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Review

Light use efficiency for vegetables production in protected and indoor environments*

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Abstract. In recent years, there is a growing interest for vegetables production in indoor or disadvantaged climatic zones by using greenhouses. The main problem of crop growing indoor or in environment with limited light availability is the correct choice of light source and the quality of lighting spectrum. In greenhouse and indoor cultivations, plant density is higher than in the open field and plants have to compete for light and nutrients. Nowadays, advanced systems for indoor horticulture use light emitting diodes (LED) for improving crop growth, enhancing the plant productivity and favouring the best nutritional quality formation. In closed environments, as indoor growing modules, the lighting system represents the only source of light and its features are fundamental for obtaining the best lighting performances for plant and the most efficient solution. LED lighting engines are more efficient compared to the lighting sources used traditionally in horticulture and allow light spectrum and intensity modulations to enhance the light use efficiency for plants. The lighting distribution and the digital controls are fundamental for tailoring the spectral distribution on each plant in specific moments of its growth and play an important role for optimizing growth and produce high-quality vegetables. LED lights can increase plant growth and yield, but also nutraceutical quality, since some light intensities increase pigments biosynthesis and enhance the antioxidants content of leaves or fruits: in this regards the selection of LED primary light sources in relation to the peaks of the absorbance curve of the plants is important.

1 Introduction

The global population has been increasing and it has been estimated to reach 9.55 billion of people in 2050. It means that the population will almost double on Earth in less than forty years and innovative food production systems are required [1]. Modern agriculture has to face this new challenge, to increase crop performance mainly yielded without negative effects on quality and sustainability. The global food production can be enhanced using geographical areas with strong limits for crops cultivation using advanced technological greenhouses or by using indoor growing modules. In both cases, crop light use efficiency (LUE) must be improved, in order to increase yield and produce quality.

Solar radiation is an environmental parameter of fundamental importance for agricultural systems. An adequate solar distribution can guarantee fast crop growth, correct morphological development, and highest yield. In open fields, light intensity and duration cannot be modified, while in greenhouse or indoor growing modules they are production factors that can be modulated and optimized.

The solar radiation entering a greenhouse can be improved by using adequate frames, structures, cover materials, and orientation [2,3]. The optimization of the light that enters in the greenhouse is very important in northern countries and during winter cultivation, when light availability represents a strong limit for crop growth. The greenhouse frames usually must be strong but thin enough to reduce the shade on the crops. The structure should be chosen among those that have higher perpendicular incidence light, such as tunnels or greenhouse with semicircular roofs.

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The cover materials for winter cultivations should be transparent to ultra-violet (UV), photosynthetically active radiation (PAR), near-infrared (NIR), and opaque to long-infrared (LIR) radiations. UV, PAR, and NIR wavelengths allow higher photosynthesis and normal plant growth. The opacity to LIR allows the entrapment of LIR radiations emitted from soil or plants inside the greenhouse, inducing the passive heating of the inside environment (greenhouse effect). Most greenhouses are designed to be used for winter production. Therefore, light management is an important issue for programming the production. The light availability during winter has to be enhanced by increasing the light intensity in the region of the PAR spectra. Light is important not only for crop growth but also for the biosynthesis of nutraceutical components of the produce, because it is involved in sugar accumulation, vitamins, and antioxidant compounds.

In protected and indoor cultivations, it is very important to identify the optimal or minimal crop light requirements in order to enhance the yield and quality of the produce. Lighting along with heating costs can be very high during winter cultivations. Therefore, they must be under control avoiding economic losses. The geographical greenhouses distribution is tightly linked with heating requirements [4] and light availability. In general, for crop cultivation the minimum light requirement has not been object of study, since a higher light availability means a higher production. The main scope of greenhouse studies was oriented to enhancing light availability inside the greenhouse during winter.

Given the spread of photovoltaic greenhouses, the minimum amount of light plant requirement has gained interest also during summer, because covering the roof with photovoltaic panels has started a strong competition between electricity production and crop yield. In a recent study, comparing the tomato performance under traditional and photovoltaic greenhouses revealed that plants under photovoltaic panels increase the LUE but the total yield is halved, because the plant density per square meter had to be reduced [5]. With regard to indoor cultivations, growing modules for home vegetables production have been increasing in number [6] and the estimation of plant light requirements is extremely important for reducing the production costs.

1.1 Applied photobiology in crops grown in closed environments

LUE in plants is regulated by environmental and biological factors. The light intensity available in a greenhouse or indoor growing module or the amount of light required by the plants has to be expressed as photon flux density (μmol m^{-2} s^{-1}) or radiant energy (W m^{-2}) for surface unit. In terms of light quality, the plants for photosynthesis use the light spectrum comprised from 400 to 700 nm, which is defined PAR and the absorbance in this region can be very different from species to species [7]. Therefore, the correct expression of plant light requirement is photosynthetic photon flux density (PPFD). In the past, the plant light requirements were expressed as lux, but this is a wrong light measurement unit, because the luxmeter measures light that can be perceived by human eyes, with a peak at 555 nm while plants, as said above, absorb the PAR spectrum (fig. 1). Therefore, if the plant light requirements are expressed as lux there is an underestimation of the real needs.

The radiations in the red (660 and 730 nm) spectrum are very important because they regulate the flowering (photoperiod) and, in many crops, they are essential for production. Light quality is also important for normal plant morphogenesis, avoiding abnormal or reduced growth, which can affect plant productivity. Plants have photoreceptors for different regions of the spectra and specific wavelengths induce specific plant responses. In the *Arabidopsis thaliana* five phytochromes (from phy A to phy E), two cryptochromes (cry1 and cry2) and phototropin have been identified [8]. Recently, ZEITLUPE, FLAVIN-BINDING, KELCH REPEAT, F-BOX1 and LOV KELCH PROTEIN2 sensors of blue light, and UV RESISTANCE LOCUS8 sensor of UV-B light have been identified [9]. All these receptors are responsible for several plant physiological responses [10].

Focusing on light and photosynthesis, light is collected from several leaf pigments, such as chlorophylls, carotenoids and other proteins complexes. The amount of light needed by the plants can vary and, considering the light requirements, the plants can be classified into two major groups, such as sun plants or shade plants, even if there are several degrees of shade tolerance. In general, crops have different light requirements for growth and productivity. Sun plants have a fast growth and require a high amount of light, but, if exposed to shade, they activate the shade avoidance mechanism, which induces a fast growth trying to overcome the shade. The result is a shoot elongation with less lignification (soft), which is more susceptible to stem break. Shade plants can grow and live under the shade of other plants and require a lower amount of light. The light intensity affects the length of the crop cycle and a lower light availability means a longer growing period, which negatively affects the all-year-around greenhouse production.

Plants increase photosynthesis by increasing the light intensity until a plateau is reached. The plant response is a curve, called light saturation curve, which is specific for each plant species and for different environmental conditions. Sun plants have a high saturation point, while shade plants reach the saturation point at low light intensities. It is important to estimate the plant light requirements, because plants do not use all solar radiation equally but they have specific spectra of absorbance. The crops LUE can be improved by the identification of the plant requirements that allow the correct planning of lighting in greenhouses or indoor modules.

