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Review

Applications and Development of LEDs as Supplementary Lighting for Tomato at Different Latitudes

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Abstract: High-tech greenhouses and artificial light applications aim to improve food production, in line with one of the sustainable development goals of the UN Agenda 2030, namely, "zero hunger". In the past, the incandescent lamps have been used for supplementary lighting (SL) at higher latitudes to increase greenhouse production during the dark season. Light-emitting diodes (LED) have been replacing gas discharge and incandescent lamps, and their development is expanding SL applications in different agricultural scenarios (e.g., urban farming, middle latitudes). In fact, recent research on LED applications in Mediterranean greenhouses have produced encouraging results. Since middle latitudes have a higher daily light integral (DLI) than higher latitudes in the dark season and climate conditions influence the installed power load of greenhouses, LED installation and management in Mediterranean greenhouses should be different and less expensive in terms of investment and energy consumption. Accordingly, the aim of this review is to outline the state of the art in LED applications and development, with a focus on latitude-related requirements. Tomato was used as a representative crop.

Keywords: daily light integral (DLI); spectral quality; photosynthetic photon flux density (PPFD); toplight; interlight; tomato

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1. Introduction

Based on the United Nations sustainable development goals, high-tech greenhouses will remain the most efficient systems for food production [1], and the use of artificial lighting, especially in northern Europe and North America, is fundamental for achieving the sustainable development goal of "zero hunger" [2].

The first use of artificial light in agriculture was in 1861 in France. It was not until the first half of the twentieth century that this technique was introduced to increase horticulture crop performance [3]. Over the years, various types of lamp have been used for artificial lighting (Table 1): incandescent, fluorescent, high-pressure mercury vapor, high-pressure sodium (HPS), and metal halide [4]. Incandescent lamps emit radiation between 400 and 700 nm, dissipating a large amount of energy in the far-red (FR) region. Since the energy conversion efficiency of such lamps is as low as 1 to 5% (Table 1), they were replaced by gas discharge lamps (fluorescent, high-pressure, and metal-halide), which became the most widely adopted solution for residential and agricultural applications. Similar to fluorescent lamps, high-pressure discharge lamps work on the principle of electric discharge through a gas, but the higher pressure enables better conversion efficiency [4]. HPS became the lamps most used in public spaces and industrial buildings, due to their high luminous efficiency and high emission peak (560 to 610 nm). Before the advent of light-emitting diodes (LEDs), HPS lamps were the most widely used in horticulture greenhouses due their electrical efficiency (30–40%; Table 1). The weak point of HPS lamps is that the emission peak does not match the absorption peaks of chlorophyll a, b, and β-carotene. To match the HPS emission spectrum to plant absorption peaks, metal halides were included in HPS lamps, obtaining metal-halide lamps. Changing the combinations of the metal halides enabled the light spectrum to be modified, but energy efficiency decreased around 25% (Table 1) [4]. During an experiment in Texas on solar cells, James Biard and Gary Pittman (1962) accidentally discovered that a gallium arsenide semiconductor emitted infrared radiation on passage of electricity. They patented the invention as a "semiconductor radiant diode" and that was the world's first LED [4]. LED technology has continued to develop different semiconductors to obtain different light emission spectra, increase energy efficiency, and match plant absorption spectra. The possibility of obtaining specific light spectra with different semiconductors makes LEDs suitable for the cultivation of plants, which need an artificial light source with the three spectral bands responsible for photosynthesis (642 and 662 nm), photomorphogenesis (730–735 nm), and phototropism (400–500 nm) [5]. Today, LED technology is the most widely adopted for artificial lighting in greenhouses, due to its spectral flexibility in the wavelengths required by plants and its energy conversion efficiency (Table 1).

Table 1. Features of various electric lamps used for plant lighting [4].

Lamp Type	Spectral Output	Energy Use Efficiency	Power Requirements	Life Span
		(µmol·W^{-1}) %	W	Hours
Incandescent	Broad spectrum	1–5	15–1000	1000
Gas discharge	Broad spectrum	>30	5–125	1000–30,000
High-pressure sodium (HPS)	Broad spectrum	30–40	100–250	10,000–30,000
Metal halide	Broad spectrum	25	34–4000	10,000–20,000
Light-emitting diodes (LED)	Specific wavelengths	>40	0.1–5	>50,000

The aim of this paper was to review the state of the art on the applications and development of LEDs in supplementary lighting (SL) of greenhouses for tomato (*Solanum lycopersicum* L.) cultivation. The effects of different spectral composition, position (interlighting and toplighting), photosynthetic photon flux density (PPFD), and daily light integral (DLI) on tomato growth are discussed, and we compare SL installation and management at middle and high latitudes.

