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Review

INFLUENCE OF WAVELENGTH OF LIGHT ON GROWTH, YIELD AND NUTRITIONAL QUALITY OF GREENHOUSE VEGETABLES

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All previous reviews of research on light-emitting diodes (LEDs) have been focused on how different light spectra generally influence plant yield and quality. There are no or almost no reviews on the effect of spectra on sugars or pigment concentration, or yield and growth etc. The role of visible light in food production, as in agriculture and horticulture, is obvious, as light drives photosynthesis, which is crucial for plant growth and development. Solid state lighting using LEDs represents a fundamentally different technology from gaseous discharge-type lamps currently in use. LEDs are important lamp types because the concentration of the light spectrum they emit can be changed to provide plants at various developmental stages with the light spectrum needed. A great deal of studies have been done on the effect of wavelengths of light on growth, yield and nutritional quality of greenhouse vegetables. However, little is known about the mechanisms by which the spectra affect sugar and pigment concentration, and yield, and growth. This article provides a list of how spectra influence the yield, growth, and nutritional quality of greenhouse-grown vegetables. Based on the given information we can conclude that blue, green, and red light are the main light colours that influence positively plant yield, growth and nutrient quality. Sometimes in specific situations, some other light colours are also beneficial, like far red light, orange light and UVA light. Future work on light colour manipulation has potential for producing lamps and greenhouse covers that better support plant yield, growth, and nutrition.

Key words: *plants, LEDs, colour, yield.*

INTRODUCTION

The role of visible light in food production, as in agriculture and horticulture, is obvious, as light drives photosynthesis, which is crucial for plant growth and development. However, less recognition is given to its usefulness in other aspects of food processing. Low quantities of light can maintain postharvest quality of several species of crops by mitigating senescence, and improving phytochemical and nutritional quality (D'Souza *et al*., 2015).

Solid state lighting using light-emitting diodes (LEDs) represents a fundamentally different technology from the gaseous discharge-type lamps in current use in horticulture (Morrow, 2008). Light-emitting diodes represent a promising technology for the greenhouse industry, which has technical advantages over traditional lighting sources, but is only recently being tested for horticultural applications (Olle and Virsile, 2013).

Testing of LEDs began in the United States in the late 1980s, and in the mid-1990s high output LEDs became available (Morrow, 2008). Horticultural lighting utilising light-emitting diodes (LEDs) was introduced to the general public in the first few years of the 21st century. Since then, improvements in technology and pricing have made LED lights a viable alternative to the traditional and very effective High Intensity Discharge (HID) systems, while using only about 35% of the electricity required by HID lights (Anonymous, 2012).

Light is the sole source of energy for plant growth and development. Light is just one portion of the electromagnetic spectrum (Ryer, 1998). Terrestrial sunlight is considered to consist of ultraviolet (UV), visible (light) and infra-red light. The wavelengths of UV radiation (UVR) lie in the range of 100–400 nm; UV light is further subdivided into: UVA (ultraviolet A radiation, 315–400 nm), UVB (ultraviolet B radiation, 280–315 nm), and UVC (ultraviolet C radiation, 100–280 nm) (Anonymous, 1992). Visible light ranges from low blue to far-red with wavelengths between 380 and 750 nm, although this varies between individuals. The region between 400 and 700 nm is used by plants to drive photosynthesis and is typically referred to as Photosynthetically Active Radiation (PAR) (Anonymous, 2012).

Capabilities controlling spectral composition and high light output, with little radiant heat, make this technology potentially one of the most significant advances in horticultural lighting since the development of HID lamps (Morrow, 2008).

The LEDs have many benefits (Morrow, 2008). They allow wavelengths to be matched to plant photoreceptors to provide optimal production and influence plant morphology and composition. As they are solid-state devices, LEDs are easily integrated into digital control systems, facilitating special lighting programmes such as "daily light integral" lighting and sunrise and sunset simulations. They are safer to operate than current lamps because they do not have glass envelopes, or high touch temperatures, and they do not contain mercury. These systems progressed from simple red-only LED arrays using the limited components available at the time to high-density, multicolour LED chip-on-board devices. As light output increases while device costs decrease, LEDs continue to move toward becoming economically feasible for even large-scale horticultural lighting applications.

The aim of this review was to examine the wavelengths of light that affect growth, nutritional quality, and yield of greenhouse grown vegetables.

OVERVIEW OF DIFFERENT LIGHT RECEPTORS AND THEIR PHYSIOLOGICAL ROLE

Plants have pigment systems that capture radiant energy in different regions of the electromagnetic spectrum. For example, photosynthetically active radiation (400–700 nm) captured by chlorophyll pigments provides the energy for photosynthesis, the process by which plants combine carbon dioxide and water to produce oxygen and carbohydrates. Carbon assimilated during photosynthesis provides the energy to sustain life on earth (Rajapakse *et al.*, 1999).

