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# The effects of light-emitting diode lighting on greenhouse plant growth and quality

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The aim of this study is to present the light emitting diode (LED) technology for greenhouse plant lighting and to give an overview about LED light effects on photosynthetic indices, growth, yield and nutritional value in green vegetables and tomato, cucumber, sweet pepper transplants. The sole LED lighting, applied in closed growth chambers, as well as combinations of LED wavelengths with conventional light sources, fluorescent and high pressure sodium lamp light, and natural illumination in greenhouses are overviewed. Red and blue light are basal in the lighting spectra for green vegetables and tomato, cucumber, and pepper transplants; far red light, important for photomorphogenetic processes in plants also results in growth promotion. However, theoretically unprofitable spectral parts as green or yellow also have significant physiological effects on investigated plants. Presented results disclose the variability of light spectral effects on different plant species and different physiological indices.

*Key words:* greenhouse vegetables, growth, light emitting diodes, metabolism, photosynthesis, vegetable transplants

## Introduction

### The technology

Light emitting diodes represent a promising technology for the greenhouse industry that has technical advantages over traditional lighting sources, but are only recently being tested for horticultural applications (Mitchell et al. 2012). Light emitting diode (LED) is a unique type of semiconductor diode. The wavelength of the light emitted (the color of light) depend on the properties of semiconductor material. LEDs can have peak emission wavelengths from UV-C (~250 nm) to infrared (~1000 nm) (Bourget 2008) and it is the first light source to have the capability of true spectral control, allowing wavelengths to be matched to plant photoreceptors to provide more optimal production and to influence plant morphology and composition (Morrow 2008). The fast technological progress of LEDs due to their extensive usage for other industrial applications provides various advancements for horticultural lighting.

The high capital cost is still an important aspect delaying the uptake of LED technology in horticultural lighting. Despite this, the technological development of LEDs is expected to reduce capital and operating costs in the future (Massa et al. 2008, Morrow 2008, Yeh and Chung 2009, Vänninen et al. 2010). Major advantage of LEDs over all other lamp types for plant lighting is that the technology is evolving in electrical-use efficiency at a rapid pace. For example blue LEDs that were only 11% efficient in 2006 were reported to be 49% efficient converting electrical energy to photon energy in 2011 (Mitchell et al. 2012). LED efficiency, in general, is projected to raise considerably, both as electrical efficiency and as photon flux efficacy over the coming decade. It is predicted, that the photosynthetic efficacy of red LEDs will be double of the HPS lamp by the year 2020 (Pinho et al. 2012). LEDs do not generally “burn out” like traditional lamps, thus their lifetime is measured as the time of LED to dim to 70% of its original intensity. The lifetime of LEDs is about 50000 h and still rising (Bourget 2008).

Along with LED energy-savings and functionality, their safety for user and environment should be mentioned. There is no fragile glass envelope to break, no high touch temperatures; LEDs contain no hazardous materials, such as mercury. Small LED size enables versatile design of the lighting unit. LED lighting systems can be configured to emit very high light fluxes, but even at the high light intensities, LED units can be placed close to plants, as they do not emit radiant heat. Because they are solid-state devices, LEDs are easily integrated into digital control systems (Morrow 2008) facilitating complex lighting program like varying intensity or spectral composition over a

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course of photoperiod or with plant developmental stage (Yeh and Chung 2009). However, overall LED efficiency and applications depend not only on the semiconductor itself, but also on the general design and technological properties of the lighting system. A properly designed LED light system is capable of providing performance and lifetime well beyond any traditional lighting source (Bourget 2008). However, when used as sole sources for photosynthetic, photomorphogenic, and/or photoperiod lighting, narrow-spectrum LEDs must be proportioned carefully to obtain desired plant responses (Mitchell 2012).

## Historical and practical perspectives

Initial researches for LED applications were done developing plant growth systems in space (Barta et al. 1992, Yorio et al. 2001, Massa et al. 2008) and these early works were a stimulus for the development of LED-based lighting systems for plant physiology experimentations (Tennessen et al. 1994, Morrow 2008). At that time, only red 660 nm LEDs were available. Despite this wavelength is close to the chlorophyll and Pr phytochrome absorption maxima, even pilot experiments with lettuce (Bula et al. 1991), potato, spinach, radish (Yorio et al. 2001) and wheat (Goins et al. 1997) revealed the necessity of the blue (400–500 nm) visible region light. It was offered to enrich red LED light with the spectra of blue fluorescent light (Bula et al. 1991, Yorio et al. 2001, Yorio et al. 2011), however the apparent era of LED researches started, when blue LEDs were introduced to the market. Far red light, acting on phytochrome photoconversions, is declared to be necessary for normal photomorphogenetic processes in plants; however, current market of FR LEDs, in the contrast to red LEDs is limited and seems to be dependent solely on demands of horticultural applications (Kubota et al. 2012).

