%), new plastic films like ETFE material (+3%) or new nano-sized surface structures (+5-8%) (e.g., Hemming et al., 2009). The possibilities for the development of lighter greenhouse constructions is limited by the requirements of strength of the structure necessary to withstand wind and snow loads. The amount of installations on top of the crop should be limited as much as possible (+1-3%). Variations in roof angle are discussed (+1%) next to greenhouse orientation (e.g., Bakker et al., 2008). However, in most practical greenhouses the most efficient way of increasing light transmission is cleaning (up to 10-15%).

Next to the covering material, the type of screens, coatings or nettings used influence the amount of light entering the greenhouse. In periods with low irradiation and low outside temperatures screens are mainly used in order to save energy. If semi-transparent screens are installed, they can also be used for light regulation. For movable screens the screening strategy is important. In earlier research Dieleman and Kempkes (2006) showed that during the winter period the strategy of energy screen operation during daytime can save energy while crop production is not influenced. In model simulations they showed that keeping a transparent energy screen more closed during the morning and evening hours, up to an outside irradiation level of 150 W m^{-2}, energy could be saved (1.6 m^3 gas m^{-2} $year^{-1}$) with only a small effect on production (-0.3 kg tomato m^{-2} $year^{-1}$). Higher humidity levels resulted. Results of the model calculations were also confirmed in an experiment where screens were opened at 50W m^{-2} (Dieleman and Kempkes, 2006).

During periods with high irradiation and in lower latitudes plants often have to be protected against too much light. Screens, temporary coatings or nettings are used to decrease light intensity. However, light protection is often used too intensively since growers need to protect crops against too high temperatures. Screens, coatings or nettings are then used to decrease solar energy entrance, causing reduction of light entrance into the greenhouse, too. The requirements of crops for light protection are different. The photosynthesis of shade loving plants is saturated already at lower light levels, while sun loving plants tolerate more light (Gijzen, 1995). Recent investigations of de Zwart et al.

(2008) have shown that more light (less screening) increases crop production even with shade loving pot plants in The Netherlands. These authors observed that more light can be tolerated if other climate factors are adapted adequately. In that case high humidity levels during daytime (80%) were important to allow higher temperatures and higher CO_2 levels in the greenhouse. With higher humidity levels more light could be tolerated without causing leaf damage. To some extend that is certainly also true for lower latitudes.

Next to the amount of light inside the greenhouse the light use efficiency of the crop is important. That can be influenced by the crop genotype, the growing system and the growing conditions. Heuvelink et al. (this conference) showed that the light use efficiency of an average tomato crop in practice varies throughout the year. The light use efficiency defined as fresh tomato yield per unit of light received on top of the plant (kg MJ^{-1}) is the parameter that determines how much production is realised per unit of intercepted light. It depends on many factors like leaf area index, carbon dioxide level, harvest index (partitioning), fruit dry matter content. Heuvelink et al. showed that in Dutch greenhouses the light use efficiency of a tomato crop is 14% lower in autumn compared to spring. Average light use efficiency in autumn was 40 g per MJ, whereas in spring this was 46 g per MJ. For conventional greenhouses, with CO_2 enrichment, in autumn vents are used more frequent which results in lower CO_2 concentrations compared to spring. Also in autumn normally leaf area index (LAI) and hence fraction of intercepted light was reduced compared to spring. An additional reason for a higher LUE in spring could be that both assimilate demand and assimilate supply increase with crop development, whereas in autumn assimilate supply decreases with crop development. Besides, in autumn a smaller fraction of radiation is diffuse and the crop is older (possible senescence effects, stem length up to 12 m). It can be concluded that several factors in the total cropping system influence light use efficiency of a crop.

Diffuse Light

Light is not evenly distributed in Dutch greenhouses horizontally and vertically in tall crops. However, this can be improved with diffuse/scattered light. Modern greenhouse coverings are able to transform most of the light entering the greenhouse into diffuse light. A quantitative foundation for the potentials of diffuse light in Dutch greenhouses was given earlier by Hemming et al. (2005, 2008a,b). It was shown in modelling and experimental studies that crops such as fruit vegetables with a high plant canopy as well as ornamentals with a small plant canopy can utilize diffuse light better than direct light. Diffuse light penetrates the middle layers of a high-grown crop and results in a better horizontal light distribution in the greenhouse (Hemming et al., 2008b). Diffuse light is absorbed to a higher degree by the middle leaf layers of cucumber, resulting in a higher photosynthesis. Dueck et al. (2009) showed that the fresh weight of cucumber fruits was increased by 6.5 to 9.7% under diffuse covering materials compared to a crop grown under a reference clear covering. Potentials are even higher at lower latitudes (Hemming et al., 2008b).

