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Optimization of basil (*Ocimum basilicum* L.) production in LED light environments – a review

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A R T I C L E I N F O

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A B S T R A C T

Basil (*Ocimum basilicum* L.) is a popular crop worldwide among farmers; it is relatively easy to grow and is well adapted to hydroponic and Controlled Environment Agriculture (CEA) systems having a high profitability margin. Several studies investigated the effect of the environmental factors on the qualitative and quantitative factors of basil: the effect of light is crucial for development, nutritional properties and sensory characteristics. The principles of sustainability, profitability and resource-effectiveness all encourages farmers to use energy-efficient LED light sources. These tools easily allow for the modification of spectral distribution and light intensity; numerous suggestions have been made for developing goal-driven light recipes for maximum cost-effectiveness and for reducing carbon footprint. Here, the results of several studies are summarized for providing a solid base for light recipe utilization of basil production in terms of light intensity, duration, and spectral distribution. Experimental results related to the impact of light treatments on vegetative parameters, phytonutrient content and sensory properties of basil are discussed, and optimal ranges of light parameters are summarized. Due to the increasing number of promising specialized research the wider application of purpose-driven high-tech production systems is expected in future basil growing.

1. Introduction

Originating from India and South-Asia, sweet basil (*Ocimum basilicum* L.) contains distinctive essential oils and is in use for both fresh and dried in culinary dishes (Klimánková et al., 2008; Lee et al., 2005), providing a variety of positive health benefits when consumed (Kopsell et al., 2005; Soran et al., 2009). Sweet basil is generally classified into seven different morphotypes, which include: 1) tall, slender types; 2) 'Italian' large-leafed types; 3) dwarf types ('bush' or "spicy globe" basils); 4) compact types ('thai' basils); 5.) purple types ('purple petra'); 6) purpurascens types ('dark opal,' sweet purple basils); and 7) citriodorum types (flavoured types) (Darrah, 1980; Wichtl, 2004; Hussain et al., 2008). For identification of cultivars, a standardized descriptor list based on morphological traits was developed by the International Union for the Protection of New Varieties of Plants (UPOV). This led to the characterization of *O. basilicum* into six distinct morphotypes: Lettuce-leaf, Small-leaf, True basil, Purple basil (A), Purple basil (B) and Purple basil (C) (Carovic-Stanko et al., 2011). Furthermore, the morphological and biochemical intraspecific characterization of *O. basilicum* is proposed into five chemotypes: (A) High-linalool, (B) Linalool/*trans*-α-bergamotene, (C) Linalool/methyl chavicol, (D) Linalool/*trans*-methyl cinnamate and (E) High-methyl chavicol chemotype, based on the essential oil composition of 85 accessions (Varga et al., 2017). Flavour profiles, medicinal uses, customer preference, and

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popularity vary greatly among different morphotypes (Klimánková et al., 2008; Tarchoune et al., 2013).

Basil is a very popular crop among farmers worldwide, because it has a high harvest index, it is relatively easy to grow, it is well adapted to hydroponic and CEA systems, having a high profitability margin at the same time (Polyakova et al., 2015).

To maintain the continuous development of the plant, with having higher amount of essential oil at least 1500 hours of sunlight/year is necessary (Szabó and Lenchés, 2013). Shading causes negative changes in the growth, in the assimilation, in the accumulation and also in the composition of essential oils. The reduction of daily light integral (DLI) from 24.9 to 13.5 moles m^{-2} d^{-1} did not cause significant changes in the fresh and dry mass of basil (Chang et al., 2009). In some locations or in unique growing situations, supplemental lighting is required to produce quality crops during winter months by the management of lighting schedules and photoperiods. When supplemental lighting is not essential, increasing the DLI and optimizing spectral quality has the potential to improve crop quality and yield as well (Hammock, 2018). A light controller in greenhouses can respond to sunlight and adjust sufficient supplemental light to the plants. (van Iersel and Gianino, 2017).

The photoperiod significantly influences yield and the accumulation of biological active compounds as well. Flower initiation and harvesting is the earliest under 18 h photoperiod, while the highest yield is reported under 24 h illumination (Skrubis and Markakis, 1976).

Basil grows wild in the subtropical and tropical areas of America, Africa, Asia, and in some southern regions of Europe (Kwee and Niemeyer, 2011). Traditionally, basil was cultivated on open fields. In warmer climates, three to five cuttings can be made per year. In cooler climates, the growing season may only allow two cuttings per year; the first usually begins in early summer and the second just before bloom (U. C. Davis, 2016). The plant part harvested depends upon projected use: for leaves it is harvested just prior the appearance of flowers, whereas for essential oil it is harvested during bloom (Kéita et al., 2001). Greenhouse hydroponic basil production provides optimal climate and fertility conditions, which has the potential to reduce variability in plant growth and development due to seasonal changes and soil conditions (Kiferle et al., 2013; Kopsell et al., 2005). For year-round production of basil, the fresh herbs in pots could be harvested every six weeks during summer and every 8 weeks during winter in greenhouses (Molin and Martin, 2018). Basil responds with better yield under soilless systems than in conventional systems (Rakocy et al., 2004). There is no interaction found between electronic conductivity (EC) and daily light integral (DLI), therefore it is not necessary to seasonally change EC in hydroponic basil production systems (Walters and Currey, 2018). Further research is needed to clarify the interaction between EC and light quality and duration parameters.