One of the most highlighted LEDs advantages is the possibility to optimize lighting spectra selecting only specific, physiologically reasoned light wavelengths and not to waste the energy for unprofitable spectral parts as green or yellow. However, these light spectral components were proved to have significant physiological effects on plants (Kim et al. 2004, Johkan et al. 2010). Moreover, plants, cultivated under blue and red light in the closed environment look purplish grey for human eye, therefore it is difficult to evaluate plant wellness and injuries visually. A small flux of green light (up to 20%) is useful solving this problem (Massa et al. 2008).

LED technology to date is still relatively expensive to displace the fluorescent or high pressure sodium (HPS) illumination. However, combining the spectra of these conventional light sources with LED wavelengths it is possible not only to optimize the spectral quality for various plants and different physiological processes (growth, flowering, photosynthetic efficiency), but also to create economically efficient lighting system. In the recent investigations the combinations of LEDs ant fluorescent (Li and Kubota 2009, Lin et al. 2013) or high pressure sodium (Menard et al. 2006, Pinho et al. 2007, Brazaitytė et al. 2009) lamps are employed seeking for positive growth or metabolic effects.

Most of the studies with LED lighting were performed in the controlled environment growth chambers, where the main environmental parameters, as temperature, humidity, $CO_2$ concentration, and photosynthetic flux daily integral can be controlled independently of external influences. Unfortunately, well-succeeded lighting strategies in phytotrons not necessarily produce the same results in greenhouse conditions (Pinho et al. 2007), especially when variable daylight effect in the complex exposure is also involved. Therefore, individual experiments, evaluating the background effects of natural lighting are necessary to predict the effects of LED supplemental lighting (Pinho et al. 2007, Samuolienė et al. 2012a, Samuolienė et al. 2012b).

## Green vegetables: photosynthesis, growth and nutritional value

Plant responses to the light under which plants are grown affect their growth and development in a complicated manner. Light quality and quantity initiate signaling cascade of specific photoreceptors, such as phytochromes, cryptochromes, and phototropins, which alter the expression of a large number of genes. Whereas specific responses of plants to a spectrum may sometimes be predictable based on published research, the overall plant response is generally difficult to predict due to the complicated interaction of many different responses (Hogewoning et al. 2010). Light emitting diodes, which are characterized by relatively narrow-band spectra, are employed analyzing specific plant responses to the light quality.

Red light usually is the basal component in lighting spectra and sole red light is sufficient for normal plant growth and photosynthesis (Table 1). However, different wavelengths of red light might have uneven effects of plants. Goins et al. (2001) evaluated the effects of different red 660, 670, 680, 690 nm LED light wavelengths on lettuce growth and photosynthesis. Results showed that biomass yield increased when the wavelength of red LED emitted light increased from 660 to 690 nm. Most recent papers declare to use ~640 nm (Lefsrud et al. 2008, Samuolienė et al. 2012c, Žukauskas et al. 2011, Samuolienė et al. 2012a) or ~660 nm (Brazaitytė et al. 2006, Mizuno et al. 2011, Li and Kubota 2009, Tarakanov et al. 2012) nm red LEDs for cultivation of lettuce and other green vegetables. Red LED light, when applied alone, or in combination with fluorescent lamps or natural illumination had no remarkable positive effect on growth and development, but activated the action of antioxidant system. 660 nm LED light, applied as sole light source in the controlled environment stimulated anthocyanin accumulation in red leaf cabbages as compared to blue or green LED wavelengths (Mizuno et al. 2011). 658 nm red light supplemental for cool white fluorescent lamps resulted in 6% higher phenolics concentration in baby leaf lettuce (Li and Kubota 2009). Short term pre-harvest treatment with red 640 nm LEDs in controlled environment resulted in enhanced lutein and glucosinolate sinigrin accumulation in red-leaf cabbages (Lefsrud et al. 2008). The results of series of experiments, performed with 638 nm LED light (supplemental for natural and HPS illumination) pre-harvest treatment in greenhouses present the increased antioxidant capacity, enhanced contents of phenolic compounds and alpha tocopherol (Žukauskas et al. 2011, Samuolienė et al. 2012a) as well as reduced nitrate contents (Samuolienė et al. 2009, Samuolienė et al. 2011) in different lettuce varieties and other leafy vegetables (Bliznikas et al. 2012).