Light Spectrum

Next to light intensity and daily light integral optimisation of light spectrum is important in order to get optimum crop growth and development. While light intensity and daily light integral mainly influence crop photosynthesis, light spectra cause several photomorphogenetic responses within a crop. The general effects of different light spectra are known. Specific light receptors in the UVB region of the solar radiation spectrum are assumed, light receptors in the blue region like phototropins and chryptochromes are described, phytochromes are identified in the red and far-red region (Kendrick and Kronenberg, 1994). Changes in light spectrum influence shoot elongation, formation of side shoots, leaf area and leaf thickness, germination processes, tropisms, flowering induction and development, colour of flowers and leaves, only to mention a few effects.

Light spectrum can be manipulated with plastic films, screens and nettings. Different coloured nets have been developed in order to reach desired physiological crop responses. The colour of a net influences the spectral distribution of the radiation passing through the net absorbing their complementary colour. Shahak (2008) and Shahak et al. (2009) e.g., describe the effect of different colours on different crop processes. For example, replacing traditional black shading net by either a red, yellow or pearl net with comparable shading factors resulted in 15-40% higher fruit production of different pepper cultivars. The major response to coloured nets was producing more fruits per plant, with essentially no reduction of fruit size or quality (Shahak et al., 2009). Many other effects are described in literature; an overview of effects of coloured nets is given by Stamps (2009). Castellano et al. (2008) quantified the radiometric properties of different agricultural nets in order to determine the shading factor and light spectrum on crop level in net covered structures. Based on that work Hemming et al. (2008c) developed a numerical model to estimate radiometric performance of net covered structures.

Coloured materials absorb the complementary colour and change light spectrum that way. Another purpose is to reduce total light transmission and increase shading factor. Next to the development of agricultural coloured nets, the last decade a lot of effort was laid in the development of photoselective plastic films which combine a desired photomorphogenetic crop response with a high light transmission. Combination of both is especially important at higher latitudes with in general lower irradiation intensities. Hemming et al. (2006) showed that the addition of blue fluorescent pigments to plastic films resulted in a higher transmission for blue light, a 1-3% higher total light transmission and in a higher production of strawberries under Dutch climatic conditions. Fluorescent pigments absorb UV radiation and emit it again in the PAR spectrum, depending on the type of pigment, as blue or red light. Strawberries were found to produce 5% more fruits under blue-fluorescent films. However, the authors describe that it was not possible to develop comparable films with red fluorescent pigments. Those pigments relatively increased the red light transmission but simultaneously decreased the total amount of light entering the greenhouse.

In most investigations with photoselective materials it is difficult to distinguish between effects due to changed light intensity and effects due to changes in light spectrum. Photomorphogenetic responses are often mixed with photosynthetic responses. Results depend on crop species, regional climate and growth conditions. Recent studies on photoselective films were carried out by de Salvador et al. (2008) on wheat, by Rajapakse and Li (2004) on vegetable seedlings, by Magnani et al. (2007) on lettuce, by Fletcher et al. (2004) on strawberry by Clifford et al. (2004) and Mata and Botto (2009) on poinsettia, by Ilias and Rajapakse (2005) on petunia and impatiens, to mention only a few.

The UV region of the solar radiation spectrum (300-380 nm) is supposed to influence crop responses as well as pest and diseases in greenhouses. UV is known to influence crop responses specifically via photoreceptors causing photomorphogenetic effects as well as via the destruction of photosystems activating protecting mechanisms. First quantitative experiments with different UV transmitting and blocking greenhouse coverings were carried out (Hoffmann, 1999a,b). The influence of different intensities of UV in the greenhouse due to several plastic film prototypes was described. Stem elongation of different cultivars of chrysanthemum was reduced by 10-15% with increasing intensity of UVA and UVB radiation in the greenhouse. Interactions with irradiation levels and outside temperature were identified. The colouring of leaves of *Coleus* × *hybrida* was intensified while the amount of chlorophyll was reduced in the same leaves. Shioshita et al. (2007) found a better colour of red lettuce under a UV-transparent film. The anthocyanin, cyanidin 3-(6-malonyl) glycoside synthesis was affected, comparable to the results of Hoffmann (1999b). However, the fresh weight was lower, probably due to a reduction of photosynthesis.