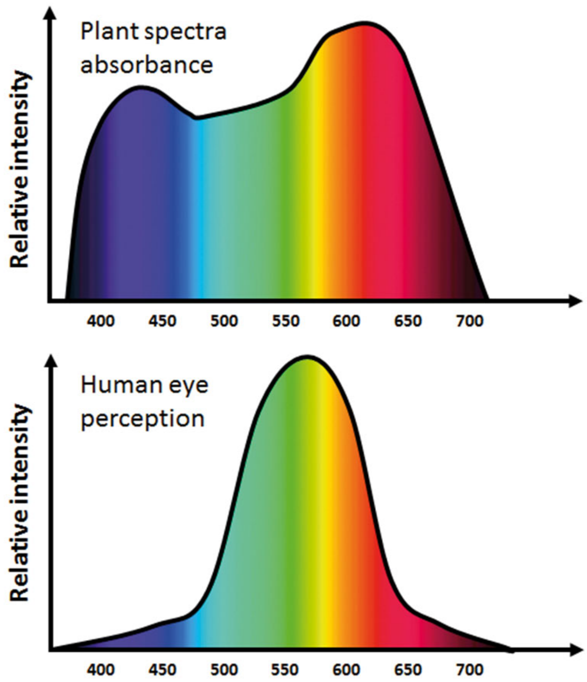

Fig. 1. Leaf absorbance spectra (nm) and human eyes light perception.

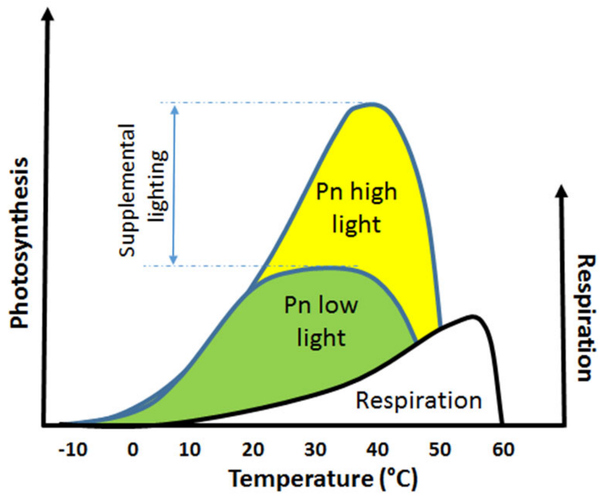

Fig. 2. Photosynthesis activity and respiration of plants at different temperatures. The effect of supplemental lighting on the photosynthesis activity. The difference between photosynthesis and respiration represents the net photosynthesis that contributes to crop growth.

2 Supplemental lighting in greenhouses

2.1 The appropriate use of lighting for vegetables crops

Supplemental lighting is used during winter when the natural solar radiation is not enough (short photoperiod and low light intensity) to provide satisfactory yield and quality of the produce. Low light availability is a limiting factor, especially in northern countries in winter. Therefore, supplemental lighting is an essential element of crop management in protected cultivations.

The supplemental lighting increases the photosynthesis, but the highest net photosynthesis (difference between photosynthesis and respiration) depends from temperature and respiration rate (fig. 2). Low temperatures slow down the photosynthesis activity and respiration rate of plants. It means that increasing the temperature increases the LUE but also the respiration [11]. Therefore, the highest net photosynthesis and LUE can be obtained in specific ranges of temperatures and light intensities that depend from species to species. The additional light supply has to be correctly planned considering the plant requirements (in terms of hours and intensity) and the daily inner temperatures. In greenhouses, the night temperature is lower than the daylight temperature in order to reduce heating costs. Therefore, the artificial lighting on the basis of fig. 2 has to be provided during the day when the LUE is higher, considering the temperature-photosynthesis activity relationship and the respiration trend. The growth rate of plants depends on the balance in a 24 h period considering daylight net photosynthesis and night respiration. The highest plant growth can be achieved lowering the night temperature, just above the minimum crop temperature and increasing the temperature during the daylight in the optimal range for the photosynthesis of the crop. Of course, these considerations have to fit with the costs of the cultivation.

The supplemental lighting is performed using fluorescent lights, metal halide, high-pressure sodium lamps (HPS), and light emitting diodes (LEDs). The performance of the lamps follows the innovation used for civil lighting. In lamps used for agricultural purposes, the absorbance spectra of the crops have to be considered. The outputs of these lamps must match with crop light utilization spectra. If the lamps have a higher emission in the regions of the leaf absorbance spectra, the LUE as well as the yield are higher.

Nowadays, LEDs are able to provide precise outputs and can be easily controlled. The emission spectra (wavelengths) can be readily adjusted on the basis of the plant requirements [12–14]. The type of lamps, the power, as well as the installation depend on plant requirements and on the costs of the lamps [15].

The LUE in greenhouses for winter cultivation depends on the lamp characteristics, but also on the following parameters:

– Greenhouse environmental temperature and variation in 24 h. A high temperature during the night reduces the plant growth.
– CO_2 concentration during the day: during winter, in closed greenhouses, the CO_2 concentration declines and becomes a limiting factor of growth.
– Leaf absorbance spectra of the crops: different species have different absorbance spectra.
– Relative humidity: low values increase transpiration, while too high values reduce photosynthesis.

2.2 Effects of supplementary lighting on growth in horticultural crops

Several studies demonstrated how it is possible to achieve higher productivity and quality of horticultural crops by controlling artificial lighting. In the recent years, most researches focused on this topic, *i.e.* the use of LEDs, because of their versatility and good adaptability to horticultural productions in greenhouses [16].

Blue light is necessary for growth and development of plants, but the effects of blue light appear to be different depending on species; moreover, it has been reported to interact with other wavelengths of light as well as the photosynthetic photon flux [16,17].

Blue light (B) significantly altered development in soybean and radish, whereas wheat was minimally responsive. Different developmental parameters that were considered by researchers responded differently to the absolute and relative amount of blue light [17,18].

In *Cucumis sativus* the deprivation of blue light determined a dysfunctional photosynthetic operation, characterized by a suboptimal and heterogeneously distributed dark-adapted chlorophyll fluorescence (Fv/Fm), a stomatal conductance unresponsive to irradiance, and a relatively low light-limited quantum yield for CO_2 fixation. On the other hand, the photosynthetic capacity was twice as high for leaves grown at 7% blue, compared with blue-deprivated ones, and it continued to increase with increasing the blue percentage during growth measured up to 50% blue [16]. It is important to notice that different experimental conditions can determine contrasting results on plant growth within the same species. In fact, Hernandez and Kubota [19] reported a negative effect on growth induced by blue light (dry mass, leaf number, and leaf area decreased with increasing the Blue : Red ratio under low solar daily light integrals conditions) in cucumbers, while Hogewoning and colleagues found an increase in the leaf area with the increase of blue light. An important role for blue light has been reported also in the stomatal control in spinach [20] and lettuce [21]. In the red-leaf lettuce (*Lactuca sativa*, cv. Outredgeous), the use of blue LEDs appeared to increase the concentration of bioprotective compounds in leaf tissue [22]. LED lighting induced a number of effects on the morphology, which increased both accumulation of bioprotective compounds and total yield.