2. LED and Light Spectra

Plants respond to a broad light spectrum ranging from UV-B to far red. It has been demonstrated that plants have distinct photoreceptors for UV-B, UV-A, blue, green, red, and far-red light (FR) [6]. The phytochrome photoreceptor family is the only one that detects red (R) and FR light [7]. The phytochrome family exists in two interconvertible forms, the R-absorbing P_r (λ = 660 nm) and the FR-absorbing P_{fr} (λ = 730 nm; Table 2). Although the two forms of phytochrome have different, albeit overlapping, spectral absorption bands, P_{fr}/P_{tot} photoequilibrium depends on wavelength and is about 80% R, 3% FR, and 40% blue (B; λ = 450 nm; Table 2) [7]. There are specific photoreceptors for the blue/UV-A region: cryptochrome (CRY1 and CRY2) and phototropin (pho; with a functional role in phototropism; Table 2) [8]. Major supplementary lighting (SL) factors include [9]: (1) photosynthetic photon flux density (PPFD µmol·m^{-2}·s^{-1}) at wavelength 400 to 700 nm; (2) spectral quality; (3) photoperiod (light/dark periods); (4) luminous flux direction (downward, sideward and upward lighting).

The spectral output of the source should, therefore, match the plant's photosynthesis and photomorphogenesis requirement [10]. Fluorescent, metal-halide, high-pressure sodium, and incandescent lamps were developed for human lighting requirements and are, therefore, not ideal light sources for plants, whereas LEDs emit specific wavelengths and can be matched to plant needs [11]. The first LEDs used in plant research were based on a gallium–aluminium–arsenide substrate (GaAIAs) with an emission peak range from 630 to 680 nm (Table 3) [10]. Bula et al. [12] report that in the 1990s, many companies worked to improve the output of blue LED.

Table 2. Summary of photoreceptors involved in physiological responses of plants to different light spectra.

Light Spectrum	Wavelength (nm)	Photoreceptor	Physiological Responses
FR	730	phy A	Germination
R	660	phy B	De-etiolation
R	660	phy C-E	Shade avoidance
Blue/UV-A	450/330	CRY 1	Shade avoidance
Blue/UV-A	450/330	CRY 2	Flowering
Blue/UV-A	450/330	PHO	Phototropism

Table 3. Semiconductors in LEDs and their emission spectra [11].

Materials	Formula	Wavelength (nm)	Light Spectra	Forward Voltage (V)
Gallium–Phosphide Aluminium–Gallium–Arsenide Gallium–Arsenide–Phosphide Aluminium–Gallium–Indium–Phosphide	GaP GaAsP AlGaAs AlGaInP	610–770	Red	1.6–2.0
Gallium–Phosphide Gallium–Arsenide–Phosphide Aluminium–Gallium–Indium–Phosphide	GaP AlGaP AlGaInP	590–610	Orange	2.0–2.1
Gallium–Phosphide Gallium–Arsenide –Phosphide	GaP GaAsP	570–590	Yellow	2.1–2.2
Gallium–Phosphide Aluminium–Gallium–Phosphide Aluminium–Gallium–Indium–Phosphide	GaP AlGaInP AlGaInP	500–570	Green	1.9–4.0
Silicon carbide Zinc sulfide	SiC ZnS	450–500	Blue	2.4–3.7
Gallium–Nitride Indium–Gallium–Nitride	GaN InGaN	400–450	Violet	2.7–4.0
Blue diode with yellow phosphor		Broad spectrum	White	3.5

Plant supplementary lighting systems are usually of three types that supply red and blue wavelengths, covering the range needed for photosynthesis [13]: (i) red and blue combinations, (ii) all blue, and (iii) all red. For photosynthesis, plants respond most strongly to red and blue light, but the spectral distribution also influences plant shape, branching, leaf colour, development, and flowering (photomorphogenesis) [14].