The UV region of the solar radiation spectrum also influences pest and diseases in greenhouses. Different types of plastic films changing the UV spectrum may have a significant influence on both the initial immigration and distribution of whitefly into greenhouses (Mutwiwa et al., 2005). Also population growth of whitefly, thrips and aphids is influenced by the amount of UV entering the greenhouse. The reduction of population growth is caused directly via changed light conditions and indirectly via changes of the plant as food source (Hemming et al., 2006). Many authors investigated this topic the last decennia. Reduction in *Bemisia tabaci* and *Franklinella occidentalis* due to UV-block films and the reduction of virus TYLCD is reported by Monci et al. (2004). Doukas and Payne (2007) found a reduction of whitefly, *Dialeurodes vaporariorum* under UV-blocking films. Rapisarda et al. (2006) report a reduction of *Bemisia tabaci* and virus TYLCD. Diaz et al. (2006) describe the reduction of several viruses in lettuce. Kumar and Poehling (2006) investigated the effect of UV-blocking plastic films and nets in humid tropics and found useful reductions of virus diseases. However, in general it can be concluded that UV blocking materials will not inhibit migration and population growth totally and will only contribute minor to integrated pest management in practical greenhouses. Other factors, like temperature, humidity and light conditions, sanitation and plant vitality are more important factors than changing light spectrum.

OPTIMISE USE OF ARTIFICIAL LIGHT

High Pressure Sodium Lamps

The traditional way of using artificial lighting in higher latitudes is the use of High Pressure Sodium lamps (HPS). Since they have an acceptable spectrum and a high energy efficiency, they are widely used in greenhouse horticulture. The last year developments concerning energy efficiency were limited, currently 1.9 µmol PAR m^{-2} s^{-1} light output per W energy input are realistic. Capacities were increased up to 1000 W and electronic devices have become common. Other lighting sources used are e.g., mercury lamps, which are used for more blue light in the spectrum, and fluorescent tubes, which are mainly used under fully artificial light conditions. In this paper no overview about all aspects of artificial lighting will be given, but the paper will be limited to a description of only the recent most important developments in artificial lighting. A major challenge for the use of artificial lighting is the reduction of energy use and costs. Reductions are possible by increasing the light use efficiency of the crop, optimising light duration and intensity, interplanting, change plant densities, changing the shape of the growing system. Other methods for higher energy use efficiency could be a change in planting date and in the future selecting of more efficient genotypes. The energy efficiency can furthermore be increased by using interlighting or changing the technical lighting system by the development of lamps with higher energy efficiency. It is expected that light emitting diodes (LED) could fulfil this requirement in the future. Currently red LED give 1.6 µmol m^{-2} s^{-1} light output per W energy input, some producers claim more, blue LED reach 0.8.

Dueck et al. (2007) carried out experiments in order to optimise light duration and light intensity within a tomato crop under Dutch conditions. Artificial lighting was applied with different durations and different intensities. They compared light treatments of 12, 15 and 18 hours at 162 µmol m^{-2} s^{-1}. The daily light integral of supplemental lighting was 7.0. 8.8 and 10.5 mol m^{-2} d^{-1} respectively. A fourth treatment of 18 hours with a lower light intensity of 135 µmol m^{-2} s^{-1} gave the same daily light integral of 8.8 mol m^{-2} d^{-1} than the 15 hours with 162 mol m^{-2} s^{-1}. As it could be expected the highest production was given by the treatment with the highest daily light integral (18 h, high light intensity, 10.5 mol m^{-2} d^{-1}). Given the same daily light integral (8.8 mol m^{-2} d^{-1}), a higher light intensity (162 vs. 135 µmol m^{-2} s^{-1}) resulted in more production compared to a longer lighting duration (15 vs. 18 h d^{-1}). Difference in production appeared until 6 weeks after the end of the lighting period. After that period production levels were similar again. Dueck et al. (2007) also analysed the net photosynthesis during the lighting period. They found that the crop needs some time to reach maximum photosynthesis after turning on the lighting system. Not all the light can directly be used after dark period. Turning on only half of the lighting capacity during the first hour after dark can save significant amounts of energy in horticultural production systems.

Näkkilä et al. (2006) showed that varying the plant densities by interplanting is a possibility to increase light use efficiency in a tomato crop. They examined different planting densities (2.0 and 2.5 plants m^{-2}). Supplemental lighting was provided by 400 W HPS lamps with 203 µmol m^{-2} s^{-1} during a photoperiod of 18 h d^{-1}. Cumulative annual yield was increased to 96.0 kg m^{-2} at high density planting compared to 81.6 kg m^{-2} at low density planting. However, yield per plant decreased from 40.8 to 38.8 kg $plant^{-1}$. The planting density had only little influence on the quality of fruits. Integrated pest control is considered to be more difficult in greenhouses with continuous production due to interplanting.