Far red LED light (700 and 725 nm) was demonstrated to be too far beyond the photosynthetically active region range to support suitable lettuce photosynthesis and growth (Goins et al. 2001). However, when applied in combination with red LEDs (Stutte et al. 2009) or cool white fluorescent light (Li and Kubota 2009) far red LEDs had pronounced effect on lettuce growth characteristics: increased biomass, leaf length but negatively affected chlorophyll, anthocyanin and carotenoids concentration. Lettuce growth promotion under supplemental far red lighting was associated with the increase in leaf area and consequently improved light interception (Kubota et al. 2012).

Positive effects of blue light, activating cryptochrome system and matching chlorophyll and carotenoids absorption spectra, were demonstrated on green vegetable morphology (Yanagi et al. 1996), growth and photosynthesis. Blue LEDs (440−476 nm), used alone or in combination with red LEDs, caused higher chlorophyll ratio in Chinese cabbage plants (Mizuno et al. 2011, Li et al. 2012); stimulated biomass accumulation in lettuce (Johkan et al. 2010) and Chinese cabbage plants (Li et al. 2012). Similar results were obtained, when red LED light was supplemented with blue light form blue fluorescent lamps (Yorio et al. 2001, Yorio et al. 2011). Supplemental blue LED light also stimulated antioxidant status in green vegetables: increased polyphenol (Johkan et al. 2010), vitamin C (Li et al. 2012), carotenoid (Lefsrud et al. 2008, Li and Kubota 2009) and anthocyanin contents (Stutte et al. 2009, Li and Kubota 2009), that affected leaf coloration (Stutte et al. 2009, Mizuno et al. 2011).

Green light also has some valuable physiological effects. 510, 520, 530 nm LED light (Johkan et al. 2012), as well as green fluorescent lamps, supplemental for red and blue LEDs (Kim et al. 2004), promoted lettuce growth. 505, 530, 535 nm green LED light, supplemental to HPS and natural illumination in greenhouse affected nutrition quality of different baby leaf lettuce varieties (Samuolienė et al. 2012b, Samuolienė et al. 2012d): reduced nitrate or increased ascorbic acid, tocopherol, anthocyanin concentrations.

Small flux of UV-A LED irradiation was also reported to be useful for anthocyanin contents in baby leaf lettuce (Li and Kubota 2009).