Red light (R) is not affecting the biomass production in horticultural crops, while it is effective in stimulating photomorphogenic responses in combination with far red (FR). Tomato and cucumber plants grown in a greenhouse under B : R LED light supplementation were more compact, but they did not show a higher dry matter content compared to those grown under HPS lamps or B : R : FR. On the other hand, plants treated with B : R : FR supplemental light, showed a significant increment in dry matter, probably due to an improvement in light interception [19]. Similar results were found in lettuce, confirming the lack of effectiveness of R light alone in increasing the dry matter content of horticultural crops [23]. On the other hand, Li and Kubota [21] showed that R light could play a key role in improving the quality and the accumulation of important phytochemicals in leafy vegetables. Yorio and colleagues [24]

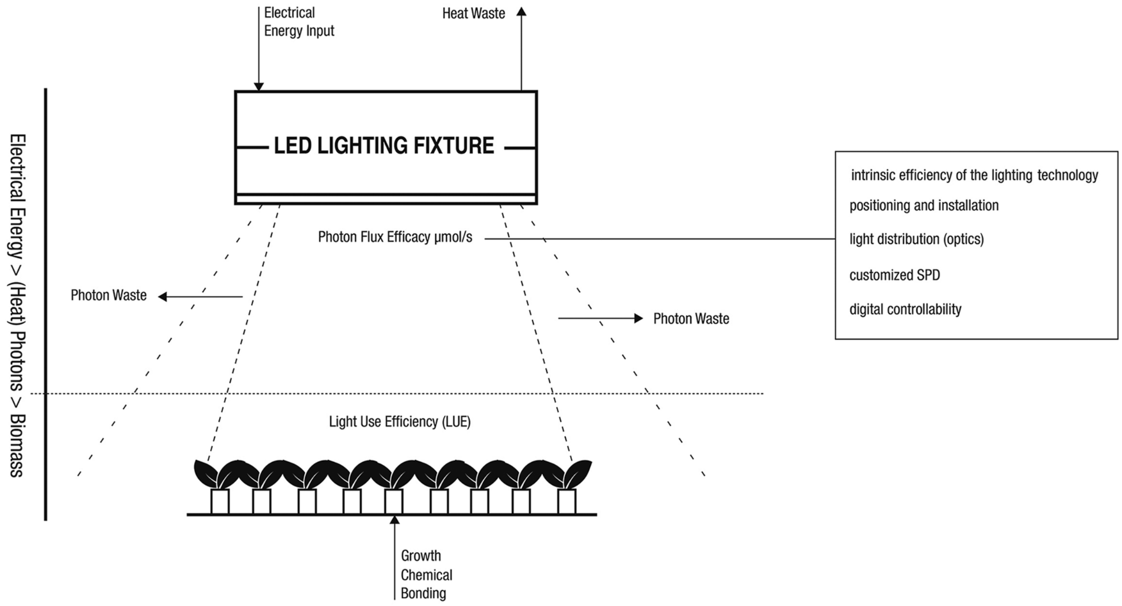

Fig. 3. Energy balance of LED lighting system for horticulture with evidenced features increasing or decreasing efficiency.

reported no positive effect of different types of LED light supplementation compared to cool-white fluorescent lamps (CWF) on the production of radish (*Raphanus sativus* L. cv. Cherriette), lettuce (*Lactuca sativa* L. cv. Waldmann's Green), and spinach (*Spinacia oleracea* L. cv. Nordic IV). The authors concluded that addition of blue light to the red LEDs was insufficient for achieving maximal growth for these crops.

3 Artificial lighting in horticulture

3.1 From traditional to LEDS lighting technologies

Energy is one of the most important aspects and the major cost in Controlled Environment Agriculture (CEA). In CEA the electrical consumption for lighting, temperature, water and air control should be reduced, maximizing, at the same time, the cultivation productivity (biomass per unit area) and nutraceutical quality of food. In the horticultural sector, energy efficiency occurs both in the lighting fixture with energy conversion from electricity to photons along with wasted heat and in the plant, by converting photons to biomass through the photosynthesis process (fig. 3).

The conversion of energy to photons is not completely efficient. A certain loss in wasted heat or lighting can occur depending both on the lighting fixture features and on the plant species. In this regard, LEDs lighting fixtures show a great potential for energy savings, by considering the following factors:

- The position of the lighting fixture in relation to plants. This feature is strictly dependent on the heat produced by the lighting systems. While traditional lighting systems emit a huge amount of heat in the infrared portion of the spectra, LEDs emit low heat directly over the plants. This allows to shorten the distance of installation and to provide more light with less energy.
- The shape of the lighting fixtures to reduce shadows on the plants. Traditional lighting fixtures equipped with HPS and metal halide (MH) lamps have generally bigger shapes than LEDs lighting systems. Having generally smaller dimensions, LEDs lighting systems can reduce the shadowing problems along with the maximisation of the natural lighting transmission.
- The spectrum customized for each plant to reduce wasted lighting. LEDs lighting is the first technology applied to the horticultural field able to use narrow-band wavelengths. The Spectral Power Distribution (SPD) can be matched to plant photoreceptors and pigment absorption, thus reducing lighting emissions in those bands which are not considered beneficial for plants [25].
- The intrinsic efficiency of the lighting technology (fig. 4). In this regard, LEDs efficiency is increasing each decade by a factor of 10, while the performance by a factor of 20 (Haitz's law) [26]. Mass production, new techniques for LED lighting system fabrication, simplified manufacturability and maintenance would ensure further cost reductions.
- The controllability of artificial lighting. This versatility is ensured by LED lighting systems which can be digitally programmed and operated instantaneously (turned on/off and dimmed) without waiting for the lamp start and run-up time and for the cooling time before restarting (peculiar of some traditional lighting sources).