Tomato is a widely cultivated species all over the world. It is cultivated in greenhouses all year round, making it an interesting species for studying the effects of supplementary lighting (SL) on plant growth and physiology. In recent years, many experiments have investigated the effects of light spectra on tomato growth, yield, and physiology (Table 4). The results have been contradictory, but all researchers confirm that tomato needs a combination of R and B light. In particular, when R light was applied alone, photosynthetic capacity and leaf thickness were the lowest, while when only B light was applied, leaves exposed to low light intensity showed the fastest stomatal closure, which was due to the smallest stomatal size and the highest stomatal density [15]. When measured under different R/B ratios, stomatal opening rate and photosynthetic induction rate barely improved with increased fractions of B light [15]; B light decreased leaf area index, shoot dry weight, and leaf weight ratio, while white (W) light increased net assimilation rate [16]; considering the chromaticity diagram from the Commission International de l'Eclairage France (CIE), the coordinates (x, y) of ideal with light are 0.33, 0.33 [17]. W light was the most efficient in increasing tomato yield and fruit growth rate [18]. The data indicate that lack of B or R light impairs early tomato development in terms of morphology and physiology [19]; in fact, monochromatic R light decreased stem diameter, leaf area, and shoot dry weight [20] and increased upward or downward leaf curling [21]. Finally, monochromatic R light reduced the leaf number before differentiation of the first truss, and this could reduce the time from transplant to the first fruit harvest [22]. The combination of B and R LED lighting increased total dry matter [21], photosynthetic pigment content, stomata number, and reasonable photosynthate distribution in cherry tomato seedlings [23]. The best effects on tomato growth and physiology with R + B LED were obtained when the LED spectra was composed of 75 to 95% R and 25 to 5% B [20–24]. However, other photons, outside the photosynthetically active radiation (PAR) spectrum, increase leaf photochemical efficiency: FR photons (701–730 nm) [25]. Although FR alone has low photosynthetic efficiency, adding it to a background of W or R + B light caused an increase in canopy gross photosynthesis rate [25]. A recent study of FR effects on tomato plant physiology confirmed that FR promotes different physiological processes when supplied on a W or R + B background. In fact, FR increased dry mass partitioning to fruits but reduced *Botrytis cinerea* resistance in tomato [26]; it promoted stem elongation and plant height, which increased light interception, improved early plant growth, and increased fruit production rate [27]. Zhang et al. [28] found that FR increased stem elongation and modified leaf morphology, which resulted in deeper light penetration and, consequently, more homogeneous light distribution in the canopy. Finally, other studies reported that FR increased stomatal behaviour and stomatal conductance, enhancing CO_2 supply and, thus, preventing stomatal closure, as well as promoting root development, thus ensuring leaf photosynthesis and dry matter production. It also alleviated intumescence injury of tomato plants, increased fruit dry weight and improved light interception [29–31]. In conclusion, FR wavelengths, which are abundant in sunlight, proved to be a fundamental spectral component for tomato growth indoors or under low sunlight conditions; under conditions of high sunlight, it may not be necessary to supply extra FR radiation [32].

Table 4. Relationship between light spectra and crop responses.

Light Spectra	Crop Response	Reference
Monochromatic R	Increased upward or downward leaf curling	[21]
Monochromatic R	Stimulated hypocotyl and epicotyl elongation, cotyledon expansion, plant height, and leaf area	[19]
Monochromatic R	Lower stem diameter, leaf area, and shoot dry weight	[20]
Monochromatic R	Enhanced photosynthesis and seedling biomass production	[19]
Monochromatic B	Increased stomatal conductance	[33]
Monochromatic B	Induced highest Rubisco content, more compact size, and reduced biomass in tomato seedlings	[19]
Monochromatic B	Increased vitamin C and TSS, reduced plant height, stimulated growth of lateral shoots, and higher leaf area	[22]
Monochromatic B	Increased net rate of photosynthesis	[23]
R + B	Increased total dry matter	[21]
R + B	Increased photosynthetic pigment content, stomata number, photosynthate distribution, and photosynthetic net rate	[23]
R + B	Increased average fruit weight	[34]
R + B	Increased leaf dry weight and fruit number	[35]
W	Increased yield and fruit growth rate	[18]
W	Increased net assimilation rate	[16]
W	Decreased lateral shoot number	[22]
FR	Increased fruit dry matter weight improving light interception	[31]
FR	Promoted stem elongation, light interception, plant growth, and fruit production	[27]
FR	Alleviated intumescence injury	[30]
FR	Increased plant total biomass production and ripe fruit yield	[15]
FR	Increased dry matter partitioning to fruits	[26]
FR	Reduced *Botrytis cinerea* resistance in tomato	[26]
FR	Could help prevent stomatal closure and promote root development, ensuring leaf photosynthesis and dry matter production	[29]

3. Photosynthetic Photon Flux Density (PPFD) and Daily Light Integral (DLI)

Accurate measurement of PAR is essential for SL management. The criteria and methods used for measuring PAR have been investigated intensively [36]. Photosynthetically active radiation is the type or spectrum of light to which plants respond best in terms of photosynthesis. PAR is typically in the range of 400 to 700 nm waveband. The light that falls on the crop, or PPFD, expressed in micromoles per meter per second ($\mu mol \cdot m^{-2} \cdot s^{-1}$) is measured. The photosynthetic photon flux (PPF) is the total amount of light in the PAR band produced by a light source per second [37]. If we know the PPF of a "grow lamp", we can calculate or estimate how many lamps we will need per unit area to supply the required light level to the plants.