Table 1. The main LED light spectra effects on green vegetables

| | Lighting conditions | Plant | Effects on growth and photosynthesis | Metabolic effects | Reference |
|---|---|---|---|---|---|
| **Far red light 700-740 nm** | Far red (730 nm, 20 µmol $m^{-2}$ $s^{-1}$) LEDs in combination with red (640 nm, 300 µmol $m^{-2}$ $s^{-1}$) | Red leaf lettuce *(Lactuca sativa)* 'Outeredgeous' | Increased total biomass, leaf elongation. | Supressed anthocyanin content and antioxidant potential. | Stutte et al. 2009 |
| | Far red LEDs (734 nm, 160 µmol $m^{-2}$ $s^{-1}$) supplemental for cool white fluorescent lamps | 'Red Cross' baby leaf lettuce (*Lactuca sativa* L.) | Decreased chlorophyll concentration by 14% as compared to white fluorescent lamps. The fresh weight, dry weight, stem length, leaf length and leaf width significantly increased by 28%, 15%, 14%, 44% and 15%, respectively, as compared to sole white fluorescent lamps. | Decreased anthocyanins and carotenoids concentration by 40% and 11% as compared to sole white fluorescent lamps. | Li and Kubota 2009 |
| **Red light 625-700 nm** | Red 660 nm LEDs (75%) in combination with blue 460 nm LEDs (25%) total PPFD ~170 µmol $m^{-2}s^{-1}$ | Indian mustard (*Brassica juncea* L.) Basil (*Ocimum gratissimum* L.) | Delayed or inhibited plant transition to flowering as compared to HPS or 460 nm+635 nm LED combination effects. | | Tarakanov et al. 2012 |
| | Red 660 nm LEDs (50 µmol $m^{-2}$ $s^{-1}$) | Cabbages (*Brasica olearacea* var. *capitata* L.) 'Kinshun' (green leaves) and 'Red Rookie' (red leaves) | | Increased anthocyanin contents in red leaf cabbages. | Mizuno et al. 2011 |
| | 640 nm red LEDs (253,3 µmol $m^{-2}$ $s^{-1}$) applied 7 days before harvesting (pretreatment with cool-white fluorescent and incandescent irradiance at 275 µmol $m^{-2}$ $s^{-1}$) in controlled environment. | Kale plants (*Brassica oleracea* L. cv Winterbor) | Enhanced chlorophyll *a*, *b* accumulation. | Enhanced lutein accumulation. | Lefsrud et al. 2008 |
| | Red LEDs (658 nm, 130 µmol $m^{-2}$ $s^{-1}$) supplemental for cool white fluorescent lamps | Baby leaf lettuce (*Lactuca sativa* L. cv. Red Cross) | | Phenolics concentration increased by 6% with supplemental red light. | Li and Kubota 2009 |
| | 638 nm LED (~500 µmol $m^{-2}$ $s^{-1}$) supplemental for HPS (130 µmol $m^{-2}$ $s^{-1}$) lighting and natural illumination in greenhouse. 3 days pre-harvest treatment. | Lettuce (*Lactuca sativa* 'Grand rapids'Marjoram (*Majorana hortensis* Moench.) Green onions (*Allium cepa* L. 'Lietuvos didieji' | | Reduction of nitrate concentration. | Samuolienė et al. 2009 |

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| **Red light 625-700 nm** | 638 nm LED lighting (~170 μmol $m^{-2}$ $s^{-1}$) supplemental for HPS (130 μmol $m^{-2}$ $s^{-1}$) lighting and natural illumination in greenhouse. 3 days pre-harvest treatment. | Lettuce (*Lactuca sativa*): green leaf 'Lolo Bionda', 'Grand rapids', red leaf 'Lolo rosa'. | | Increased DPPH free radical scavenging activity. Increased phenolic compound and α tocopherol content. | Žukauskas et al. 2011 |
| | 638 nm LEDs (210 μmol $m^{-2}s^{-1}$) in combination with HPS lighting (300 μmol $m^{-2}s^{-1}$) and natural illumination 3 days before harvesting in greenhouse | Green baby leaf lettuce (*Lactuca sativa* L.) 'Thumper' and 'Multibaby' | | Increased concentration of total phenolics (28,5%), tocopherols (33,5% in 'Multibaby'), sugars (52,0%) and antioxidant capacity (14,5%) but decreased concentration of ascorbic acid. | Samuolienė et al. 2012a |
| | 638-nm LEDs (300 μmol $m^{-2}s^{-1}$) in combination with HPS lighting (90 μmol $m^{-2}s^{-1}$) and natural illumination 3 days before harvesting in greenhouse | Red leaf 'Multired 4', green leaf 'Multigreen 3' and light green leaf 'Multiblond 2' lettuces (*Lactuca sativa* L.) | | Reduced content of nitrate in red (56,2%) and green (20,0%) leaf lettuce, but nitrate contents increased in light green leaf lettuce. | Samuolienė et al. 2011 |
| | 638-nm LEDs (photoregulated flux) in combination with HPS lighting (90 μmol $m^{-2}s^{-1}$) and natural illumination 3 days before harvesting in greenhouse, total PPFD maintained at 300 μmol $m^{-2}s^{-1}$ | White mustard (*Sinapsis alba* 'Yellow mustard'), Spinach (*Spinacia oleracea)* 'Giant d'hiver', Rocket (*Eruca sativa)* 'Rucola', Dill (*Anethum graveolens)* 'Mammouth', Parsley (*Petroselinum crispum)* 'Plain leaved', Green onions (*Allium cepa)* 'White lisbon'. | | Altered antioxidant activity, increased monosaccharide and decreased nitrate accumulation in dill and parsley. Increase in vitamin C content in mustard, spinach, rocket, dill and green onion. | Bliznikas et al. 2012 |
| **Green light 490-550 nm** | Green 510, 520 or 530 nm LEDs (PPFD 100, 200 and 300 μmol $m^{-2}$ $s^{-1}$) | Red leaf lettuce (*Lactuca sativa* L. cv Banchu Red Fire) | High intensity (300 μmol $m^{-2}$ $s^{-1}$) green LED light was effective to promote lettuce growth (as compared to fluorescent light); 510 nm light had the greatest effect on plant growth. | | Johkan et al. 2012 |
| | Green 530 nm LEDs (30 μmol $m^{-2}s^{-1}$) supplemental for natural solar and HPS lamp (170 μmol $m^{-2}$ $s^{-1}$) illumination in greenhouse | Baby leaf lettuce: red leaf "Multired 4", green leaf "Multigreen 3" and light green leaf "Multiblond 2" | | Reduction of nitrate concentration and increase in saccharide contents in all baby leaf lettuce varieties. | Samuolienė et al. 2012d |
| | 505, 535 nm LEDs (30 μmol $m^{-2}$ $s^{-1}$) supplemental for HPS lighting (170 μmol $m^{-2}$ $s^{-1}$) and natural illumination in the greenhouse | Red leaf 'Multired 4', green leaf 'Multigreen 3' and light green leaf 'Multiblond 2' baby leaf lettuce (*Lactuca sativa* L.) | | 535 nm green LEDs had greater positive effect on ascorbic acid, tocopherol contents and DPPH free-radical scavenging capacity, when 505 nm LEDs had greater effect on total phenol and anthocyanin contents. | Samuolienė et al. 2012b |