Interlighting

Since the energy consumption of traditional lighting systems such as HPS is high, new ways of using artificial light within a growing system are developed, such as inter-lighting (Gunnlaugsson and Adalsteinsson, 2006; Hovi et al., 2004). Mobile lighting had been another attempt to use lighting in a more energy efficient way. Several evaluations are available in literature (e.g., Blom and Zheng, 2009; Marissen et al., 2006). However, already in Lightsym2005 it was concluded that mobile lighting does not lead to higher energy efficiency in crop production (Heuvelink et al., 2006).

The hypothesis behind interlighting is that the energy used for lighting is used more efficiently by the crop. Part of the light is given to the middle/lower parts of the canopy, those parts are then able to contribute more to light absorption and photosynthesis and therefore to total crop yield (Hovi et al., 2004). The effect can probably be compared with the principles described in the chapter about diffuse light above. In order to prove this hypothesis several experiments were carried out comparing interlighting with traditional toplighting. Gunnlaugsson and Adalsteinsson (2006) carried out an experiment where they applied either toplighting only as a reference or partly toplighting and partly interlighting. They concluded that interlighting had no effect on yield of tomato ‘Geysir’, while 45% interlighting combined with 55% toplighting gave highest yield on tomato ‘Espero’ compared to toplighting only. Hovi-Pekkanen and Tahvonen (2008) showed in their experiments that indeed interlighting gave higher light intensities with the middle and lower layers of the crop depending on crop height and the amount of interlighting applied. In their extended study they showed that interlighting resulted in higher yield and better quality of cucumber especially in spring, but not significantly in the summer crop. The effects of interlighting during lower natural light conditions were highest. All those experiments were carried out with traditional artificial lamps.

Trouwborst et al. (2009) were the first to carry out experiments with LED used as interlighting in greenhouses. They investigated the effect of interlighting with LED on crop production and development in high-wire grown *Cucumis sativa* ‘Samona’. Plants were grown in a greenhouse under low natural irradiance (winter) with a supplemental light input of 221 µmol PAR s^{-1} m^{-2} (20 h d^{-1}). In the interlighting treatment, LED consisting of 80% red and 20% blue, supplied 37% of the light, 63% was supplied as toplighting by HPS lamps. In the control treatment all supplemental light was applied as toplighting by HPS lamps. Although leaf photosynthetic characteristics were significantly improved in the lower leaf layers, interlighting did neither increase total dry weight nor fruit production in their experiments. The light extinction profiles indicate that a lower percentage of supplemental toplighting and natural light was absorbed in the interlighting treatment, mainly due to extreme leaf curling. Further research is needed to explain the physiological behaviour of the crop. In general it can be concluded that interlighting gives potentials for energy saving and higher light use efficiency of crops for the future. LED could potentially play a major role in that since they can be placed everywhere in the crop due to their small size and giving “cold light”.

Light Emitting Diodes

Since the energy consumption of HPS is high, new artificial lighting systems have been developed such as light emitting diodes (LED) (e.g., Bula et al., 1991; Morrow, 2008; Massa et al., 2008). A lot of experiments with LED have been conducted under a controlled environment with artificial light only (e.g., Avercheva et al., 2009; Brown et al., 1995; Goins et al., 1997; Kim et al., 2004; Ménard et al., 2006; Tamulaitis et al., 2005). However, only a limited number of studies under greenhouse environment with supplemental LED have been carried out (e.g., Pinho, 2007; van Ieperen and Trouwborst, 2008). In The Netherlands LED are currently tested under greenhouse environment conditions at different growers cultivating different crops (sweet pepper, tomato, roses). One of those first experiences with LED in practice is described by Dueck et al. (2009b). Supplemental lighting is given to cut roses in a commercial greenhouse. Plants were illuminated from above with HPS lamps or LED lamps (ratio red to blue LED 95:5 in numbers of LED), both at an intensity of 110 µmol m^{-2} s^{-1}. In a third and fourth treatment, interlighting with red LED (40 µmol m^{-2} s^{-1}) was added to both HPS and LED top lighting. The major endpoints were crop growth and production. The balance between light intensity and temperature appeared to have a considerable influence on crop growth. It could be concluded that the production of roses under LED in practice currently is comparable or even higher than under traditional HPS lamps due to higher light use efficiencies of the crop. The exact interaction of crop temperature, light levels and light spectrum still have to be sorted out on crop level.