The photosynthetic photon flux density (PPFD) is currently the best available measure to compare commercial grow lamps. However, this parameter weighs all photons in the spectrum equally, which is not valid, because the energy of photons depends on their wavelength [37]. To link light spectra with the photosynthesis, yield photon flux (YPF), may be calculated. It weights photons in the PAR region according to the photosynthetic response of plants. So, if we know the exact spectrum of the grow lamp, the PPF values in $\mu mol\ s^{-1}$ can be modified, applying different weighting factors to different wavelengths and colours. This gives us the YPF. The relationship between wavelength and energy is described by Planck's Law. This law explains why for the same amount of energy, photons in the red spectrum have a higher impact on plant photosynthesis than for example blue photons [37]:

$$\text{Energy of a photon of wavelength } \lambda = hc/\lambda = 2 \times 10^{-25}\ (\text{J}\cdot\text{m})\ \lambda^{-1} \quad (1)$$

$$\text{Energy of a } \mu\text{mol } (\approx 6.1017) \text{ of photons of wavelength } \lambda \approx 12 \times 10^{-8}\ (\text{J}\cdot\text{m})\cdot\lambda^{-1} \quad (2)$$

As a rule of thumb, the energy of a µmol of photons in joules ≈ 120 λ^{-1}, where λ = the wavelength of the photon in nm. From this relation between the wavelength and the energy of light, we obtain that red photons in the 660 nm bandwidth can carry much more energy than shorter wavelengths such as blue 450 nm:

$$\text{Maximum energy of a 660 nm deep red photon} \approx 660\ \text{nm}/120 \approx 5.5\ \mu\text{mol}\cdot\text{J}^{-1} \quad (3)$$

$$\text{Maximum energy of a 450 nm blue photon} \approx 450\ \text{nm}/120 \approx 3.75\ \mu\text{mol}\cdot\text{J}^{-1} \quad (4)$$

Of course, the above values are absolute maximum ratings. The highest efficiency so far reached by a 660 nm LED package is 4.2 $\mu mol \cdot J^{-1}$ (Osram Oslon Square V4–Q1 2020), while the most efficient LED grow lamps today have an efficiency around 3.5 $\mu mol \cdot J^{-1}$. Even greater improvements in efficiency can be expected [37]. The higher efficiency of LEDs in recent years was obtained due to improved technology: multicolour LED COB (chip-on-board) devices are usually used instead of SMD.

Finally, the daily light integral (DLI) is a cumulative measurement of the total number of photons that reach the plant during the daily photoperiod. The DLI measures the number of "moles" of photons in the PAR region per square meter per day, expressed in $mol \cdot d^{-1} \cdot m^{-2}$. DLI is useful for implementing light strategy in greenhouse projects with supplementary lighting. For most crops, we can define the ideal total light sum per day the plants can efficiently use. The total light sum is the sum of the light received from the sun plus the sum of the artificial light supplied per day. To calculate the DLI in a greenhouse we must convert solarimeter values in $J \cdot cm^{-2}$ to mols. Since the solarimeter is on the roof, we must allow for the transmittance of the greenhouse glass. Conversion of solarimeter values to DLI from the sun is as follows ($J \cdot cm^{-2}$ to $mol \cdot d^{-1} \cdot m^{-2}$) [37]:

$$\text{DLI from the sun} = [(\text{measured J}\cdot\text{cm}^{-2})/100] \times 2.15 \times \text{glass transmittance } \% \quad (5)$$

The extra light received by plants from grow lamps can also be calculated. We convert PPFD to DLI with the number of lighted hours ($\mu mol \cdot m^{-2} \cdot s^{-1}$ to $mol \cdot d^{-1} \cdot m^{-2}$):

$$\text{DLI from grow lamps} = (\text{hours} \times \text{PPFD} \times 3600)/10^6 \quad (6)$$