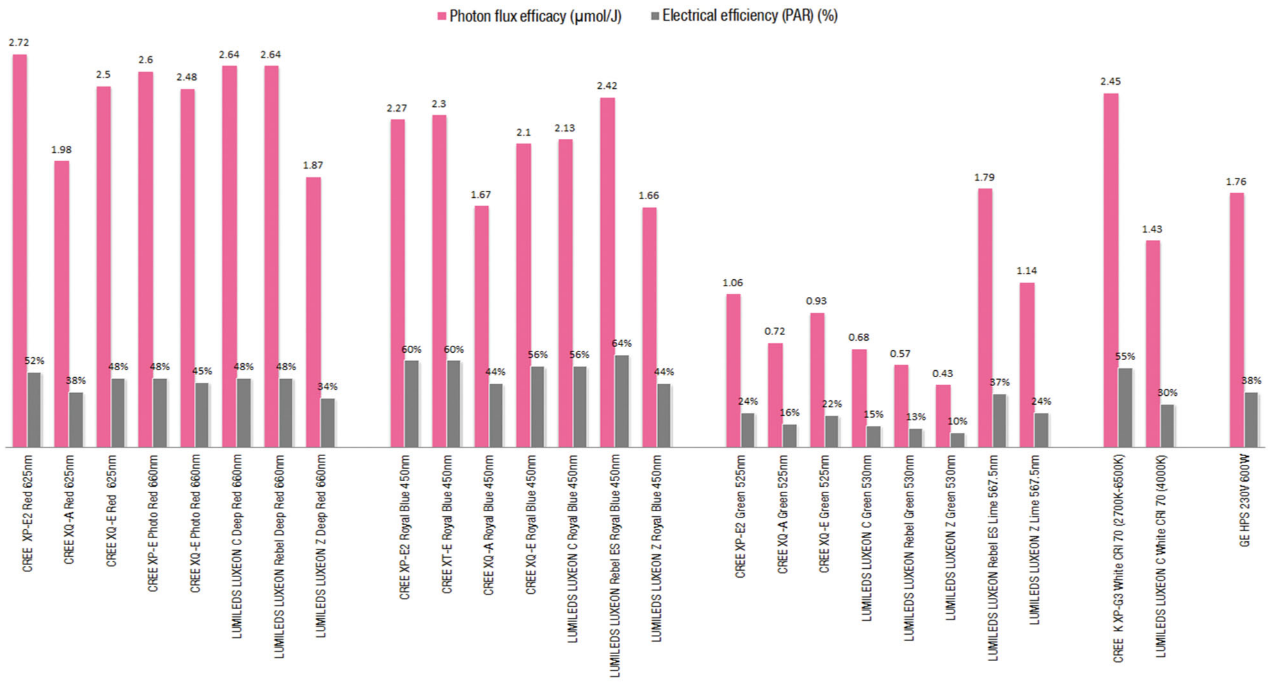

Fig. 4. The diagram reports and compares the typical photon flux efficacy and electrical efficiency of a traditional HPS (right) and different LEDS lighting sources: phosphor-converted white CREE XP-G3 family LEDs with correlated colour temperatures (CCTs) of 2700 K–6000 K and phosphor-converted white Lumileds Luxeon C at 4000 K; red, blue and green LEDs with peak wavelengths at 625 nm, 660 nm, 730 nm, 450 nm, 525 nm, 530 nm and 567.5 nm, respectively, of the major LEDs family of CREE (data obtained @350 mA and T_{j} 25 °C) and Lumileds (data obtained @350 mA and T_{j} 85 °C). The PPF/W and the electrical efficiency values are based on data derived by product catalogues of the cited manufacturers (2016).

LUE deals with the understanding of the interaction between photons and plants, in particular with the photosynthetic activity and the desired plant response. Even if the correlations of lighting features and plants responses are not completely understood because of the differences between plant species [27], LED lighting systems applied in CEA (*e.g.* industrial factories, multi-tiered vertical farms and greenhouses) are used to gain certain influence on plants. In particular:

- Photoperiodic lighting to induce early or out-of-season flowering through the use of end-of-day or night-interruption low-intensity lighting. An artificial short night promotes flowering of long-day species and inhibits flowering of short-day species with red and far red wavelengths.
- Seasonal supplemental (high-intensity) lighting to improve the photosynthesis of crop production, particularly in natural lighting limited periods of the year [28].
- Photosynthetic and photomorphogenic lighting (end-of-day light treatment for controlling morphology) for rooting of cuttings, propagation of seedlings and transplant of young plants.
- Sole source lighting for year-round indoor agriculture [29].

In addition to these industrial applications, horticultural lighting is applied to urban farming solutions, which are agglomerated vertical arrangement for leafy vegetables and soft fruit cultivation located in the cities. It is also extremely interesting in research applications spanning from phytotrons, growth chambers to space stations growing systems. More than this, an increasing trend is the indoor consumer residential horticulture aimed at eating healthy and origin-controlled food through sustainable behaviours and responsible choices [30].

3.2 LED lighting systems' features and design specifications

LEDs were preliminarily adopted in the research of lighting for plants growth in the middle of the 1980s and early 1990s by the University of Wisconsin Center for Space Automation and Robotics, NASA and the Kennedy Space Center [31]. Nowadays, after continuous technological innovations, testing and performance assessments, LEDs show to have interesting electrical, physical and operational features which are extremely advantageous for horticulture.

However, LEDs technology needs several precautions and an overall design approach to work properly and ensure the best performances. Furthermore, the research around LEDs technology applied to horticulture is still evolving by exploring the following topics:

- Manufacturing and design recommendations in terms of LED selection along with optical, thermal and electrical management.
- Operating standards in terms of energy consumption and efficiency, lighting quality (intensity, distribution, duration, SPD), control strategies, lifetime durability and reliability.
- Installation recommendations in terms of mounting distance and positioning, serviceability and resistance to environmental factors (humidity, moisture, temperature and chemicals).
- Metrics, measurements protocols and guidelines in order to compare the photosynthetic performance of different lighting systems [32].
- Users requirements in terms of lighting pollution and psychological influence on workers.
- Economic specifications in terms of operating and installation costs and investment returns.

In the following, several of these aspects are discussed.

3.2.1 Manufacturing and design recommendations: LED selection

LEDs lighting systems require an accurate design and management practices in order to obtain the best performances in CEA. The fundamental component, the LED, is basically a junction doped with different semiconductor materials and impurities that enable the emission, based on electroluminescence, of different wavelengths of coloured lighting.

From the first red LEDs (1960s) and the shorter wavelengths developed during the 1970s (orange, yellow, green), the first practical blue light was achieved in 1993 with a subsequently phosphor coating to achieve the first white LEDs useful for lighting application [33]. Even though the electrical use efficiency of LEDs is evolving continuously, phosphor-converted white LEDs are generally less efficient (radiated power output divided by electrical power input) than monochromatic LEDs, because much of the efficiency loss occurs in the phosphor conversion process. The most efficient LEDs (PPF/W) are the Blue and Red ones [15] which are based on two different technologies: the InGaN (indium gallium nitride) structure for Blue (and Green) and the InGaAlP (indium gallium aluminium phosphide) structure for Red (fig. 4). These two technologies show a different behaviour in the relation between emitted radiant flux and junction temperature (T_{j}).

Though the white light derived from RGB LEDs is more electrically efficient than the one derived from phosphor-converted LEDs, it needs more control in order to maintain optimal features for the photosynthesis. In fact, considering that the chromatic coordinates of the peaks of each coloured LED are dependent on its T_{j}, it is important to maintain the T_{j} as constant as possible or to use sensors on the printed circuit board (PCB) to correct the driving current and so the luminous output accordingly.