Basil is an ideal crop for vertical farming because it is sensitive to cold temperatures. It responds to the climate-controlled conditions of vertical farming with richer flavour than that of field-grown basil. Vertical farming can only suit a selection of crops, mainly salads and herbs, that will not grow taller than the average height of the shelves, which is around 40 cm (Kozai, et al., 2016). The plants in the vertical farms are fast-growing, meaning that they will be harvested within roughly one month after planting, require low intensity of light and tolerate high plant density. However, such systems will not replace open-field production or the conventional greenhouses, but could serve as a much-needed compliment, and it will also allow for innovation in the food sector and a number of new business opportunities (Kozai, et al., 2016). From sowing to irrigation and harvesting, machines can take over the work fully automatically in vertical production systems (Migros Basel, 2020).

Basil is usually sold fresh for culinary uses, but it can be preserved easily by freezing, air-drying, freeze-drying, extracting essential oils, or through the manufacturing of basil-related products (Raimondi et al., 2006). The plant is considered as an aromatic herb due to its antioxidant compounds and essential oils content (Giurgiu, 2017). It has appetizing, carminative and cough suppressant effect. Its essential oil reduces bloating and helps with stomach upset. Traditionally, the essential oils are the most valuable commercial forms of basil and contribute with flavors and aromas to a variety of products in the food and cosmetic industries (Kopsell et al., 2005). Basil extracts such as powder, capsules and oil are rich sources of calcium, zinc, vitamin A, and iron. In addition, the antioxidant properties associated with basil extracts increased its demand in various health care products, such as medicine (Bora et al., 2011; Purushothaman et al., 2018) native medicine (Pandey et al., 2014), ethnomedicine (Siddiqui et al., 2012), or cosmetics (Giurgiu, 2017). Fresh packed cut basil is categorized as an ultra-niche and high-value crop. It is also grown as a microgreen with a strong taste due to the high concentration of secondary metabolites -mainly polyphenols- in young plants (Xiao et al., 2015), which enrich health promoting properties of foodstuffs (Lobiuc et al., 2017). Red and blue LED ratios can be tailored to induce superior growth and phenolic contents in both red and green basil microgreens (Shoji et al., 2009; Lobiuc et al., 2017). Different forms of the dried basil leaves are whole, crushed, and powdered. Crushed was later changed to “crushed/rubbed/flaked” as it is commonly used in trade (Codex Alimentarius Commission, FAO, WHO, 2019). Flowers of culinary herbs, such as basil (Soler, 2011), sage and thyme can be used as edible flowers (Byczynski, 2013). Basil seeds are pharmaceutical materials, which were used from ancient times to dispel many diseases (Naji-Tabasi and Razavi, 2017). In Iran and India, basil seeds are frequently included in beverages and desserts for aesthetic purposes as well as a source of dietary fiber (Mäkinen and Pääkkönen, 1999). Basil seed gum is suggested to use as thickening and gelling agents in the food industry due to its particular behaviour and convenience of extraction (Naji-Tabasi and Razavi, 2017). Basil is usually cultivated as an ornamental in Middle Eastern countries due to its attractive flowers and aroma (Lupton et al., 2016). Even if there are many available basil cultivars, selection-breeding work is still important. According to the final purpose – higher essential oil content, improved essential oil composition, higher flavonoid content, resistance against drought, pest, and pathogens – new cultivars are suggested to be selected and at the same time the cultivation parameters should be optimized. For the comparative evaluation of gene bank accessions sum of ranking differences (SRD) method can be applied, as we have already described it in the case of basil (Bernhard et al., 2015a, Sipos et al., 2016). The taxonomy of sweet basil is complicated due to the hybridization, the commercially and sometimes inaccurately used names and also due to the huge number of cultivars. It was revealed that cultivars with similar morphological and essential oil characteristics and sometimes with the same cultivar name are genetically not the totally same (De Masi et al., 2006, Bernhard et al., 2015b).

The optimization of basil production depends on several factors. In our work, we focus solely on the optimization of light parameters. The objective of this review is to summarize the tendencies and future perspectives of basil production supported with LED based horticultural lighting systems.

2. The role of light spectrum and intensity

2.1. Impact on vegetative growth and plant physiology

Basil can be grown with a light intensity from 180 to 300 μmol/m^2/s (Beadle, 1985; Bånkestad and Wik, 2016). Production of edible biomass of basil was optimized at an irradiance of 500 μmol/m^2/s using environmental conditions of 25 ± 4°C, uncontrolled relative humidity, no carbon dioxide enrichment, and mineral nutrition using a modified Hoagland’s solution (Beaman et al., 2009).

Reduced irradiance and manipulation of photoperiod for basil may lower nitrate content and increase chlorophyll concentration, resulting in increased carotenoid concentration (Beaman et al., 2009). Greenhouse-grown basil plants are highly affected by seasonal effects which bring changes in light spectrum, photoperiod, and temperature as well.

Sweet basil was positively affected by blue light when measuring fresh weight (FW) (at 200 μmol m^{-2} s^{-1}); when the same light quality was compared with low light intensity (at 100 μmol m^{-2} s^{-1}) the FW was lower indicating the importance of combinations of wavelengths and quantity to promote high yielding plants (Dou et al., 2018). The production performance and energy use efficiency of sweet basil grown under mixed red and blue lighting was recently shown to vary in response to the relative red and blue components in the spectrum, reaching the maximum yield when the ratio between the red and blue spectral fractions (R:B ratio) was 3:1 (Pennisi et al., 2019b). Biomass peaked after 63 days at 16% blue (40B:20W:190R), dropped a little bit at 24% blue (60B:20W:170R) and subsequently dropped as the blue ratio increased to 32% blue (80B:20W:150R) (Yelton et al., 2017). In "Sweet Genovese" basil, highest leaf areas were recorded for 100% red and for 33% blue and lower values were measured for 8–25% blue, but the differences were not significant (Vaštakaitė et al., 2015).