Tomato has high light requirements, needing a total DLI (supplementary light + natural light) of 20–30 $mol \cdot m^{-2} \cdot d^{-1}$. Since it is generally grown at high plant density, correct light levels are fundamental [38]. The reduction in tomato yield due to 1% less radiation is reported to vary between 0.6 and 1.1% [39]. It is, therefore, necessary to avoid light stress by optimizing SL installation and management. There have been many studies on the application of PPFD, DLI, and photoperiod to tomato growth (Table 5). Tomato plants are generally grown with a photoperiod between 16 and 18 h [22,34,40,41], but if they could be grown under continuous light, a substantial increase in production would be expected. In practice, tomato plants grown with continuous light develop potentially lethal mottled chlorosis. A recent simulation study showed that with an ideal continuous-light-tolerant tomato genotype, greenhouse tomato production could be 26% higher with a 24 h photoperiod instead of 18 h [42]. Demers [43] found that the best photoperiod for a greenhouse tomato crop was 14 h. Longer photoperiods did not increase plant growth or yields, while photoperiods of 20 h or more caused leaf chlorosis. However, leaf injury could be avoided if continuous light was not applied for more than five consecutive days [43]. Moreover, using a photoperiod of 16–18 h and increasing PPFD, fruit set ratio and fruit growth increased, but more than 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ caused leaf stress [44]. These results were confirmed by Wei et al. [45], because light intensities of 100 and 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ significantly improved the quality of grafted tomato seedlings with respect to light intensity of 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Deram [34] found that an increase in light intensity obtained higher fruit mass and plant biomass. Table 5 shows the photoperiod, PPFD, and DLI used in recent trials on tomato plants.

Table 5. Overview of experiments on tomato growth and production applying different PPFDs and/or different photoperiods.

SL PPFD ($\mu mol\ m^{-2} \cdot s^{-1}$)	Photoperiod (Hours)	SL DLI ($mol\ m^{-2} \cdot d^{-1}$)	Reported Efficacy	Reference
50, 150, 200, 300, 450, 550	12	2.2, 6.5, 8.6, 13.0, 19.4, 23.8	300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ induced highest energy efficiency	[46]
200	16	11.5	Satisfactory growth and photosynthesis	[40]
110	14, 16, 20, 24	5.5, 6.3, 7.9, 9.5	Photoperiods > 14 h did not increase tomato plant growth and yields	[43]
110, 115, 135	16	6.3, 6.6, 7.8	Increasing light intensity induced higher fruit mass and plant biomass	[34]
300	16	17.3	Optimal plant growth	[22]
110	12, 24	4.8, 9.5	Continuous light caused leaf injury	[47]
200, 500, 1000	16	11.5, 28.8, 57.6	PPFD > 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ caused leaf stress and physiological disorders	[44]
200, 500, 1000	16	11.5, 28.8, 57.6	Increasing light intensity to promote stomatal closure, reducing gas exchange	[48]
161, 162, 163, 174, 243, 247, 250, 260, 319, 329	18	10.4, 10.5, 10.6, 11.3, 15.7, 16.0, 16.2, 16.8, 20.7, 21.3	Fruit weight and total yield increased linearly with increasing installed light intensity, without loss of fruit quality. Maximum yield potential was not established in the range of light intensities tested	[49]
50, 100, 150	16	2.9, 5.8, 8.6	In terms of power consumption and economic benefits, SL with a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was the best choice to improve the quality of grafted vegetable seedlings	[45]

4. Toplighting (Overhead) and/or Interlighting (Intracanopy)

Intracanopy light or interlighting consists of LED modules placed within the plant canopy as a sole source of light or as a source supplementing solar or overhead electric lighting in a greenhouse or growing chamber [50]. With overhead lighting, the lower leaves of the canopy receive less light, and this reduces photosynthesis [51]. Interlighting improves light distribution throughout the canopy of the crop, increasing active photosynthetic leaf area and biomass production per unit of light [50]. The technology of cultivation of high-growing plants such as tomato and cucumber with LED interlighting modules was developed in northern hemispheres especially due to low heat emission by diodes (Figure 1).

Figure 1. Overhead LED system + intracanopy LED installation (**a**); two lines of intracanopy LED installation as sole SL source (**b**); LED overhead-distributed SL source (**c**); HPS overhead point SL source (**d**).