Horticultural research has already established that radiations at narrow spectral bands can optimize chlorophyll absorption in plants and influence photosynthesis process and plant growth [34,35]. Since the main colours in horticulture are Red and Blue at a certain ratio, recently LEDs which cover this combined spectrum have been developed: an example is the Lumileds Luxeon 3535L Purple, which is still under development [36]. Differently, the inclusion of White or Green LEDs on the array has been considered to be useful to achieve both a deeper absorption of the inner canopy [37] and a broadband spectra for visual inspections of workers on the plants. In addition to this, newer studies are exploring deeply the relationship between specific spectral bands and vegetable/flower production: the recent discovery of chlorophyll f [38] suggests that photosynthesis extends also into the infrared region. In this regard, new LEDs have been recently manufactured with higher efficiencies in the far-red region of the spectrum (centred at 730–740 nm) [39–43]. The UV-A and UV-B lights have also been studied for their positive effects on preventing intumescence formation [44] and controlling the development of diseases [45]. Since the UV LEDs nowadays show extremely low efficiencies and can be dangerous for workers' health, LEDs with a violet wavelength centred at 425 nm are generally used to create broadband blue emissions.

3.2.2 LEDs optical and thermal management design

Present LED lighting system packages for horticulture applications are configured as point sources or planar/linear arrays, which can be operated both horizontally and vertically [46]. LEDs point source lightings are the "bulb-type" systems which have been marketed for residential applications and present a low light output at the canopy level. On the other hand, several "bulb-type" lighting matrices equipped with high-density chip-on-board technology are used in research studies to have high intensity and colour mixing by closely lighting the crops with a uniform coloured light [47, 48]. Planar/linear arrays are generally configured like bars or rails, which can be operated both horizontally and vertically within the plant canopy and, in several occasions, can be used as repeated modules in parallel configurations to achieve the optimal intensity of photosynthetic lighting.

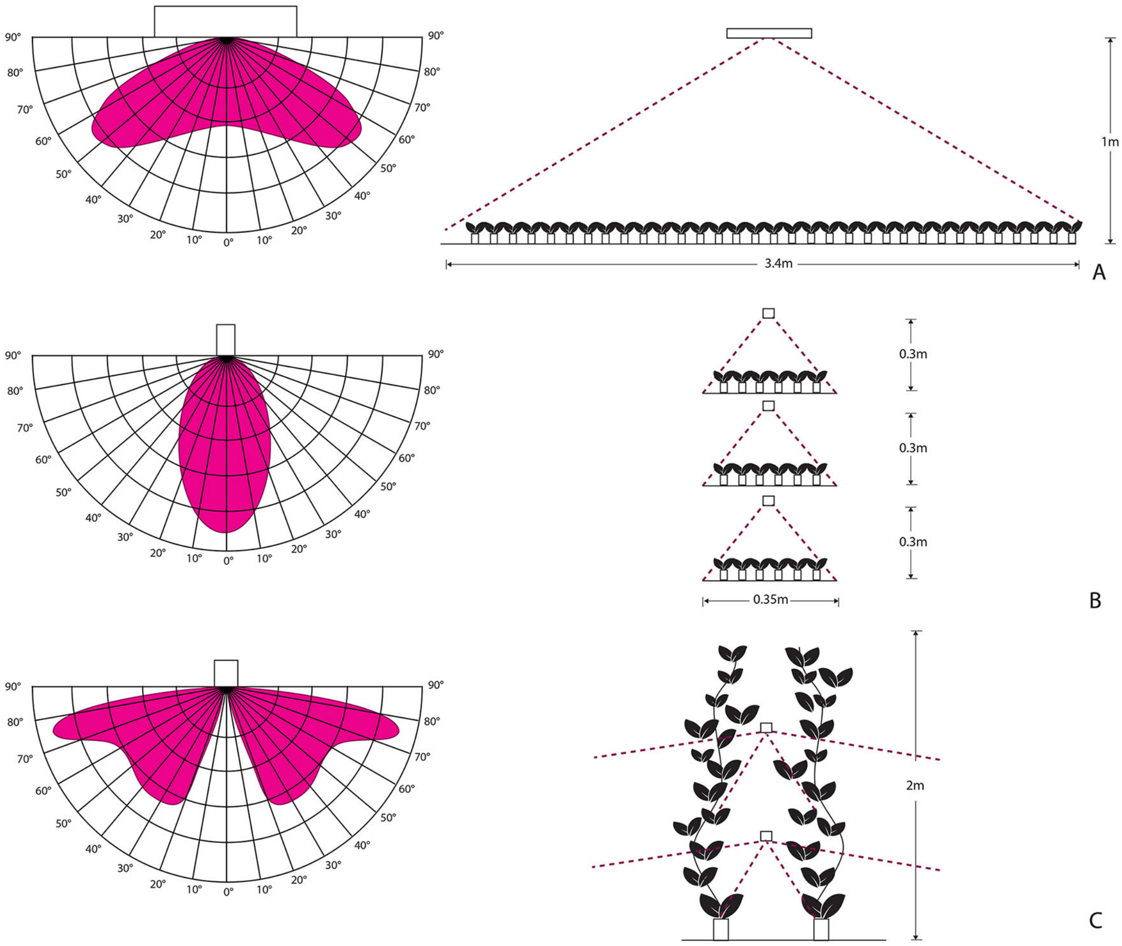

Fig. 5. Different horticultural lighting configurations: A represents an OHL installation with an optical system of 110° beam aperture; B represents a close-canopy overhead installation for vertical and multi-tiered farming with an optical system of 60° beam aperture; C represents an ICL installation for high-wire crops.

Another important aspect to control is the lighting distribution for different applications. LEDs are directional lighting sources equipped with primary optics, whose angular distribution of radiation is about 120° (for the majority of producers). This lighting distribution is used for retrofit of traditional lighting systems where LEDs lighting systems are positioned overhead and far away from the canopy. In this position, lighting is spread to fill wide cultivating areas (fig. 5A). When used in vertical multi-tiered applications, LEDs need properly designed optical systems, such as individual collimating lenses with total internal reflection (TIR) or parabolic reflectors, in order to produce the desired light distribution and target it precisely toward the canopy with higher intensities and fewer loss. Properly designed optical systems have optical efficiencies around 80–90% and can reduce the number of LEDs used by increasing the canopy photon capture efficiency. This allows light waste reductions and an increase in the overall electrical efficiency at the expenses of chromatic uniformity [15]. In fact, when using multispectral single LEDs, the colour mixing may not be as smooth as desired: edge-to-edge chromatic uniformity on the canopy is an issue to be considered, especially when working at very low distances between lighting systems and crops. Proper optical systems can solve this problem by ensuring that the spectrum reaching the tissues of the cultivation is uniformly mixed and not characterized by heterogeneous chromatic spots over different parts of the plants.

In terms of thermal management, LED lighting systems have the advantage of radiating very little heat from the emitting surface directly to the crops. On the other hand, a considerable amount of heat is radiated back from the base of the LED devices and needs to be conducted out of the device through the mounting surfaces. This is essential to ensure maximum luminous performances, chromatic reliabilities, long-lasting operating lifetime [49] and to avoid the overheat and stress of the plants. Properly designed heat-sinks are integrated in the lighting fixture to ensure the heat removal through different cooling techniques:

– Passive air-cooled heat-sink for direct conduction or natural convection of the heat.
– Active air-cooled heat-sinks through forced air (fan-cooled).
– Active liquid/water-cooled systems.

The wasted heat can be re-used for greenhouse heating or for heating the water in small hydroponic systems when desired or needed.