Light also acts as a signal of environmental conditions surrounding the plants. Photoreceptors act as signal transducers to provide information that controls physiological and morphological responses. Through these pigments, plants have the ability to perceive small changes in light composition for initiation of physiological and morphological changes. This ability of light to control plant morphology is independent of photosynthesis and is known as photomorphogenesis. In photomorphogenesis, photons in specific regions of the spectrum are perceived by the photoreceptors present in smaller quantities. Known photomorphogenic receptors include phytochrome (the red and far-red light sensor that has absorption peaks in red and far-red regions of the spectrum, respectively) and "cryptochrome" (the hypothetical UV-B and blue light sensor) (Rajapakse *et al.*, 1999).

Phytochrome is the most intensively studied sensory pigment that controls photomorphogenesis. Phytochrome is capable of detecting wavelengths from 300 to 800 nm with maximum sensitivity in red (R, 600 to 700 nm with peak absorption at 660 nm) and far-red (FR, 700 to 800 nm with peak absorption at 730 nm) wavelengths of the spectrum (Rajapakse *et al.*, 1999).

The relationship between light and plant growth can be demonstrated by exposing leaves to various colours of light. Light supplies the power to carry out photosynthesis, the food-making process in leaves. However, the spectrum of light most utilised by a leaf is limited to three distinct colours: red, blue, and yellow. For example, leaves appear green because green is the colour most leaves reflect rather than absorb and use.

FOREWORD

Far red light increases total biomass (Lee *et al.*, 2016; Pinho *et al.*, 2017), while at the same time increases plant elongation (Stutte *et al.*, 2009) and decreases pigment concentration of plants (Li and Kubota, 2009). As plant elongation and decrease in pigment concentration are not desirable, this increase of biomass is not very advantageous.

Red light benefits reproductive growth (Li *et al.*, 2012), increases tomato yield (Lu *et al.*, 2012), reduces nitrate concentration (Samuoliene *et al.*, 2011) and increases vitamin C concentration (Bliznikas *et al.*, 2012) in plants. As red colour of light increases yield by decreasing nitrate content and increasing C-vitamin content, and considering that both factors are highly desirable, then this colour has big potential use in plant production.

Orange light accelerates growth of transplants (Brazaityte *et al.*, 2009), and therefore this light colour is also desirable in plant production.

Green light promotes growth (Johkan *et al.*, 2012), reduces nitrate concentration (Samuoliene *et al.*, 2012d) and increases saccharide concentration (Samuoliene *et al.*, 2012d) of plants. Green light also has positive effect on vitamin C concentration (Samuoliene *et al.*, 2012b) of plants. This colour of light contributes only to desirable factors in plant production and also has big potential use in plant production.

Blue light results in compact plants (Sergejeva *et al.*, 2018). Blue light benefits vegetative growth (Li *et al.*, 2012). Blue light increases pigment concentration (Sergejeva *et al.*, 2018) in plants. The concentration of vitamin C is greatest under blue light (Li *et al.*, 2012). This colour of light contributes to desirable factors in plant production and also has big potential use in plant production.

Like all living organisms, plants sense and respond to UV radiation, both the wavelengths present in sunlight (UV-A and UV-B) and the wavelengths below 280 nm (UV-C). All types of UV radiation are known to damage various plant processes. Such damage can be classified into two categories: damage to DNA (which can cause heritable mutations) and damage to physiological processes (Stapleton, 1992). UVA light can have also positive effects on plants, such as increase of anthocyanin concentration in baby leaf lettuce (Li and Kubota, 2009). However, UV radiation is rarely used in plant production.

GROWTH

Additional and supplemental lighting refers to all spectra applied in experimental or production conditions. Greenhouse vegetable growth is influenced by light colour (Table 1). Far red lighting increases growth of lettuce (Lee *et al.*, 2016; Pinho *et al.* 2017). It elongates leaves in baby leaf lettuce (Li and Kubota, 2009), red lettuce (Lee *et al.*, 2015) and in red leaf lettuce (Stutte *et al.*, 2009) resulting in taller plants (Brown *et al.*, 1995). Additional red light was observed to delay or inhibit transition to flowering in basil (Tarakanov *et al.*, 2012). Red light induced upward or downward leaf curling in tomato (Ouzounis *et al.*, 2016). Orange light accelerated growth of cucumber transplants (Brazaityte *et al.*, 2009). Additional green light accelerated