Overhead lighting or toplighting consists of a light module placed above the plants (Figure 1). Before the development of LEDs, HPS lamps were used as overhead point source lighting. This is not the best solution, because it gives bad horizontal light distribution and uneven temperature. In fact, since the introduction of LED technology, overhead point sources have been dropped in favour of an overhead-distributed source. LEDs are distributed over the growing area, giving greater horizontal light uniformity and fewer temperature gradients in the greenhouse [50]. A number of studies have reported that overhead-distributed sources were more economical and better for plant cultivation than overhead point source lighting [52–55], although toplighting systems consumed less electric energy per day than an interlighting system for greenhouse cultivation of tomato [56] and increased fruit yield and biomass production compared with HPS overhead point sources [57]. LED interlighting may be installed vertically or horizontally. Vertical installations are less likely to become entangled with tomato plants and are more adaptable, whereas horizontal installations avoid interference with watering systems and may require less hardware [50]. LEDs installed as vertical towers within the canopy of tomato plants allocated biomass preferentially to fruits [58], and it was possible to improve productivity [59].

LED toplighting and interlighting influence tomato plants differently in relation to season. Tomato stem density has been increased by LED interlighting, especially in summer [60]. This has led to studies on the positive effects for plant growth and production of LED interlighting as a sole source of SL or in combination with overhead point sources or overhead-distributed sources [61–64]. Nowadays, toplighting alone or with interlighting is the SL system most widely used in horticulture, because overhead lights give better artificial light distribution in the greenhouse or grow chamber, and the maintenance and installation costs of toplight LED are lower than those of interlight LED. Due to their contact with vegetation, interlights become dirty, decreasing PPFD output.

5. Light-Emitting Diode Development

LEDs are displacing incandescent, fluorescent, and high-intensity discharge lamps. In a previous section, we described the properties that make LED technology suitable for residential and agricultural applications. Deep tech innovation efforts are increasingly concentrated on LEDs at the expense of traditional types of lamp. LEDs are becoming increasingly more efficient and economically competitive in the residential and greenhouse sectors. For example, the cost of white light LED dropped [65] from EUR 100 W^{-1} in 2007 and around EUR 4 W^{-1} in 2014 to around EUR 1 W^{-1} today [65]. An economic analysis proposed by Nelson and Bugbee in 2014 [55], comparing ten different types of LED fixture, reported that LED and HPS lamps had similar electrical efficiencies in the 1.6–1.7 $\mu mol \cdot J^{-1}$ range. The same study reported that the initial capital cost of LEDs was five to ten times higher than HPS. It pointed out that over a period of five years, HPS lamps were more economical than LED lamps and that the sole advantages of LEDs was to focus photons on specific areas, which is useful for improving photon capture by plant canopies [66]. There is no recent economic analysis similar to that of Nelson and Bugbee [55], but the purchase cost of LEDs has certainly decreased and their electrical efficiency has exceeded 3.0 $\mu mol \cdot J^{-1}$.

The low price of LEDs and the interest of the growers in investing in this technology has induced several companies to produce LED lighting systems for agriculture. The horticultural LED lighting market is promising and is expected to grow from USD 576 million in 2016 to USD 5.11 billion by 2022 [67]. In fact, in recent years, owners of high-latitude greenhouses have shown interest in replacing HPS lamps with more efficient LED modules, while owners of mid-latitude, e.g., Mediterranean, greenhouses are interested in installing SL. Growers were encouraged by the positive effects of SL on horticulture crops obtained by researchers at Bari University [32,35,67,68]. High-latitude greenhouses tend only to replace their HPS lamps with LEDs, whereas new greenhouses or those installing artificial light for the first time have to design all the electrical components necessary for LED function (electrical cables, switch panels, hooks, software, etc.). Those who replace HPS lamps, therefore, generally keep their overhead point source light system (few LED modules per square meter but with high PPF), saving on installation time and changes in other electrical components, whereas those who install LED SL for the first time choose overhead-distributed source lighting or overhead-distributed plus intracanopy lighting to obtain even distribution of SL within the canopy. A word is necessary about the variety of SL, because there are various types of LED module [67]. LEDs, therefore, have big advantages over other types of artificial illumination in agriculture, including higher efficiency (light per energy consumed, quantum efficiency), longer lifespan, controllable emission spectrum, safer handling, and safer disposal [5,69]. LED solutions are particularly promising for vertical farming, where Heliospectra, Vividgro, Valoya, and other companies are investing millions in research to drive the industry forward. Today, these players achieve yield increases of up to 20% and, therefore, add up to 20% to farmers' profit margins. Lighting is typically the highest electricity end use (up to 70%) in most controlled environment agriculture applications [70]. Thus, researchers have been investigating other technologies to achieve high yield increases by manipulating the LED photon sequence and establishing a feedback loop to accurately measure and adjust the optimal amount of light for a given plant at different growth stages. LED-based pulsed light techniques have been applied with different frequencies and work cycles in the study of phototropism in *Arabidopsis thaliana* seedlings [71]. Yoneda and Mori [72] applied different frequencies of pulsed light and continuous light to lettuce plants by means of LEDs. Pulsed light is, therefore, a field in the development of artificial lighting systems for plant growth. Work is being done on intelligent systems that modify light quality and use feedback control and monitoring. The aim of intelligent illumination systems is to save electricity and decrease operating costs of artificial light farms [70]. Research on the frequency, light quality, and pulse width of commercial LED lamps aims to obtain insights into plant–light interactions [73].