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| **Blue light 425-490 nm** | Sole 440 nm blue LEDs (10,6 µmol $m^{-2}$ $s^{-1}$) applied 7 days before harvesting (pretreatment with cool-white fluorescent and incandesncent irradiance at 275 µmol $m^{-2}$ $s^{-1}$) | Kale plants (*Brassica oleracea* L. cv Winterbor) | | Enhanced β-carotene contents. | Lefsrud et al. 2008 |
| | Blue (468 nm) LEDs alone or in combination with red (655 nm) LEDs. Total PPFD ~100 µmol $m^{-2}$ $s^{-1}$ | Red leaf lettuce seedlings (Lactuca sativa L. cv.Banchu Red Fire) | Stimulated biomass accumulation in the roots; Resulted in compact lettuce seedling morphology; Promoted the growth of lettuce after transplanting. | Greater polyphenol contents and total antioxidant status. | Johkan et al. 2010 |
| | Blue (440 nm, 30 µmol $m^{-2}$ $s^{-1}$) LEDs in combination with red (640 nm, 270 µmol $m^{-2}$ $s^{-1}$) | Red leaf lettuce *(Lactuca sativa* L. cv. Outeredgeous) | Leaf expansion. | Increased concentration of anthocyanins, higher antioxidant potential. | Stutte et al. 2009 |
| | Blue LEDs (476 nm, 130 µmol $m^{-2}$ $s^{-1}$) supplemental for cool white fluorescent lamps | Baby leaf lettuce (*Lactuca sativa* L.) 'Red Cross' | | Anthocyanins concentration increased by 31%; Carotenoids concentration increased by 12%. | Li and Kubota 2009 |
| | Blue 470 nm LEDs 50 µmol $m^{-2}$ $s^{-1}$ | Seedlings of cabbages (*Brasica olearacea* var. *capitata* L.) 'Kinshun' (green leaves) and 'Red Rookie' (red leaves) | Promoted petiole elongation in both cabbage varieties; Higher chlorophyll contents in green leaf cabbages. | | Mizuno et al. 2011 |
| | Blue 460 nm LEDs alone and in combination with red 660 nm light (11,1% of blue light) Total PPFD of 80 µ mol $m^{-2}s^{-1}$ | non-heading Chinese cabbage (*Brassica campestris* L.) | Higher chlorophyll concentration. Blue LEDs benefit vegetative growth, while red LEDs and blue plus red LEDs support reproductive growth. | Concentration of vitamin C was the greatest under blue LEDs; | Li et al. 2012 |
| **UV-A light 380-315 nm** | UV-A LEDs (373 nm, 18±2 µmol $m^{-2}$ $s^{-1}$) supplemental for cool white fluorescent lamps | 'Red Cross' baby leaf lettuce (*Lactuca sativa* L.) | | Anthocyanin concentration increased by 11% | Li Kubota 2009 |