Table 1

THE EFFECT OF LIGHT COLOUR ON GROWTH OF GREENHOUSE VEGETABLES

Plant	Effect on growth	Light colour	Reference
Lettuce (*Lactuca sativa* L.) 'Frillice Crisp'	Addition of far red light increased leaf area index Faster growth may have caused decrease in dry weight content by 27% and 7%, respectively	Far red 700–850 nm	Pinho *et al.*, 2017
Lettuce (*Lactuca sativa* L.) 'Sunmang' seedlings from 16 days-old	Improved shoot and root growth	Far red 700–850 nm	Lee *et al.*, 2016
Baby leaf lettuce (*Lactuca sativa* L.) 'Red Cross'	Increased stem length and leaf length	Far red 700–850 nm	Li and Kubota, 2009
Red lettuce (*Lactuca sativa* L.) 'Sunmang'	The number of leaves increased, leaves were longer	Far red 700–850 nm	Lee *et al.*, 2015
Red leaf lettuce *(Lactuca sativa* L.*)* 'Outeredgeous	Leaf elongation	Far red 700–850 nm	Stutte *et al.*, 2009
Sweet pepper (*Capsicum annuum* L.) 'Hungarian Wax'	Addition of far-red radiation increased plant height and greater stem mass more than red LEDs alone	Far red 700–740 nm	Brown *et al.*, 1995
Tomato (*Solanum lycopersicum*) genotypes	Upward or downward leaf curling in all genotypes in the 100% red treatment	Red 620–700 nm	Ouzounis *et al.*, 2016
Indian mustard (*Brassica juncea* L.), Basil (*Ocimum gratissimum* L.)	Delayed or inhibited plant transition to flowerin	Red 620–700 nm	Tarakanov *et al.*, 2012
Transplants of cucumber 'Mandy' F1	Accelerated growth	Orange 585–620 nm	Brazaityte *et al.*, 2009
Red leaf lettuce (*Lactuca sativa* L.) 'Banchu Ref Fire'	High intensity (300 $\mu mol \cdot m^{-2} \cdot s^{-1}$) green LED light promoted lettuce growth (as compared to FL); 510 nm light had the greatest effect on plant growth	Green 490–550 nm	Johkan *et al.*, 2012
Lettuce (*Lactuca sativa*) cultivars, red leaf 'Sunmang' and green leaf 'Grand Rapid TBR' 18 day seedlings for 4 weeks	The substitution of blue with green LEDs in the presence of a fixed proportion of red enhanced growth of lettuce; Fresh weights of red leaf lettuce shoots under R8G1B1 were about 61% higher than those under R8B2	Green 490–550 nm	Son and Oh, 2015
Transplants of cucumber 'Mandy' F1	Accelerated growth	Green 490–550 nm	Brazaityte *et al.*, 2009
Transplants of cucumber 'Mirabelle' F1, Tomato 'Magnus' F1 and Sweet pepper 'Reda'	Supplemental 505 nm LED light increased leaf area in all vegetable transplants	Green 490–550 nm	Samuoliene *et al.*, 2012c
Transplants of cucumber 'Mandy' F1	Increased leaf area, decreased hypocotyl elongation	Green 490–550 nm	Novičkovas *et al.*, 2012
Tomato seedlings 'Reiyo'	Higher B/R ratio (1.0) resulted in shorter stem length	Blue 425–490 nm	Nanya *et al.*, 2012
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	Blue 425–490 nm	Hogewoning *et al.*, 2010
Cucumber (*Cucumis sativus*) 'Cumlaude'	Hypocotyl length decreased with increasing blue light up to 75%, and was significantly higher under 100% blue treatment; Leaf area decreased with the increase of the percentage of blue up to 75%. 100% blue increased leaf area	Blue 425–490 nm	Hernandez and Kubota, 2016
Seedlings of cabbages (*Brasica olearacea* var. *capitata* L.) 'Kinshun' (green leaves) and 'Red Rookie' (red leaves)	Promoted petiole elongation in both cabbage varieties	Blue 425–490 nm	Mizuno *et al.*, 2011

Table 1 (continued)