Green-leaved basil under blue LED light showed a compact growth pattern in contrast to plants grown under red and white LED lights. Green-leaved sweet basil and purple-leaved basil were less responsive to light quality in terms of biomass production (Matysiak and Kowalski, 2019).

Higher levels of blue light reduced the incidence of edema. Edema is generally recognized as the inability of plants to transpire water quickly enough, thus causing blistering on the leaf surface (Yelton et al., 2017). Flower structures increased with increased levels of blue light, which is in contrast to what occurs in many other plant species (Yelton et al., 2017).

Light intensity for photosynthesis is defined as photosynthetic photon flux density (PPFD, micromoles per second per square meter: μmol/m^2/s) ranging from 400–700 nm (McCree, 1972; Poorter et al., 2019). If light intensities are too low, plants, e.g. sweet basil seedlings become leggy, remain small, have weak root systems and grow poorly after transplanted into their final production environment. When the light intensity is too high, the plants may not use the light efficiently and energy is wasted. Also, it may cause leaf damage and reduce plant growth and quality (Walters and Lopez, 2019). According to a study in Brazil, 50% shading resulted in higher plant height, stalk diameter, branch growth, fresh and dry mass of leaves, and number of leaves than in full sun environment, which provided an increase in root dry mass and volume in basil (Oliveira et al., 2020). In sweet basil, plant growth and dry matter content were found to increase under rising light intensity, but only until an optimum level, after which it was limited by other environmental factors (Pennisi et al., 2020). Basil grown with increasing light intensities from 160–310 μmol/m^2/s showed a saturating net leaf photosynthesis above 220 μmol/m^2/s but shoot fresh mass and dry matter content increased linearly with light intensity (Dou et al., 2018). Literature often adopts light intensities from 100 to 300 μmol/m^2/s (Pennisi et al., 2020). In addition, interaction of light quality (spectral composition) and light intensity may influence the magnitude of plant responses. Secondary effects of light quality were reported, such as increased production of photoprotective pigments under higher light intensity (Bugbee, 2016). Apart from light intensity, gas exchange of basil is intrinsically affected by light quality (Litvin et al., 2020). Furthermore, many research refers to the McCree curve in choosing the right quality of light for crop cultivation. However, the McCree study was conducted under low light intensity (approx. 50 μmol/m^2/s) which has a major limiting impact on plant growth and development (Lichtenthaler et al., 1981; Rihan et al., 2020).

Light use efficiency (LUE) based on fresh mass decreased whereas based on dry mass increased with increasing PPFD, when given as end of production (EOP) treatments, shortly before harvest in a vertical farming set-up in a Dutch study with two green and one purple sweet basil cultivars. For growers, the LUE based on fresh mass is probably more interesting, but basil with a higher dry matter content might have a better postharvest quality. Research suggests the combination of initially raising the plants at a PPFD of 150 μmol/m^2/s and an EOP of 300 μmol/m^2/s (DLI 19.4 mol/m^2/d). Addition of far-red during growth is the most beneficial when added as EOP treatment before harvest and only in a lower dosage at a high PPFD as it increases dry matter content of the leaves and the stem (Larsen et al., 2020).

Daily light integral (DLI) is the amount of photosynthetically active photons in photosynthetically active region (PAR) range received in a day as a function of light intensity (PPFD and duration (day). It is expressed as mol photons of light (mol) per square meter per day (mol/m^2/d). The quantity of light a plant receives can be manipulated through both intensity and photoperiod. Throughout the year, outdoor DLI ranges from 5 to 60 mol/m^2/d, but in the greenhouse, its values seldom exceed 25 mol/m^2/d (Korczynski et al., 2002). As DLI increases, light intensity can become supra-optimal for growth as the whole plant's photosynthesis reaches saturation, resulting in diminishing rates of increase in yield per incremental increase in light (Currey et al., 2012; Beaman et al., 2009; Faust et al., 2005). Inevitably, this reduces the efficacy of supplemental lighting, and can result in rising production costs per unit due to the reduced effect of additional light and associated electrical use (Litvin-Zabal, 2019). The relationship between DLI and shoot fresh mass (SFM) was linear for basil between 2 to 20 mol/m^2/d (Litvin-Zabal, 2019). Basil grown at 15 mol/m^2/d has two- to three-fold greater SFM compared to plants grown under 7 mol/m^2/d depending on the cultivar (Walters and Currey, 2018), and SFM increases are linear between 9.3 and 17.8 mol/m^2/d for basil (Dou et al., 2018). As DLI increases, allocation of growth and plant physiology may change to support larger structures. It is suggested, that increases in proportional shoot dry matter (SDM) to SFM at higher DLI could be attributed in part to toning, and to that additional structural components and carbohydrates produced in plant stem tissue may play a role in proportional increase of SDM (Faust et al. 2005; Haque et al., 2015). Literature suggests grouping species based on DLI requirements as low (5-10 mol/m^2/d), medium (10-20 mol/m^2/d), high (20-30 mol/m^2/d), and very high (>30 mol/m^2/d) light demanding plants. One strategy towards the efficient light management in a greenhouse is grouping species by similar light requirements. Fresh mass is the primary interest of a fresh-cut hydroponic herb producers, so herb species should be classified based on the impact of DLI on fresh mass. Basil, cilantro, dill, thyme, and oregano may be classified as high or very high-light plants, as their optimal DLIs are above 20 mol/m^2/d (Faust, 2011). Recommended DLIs for commercial basil production range between 13 and 35 mol/m^2/d (Beaman et al., 2009; Dou et al., 2017; Moya et al., 2014; Walters and Currey, 2018). Optimal light for basil growth (i.e., highest LUE for plant dry mass) was suggested to be 14.4 mol/m^2/d (Pennisi et al., 2020), 12.9 mol/m^2/d (Dou et al., 2018) and 28.8 mol/m^2/d (Beaman et al., 2009; Walters and Currey, 2018). Increasing DLI up to 20 mol/m^2/d increased growth index for basil (Litvin-Zabal, 2019). Combining results in growth, yield, and nutritional quality of sweet basil, 12.9 mol/m^2/d DLI is suggested for commercial basil production in indoor vertical farming to minimize energy cost, while maintaining a high yield and valuable nutritional quality (Dou et al., 2018). Further studies are needed for more precise classification, because DLIs of that magnitude are seldom used for greenhouse production, either due to cost prohibitive amount of supplemental lighting or excessive thermal radiation from ambient sunlight.