## Vegetable transplants: photosynthesis, growth and development

Supplemental lighting is proven to increase transplant growth and quality in vegetable nursery greenhouses (Hernandez and Kubota 2012). HPS lamps are the most commonly used type of light source, however they are relatively poor in blue and far-red compared to the solar PPF radiation (Menard et al. 2006). Numerous experiments were done to evaluate the effects of blue LEDs, supplemental for HPS lighting, as well as in combination with red LEDs in different ratios on growth and development of tomato, cucumber and pepper plants in greenhouses or controlled environment chambers (Table 2). It was determined, that blue light in the lighting spectra is required for normal chloroplast structure, leaf anatomy (Liu et al. 2011b) and to prevent any overt disfunctional photosynthesis (Hogewoning et al. 2010). Blue LEDs (450, 455 or 470 nm) supplemental for red LEDs or high pressure sodium lamps, signifficantly increased photosynthetic capacity and plant biomass in tomato (Menard et al. 2006, Liu et al. 2011a, Dueck et al. 2012, Samuolienė et al. 2012c), cucumber plants (Menard et al 2006, Hogewoning et al. 2010, Novičkovas et al. 2012, Samuolienė et al. 2012c) and pepper (Samuolienė et al. 2012c). Blue light effects on decreased elongation growth (Nanya et al. 2012, Menard et al. 2006, Javanmardi and Emami 2013) and leaf area expansion (Novičkovas et al. 2012, Samuolienė et al. 2012c) in tomato and cucumber transplants were also described. Even small flux of blue LED light (7–16 µmol $m^{-2}$ $s^{-1}$) supplemental for high pressure sodium lamp and natural illumination in greenhouse was reported to affect positively different vegetable transplant varieties (Menard et al. 2006, Novičkovas et al. 2012, Samuolienė et al. 2012c) (Table 2). However Hernandez and Kubota (2012) reported, that no signifficant differences in young tomato seedlings (until the second true leaf stage) growth and morphological parameters were observed when different red:blue LED light ratios (table 2) were applied to supplement natural lighting in greenhouse.

Other LED light wavelengths were also useful for transplant quality. Supplemental far red light resulted in tomato hypocotyl elongation (Brown et al. 1995, Kubota et al. 2012); a small flux of green light (505, 530 nm), supplemental for HPS and natural illumination in greenhouse promoted leaf area, fresh and dry weight in transplants of cucumber, tomato and pepper (Samuolienė et al. 2012c, Novičkovas et al. 2012). Orange and green LEDs, supplemental for the main light flux of red, blue and far red LEDs in growth chamber, accelerated growth in cucumber transplants (Brazaitytė et al. 2009), but negatively affected tomato transplant growth, that needs supplemental UV LED light (Brazaitytė et al. 2010). These LED light effects were also revealed in the later transplant growth in greenhouse under HPS illumination (Brazaitytė et al. 2010).

## Inter-lighting systems for greenhouse vegetable crop growth and yield

A novel approach in greenhouse lighting systems is inter-lighting, especialy potent for tomato, pepper and cucumber illumination during the whole growth cycle. Applying part of supplemental light within crop canopy, can improve light distribution within canopy and thus increase crop yield and light use efficiency. The high bulb temperature of HPS lamps has prevented its use for inter-lighting, when light emitting diodes have low bulb temperature, making it a potentially suitable light system for inter-lighting (Hao et al. 2012). Blue/Red LEDs inter-lighting was reported to act positively on cucumber leaf photosynthetic characteristics in the lower leaf layers, greater leaf mass per area and dry mass allocation to leaves, but had no effect on total biomass or fruit production (Trouwborst et al. 2010). However, Hao et al. (2012) revealed that using inter-lighting system, cucumber fruit visual quality improved, but fruit yield was increased only in early production period and gradually diminished toward the late production period. The smaller crop canopy and lower canopy coverage over the LED inter-lighting system in the late growing season might have reduced inter-light interception, decreasing its beneficial effects (Hao et al. 2012). Inter-lighting cultivating sweet pepper plants resulted in increased total marketable yield (by 16%) mainly due to increased fruit number, faster fruit maturation (Jokinen et al. 2012). Gomez with co-authors (2013) compared effects of supplemental LED inter-lighting and HPS lamp overhead lighting for greenhouse cultivated tomato yield, but found no productivity differences between two supplemental lighting treatments. However, significant energy savings for lighting occurred without compromising fruit yield. The electrical conversion efficiency for LED intercanopy lighting into fruit biomass was 75% higher than that for HPS overhead lighting (Gomez et al. 2013).