Plant	Effect on growth	Light colour	Reference
Red leaf lettuce seedlings (*Lactuca sativa* L. cv. Banchu Red Fire)	Resulted in compact lettuce seedling morphology; Promoted the growth of lettuce after transplanting	Blue 425–490 nm	Johkan *et al*., 2010
Non-heading Chinese cabbage (*Brassica campestris* L.)	Blue LEDs benefit vegetative growth, while red LEDs and blue plus red LEDs support reproductive growth	Blue 425–490 nm	Li *et al*., 2012
Red leaf lettuce *(Lactuca sativa* L. cv. Outeredgeous)	Leaf expansion	Blue 425–490 nm	Stutte *et al*., 2009
Lettuce (*Lactuca sativa* L. *var foliosum* cv. 'Dubacek' and *L. sativa* L. cv. 'Michalina')	Compact plant morphology	Blue 440 nm	Sergejeva *et al*., 2018
Transplants of cucumber hybrid 'Mirabelle' F1, tomato hybrid 'Magnus' F1 and sweet pepper 'Reda'	Supplemental blue light increased leaf area in all vegetable transplants	Blue 425–490 nm	Samuoliene *et al*., 2012c
Transplants of cucumber 'Mandy' F1	Supplemental 470 nm LED lighting increased leaf area, decreased hypocotyl length; 455 nm LED light caused slower growth and development of transplants	Blue 425–490 nm	Novickovas *et al*., 2012
Cucumber (*Cucumis sativus*) 'Cumlaude' and tomato (*Solanum lycopersicum* 'Komeett')	Cucumber hypocotyl length decreased with increasing blue up to 75% Tomato hypocotyl length decreased with increasing blue up to 75%	Blue 425–490 nm	Hernandez *et al*., 2016
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 Increased in leaf mass per unit leaf area	Blue 425–490 nm	Hogewoning *et al*., 2010

*PPFD, photosynthetic photon flux density; PP, photoperiod; B, blue; R, red; FR, far red; G, green, FL, fluorescent, WF, white fluorescent, HPS, high pressure sodium

growth in lettuce (Johkan *et al*., 2012; Son and Oh, 2015). Supplemental green light increased transplant growth of cucumber transplants (Brazaityte *et al*., 2009; Novickovas *et al*., 2012; Samuoliene *et al*., 2012c) and tomato and sweet pepper transplants (Samuoliene *et al*., 2012c). Blue light resulted in compact lettuce seedlings (Johkan *et al*., 2010). Blue light promoted petiole elongation in cabbage (Mizuno *et al*., 2011). Decreased hypocotyl length in cucumber transplants was observed under blue light (Novickovas *et al*., 2012; Hernandez *et al*., 2016; Hernandez and Kubota, 2016). Blue light accelerated leaf expansion in lettuce, and in tomato, cucumber and sweet pepper transplants (Stutte *et al*., 2009; Novickovas *et al*., 2012; Samuoliene *et al*., 2012c; Hernandez and Kubota, 2016). Tomato seedlings had shorter stem length under blue light (Nanya *et al*., 2012). In non-heading Chinese cabbage blue light benefitted vegetative growth, while blue light in combination with red light supported reproductive growth (Li *et al*., 2012).

YIELD OF VEGETABLES INFLUENCED BY DIFFERENT LIGHT COLOURS

Greenhouse vegetable yield is influenced by different light colours (Table 2). Fresh weight of lettuce, baby leaf lettuce and red leaf lettuce was observed to increase under additional far red lighting (Li and Kubota, 2009; Stutte *et al*, 2009; Lee *et al*., 2015; Chen *et al*., 2016; Lee *et al*., 2016; Pinho *et al*., 2017).

Red light enhanced tomato yield (Lu *et al*., 2012). In addition to effect of red light, green light increased lettuce fresh weight (Son and Oh, 2015). Similar effects on fresh weight of cucumber transplants were obtained by Novickovas *et al.* (2012) and Samuoliene *et al.* (2012c). Blue light stimulated biomass accumulation in red leaf lettuce seedlings (Johkan *et al*., 2010). Increased fresh weight was obtained in coriander under blue light (Naznin *et al.*, 2016). In contrast, blue light decreased shoot dry weight in Chinese kale (Xin *et al.*, 2015). All spectra combined with additional blue light increased fresh weight of cucumber transplants (Novickovas *et al*., 2012; Samuoliene *et al*., 2012c). Similarly, all spectra plus additional blue light increased fresh weight of cucumber and tomato transplants (Hernandez and Kubota, 2016, Menard *et al*., 2006) but decreased fruit yield (Menard *et al*., 2006).

UVA light increased fresh weight in lettuce (Chang and Chang, 2014).

NUTRITIONAL QUALITY

Greenhouse vegetables nutritional quality is influenced by different light colours (Table 3).