The introduction of LED gives the possibility to influence light spectrum specifically next to light intensity. Though many research has been carried out on the action spectrum of photosynthesis in the past (McCree, 1972) and on the effect of light colours on photomorphogenesis (Kendrick and Kronenberg, 1994), still more research is needed on the optimum light spectrum per crop when LED are applied as supplemental lighting in greenhouses. Effects on crop level are still unclear. In order to improve our knowledge on the photosynthesis action spectrum of major Dutch greenhouse crops Marcelis et al. (2009) have determined optical properties (reflection, absorption and transmission), action spectrum (CO_2 assimilated at the different wavelengths per incident light) and the spectral quantum yield (CO_2 assimilated per absorbed quantum of light) of photosynthesis of rose and tomato leaves in the laboratory as well as in a greenhouse. They found lower light absorption in the green (~550 nm) part of the PAR spectrum on leaf level, compared to the red and blue part, which was more pronounced in green than reddish rose leaves. At canopy level spectral differences in total light absorption of full grown canopies were smaller than at single leaf level. The spectral quantum yield was highest for red light (about 640-680 nm) and approximately comparable to earlier results of McCree (1972). No standard spectrum could be determined, though. Effects of wavelength on quantum yield were comparable for green leaves of tomato and rose. However, reddish rose leaves had a lower quantum yield in green light (around 550 nm), probably due to partial absorption by the non-photosynthetic pigment anthocyanin. The authors estimated the energy efficiency of current red LED is on leaf level up to 35% higher than HPS assuming the same light intensity. That indicates possibilities for improving energy efficiency in greenhouses in the future.

Hogewoning et al. (2009) analysed the action spectrum of cucumbers in more detail. Light spectrum influences leaf photosynthesis and plant morphology via short term responses and longer term acclimation. So far, it is unclear to which extent the well known spectral dependency of the quantum efficiency for CO_2 fixation is maintained when plants are grown under spectra different from day-light. Cucumber plants were grown under 100 µmol m^{-2} s^{-1} irradiance using red, blue and mixed red/blue LED and also an artificial sun and shade-light spectrum. Quantum yield of photosynthesis and light absorption were measured, quantum efficiency for photosynthesis on incident and absorbed light basis was calculated. Simultaneously photosystem I and II electron transport efficiency was measured, allowing a quantification of excitation balance of the two photosystems across the visible spectrum in vivo for the first time. The different light treatments changed quantum efficiency for photosynthesis considerably, which could largely be explained by light spectrum induced changes in the excitation balance of the two photosystems.

In general it can be concluded that LED are different from HPS. They emit a mono wavelength light colour which causes next to photosynthetically effects photomorphogentical responses. LED cause at the same light intensity a lower crop head temperature compared to HPS since they do not emit any near infrared radiation, which contributes to increasing crop temperature. LED influence transpiration and probably water and nutrient uptake. Growers still need to “learn to grow with LED”; the way of growing needs to be changed. Improvements of LED can be expected in the future. Until now the energy-efficiency of LED systems used in practice did not reach the level of HPS, however, they are close to that. Energy-efficiency can be expected to increase more in the future. Next to that it will be possible to give full light spectrum control to the crop. Costs will probably decrease. It will be necessary to optimize the use of LED within the total horticultural system.

CONCLUSIONS

For an optimum plant production and product quality light intensity, light spectrum and photoperiod have to be adapted to the needs of the plants at every moment. It is necessary to adapt the technological developments to the crop needs. Within that optimization it has to be taken into account that controlled and fully artificial light conditions are totally different from greenhouse conditions. Experimental results obtained under fully artificial light conditions are often not transferrable to greenhouse conditions. Next to that results obtained on leaf level are different from integrated results on crop level.

In order to optimize light, as well light intensity, daily light integral, light spectrum and the desired photoperiod have to be considered. While optimizing light it has to be considered that light is only one of the production factors. Since it interacts with others, it has to be optimized together with all other growth factors like temperature, humidity and CO_2, nutrients and water. First research shows that light could have a strong influence on pest and diseases (e.g., Suthaparan, 2009), therefore also new strategies for integrated pest control should be considered. More research is needed on that field. Since natural sun light and energy is available without any costs, it has to be preferred above artificial light. In order to reach a high sustainable and economic beneficial production the factor light has to be integrated and optimized within the total horticultural system.

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