Table 2. The main LED light spectra effects on the greenhouse vegetable transplants

| | Lighting conditions | Plant | Effect | Reference |
|---|---|---|---|---|
| **Far red light 700-740 nm** | Red (660 nm) and far-red (735 nm) LED light, total PPFD 300 µmol $m^{-2}$ $s^{-1}$ | Sweet pepper (*Capsicum annuum* L.) 'Hungarian Wax' | The addition of far-red radiation resulted in taller plants with greater stem mass than red LEDs alone. | Brown et al. 1995 |
| **Red light 625-700 nm** | 660 nm LEDs (34 µmol $m^{-2}$ $s^{-1}$) supplemental for fluorescent lamp illumination (360 µmol $m^{-2}$ $s^{-1}$) | Tomato (*Lycopersicon esculentum* L. cv. Momotaro Natsumi) | Red LEDs were effective enhancing tomato yield. | Lu et al. 2012 |
| **Orange light 590-625 nm** | 622 nm orange LEDs (30 µmol $m^{-2}$ $s^{-1}$) supplemental for the main 638 nm, 447 nm, 669 nm and 731 nm LEDs lighting (total PPFD ~200 µmol $m^{-2}$ $s^{-1}$) in the growth chamber. | Transplants of cucumber 'Mandy' F1 | Accelerated growth. | Brazaitytė et al. 2009 |
| **Green light 490-550 nm** | 520 nm green LEDs (12 µmol $m^{-2}$ $s^{-1}$) supplemental for the main 638 nm, 447 nm, 669 nm and 731 nm LEDs lighting (total PPFD ~200 µmol $m^{-2}$ $s^{-1}$) in the growth chamber. | Transplants of cucumber 'Mandy' F1 | Accelerated growth. | Brazaitytė et al. 2009 |
| | 505, 530 nm LEDs (15 µmol $m^{-2}$ $s^{-1}$) supplemental for HPS lighting (90 µmol $m^{-2}$ $s^{-1}$) and natural illumination in the greenhouse | Transplants of cucumber 'Mirabelle' F1<br>Tomato 'Magnus' F1<br>Sweet pepper 'Reda' | 505 nm LED light resulted in increased leaf area, fresh and dry weight and photosynthetic pigment contents in all vegetable transplants.<br>530 nm light had positive effect on development and photosynthetic pigment accumulation in cucumber transplants only. | Samuolienė et al. 2012c |
| | 05, 530 nm LEDs (15 µmol $m^{-2}$ $s^{-1}$) supplemental for HPS lighting (90 µmol $m^{-2}$ $s^{-1}$) and natural illumination (100-200 µmol $m^{-2}$ $s^{-1}$) in the greenhouse | Transplants of cucumber 'Mandy' F1 | Increased leaf area, fresh and dry weight, decreased hypocotyl elongation. | Novičkovas et al. 2012 |