Vitamin C concentration. Vitamin C concentration in mustard, spinach, rocket, dill and green onion was observed to increase due to exposure to red light (Bliznikas *et al*., 2012). Lower concentration of C-vitamin occurred under red light in Lamb's lettuce and green baby leaf lettuce (Samuoliene *et al*., 2012a; Wojciechowska *et al*., 2015). Green light increased vitamin C concentration in different types of lettuce (Samuoliene *et al*., 2012b). Blue light in-

Table 2

THE EFFECT OF LIGHT COLOUR ON YIELD OF GREENHOUSE VEGETABLES

Plant	Effect on yield	Light colour	Reference
Lettuce (*Lactuca sativa* var. *crispa)* 'Green Oak Leaf'	Shoot fresh weight decreased by 36% compared to sole white LEDs, plants were sparse, twisted	Far red 700–850 nm	Chen *et al*., 2016
Lettuce (*Lactuca sativa* L.) 'Frillice Crisp'	Addition of far red light increased fresh weight	Far red 700–850 nm	Pinho *et al*., 2017
Lettuce (*Lactuca sativa* L.) 'Sunmang' seedlings from 16 days-old	Increased fresh weight	Far red 700–850 nm	Lee *et al*., 2016
Baby leaf lettuce (*Lactuca sativa* L.) 'Red Cross'	Fresh weight, dry weight increased	Far red 700–850 nm	Li and Kubota, 2009
Red lettuce (*Lactuca sativa* L.) 'Sunmang'	Fresh and dry weight was highest, when R/FR ratio was 1.2	Far red 700–850 nm	Lee *et al*., 2015
Red leaf lettuce *(Lactuca sativa* L.*)* 'Outeredgeous'	Increased total biomass	Far red 700–850 nm	Stutte *et al*., 2009
Tomato (*Lycopersicon esculentum* L. cv. Momotaro Natsumi)	Red LEDs enhanced tomato yield	Red 620–700 nm	Lu *et al*., 2012
Transplants of cucumber 'Mirabelle' F1, Tomato 'Magnus' F1 and Sweet pepper 'Reda'	Supplemental 505 nm LED light increased fresh and dry weight	Green 490–550 nm	Samuoliene *et al*., 2012c
Transplants of cucumber 'Mandy' F1	Higher fresh and dry weight	Green 490–550 nm	Novickovas *et al*., 2012
Lettuce (*Lactuca sativa*) cultivars, red leaf 'Sunmang' and green leaf 'Grand Rapid TBR' 18 day seedlings for 4 weeks.	Fresh weights of red leaf lettuce shoots under R8G1B1 were about 61% higher than those under R8B2	Green 490–550 nm	Son and Oh, 2015
Cucumber (*Cucumis sativus*) 'Cumlaude'	Shoot dry and fresh mass decreased with the increase of blue light percentage. Plants under 0% blue had the lowest fresh and dry mass, whereas plants under 100% blue had the highest fresh mass	Blue 425–490 nm	Hernandez and Kubota, 2016
Transplants of cucumber hybrid 'Mirabelle' F1, tomato hybrid 'Magnus' F1 and sweet pepper 'Reda'	Supplemental blue light increased fresh and dry weight in all vegetable transplants	Blue 425–490 nm	Samuolienė *et al*., 2012c
Transplants of cucumber 'Mandy' F1	Supplemental 470 nm LED lighting increased fresh and dry weight	Blue 425–490 nm	Novičkovas *et al*., 2012
Tomato (*Lycopersicon esculentum* 'Trust') and cucumber (*Cucumis sativus* 'Bodega')	Supplemental blue light inside the canopy increased plant biomass, reduced fruit yield	Blue 425–490 nm	Menard *et al*., 2006
Cucumber (*Cucumis sativus*) 'Cumlaude' and tomato (*Solanum lycopersicum* 'Komeett')	Dry mass and leaf area decreased, when blue increased from 10% to 75%. Optimal amount of blue was 10%, which still produced seedlings with less dry mass compared to FL; Dry mass increased with increasing blue up to 30–50% and then decreased from 50 to 100%. Optimal amount was 30–50% of blue	Blue 425–490 nm	Hernandez *et al*., 2016
Lactuca sativa var. crispa	Increased shoot fresh mass	UVA 315–400 nm	Chang and Chang, 2014

*PPFD, photosynthetic photon flux density; PP, photoperiod; B, blue; R, red; FR, far red; G, green, FL, fluorescent, WF, white fluorescent, HPS, high pressure sodium

creased vitamin C concentration in non-heading Chinese cabbage (Li *et al*., 2012).

Mineral elements. Far red light stimulated uptake of N and K, Ca, and Mg with the latter increasing by 27%, 25%, and 28%, respectively, compared to plants illuminated with red and blue light (Pinho *et al*., 2017). Blue light increased N concentration in cucumber plants (Hogewoning *et al*., 2010) but reduced nitrate concentration in Chinese kale (Xin *et al*., 2015). Green light decreased nitrate concentration in butterhead lettuce and baby leaf lettuce (Bian *et al*., 2016; Samuoliene *et al*., 2012d).