3.2.3 LED lighting control strategies for horticulture

One of the major advantages of LED lighting systems is the digital controllability and flexibility of lighting performances and regimes through integrated controllers, efficient drivers and electronics designed to take into account sensors' feedbacks from the environment and the plants. Manual or fully automated controllability of light quantity (intensity), periodicity (time, cycles and duration) and light quality (colour mixing and SPD) may have a strong impact on plants' productivity and conversion efficiency of the radiation into biomass.

Through dynamic controls, LED supplemental lighting can occur where, when and to the extent needed, by dimming from zero to the maximum intensity, depending on solar availability or creating specific lighting programs, such as sunrise or sunset simulations. This kind of controls have shown enormous potentials in terms of energy efficiency [50]. According to the studies of Pinho *et al.* [32], when LED lighting systems with Dynamic Lighting Controls (DLC) are continuously controlled (dimmed) in order to maintain a constant PPFD at the plant canopy, a 20% reduction of energy consumption is obtained in comparison to the same LED lighting systems operated under discontinuous on-off regime. More than this, a continuous DLC system may create a less stressful lighting environment for workers by avoiding sudden changes in lighting levels due to the on/off switching of the supplemental lighting system.

In addition to the instantaneous PPFD, LED DLC systems can control their performance also in relation to the lighting accumulation to reach the necessary Daily Light Integral (DLI), which is the amount of PAR received each day as a function of lighting intensity and duration. Additional challenging improvements of controls may include the opportunity to optimize the SPD by considering the local, seasonal and daily variations of the daylight spectrum depending on the specific solar availability and quality [28].

Several studies [51,52] have dealt with pulsed lighting *versus* continuous lighting by analysing the quantum efficiency and photosynthetic plants' response in relation to lighting regimes by variating frequency, cycles and pulse width. In comparison to continuous lighting, a statistically significant increase in quantum efficiency with pulsed lighting with low frequencies has been found [53].

The digitalization of LED lighting systems has also provided research solutions which enabled the sequential and selective switching of single LEDs modules in order to target the light to the height of plants by following their growth phases. This was achieved by using sensors of proximity for automatic detection of size and position of plants [54,55]. In this way, with LEDs lighting systems configured in arrays, only areas with plants would receive light.

The advancements in solid-state lighting are offering unprecedented opportunities for the research to explore plants-lighting relationships through the selective manipulation of light wavelengths. Further researches would focus on Adaptive Lighting Controls (ALC) which are aimed at tailoring light regimes to specific plant species by controlling independently SPD, duration and timing. These researches would focus on the definition of novel spectral combinations calibrated for specific crops in order to enhance biomass and yield production, to maximise specific nutraceutical growth (*i.e.* antioxidant contents, anthocyanin biosynthesis accumulation), to optimize organoleptic qualities and to suppress pathogens for plants' health. In addition to this, ALC can become early warning systems, by adapting lighting in relation to the biological feedbacks from the plants. Continuous light adaptations would occur through monitoring the physiological state of crops (*e.g.*, stress detection, pigmentation, etc.) before visual symptoms detection [56].

3.2.4 Light distribution and installation recommendations

According to Massa *et al.* [34], the lighting fixture position influences both the cultivation productivity and the system lighting efficiency. The basic reason for this is that the PPF decreases as the height of the lighting fixture increases by the inverse square law. Since the heat is removed remotely from the lighting emitting surface through proper designed heat-sinks, LEDs lighting systems can be placed closer to the crop tissues [54]. Reducing the distance of installation and directing lighting toward the canopy means reducing also lighting pollution and energy consumption. If the use of reflective surfaces allows the light photons to reflect back toward the canvas, the installation, placement and distribution of lighting specified for the morphology of the crops by considering their height, size and shape is extremely important for enhancing the profitability and sustainability of indoor cultivation [57]. In this regard, LEDs systems allow an overhead supplemental lighting (OHL) installation for low vertical profile cultivations (fig. 3A) in order to minimize shading and to ensure maximum uniformity of light distribution over the crops. In addition to this, LEDs lighting systems can be installed as intra-canopy lighting (ICL) for high-wire crops which form tall and solid blocks of vegetation. Preliminary proof of concepts with LFL [58] and experiments run with LED ICL systems have been found to be useful in preventing plants mutual shading, enhancing the productivity of biomass of closed-canopy crops, preventing the loss of chlorophyll fluorescence, eliminating lower leaf senescence along with abscission of flowers and fruits [34,57]. In addition to this, they have been found to be important for reducing considerably the energy consumption and enhancing the electrical conversion efficiency into biomass (fig. 5B) [54,55].

LEDs can be extremely useful also in multilayer cultivations where close-canopy overhead installation is used with separation distances between layers $\leq 10\,\text{cm}$. This is considered the minimum height required for achieving the spectral blending from individual LEDs of a matrix (fig. 5C). Those systems allow a greater plant density and improved plant productivity per unit area in comparison to the conventional approach with OHL placed at 30/40 cm from a single growing layer [29].

3.2.5 Metrics and measurements protocols for LED lighting systems

An important aspect to consider when evaluating LED lighting systems in horticulture is the measurements methods and protocols used to assess the impact of artificial lighting on the PAR wavelengths. To evaluate the $\mu\text{mol m}^{-2}\,\text{s}^{-1}$ for quantifying the lighting systems, it is nowadays possible to use specific tools, such as quantum meters. These instruments show some limitations with LEDs which are able to produce heterogeneous SPDs. In fact, since every LED lighting fixture is equipped with different LEDs and can produce different lighting regimes and SPDs, even if an identical PPF is measured, the lighting influence on the photo-morphogenesis and photosynthesis of plants can induce different results. In relation to this, a coherent and unifying system to measure and quantify the lighting radiation for horticulture is needed in order to provide a better characterization of the lighting systems. This new metric should be effective in comparing the features of energy consumption, lighting output, lighting intensity and spectral qualities in order to allow reproducibility of results in the research of plants growth [32].

New procedures, tools (hardware) and software calibrations should be defined and tested in order to accurately quantify PPF for LEDs lighting systems and also the amount of light absorbed by crops, especially for non-traditional lighting regimes (DLC-ALC) and configurations (ICL) [34].

4 Light quality and produce quality

4.1 Effect of light on antioxidant compounds accumulation in leaves and fruits

Accumulation of many compounds important in human diet in plant tissue is affected by light.