Guidelines typically recommend lower DLIs to be used during propagation compared with production (Currey et al., 2017). Research data from walk-in growth chambers indicate that providing a constantly high DLI throughout the first 8 weeks is more beneficial for the development of basil grown for indoor gardening than increasing the DLI over time, because it increases yield (Solis-Toapanta and Gomez, 2019). Also, the objective of identifying minimum DLIs below the recommended ranges is to sustain basil production for human comfort in indoor gardening. The latter might be in the consumer's home, within an office building, a restaurant, a classroom, or any other enclosed area (Solis-Toapanta and Celina Gómez, 2019).

2.2. Impact on phytonutrient content

Similarly to lettuce, sweet basil has been extensively studied for indoor cultivation under artificial lighting, with interesting applications in terms of quality improvements, including changes in both the metabolic and aromatic profiles (Sakalauskaitė et al., 2013). Although basil grows well under sunny conditions (Putievsky and Galambosi, 1999), it can tolerate light, but not heavy shade (Chang et al., 2008). The initial part of the light response curve is linear because light is the dominant limiting factor. On reaching light saturation, the curve becomes horizontal because resources other than light become limiting (Nilsen and Orcutt, 1996). It is suggested that, similarly to secondary metabolites, the synthesis of volatile oils has a very close relationship with primary metabolism, i.e., the more photosynthates produced, the more secondary metabolites accumulated (Chang et al, 2008).

Leafy greens contain a lower concentration of polyphenols when cultivated in a greenhouse without supplementary lighting, than when grown in the field, which may be explained by differing radiation intensities and spectra, e. g. greenhouse glass absorbs UV radiation (Matysiak and Kowalski, 2019). Supplemental UV-B light at 2.5μmol m^{-2} s^{-1} for 1h each day and 2h each day for seven days significantly increased the content of total phenolic compounds and anthocyanin concentrations in sweet basil, with the short time UV-B treatment being more efficient for anthocyanin accumulation, than the long-time UV-B treatment (Sakalauskaitė et al., 2013). Supplemental UV-B radiation increased the concentrations of anthocyanin, phenolics, and flavonoids in green basil leaves by 9-18%, 28-126%, and 80-169%, respectively, and the antioxidant capacity of basil leaves was positively correlated to UV-B radiation doses. However, supplemental UV-B radiation generally decreased the crop yield in both green and purple basil plants (Dou and Niu, 2020).

Red spectrum (638 nm) can improve its antioxidant properties, while blue light improves the yield of other phytochemicals related to high quality products (Taulavuori et al., 2013; Samuolienė et al., 2016). Also, these lighting effects are cultivar dependent (Bantis et al., 2016).

Blue light irradiation could enhance the metabolism of aromatic compounds and improve the composition of essential oils in leaves of sweet basil (Amaki et al., 2011). A Greek study showed that total phenolic content in sweet basil leaves was higher when plants were exposed to light with a relatively high portion of blue (Bantis et al., 2016). In a recent Polish study conducted in a greenhouse during a low-level natural light period in winter, the highest flavonol content in green-leaved basil ‘Sweet Genovese’ was shown under supplementary blue LED light. However, anthocyanin content in purple-leaved basil ‘Red Rubin’ was not dependent on the light quality (Matysiak and Kowalski, 2019).

Research indicates that essential oil content in basil increases with greater irradiance, whereas the concentration of the principal component of the essential oil, methyl eugenol, decreased with UV-B treatment (Nitz and Schnitzler, 2004). Methyl eugenol is carcinogenic in large amounts and, therefore, a reduction in the concentration of this compound with the increase in irradiance would be beneficial for human health (Nitz and Schnitzler, 2004). According to British shading experiments in glasshouses with supplementary lighting 400W HPS lamps, linalool and eugenol, which contribute to the characteristic taste of basil, were significantly increased by high DLIs, whereas methyl eugenol was increased by lower DLIs (Chang et al., 2008).