Pigments. Far red light decreased chlorophyll and carotenoid concentration in baby leaf lettuce (Li and Kubota, 2009). Red light increased chlorophyll concentration in lettuce and kale (Lefsrud *et al*., 2008; Chen *et al*., 2016). Red light increased carotenoid concentration of lettuce (Chen *et al*., 2016) and anthocyanin concentration of cabbage (Mizuno *et al*., 2011). Total carotenoid concentration in mustard and parsley increased, and in pak choi and tatsoi decreased, due to exposure to green light in addition to all other spectra (Brazaityte *et al*., 2016). Green light supplemental to all other spectra increased pigment concentration of cucumber, tomato and sweet pepper transplants (Samuoliene *et al*., 2012c). Blue light resulted in enhanced chlorophyll concentration of cabbage seedlings, in non-heading Chinese cabbage and cucumber transplants (Hogewoning *et al*., 2010; Mizuno *et al*., 2011; Li *et al*., 2012). Blue light increased anthocyanin concentration in baby leaf and red leaf lettuce (Li and Kubota, 2009; Stutte *et al*., 2009). Carotene concentration increased under blue light in baby leaf lettuce and in kale (Lefsrud *et al*., 2008; Li and Kubota, 2009). Blue light supplemental to all other spectra increased pigment concentration in cucumber, tomato and sweet pepper transplants, lettuce (Novickovas *et al*., 2012; Samuoliene *et al*., 2012c; Sergejeva *et al*., 2018). UVA and UVB light increased anthocyanin concentration in lettuce and baby leaf lettuce (Li and Kubota, 2009; Goto *et al*., 2016).

Table 3

EFFECT OF LIGHT COLOUR ON NUTRITIONAL QUALITY OF GREENHOUSE VEGETABLES

Nutrient	Plant	Effect	Light colours	Reference
Antioxidant	Lamb's lettuce (*Valerianella locusta* L.) 'Nordhollandse'	Reduced ascorbic acid concentration	Red 620–700 nm	Wojciechowska *et al*., 2015
	Green baby leaf lettuce (*Lactuca sativa* L.) 'Thumper' and 'Multibaby'	Increased antioxidant properties in 'Multibaby' lettuce: higher concentration of total phenolic (28.5%), tocopherols (33.5%), antioxidant capacity (14.5%) and sugars (52.0%); Decreased concentration of ascorbic acid, as compared to untreated plants	Red 620–700 nm	Samuolienė *et al*., 2012a
	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. Increase in vitamin C content in mustard, spinach, rocket, dill and green onion	Red 620–700 nm	Bliznikas *et al*., 2012
	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	Green 490–550 nm	Samuoliene *et al*., 2012b
	Red leaf lettuce seedlings (*Lactuca sativa* L. cv. Banchu Red Fire)	Greater polyphenol concentrations and total antioxidant status	Blue 425–490 nm	Johkan *et al*., 2010
	Non-heading Chinese cabbage (*Brassica campestris* L.)	Concentration of vitamin C was the greatest under blue LEDs	Blue 425–490 nm	Li *et al*., 2012
Minerals	Lettuce (*Lactuca sativa* L.) 'Frillice Crisp'	Far red light stimulated the uptake of N; The uptake of K, Ca and Mg by plants under additional far red light increased by 27%, 25% and 28%, respectively, as compared to plants, illuminated with red and blue light	Far red 700–850 nm	Pinho *et al*., 2017
	Cucumber plants (*Cucumis sativus* cv. Hoffmann's Giganta)	Increase in nitrogen concentration per area	Blue 425–490 nm	Hogewoning *et al*., 2010
	Butterhead lettuce 'De Lier'	Decreased nitrate concentrations	Green 490–550 nm	Bian *et al*., 2016
	Baby leaf lettuce: red leaf 'Multired 4', green leaf 'Multigreen 3' and light green leaf 'Multiblond 2'	Reduced nitrate concentration in all baby leaf lettuce varieties	Green 490–550 nm	Samuoliene *et al*., 2012d
	Chinese kale 'Lybao'	Reduced nitrate concentration at higher blue light rates	Blue 425–490 nm	Xin *et al*., 2015
Pigments	Baby leaf lettuce (*Lactuca sativa* L.) 'Red Cross'	Decreased chlorophyll and carotenoid concentration by 14% and 11% as compared to WF	Far red 700–850 nm	Li and Kubota, 2009
	Cabbages (*Brasica olearacea* var. *capitata* L.) 'Kinshun' (green leaves) and 'Red Rookie' (red leaves)	Increased anthocyanin contents and leaf pigmentation in red leaf cabbages comparing to FL, 470-, 500-, 525 nm LEDs	Red 620–700 nm	Mizuno *et al*., 2011
	Lettuce (*L. sativa* var. *crispa*) 'Green Oak Leaf'	Increased chlorophyll and carotenoids concentrations	Red 620–700 nm	Chen *et al*., 2016
	Kale (*Brassica oleracea* L). 'Winterbor'	Enhanced chlorophyll *a, b* accumulation	Red 620–700 nm	Lefsrud *et al*., 2008
	Various microgreens	Increased total carotenoids in mustard and parsley microgreens; Decreased total carotenoids in red pak choi and tatsoi microgreens	Green 490–550 nm	Brazaityte *et al*., 2016
	Transplants of cucumber 'Mirabelle' F1, Tomato 'Magnus' F1 and Sweet pepper 'Reda'	Supplemental 505 nm LED light increased photosynthetic pigment concentrations in all vegetable transplants Supplemental 530 nm light had positive effect on development and photosynthetic pigment accumulation in cucumber transplants	Green 490–550 nm	Samuoliene *et al*., 2012c
	Cucumber plants (*Cucumis sativus* cv. Hoffmann's Giganta)	Increased chlorophyll concentration per area	Blue 425–490 nm	Hogewoning *et al*., 2010
	Transplants of cucumber hybrid 'Mirabelle' F1, tomato hybrid 'Magnus' F1 and sweet pepper 'Reda'	Supplemental blue light increased photosynthetic pigment concentrations in all vegetable transplants	Blue 425–490 nm	Samuoliene *et al*., 2012c
	Transplants of cucumber 'Mandy' F1	Both 455 and 470 nm enhanced photosynthetic pigment concentrations	Blue 425–490 nm	Novickovas *et al*., 2012