4.1.1 Ascorbic acid

One of the important compounds for humans is ascorbic acid (AsA). This metabolite is not synthesized by humans, because of lack of one enzyme: L-gulonolactone oxidase (GLO) [59]. The biosynthesis of AsA is possible in plant tissues, so they are a vital source of this vitamin for human. AsA biosynthesis occurrs in many plant organs (leaves, roots, stems, fruits, etc.) [60,61]. The precursor of AsA biosynthesis is usually a sugar, the D-glucose or D-galactose [62,63]. Therefore, the AsA biosynthesis is controlled by carbohydrates pool among others. The positive correlation between soluble sugars and AsA concentration in lamb's lettuce leaves has been observed [64], red and blue LED supplemental lighting increased the content of both compounds. The best effect was observed using 90% red and 10% blue LED light. Smirnoff *et al.* [63] reported that a higher intensity of light stimulated the activity of some enzymes involved in AsA biosynthesis. As a result, plants accumulated more AsA at higher light intensities. Mastropasqua *et al.* [60] reported that blue and red light affected AsA biosynthesis. The AsA pool in detached oat leaves treated with red or blue light was higher than in the dark treated ones. Authors reported that the L-galactono-1,4-lactone dehydrogenase (GLDH) enzyme was involved in the AsA biosynthesis and it is also dependent on light. In another study [65] the 5 minutes irradiation with red or UVB light on the dark-grown soybean increased the AsA level. Plants treated with far red light exhibit the same level of AsA as the dark-treated ones. The enhancement of AsA content by UVB was not reversible with far red light. This suggests the involvement of phytochrome and blue light receptors in this process. The stimulation of AsA biosynthesis by a mixture of red and blue light in lamb's lettuce leaves was also observed [64]. Plants grown with supplementary mixed red and blue light accumulated more AsA than the ones treated only with red LED lamps. This confirmed the involvement of red and blue light photoreceptors in the AsA biosynthesis. The control of the AsA biosynthesis by phytochrome and also the ratio of red/far red light is reported by Bartoli and coauthors [66]. Growth under a low R/FR ratio resulted in a lower AsA content in *Phaseolus* leaves. Even when plants were transferred from a high to a low R/FR ratio, the concentration of AsA decreased in the leaves. Changes in AsA pool connected with R/FR reduction were observed after just a single photoperiod.

It may be summarized that the light affects accumulation of AsA in plants due to 1) stimulation of photosynthesis (sugar and reduced nucleotide accumulation) and/or 2) activation of some enzymes in the AsA biosynthesis by red, blue and UVB light and also by the R/FR ratio.

4.1.2 Phenols and anthocyanins

Plant phenolics are secondary metabolites with antioxidant properties commonly occurring in many edible plant organs, like fruits, leaves, roots, seeds or flowers and they might be beneficial for human health [67]. Many environmental factors influence phenolics biosynthesis in plants during cultivation and in particular by light. Phenylalanine ammonia-lyase (PAL; EC 4.3.1.24) is the first enzyme in the biosynthesis of two main groups of phenolic compounds in plants: flavonoids and phenylpropanoids [68]. PAL activity as well as *PAL* genes expression are dependent on light conditions. In tomato leaves, enhanced expression of *PAL5* and *PAL6* genes and also a higher PAL activity were higher at $200\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ than at $100\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ light intensity [69]. However, not only the light intensity but also the light quality affects the enzymes activity in phenols biosynthesis. Red light enhanced PAL activity in tomato seedlings suggesting the role of phytochrome [70]. UVB radiation influenced flavonol glycosides accumulation and also activated genes of many enzymes in phenylpropanoids pathway in *Arabidopsis* seedling [71]. This suggests that light intensity, but also quality (red, blue or UVB), may affect the biosynthesis of phenolic compounds in plants. In another study, Chinese cabbage was cultivated under white, red or blue LED lamps [67]. The authors evaluated the concentration of various phenolic compounds as well as the expression profile of 11 genes encoding for enzymes involved in the phenols biosynthesis. Blue light increased the accumulation of most investigated phenolic compounds in Chinese cabbage seedlings. Light quality also affected the expression level of tested genes. In lamb's lettuce leaves, a higher concentration of total phenols, phenylpropanoids as well as flavonols was observed in the case of plants treated with 90% red and 10% blue LED lamps in comparison with 100% red as supplemental lighting [64]. These results suggest that mixed lightning increases the concentration of these compounds, but the best red : blue light ratio might be species specific. A similar observation, that blue light might enhanced the accumulation of phenols in plants, was reported by Taulavuori *et al.* [72]. The authors also suggested that this phenomenon is species-specific and lettuce reaction to the enhanced blue light was different from basil. Son and Oh [73] also reported that the addition of blue light changed the phenols concentration in lettuce leaves. A high ratio of blue LED light (as 59%, 47% and 35%) increased the total phenols and flavonoid content in lettuce. Supplemental UVA and UVB LED light also increased the anthocyanins content in lettuce leaves but FR light decreased these compounds [74].

These findings suggest that light intensity and quality affect the biosynthesis of phenolic compounds. The effect of light quality on phenolics biosynthesis depends on red, blue, UV, far red light, and also the ratio among them.

4.1.3 Nitrates

Nitrates might be accumulated in plant tissues up to high amounts without harmful effect on plants. However, a high nitrate concentration in edible parts of plants may be dangerous for human health [75]. On the contrary, some of medicinal scientists reported the beneficial function of nitrates in human body [76]. The discussion is still open.

Nitrate content in plant tissue depends on many factors including light conditions during cultivation [77]. Light intensity and quality influence nitrate uptake, translocation and reduction in plant organs (for a review, see [78]). Nitrate reduction is controlled by two enzymes: nitrate reductase (NR, E.C. 1.6.6.1) and nitrite reductase (NiR, E.C. 1.7.1.4), both of them are regulated by light [79]. Usually mixed red and blue radiation increased NR activity [80]. Phytochrome participation in NiR activity was also demonstrated [77].

Spinach, lettuce and komatsuna were grown under four different fluorescent lamps: white, red, mixed red and blue, and blue [81]. All treatments included red and blue radiation as well as UV, far red and green in a different ratio. Red or blue treatments decreased the concentration of nitrates in lettuce in comparison with white ones, while in the case of spinach, a similar observation was under red and mixed (red and blue) light. Komatsuna plants accumulated similar amounts of nitrates in each light treatments. This suggests that light treatment might control nitrate accumulation in plants, but the reaction depends on the plant species. The reduction of nitrates in lettuce, marjoram, and green onion was observed after lighting for 3 days before the harvest with red LED lamps [82]. Mixed red and blue LED light reduced the content of nitrates in basil leaves compared to white fluorescent lamps [83]. In lamb's lettuce the highest reduction of nitrates in leaves was observed using 90% red and 10% blue LED light as supplemental lighting in comparison with HPS lamps [84]. We can conclude that red and blue lights decrease the nitrate accumulation in edible parts of plants but there is still question concerning the best ratio of them.