In general, overall volatile organic compound (VOC) concentration increases as DLI rises; the source of radiation can be the sun or an artificial sole-source lighting from LEDs (Chang et al., 2008). However, trends differ among individual compounds and this has been demonstrated in many culinary herbs. In basil, linalool and eugenol concentrations increased 3- and 4-fold respectively, whereas methyl eugenol decreased by 80%, and 1,8-cineole was unaffected as DLI increased from 5 to 25 mol/m^2/d (Chang et al., 2008). Increasing the DLI from 9 to 18 mol/m^2/d not only increased basil fresh mass, net photosynthesis, and leaf area and thickness, but also increased anthocyanin, phenolic, and flavonoid concentrations (Dou et al., 2018).

2.3. Impact on sensory properties

Rising photosynthetic photon flux density from 100 to 600 μmol/m^2/s increased cineole, linalool, and eugenol concentrations 4-, 8.8-, and 3.3-fold in sweet basil “Nufar”, respectively, however increased VOC concentrations did not correlate with consumer preference in a study at Michigan State University, East Lansing, MI, USA (Walters et al., 2021). Increasing VOC concentrations to increase flavor did not improve flavor preference according to the Paid Research Pool (Walters et al., 2021). The increased bitterness reported in basil grown under 400 and 600 μmol/m^2/s may have contributed to the flavor and aftertaste preferences. Basil grown under 600 μmol/m^2/s exhibited the least liked color and had the lowest appearance and texture likeability. The color was described by panelists as “brown” with symptoms of leaf damage due to the high radiation intensity. Additionally, consumers described the texture as “chewy” and “wilted”. This may be due to greater stomatal opening and gas exchange of plants grown under higher irradiances, which could have increased water loss and desiccation (Davies and Kozlowski, 1975) in the time between harvest and the panelist evaluation.

Subjective taste testing showed that the 32% blue (80B:20W:150R) treatment had the highest rating for taste, aroma, and spiciness. The basil described as bitterest was grown under the 24% blue (60B:20W:170R) treatment (Yelton et al., 2017).

Available details of different light recipes and investigated parameters are demonstrated in Table 1.

In general, UV-B had a negative effect on plant biomass, photosynthetic activity, and plant height (320-400 nm). On the other hand, UV-B has a positive impact on the phytonutrient levels (phenolic components, flavonoids, anthocyanins, antioxidant capacity) of basil. The effect of UV-A (390-420 nm) was investigated only in a few studies; this is probably due to the overlapping with UV-B wavelength. Regarding vegetative parameters, contractionary results were found, while the phytonutrient content was elevated as a consequence of using UV-A. The most effective wavelength for early vegetative growth is between 420 and 490 nm. For the highest aroma, antioxidant and anti-inflammatory compounds content, basil is suggested to grow under 510-570 nm wavelength. The largest leaves and the highest moisture content were recorded, when the wavelength was between 650 and 710 nm. Despite the fact, that basil is primarily consumed as a spice plant, there is a surprisingly low number of LED light studies focusing on sensory properties. Limitation of the literature reviews is that there are over 60 varieties of *Ocimum basilicum* with a great number of sub species, varieties and forms that tend to adapt to the radiation conditions of the environment in which they develop. This makes the comparison of the studies found in literature difficult (Blank et al., 2004).

3. The role of light duration

Scientists growing basil in a shipping container found that a 24-hour photoperiod of photosynthetic-active radiation, the equivalent of all-day light, induces the most intense flavor molecule production in basil (Johnson et al., 2019). But experiments also showed that basil requires a dark period for normal growth, because grown for 15 days under 24h irradiance exhibited stunting, chlorosis, and development of leaf necrosis. The same plants also exhibited lignified stem tissue and an unusual dark green coloration on all shoot tissues (Beaman et al., 2009). Exposure to red light at night can increase the number of basil leaves per plant, plant height, leaf size, and leaf fresh and dry weight compared with plants grown in darkness at night (Patel et al., 2018). Two weeks of supplemental UV-B light for 2.5 h each day enriched the levels of phenylpropanoid and terpenoid concentrations in sweet basil, which were three times higher than the plants under sunlight (Johnson et al., 1999).

Table 1
Effect of light recipes on different parameters of basil plantParameter (effect)