Table 3 (continued)

Nutrient	Plant	Effect	Light colours	Reference
	Baby leaf lettuce (*Lactuca sativa* L.) 'Red Cross'	Anthocyanins concentration increased by 31%; Carotenoids concentration increased by 12%	Blue 425–490 nm	Li and Kubota, 2009
	Seedlings of cabbages (*Brasica olearacea* var. *capitata* L.) 'Kinshun' (green leaves) and 'Red Rookie' (red leaves)	Higher chlorophyll concentrations in green leaf cabbages	Blue 425–490 nm	Mizuno *et al*., 2011
	Non-heading Chinese cabbage (*Brassica campestris* L.)	Higher chlorophyll concentration	Blue 425–490 nm	Li *et al*., 2012
	Kale plants (*Brassica oleracea* L. cv Winterbor)	Enhanced β-carotene concentration	Blue 425–490 nm	Lefsrud *et al*., 2008
	Lettuce (*Lactuca sativa* L. *var. foliosum* cv. 'Dubacek' and *L. sativa* L. cv. 'Michalina')	Increased chlorophyll concentration	Blue 440 nm	Sergejeva *et al*., 2018
	Red leaf lettuce *(Lactuca sativa* L. cv. Outeredgeous)	Increased concentration of anthocyanins, higher antioxidant potential	Blue 425–490 nm	Stutte *et al*., 2009
	'Red Cross' baby leaf lettuce (*Lactuca sativa* L.)	Anthocyanin concentration increased by 11%	UVA 315–400 nm	Li and Kubota, 2009
	Lettuce (*Lactuca sativa L.*) 'Red fire'	Pre-harvest UV-B light stimulated anthocyanin concentration Anthocyanin concentration was significantly higher at 310 nm as compared to 325 and 340 nm	UVA 315–400 nm and UVB 280–315 nm	Goto *et al*., 2016
Sugars	Dill (*Anethum graveolens*) 'Mammouth', Parsley (*Petroselinum crispum*) 'Plain leaved'	Increased monosaccharide concentration	Red 620–700 nm	Bliznikas *et al*., 2012
	Baby leaf lettuce: red leaf 'Multired 4', green leaf 'Multigreen 3' and light green leaf 'Multiblond 2'	Increase in saccharide concentrations in all baby leaf lettuce varieties	Green 490–550 nm	Samuoliene *et al*., 2012d
	Chinese kale 'Lybao'	Increased soluble sugar concentration	Blue 425–490 nm	Xin *et al*., 2015

*PPFD, photosynthetic photon flux density; PP, photoperiod; B, blue; R, red; FR, far red; G, green, FL, fluorescent, WF, white fluorescent, HPS, high pressure sodium

Sugars. Red light increased monosaccharide concentration of dill and parsley (Bliznikas *et al*., 2012). Green light increased saccharide concentration in baby leaf lettuce (Samuoliene *et al*., 2012d). Blue light increased soluble sugar concentration in Chinese kale, and the combinations red : blue = 8 : 1 (8R1B), red : blue = 6 : 3 (6R3B) and 6R3B gave higher soluble sugar concentration (Xin *et al*., 2015).