4.1.4 Carotenoids

Carotenoids provide health benefits for humans as pro-vitamin A and antioxidants. Carotenoids are a group of isoprenoid compounds with 40 carbon in skeleton. In the structure of carotenoids, double bounds are responsible for light absorption. In plant tissues, carotenoids can be responsible for red, orange and yellow colours. Carotenoids biosynthesis is possible in many organs: leaves, flowers, fruits, roots or seeds. It is observed usually in plastids (chromoplasts or chloroplasts). The precursor of the biosynthesis is a five carbon prenyl diphosphate. In plant tissue, two pathways producing prenyl diphosphate exist: methylerythritol 4-phosphate (MEP) and via mevalonic acid (MVA) [85,86]. One of the enzymes involved in carotenoids biosynthesis is the phytoene synthase (PSY), which regulates the condensation of two twenty-carbon molecules in the first C40 molecule. The biosynthesis is possible in dark conditions —the etiolated seedlings are yellow, but it is enhanced by light. Light stimulates the de-etiolation process when the production of high levels of chlorophylls and carotenoids is observed [87]. Fast biosynthesis of carotenoids during de-etiolation of *Arabidopsis* seedlings is correlated with up-regulation of PSY activity, which is connected with red light and phytochrome photoreceptor. It suggests that red light plays a role in carotenoids biosynthesis. Stimulation of carotenoid accumulation as well as expression of genes involved in carotenoid biosynthesis by red light was observed in *Citrus flavedo* in comparison with dark conditions [88,89]. Other authors also suggest that blue and UV lights are essential for carotenoids accumulation. For example, broccoli microgreens treated for 5 days with blue LED light accumulated more β-carotene and violaxanthine but similar amounts of lutein as plants treated with red LED [90]. Blue supplemental lighting increased the carotenoids content in baby leaf lettuce but far red decreased the concentration of these compounds [74]. Lighted tomato fruits after harvest with UVB or UVC induced carotenoids accumulation [91,92]. Some researchers suggest that mixed (red and blue) or white light stimulate carotenoids content in plants in comparison to sole red or blue light [93,94]. In conclusion, we can say that carotenoids biosynthesis is affected by light but the effect is species-specific, that it also depends on the kind of carotenoid and it still needs research.

4.1.5 Chlorophylls

Among plant pigments, chlorophylls are very popular in edible parts of vegetables and fruits. That is way the consumption of chlorophylls is quite high especially from leafy vegetables. It was proven that chlorophylls have a beneficial influence on human health. They act as anticarcinogenic, antimutagenic and antioxidative components of diet [95, 96]. Biosynthesis of chlorophylls and its regulation is described (for a review, see [97,98]). It is well known and well documented that light is necessary for chlorophyll biosynthesis. In many plants accumulation of chlorophylls occurred only during the light phase in the 24 h cycle. Light intensity and also quality influenced biosynthesis of these health promoting compound in plants. In some cases, high light intensity may reduce accumulation of chlorophylls or their precursors [99,100]. Chinese cabbage was treated with red, blue, green, yellow and mixed red and blue LED lamps [101]. Control plants were treated with a dysprosium lamp. Authors reported that the highest concentration of chlorophyll *a* and *b* was observed in the case of plants treated with mixed red and blue LED lights, and it was similar to control treatments. The lowest concentration of both chlorophylls was observed in the case of sole red light. Red (R) light also reduced accumulation of chlorophyll precursors (ALA, Proto IX, Mg-proto IX, Pchlid). Precursors' level in cabbage was similar under control and mixed (red and blue) LED lamps. Supplemental far red (FR) radiation decreased chlorophylls content in lettuce leaves in compare with white light [74]. Chlorophyll content measured by SPAD technique in two lettuce cultivars was the lowest in the case of sole red lighting during cultivation [73]. Authors proved that any addition of blue light enhanced accumulation of chlorophylls. Lamb's lettuce plants were cultivated in greenhouse during autumn and winter with supplementary lighting [102]. The use of mixed (red and blue) LED lamps enhanced chlorophyll *a* and total content in compare with white LED lamps in plants leaves. Also the R/FR ratio plays role in green pigments synthesis. Demote-Mainard *et al.* [103] in their review article demonstrated that in many plants a low R/FR ratio reduced the concentration of chlorophylls.

4.1.6 Folates

Folates are tripartite of molecules including pterin, *p*-aminobenzoate (*p*ABA) and glutamate moieties. Plants, fungi, and most microbes synthesize folates. Humans and animals are not able to synthesize them due to the lack of necessary enzymes. Three subcellular compartments participate in the biosynthesis of folates in plants (mitochondrion, plastid, cytosol) (for a review, see [104,105]). Some precursors of folates biosynthesis are amino acids, so it is linked to nitrogen metabolism [106]. Folates and primarily tetrahydrofolate (THF) are responsible for one carbon reaction that form amino acids, purines, thymidylate, lignin, alkaloids, betaines, ethylene, chlorophylls and many more. They are necessary for DNA formation but they also have antioxidative properties [107]. Folates occurred in each plant organ (flowers, leaves, roots, stems, seeds, fruits, tubers) and organelle. Folates level changed during the development or ripening of fruits. For example, the concentration of folates in tomato fruits decreased during ripening, as it also decreased during storage for strawberries [104]. Many scientists agreed that folate level and synthesis are controlled by light. The content of folate was higher in green compared to etiolated leaves of *Arabidopsis* [108]. However, the folate content in mustard was similar in the case of ambient or reduced irradiation [109]. The accumulation of folates in green *Pisum sativum* leaves was twice as high than in the etiolated ones [110]. Also the expression of HPPK-DHPS (dihydropterin pyrophospokinase-dihydropteroate synthase), enzyme that catalyzes first two reactions in THF synthesis, as well as its protein accumulation was higher in green leaves treated with white light compared to those kept in dark. The authors conclude that the influence of light on folate synthesis is indirect and it probably is a consequence of other processes stimulated by light (photosynthesis or photorespiration). Spinach leaves (from top, middle and bottom of canopy) of two cultivars were harvested and stored in dark and light conditions at 4 °C [111]. Leaf orientation influenced the concentration of folates, top leaves accumulated more THF and its derivatives. Light condition during storage stimulated folates biosynthesis, dark conditions stimulated degradation of these compounds. During another experiment, spinach was exposed to longer (15 h) and shorter (10 hour) day lengths [112]. The longer day length stimulated folate accumulation in spinach leaves, also top leaves were richer in folate than the bottom ones. Folate is one of the chromophores in cryptochrome photoreceptor [113]. So we hypothesized that maybe not only light intensity but also light quality affects folate accumulation in plants. Lamb's lettuce was grown in greenhouse during winter and autumn and LED supplemental lighting was used [114]. Leaves treated with mixed light (90% red and 10% blue as well as 70% red and 30% blue) accumulated higher amounts of total folate than the ones irradiated with sole red light. This phenomenon needs further research, but it suggests that the folate content in plants is affected by light intensity and also quality.

5 Conclusion

The use of supplemental light in greenhouses or indoor environments has been gaining worldwide importance for extending the crop production in urbanized and geographical areas with limited agriculture environment conditions. The research in this sector has to face the sustainability of crop production, limiting the use of fossil energy, which, in the meantime, guarantees high-quality product and good yield.

In the literature, there is few information on the minimum plant light requirements, in terms of intensity and photoperiod, for the sustainable production. The availability of innovative LED lamps can provide the exact light requirements for the specific crop species in the different phenological stages. The future crop management has to take into consideration, beside the mineral nutrition, also the correct "light recipe" for high-quality production.

In the future, LED lighting systems should provide enhanced crops by continually monitoring and calibrating lighting features, such as intensity, spectra, timing and duration to the plant's needs. Further researches in this direction are required for smart lighting systems to optimize horticulture with greater energy savings and sustainability.

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