	Light specification	PPFD	Duration of treatment	Reference
Impact on vegetative growth/plant physiology				
plant biomass (-)	UV-B			Dou and Niu, 2020
plant biomass (-)	UV-B (270–400 nm)	16 μmol•m^{-2}•s^{-1}	1 h d^{-1} (2d), 2 h d^{-1} (2d), 1 h d^{-1} (5d), 2 h d^{-1} (5d)	Dou et al., 2018
plant biomass (FW, DW)(+) plant height (+), leaf area (+)	UV-B (290-320 nm)	2 kJ m^{-2} day^{-1}, 4 kJ m^{-2} d^{-1}	1 h d^{-1}, 2 h d^{-1}, (7d)	Sakalauskaitė et al., 2012
leaf area (-), leaf DW (-)	UV-B (np)	np	2,5 h d^{-1} (14d)	Johnson et al., 1999
photosynthetic efficiency (-)	UV-B (270-400 nm)	8.5, 17, 34, 51, 68, 85, 102 kJ m^{-2} day^{-1}	8 h d^{-1} (6d)	Mosadegh et al, 2018
plant height (-), dry matter (+), leaf thickness (+), nr of axillary shoots (+)	UV-B	444 μmol•m^{-2}•s^{-1}	3 h d^{-1} (14d)	Chang et al., 2009
hipocotyl length (+), fresh weight (+), leaf area (+)	UV-A (402 nm)	300 μmol•m^{-2}•s^{-1}	16 h d^{-1} (10d)	Brazaitytė et al., 2015
plant growth (-), hipocotyl length (-)	UV-A (390 nm)	125 μmol•m^{-2}•s^{-1}	16 h d^{-1} (7-14d)	Vaštakaitė et al., 2015b
flower development (+)	B (np)	250 μmol•m^{-2}•s^{-1}	14 h d^{-1}	Yelton et al., 2017
edema occurence (-)	B (np)	250 μmol•m^{-2}•s^{-1}	14 h d^{-1}	Yelton et al., 2017
root development (+)	B (460 nm)	30 μmol•m^{-2}•s^{-1}	16 h d^{-1}	Lim and Eom, 2013
etiolation of older leaves (+)	B (460 nm)	30 μmol•m^{-2}•s^{-1}	16 h d^{-1} (42d)	Lim and Eom, 2013
plant biomass (+), dry mass partitioning of leaves (-)	B (400-500 nm)	100-300 μmol•m^{-2}•s^{-1}	16 h d^{-1} (5d), 18 h d^{-1} (25d)	Larsen et al., 2020
plant biomass (+), number of leaves per pot (+), number of leaves per stem (+), stem length (+), individual leaf area (+)	G (505 nm)	15 μmol•m^{-2}•s^{-1}	20 h d^{-1}	Schenkels et al., 2019
plant fresh weight (+), leaf weight and area (+)	G (525 nm)	50 μmol•m^{-2}•s^{-1}	16 h d^{-1} (70d)	Amaki et al., 2011
plant dry matter (+)	FR (700-800 nm)	300 μmol•m^{-2}•s^{-1}	16 and 18 h d^{-1} (5, 7, 21d)	Larsen et al., 2020
Stem height, root length, nr of leaves (neutral)	R (650 nm) G (525 nm)	np	16 h d^{-1} (60d)	Ardelean et al., 2018
plant biomass (ns)	B (400-480 nm), R and NIR (610-720 nm), ratio np	np	14 h, intermittent light	Avgoustaki et al., 2020
chilling tolerance (-), shelf life (-), stomatal density (+)	R (657 nm) and B (447 nm), 40:60	YPFD: 195,6 μmol•m^{-2}•s^{-1}	daily until harvest	Jensen et al, 2018
plant biomass (+), stomatal conductance (+), water use efficiency (+), energy and light use efficiency (+)	R (600-700 nm) and B (400-500 nm), 3:1	250 μmol•m^{-2}•s^{-1}	(21d)	Pennisi et al., 2020
chilling tolerance (+), shelf life (+), stomatal density (-)	R (657 nm) and G (527 nm), 80:20	YPFD: ~175 μmol•m^{-2}•s^{-1}	daily until harvest	Jensen et al, 2018
plant biomass (+)	R (600-700 nm) and FR (700-800 nm), 2.77:1	200 ± 20 μmol•m^{-2}•s^{-1}	(28d)	Bantis et al, 2016
plant biomass (+)	B (400-500 nm) and R (600-700 nm), 1:1	200 ± 20 μmol•m^{-2}•s^{-1}	(28d)	Bantis et al, 2016
plant biomass (+), root:shoot ratio (+)	B (400-500 nm) and G (500-600 nm), 1:2; R (600-700 nm), FR (700-800 nm) and UV (<400 nm), 35:5:1	200 ± 20 μmol•m^{-2}•s^{-1}	(28d)	Bantis et al, 2016
plant biomass (+), energy use efficiency (+)	R (635-700 nm) and B (450-490 nm) ratio of 0.7	200 μmol•m^{-2}•s^{-1}	16 h d^{-1} (31d)	Piovene et al, 2015
plant height (+), photosynthetic capacity (+), quantum yield (+), photosynthetic electron transport (+)	R (628 nm), B (460 nm) and G (530 nm), 4:1:1	180 μmol•m^{-2}•s^{-1}	12 h d^{-1}	Lin et al., 2021
Root development (+)	R (600-700 nm); R (600-700 nm) and FR (700-800 nm), 2.51:1	200 ± 20 μmol•m^{-2}•s^{-1}	(28d)	Bantis et al, 2016
Plant height (+), stem diameter (+), leaf number (+), biomass yield (+)	R (663 nm) and B (435 nm), 1:1	300 ± 20 μmol•m^{-2}•s^{-1}	16 h d^{-1} (40d)	Rihan et al., 2020
Impact on phytonutrient content				
phenylpropanoids (+), terpenoids (+)	UV-B (np)	(np)	2,5 h d^{-1}	Johnson et al., 1999
phenolic compounds (+)	UV-B (290-320 nm)	2.5 μmol•m^{-2}•s^{-1}	1 and 2h d^{-1}	Sakalauskaitė et al., 2019
phenolic compounds (+),anthocyanins (+),flavonoids (+)	UV-B (270–400 nm)	16 μmol•m^{-2}•s^{-1}	1 h d^{-1} (2d), 2 h d^{-1} (2d), 1 h d^{-1} (5d), 2 h d^{-1} (5d)	Dou et al., 2018
phenolic compounds (+),flavonoids (+)flavonoids (+), anthocyanins (+)	UV-B			Dou and Niu, 2020
phenolic compounds (+)	UV-B (270-400 nm)	8.5, 17, 34, 51, 68, 85, 102 kJ m^{-2} day^{-1}	8 h d^{-1} (6d)	Mosadegh et al, 2018
anthocyanins (+)	UV-B (290-320 nm)	2.5 μmol•m^{-2}•s^{-1}	1 and 2 h d^{-1}	Sakalauskaitė et al., 2013
antioxidant capacity (+), polyphenols (caffeic acid, chlorogenic acid, rosmarininc acid, catechin derivatives, hydroxycinnamic acid derivatives) (+), chlorophyll content (neutral) post-harvest	UV-B (290-320 nm)	14.4 kJ m^{-2}d^{-1}	(4d) pre-harvest	Nascimento et al., 2020