PRACTICAL CONCLUSIONS

Fresh weight of leafy vegetable crops and transplants can be increased by increasing by supplemental green light, far red light (while can be accompanied with elongation of plants) and in some cases with UVA light. Increases of fruiting crops yield can be achieved by supplemental red light, and decreases by blue light.

Growth of leafy vegetables crops and transplants are increased by added green light, blue light (leaf expansion, while can be accompanied with compactness of plants, which is desirable in most of cases), far red light (while can be accompanied with elongation of plants) and orange light.

Vitamin C concentration is increased under green and blue light. The concentration of nitrates in plants is decreased under blue and green light. The pigment concentration in plants is increased under green, blue and red light. Sugar contents in plants are increased by green, blue and red light.

As plant elongation and decrease in pigment concentration are not desirable, far red light should not be used to increase biomass. As red light increases yield by decreasing nitrate content and increasing C-vitamin content, and considering that both factors are highly desirable, then this colour has big potential use in plant production. Orange light accelerates growth of transplants, and therefore this light colour is also desirable in plant production. As green light contributes to only desirable factors (promotes growth, reduces nitrate concentration, increases saccharide concentration of plants, and increases vitamin C concentration in plants), then green light is desirable in plant production and has also big potential use in plant production. As blue light contributes to desirable factors only (results in compact plants, benefits vegetative growth, increases pigment and vitamin C concentration in plants), then green light is desirable in plant production and has also big potential use in plant production.

FINAL CONCLUSION

Based on the given information we can conclude that blue, green, and red light are the main light colours that influence positively plant yield, growth and nutrient quality. Sometimes in specific situations some other light colours are also beneficial, like far red light, orange light and UVA light. Future work on light colour manipulation has potential for producing lamps and greenhouse covers that better support plant yield, growth and nutrition.

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GAISMAS VIĻŅU GARUMA IETEKME UZ SILTUMNĪCĀ AUDZĒTU DĀRZEŅU AUGŠANU, RAŽU UN BARĪBAS VIELU SATURU

Vairumā zinātnisko apskatrakstu tiek analizēta gaismas spektrālā sastāva ietekme uz augu ražu un kvalitāti, bet tādu, kur apkopota informācija par noteiktu gaismas spektra daļu ietekmi uz cukuru vai pigmentu saturu, augšanas un/vai attīstības regulēšanas iespējām, ir ļoti maz. Redzamās gaismas loma tādās pārtikas ražošanas nozarēs kā laukkopība un dārzkopība ir vispārzināma, jo gaisma ir fotosintēzes procesu enerģētiskais pamats, kas nosaka augu augšanu un attīstību. Salīdzinot ar plaši izmantotajām gāzizlādes vai nātrija lampām, gaismu emitējošās diodes (LED) ir būtiski atšķirīga tehnoloģija. LED lampas ir apgaismojuma veids, kura apgaismojuma spektrālo sastāvu var mainīt, lai nodrošinātu dažādos augu augšanas un attīstības posmos nepieciešamo apgaismojuma kvantitatīvo un kvalitatīvo sastāvu. Neraugoties uz to, ka veikti daudzi un dažādi eksperimenti, lai noskaidrotu, kā dažādi gaismas viļņu garumi ietekmē siltumnīcā audzētu dārzeņu ražas veidošanos, maz ir zināms par fizioloģiskajiem mehānismiem, kas ietekmē cukuru vai pigmentu saturu, kā arī ražas pieaugumu. Šajā rakstā apskatīts, kā noteikts gaismas spektrālais diapazons ietekmē siltumnīcas dārzeņu augšanu, ražu un to uzturvērtību. Pamatojoties uz iegūto informāciju, var secināt, ka zila, zaļa un sarkana gaisma ir galvenās augu ražu, augšanu un uzturvērtību pozitīvi ietekmējošās spektra daļas. Atsevišķās situācijās novēro arī citu spektra daļu (tālā sarkanā, oranžā un UVA) pozitīvo ietekmi. Turpmākie gaismas spektrālā sastāva ietekmes pētījumi ir nozīmīgi, jo tie veicinās lampu un siltumnīcu segumu pilnveidošanu, tādējādi uzlabojot augu augšanu, ražu un tās kvalitāti.