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| Blue light 425-490 nm | Blue LEDs alone and in combination with red and green LEDs Total PPFD ~300 µmol $m^{-2}$ $s^{-1}$ | Cherry tomato seedling | Required for normal chloroplast structure and leaf anatomy; Significantly increased net photosynthesis; Increased stomatal numbers per $mm^2$. | Liu et al. 2011b |
| | Blue 455, 470 nm LEDs (15 µmol $m^{-2}s^{-1}$) supplemental for natural solar and HPS lamp (90 µmol $m^{-2}$ $s^{-1}$) illumination in greenhouse | Transplants of cucumber hybrid 'Mirabelle' F1 Transplants of tomato hybrid 'Magnus' F1 Transplants of sweet pepper 'Reda' | Increase in leaf area, fresh and dry weight and photosynthetic pigment contents in all vegetable transplants. | Samuolienė et al. 2012c |
| | Blue 455, 470 nm LEDs (15 µmol $m^{-2}s^{-1}$) supplemental for natural solar and HPS lamp (90 µmol $m^{-2}$ $s^{-1}$) illumination in greenhouse | Transplants of cucumber 'Mandy' F1 | Supplemental 470 nm LED illumination resulted in increased leaf area, fresh and dry weight, decreased hypocotyl elongation. 455 nm LED illumination caused slower growth and development of transplants. Both 455 and 470 nm enhances photosynthetic pigment contents. | Novičkovas et al. 2012 |
| | Red 661 nm : blue 455 nm supplemental LED light (PPFD 55,5 µmol $m^{-2}$ $s^{-1}$) in different photon flux ratios in greenhouse under low (8,9 mol $m^{-2}d^{-1}$) and high (19,4 mol $m^{-2}d^{-}1$) daily solar integrals | Tomato seedlings 'Komeett' until the second true leaf stage | No significant differences in growth and morphological parameters between different red: blue ratios (0, 4 or 16% of blue LED light). | Hernández and Kubota 2012 |
| | Blue (450 nm) and red (660 nm) LEDs in different ratios: 0.1 (B15R135 µmol $m^{-2}$ $s^{-1}$), 0.4 (B45R105) and 1.0 (B75R75) | Tomato seedlings 'Reiyo' | Higher B/R ratio (1.0) resulted in shorter stem length. | Nanya et al. 2012 |
| | Blue LEDs (455 nm; 6,7-16 µmol $m^{-2}$ $s^{-1}$) supplemental for HPS (400-520 µmol $m^{-2}$ $s^{-1}$) illumination | Tomato (*Lycopersicon esculentum* 'Trust') and cucumber (*Cucumis sativus* 'Bodega') | Supplemental blue light inside the canopy increased plant biomass, reduced internode length and fruit yield. | Menard et al. 2006 |
| | Blue LEDs (450 nm) supplemental to red (638 nm) light. Total PPFD 100±5 µmol $m^{-2}$ $s^{-1}$; blue (B) light percentage: 0B, 7B, 15B, 22B, 30B, 50B, and 100B. | Cucumber plants (*Cucumis sativus* cv. Hoffmann's Giganta) | Necessary to prevent any overt dysfunctional photosynthesis. Photosynthetic capacity increased with increasing blue percentage during growth measured up to 50% blue. It was associated with an increase in leaf mass per unit leaf area, nitrogen content per area, chlorophyll content per area, and stomatal conductance. | Hogewoning et al. 2010 |

## Incidence of diseases and pest management

In 2008 Massa et al. presented a review about LED and plant productivity, also here predicting the future trends of LED usage for plant lighting. He presented scenario that custom-designed lighting systems could significantly reduce insect, disease, or pathogen loads on certain crops. Certain wavelengths could be used to eliminate or minimize the abilities of fungi to proliferate or insects to navigate to host species, reproduce (Massa et al. 2008). To date, it is still an "easy to imagine scenario", as only discrete results are published in scientific literature.

It was proposed, that light color induced changes in primary or secondary plant metabolites could be associated to the disease development and interaction with pests (Vänninen et al. 2010, Johansen et al. 2011, Vänninen et al. 2012). The differential effect of LED lighting spectra was observed on the development of diseases caused by tomato mosaic virus on pepper, powdery mildew on cucumber and bacterial wilt on tomato plants (Shuerger and Brown 1997). Cucumber plants, grown under monochromatic red LED light were more resistant to powdery mildew as compared to other monochromatic light colors and this effect correlated with enhanced salicylic acid-dependent signaling pathway (Wang et al. 2010). The results, presented by Kook et al. (2013) also suggest that the control efficacy of gray mold (*Botrytis cinerea*) in lettuce is closely associated with the increase of antioxidant capacity as well as the development of compact morphology by blue-light treatment. Direct light colors effects on insect phototactic behavior are also pronounced, such as inability of locating host plants by visually orienting pests in red and blue light or attraction to yellow-green wavelengths (Vanninen et al. 2012).

The light effects on pathogen and arthropod management with less chemicals is an attractive and promising technology, however, according to the results of present studies, it appears that some effects are species or cultivar specific.

## Conclusion

The researches of solid state lighting for plant illumination applications have lasted already for two decades. However, the questions, what specific spectra and photosynthetic flux densities are required by different plant species and varieties in different ontogenesis stages, what wavelength combinations should be selected seeking for maximal productivity, optimal nutrition quality, are still open. The use of LED technology can be promising for greenhouse horticulture, but to-date more knowledge must be acquired on the effects of LEDs on various vegetables for larger scale industrial applications.

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