(continued on next page)

Table 1 (*continued*)

	Light specification	PPFD	Duration of treatment	Reference
phenyl-propanoid (+), eugenol (+), 1 8-cineole (+), linalool (+)	UV-B	444 $\mu mol \cdot m^{-2} \cdot s^{-1}$	3 h d^{-1} (14d)	Chang et al., 2009
acsorbic acid (+), total anthocyanins (+), flavonols (+)	UV-A (390 nm)	125 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (1-14d)	Vaštakaitė et al., 2015a
essential oil composition (+)	B (500 nm)	50 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (70d)	Amaki et al., 2011
phenolic content (+)	B (np)	200 ± 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$	(28d)	Bantis et al., 2016
flavonols (+), anthocyanins (neutral)	B (450 nm)	130 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (45d)	Matysiak and Kowalski, 2019
nitrates (-)	B (455 nm)	200 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (19d)	Samuolienė et al., 2014
total phenolic content (+), rosmarinic acid (+), eugenol (+) (callus culture)	B (460 nm)	40 $\mu mol \cdot m^{-2} \cdot s^{-1}$	24 h d^{-1}	Nadeem et al., 2019
total phenolic content (+), total anthocyanins (+)	B (470 nm)	20 $\mu mol \cdot m^{-2} \cdot s^{-1}$	(14d)	Vaštakaitė et al., 2018
chlorogenic, chicoric, hydroxcinnamic acid (+)	B (450 nm)	300±10 $\mu mol \cdot m^{-2} \cdot s^{-1}$	24 h d^{-1} (39d)	Taulavuori et al., 2018
chicoric, hydroxcinnamic acid (+)	B (420-440 nm)	300±10 $\mu mol \cdot m^{-2} \cdot s^{-1}$	24 h d^{-1} (39d)	Taulavuori et al., 2018
chicoric acid, quercetin rhamnoside	B (400-500 nm)	300 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (36, 48d)	Taulavuori et al., 2016
total phenolic content (+), flavonoids (+) (in vitro)	B (470 nm)	np	16 h d^{-1} (60d)	Ardelean et al., 2018
total phenolic content (+), total flavonoids (+), DPPH, FRAP, ABTS (+), superoxide dismutase activity (+) (callus culture)	B (460 nm)	40-50 $\mu mol \cdot m^{-2} \cdot s^{-1}$	24 h d^{-1} (28d)	Nazir et al., 2020
eugenol (+), linalool (+),monoterpenoids (+), phenylpropanoids (-)	G (520 nm)	150 $\mu mol \cdot m^{-2} \cdot s^{-1}$	12 h d^{-1} (42d)	Carvalho et al., 2016
nitrates (-)	G (530 nm)	200 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (19d)	Samuolienė et al., 2014
monoterpenoids (+), phenylpropanoids (-)	Y (600 nm)	150 $\mu mol \cdot m^{-2} \cdot s^{-1}$	12 h d^{-1} (42d)	Carvalho et al., 2016
lutein (+)	R (638 nm)	300 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (10d)	Brazaitytė et al., 2015
nitrates (+)	R (638-660 nm)	200 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (19d)	Samuolienė et al., 2014
phenolics (+) α-tocopherol (+), ascorbic acid (+), DPPH (+), lutein (-), β-carotene (-)	R (638 nm)	210 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (19d)	Samuolienė et al., 2016
total flavonoid content (+), anthocyanins (+), peonidin (+), cyanidin (+) (callus culture)	R (660 nm)	40 $\mu mol \cdot m^{-2} \cdot s^{-1}$	24 h d^{-1}	Nadeem et al., 2019
total phenolic content (+), total anthocyanins (+)	R (627 nm)	20 $\mu mol \cdot m^{-2} \cdot s^{-1}$	(14d)	Vaštakaitė et al., 2018
total phenolics (+), ascorbic acid (-)	R (638 nm)	170 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (3d) pre-harvest	Samuolienė et al., 2012
rosmarinic acid (+)	R (600-700 nm)	100 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (14d)	Shiga et al., 2009
peroxidase activity (+), chicoric acid (+) (callus culture)	R (660 nm)	40-50 $\mu mol \cdot m^{-2} \cdot s^{-1}$	24 h d^{-1} (28d)	Nazir et al., 2020
sesquiterpenoids (+)	FR (735 nm)	150 $\mu mol \cdot m^{-2} \cdot s^{-1}$	12 h d^{-1} (42d)	Carvalho et al., 2016
chicoric acid (+)	W (np)	100 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (42d)	Shoji et al., 2011
Chl a+b (+), phenolic content (+), carotenoids (+), anthocyanins (+)	W (np)	1350 $\mu mol \cdot m^{-2} \cdot s^{-1}$	12 h d^{-1} (7-21d)	Stetsenko et al., 2020
anthocyanins (+)	R (675 nm) and B (450 nm), 1:2	120 $\mu mol \cdot m^{-2} \cdot s^{-1}$	12 h d^{-1} (15d)	Lobiuc et al., 2017
DPPH (+), total phenolic content (+), anthocyanins (+), limonene (+),α-pinene (+) β-myrcene (+)	R (660 nm) and B (440 nm), 70:30	250±10 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (30d)	Hosseini et al., 2018
total polyphenolic content (+)	B (400-500 nm) and G (500-600 nm), 1:2; R (600-700 nm), FR (700-800 nm) and UV (<400 nm), 35:5:1	200 ± 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$	(28d)	Bantis et al, 2016
antioxidant compounds (+), nitrate content of leaves (-)	R (635-700 nm) and B (450-490 nm), ratio of 0.7	200 $\mu mol \cdot m^{-2} \cdot s^{-1}$	16 h d^{-1} (31d)	Piovene et al, 2015
antioxidant capacity (+), polyphenols (+), flavonoids (+)	R (600-700 nm) and B (400-500 nm), 3:1	250 $\mu mol \cdot m^{-2} \cdot s^{-1}$	42 DAS	Pennisi et al., 2019a
Impact on sensory properties				
taste (+), aroma (+), spiciness (+)	B, W and R, 80:20:150	250 $\mu mol \cdot m^{-2} \cdot s^{-1}$	14 h d^{-1}	Yelton et al., 2017
bitterness (+)	B, W and R, 60:20:170	250 $\mu mol \cdot m^{-2} \cdot s^{-1}$	14 h d^{-1}	Yelton et al., 2017
Other				
energy consumption without measurable quantitative and qualitative losses (-)	B (400-480 nm), R and NIR (610-720 nm), ratio np	np	14 h intermittent light	Avgoustaki et al., 2020
Peronospora belbahrii oomycete sporulation inhibition	W	45 $\mu mol \cdot m^{-2} \cdot s^{-1}$	20 h	Cohen et al., 2013