Most of the solutions proposed in commercial applications use some level of cloud connectivity to create a user-friendly experience, ranging from remote control of the lighting to fully integrated software and control systems. Solutions that attempt to effectively match the light and dark phases of photosynthesis seem to be particularly promising. A key research challenge here is implementation of the high-precision pulse sequences necessary to optimise yield and energy savings [74].

6. Greenhouse Technology in Different Climatic Regions

Greenhouses initially developed in relatively cold regions to avoid low temperatures during the cold seasons and to cultivate exotic and/or out of season crops. With the advent of plastics, the cost of greenhouse covering materials decreased, enabling, for example, shelters to prevent rain damage in rainy sub-tropical regions and net houses to limit crop evaporation and prevent leaf burn in desert regions [75]. Today, it is difficult to estimate the hectares of greenhouses for vegetable production in the world, because some statistics include temporary structures and some do not, and because this sector is very dynamic, quickly making statistical data out of date. Hickman [76] estimated the area of greenhouse vegetable production worldwide in major climate zones (Figure 2). He found that more than 85% of greenhouses were in the Mediterranean to sub-tropical climate zones (Figure 2), where the conversion of land from open field to greenhouse cultivation makes more efficient use of scarce resources (water) and enormously increases income per unit area of soil [75].

Climatic region	Limiting factors	Remedies	Consequences	Estimated area of greenhouse (1000 ha)
Sub- arctic to Temperate	Low temperature in winter Low light in winter	Heating Artificial lighting	High energy use or poor production	51.7
Mediterranean to Sub- tropic	High temperature in spring/ summer Marginal light and temperature in winter	Ventilation and/or whitewash	No summer production Low winter production	416.2
Tropic to Equatorial	High light High temperature	Elevation Evaporative cooling Permanent shading	Very high water use Low productivity	7.5

Figure 2. Limiting factors of greenhouse cultivation, remedies, consequences, and estimated area of greenhouses in the main climatic regions of the world [76].

It must be clear that greenhouse technology depends on various factors: climate conditions, access to finance, cost of production, internal market, etc. Climate is the most important factor from an agronomic point of view, because in certain places (sub-arctic to temperate zone), growers need to use heating and artificial lighting to produce horticulture species all year round, while in other areas (Mediterranean to sub-tropical zone), they need to whitewash the greenhouse covering material to reduce light intensity and temperature in the greenhouse, especially in the warm season. In the tropical to equatorial zone, growers need to reduce light intensity and temperature all year round, using evaporative cooling and permanent shading (Figure 2).

In Europe, there are about 200,000 hectares of greenhouses with an economy of 7 billion euro; Italy, Spain, The Netherlands, and Greece are the main countries for this sector [77]. Climate conditions influence the installed power load of a greenhouse [78]. In southern Europe, heating and artificial light systems are only used between October and March, so the power load of these greenhouses is around 50–150 $W{\cdot}m^{-2}$, while in northern and central Europe, heating and lighting are needed for most of the year and the power load is around 200–280 $W{\cdot}m^{-2}$ [77]. Mild winter temperatures in Mediterranean countries make it possible to produce vegetable crops economically in very simple shelters, but a technological upgrade is needed due to globalization and increasing competition [79]. The Netherlands has the highest greenhouse technology in the world and the highest yields. Regarding fresh tomato production, The Netherland's greenhouses have an average yield of 65–70 $kg{\cdot}m^{-2}$ with peak of 80–85 $kg{\cdot}m^{-2}$, while in Italy, the average yield is around 20–25 $kg{\cdot}m^{-2}$, and in Spain, it is 16–18 $kg{\cdot}m^{-2}$ [80]. Light is often the main environmental factor reducing crop yield in the Mediterranean basin; other phenomena such as "global dimming" accentuate light deficiency in the dark season [81].

As shown in Table 6, the optimal DLI for tomato is around 25 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. While, Table 7 shows the average DLI values of different European countries. At Piikkio (60°23′ N; 22°33′ E) in southern Finland, outdoor DLI is about 36.8 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in summer, 5.3 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in fall-winter, and 19.9 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in spring [61]. If high-tech greenhouse transmissivity of PAR is around 70%, it is evident why it is impossible to grow tomato without artificial lighting in northern Europe, particularly in fall–winter. It is, therefore, more feasible to grow tomato in the Mediterranean basin in the dark season. In fact, at Monopoli (40°90′ N; 17°33′ E) in southern Italy, the outside DLI from April to mid-September is on average higher than the optimal DLI required for tomato, while from mid-September to January, it is only 8–9 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, increasing again from January to June to reach 25 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in April [35].

Table 6. SL PPFD min (in $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$), SL PPFD max (in $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$), and SL DLI (in $mol{\cdot}m^{-2}{\cdot}d^{-1}$) for the three types of vegetable most cultivated with SL.

Crop	SL PPFD Min ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$)	SL PPFD Max ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$)	SL DLI Range ($mol{\cdot}m^{-2}{\cdot}d^{-1}$)
Tomato	170	350	11–23
Pepper	120	300	8–20
Cucumber	120	350	8–23

Since greenhouse transmissivity of PAR in the Mediterranean is around 60% (due to the plastic covering material), plants receive only 60% of the outdoor DLI. For tomato and other horticultural species, it is assumed that 1% less PAR results in 1% less production [39]. For a greenhouse without SL at Piikkio in fall–winter, DLI is around 3.71 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ (considering a PAR transmissivity of 70%) and tomato production would be about 85% less than optimal (i.e., the production obtained at DLI 25 $mol{\cdot}m^{-2}{\cdot}d^{-1}$). This explains why tomatoes are not produced all year round without SL in northern Europe. For a similar greenhouse in the Mediterranean basin (with 60% PAR transmissivity), average winter DLI outside is 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in December/January and 6 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in the greenhouse (considering transmittance). So, tomato production is about 76% below optimal (if light is assumed to be the only limiting factor). As expected, without SL and assuming DLI to be the only factor that influences tomato yield, due to the higher natural DLI, tomato production decreases less in the Mediterranean greenhouse in winter than in the Finland greenhouse. However, while high-latitude countries use SL to improve crop production in the dark season, this technology has only recently been introduced in a few Mediterranean greenhouses. Today, it is possible to compensate for natural light deficiency in the dark season using LED SL for greenhouse horticulture. Based on the literature cited in Table 6, the SL PPFD most used to increase the DLI in greenhouses for tomato is around 180–200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with a photoperiod of 18 h. Considering this data, when an SL LED system emitting 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PAR with a photoperiod of 18 h is used in fall–winter in a northern European greenhouse, the total DLI supplied to the tomato plants is around 17 $mol \cdot m^{-2} \cdot d^{-1}$ with a hypothetical production 32% below optimal (Table 6). If the same SL system is applied in a Mediterranean greenhouse, the total DLI supplied could be around 19 $mol \cdot m^{-2} \cdot d^{-1}$ with a hypothetical reduction in the production of 24%. To reach the DLI obtained in the northern greenhouse, the SL system could alternatively be switched on for around 15 h of photoperiod, decreasing electrical consumption and increasing the life span of the LED modules.

Table 7. Average annual daily light integral (DLI) in Europe [82].

Country	Average DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Country	Average DLI ($mol \cdot m^{-2} \cdot d^{-1}$)
Austria	21–35	Italy	31–35
Belarus	21–25	Latvia	16–20
Belgium	21–25	Lithuania	16–20
Bulgaria	31–35	Montenegro	31–35
Croatia	31–35	The Netherlands	21–25
Czech Republic	21–25	Poland	21–25
Denmark	16–20	Portugal	31–35
Estonia	10–15	Romania	26–30
France	26–30	Spain	31–40
Germany	16–20	Switzerland	26–30
Greece	36–40	Turkey	31–40
Hungary	26–30	Ukraine	21–30
Ireland	16–20	United Kingdom	10–20

7. Conclusions

In conclusion, SL is fundamental to produce vegetables such as tomato or cucumber all year round at high latitudes, whereas at middle latitudes, SL is strongly recommended to overcome the limiting factor of natural DLI and to obtain tomato yields comparable to those obtained in northern Europe with SL. Mediterranean regions could install SL systems with a lower PPFD due to the higher natural DLI, decreasing installation and operating costs with respect to northern greenhouses for a given yield.

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