B: blue, R: red, Y: yellow, G: green, FR: far-red, W: white, np: not provided, DAS: day after sowing, YPFD: yield photon flux density, (d): duration of light treatment in days

Photoperiod was shown to change the volatile profile of basil (Skrubis and Markakis, 1976). LED lamps have the capability to blink or flash in short time spans in which the lamp emission is turned on and off at fast intervals (μs) producing pulsed light with high intensity and less consumption of energy. Given that vertical farms and plant factories use artificial lighting systems for extended periods of time ranging from eight to sixteen hour per day, energy saving for these operations could be significant if they used light in the pulsed LED light mode. However, it may not be possible to pulsate light in some commercial systems because the lights were not designed to operate in this mode. Systems, that can accommodate light pulsing may see shorter life spans of the light bulbs used (Olvera-Gonzalez et al., 2021). Pulsed light may not provide the desired effects in a glasshouse setting where natural light is present, but several research groups are developing sensor-controlled lighting systems that modulate the light regime to match ongoing plant needs. In instances where only low doses of light are required (for example, end-of-day light treatments, or UV-C/UV-B treatments), mobile lights mounted on irrigation booms may provide an economically viable way of installing lamps (Davis and Burns, 2016).

The optimal ranges of light factors and their impact on basil plant is a complex process, however, the effect of single factors can be clearly identified (Fig. 1). The optimal range of every environmental factor is provided in Fig. S1.

4. Trends and future of basil production

Consumption of basil is steadily increasing in the world. Global basil leaves market is expected to grow from 57 million USD to 62 million USD with a 1.3% cumulative average growth rate between 2021 and 2026 (Absolute Reports, 2020). New culinary trends favor fresh herb over traditional dried leaves, the demand for locally grown products is increasing. Expanding market for fresh culinary basil shifts focus from field production to year-round cultivation in enclosed controlled environments like greenhouses and vertical farms (CBI, 2020).

Vertical farms, plant factories provide the highest level of control for basil cultivation (Butturini et al., 2019). The cultivation area is completely isolated from outdoor environment, LED light replaces solar radiation. Despite the high energy consumption of artificial lighting vertical farming of basil has several environmental advantages over greenhouse production: water and nutrient efficiency is significantly increased, use of pesticides and herbicides can be significantly reduced or completely eliminated. Urban farming is a young, but rapidly expanding sector exhibiting a wide range of applications and production models. On top of large-scale production in plant factories, medium and small-scale farming methods of basil have been developed. In-store farms grow and directly sell fresh herbs including basil in food retail stores (Butturini et al., 2015, Cointet et al., 2019). For non-commercial use basil is also grown in home appliances developed for do-it yourself indoor plant cultivation. In its simplest forms home gardening kits provide supplemental LED light to boost DLI to the proximity of the recommended DLI range between 13 and 35 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ (Solis-Toapanta and Gomez, 2019). Holy basilic has been grown successfully under microgravity environment in the International Space Station as part of the Asian Herb in Space program (KUOA, 2020). In more sophisticated systems growing conditions are automatically measured and regulated according to the plant's specific needs (Lepp and Pedastaar, 2016).

Monitoring and controlling temperature, air humidity, water supply and concentration of fertilizers has been a common practice in horticultural production facilities for a long time but adjusting the intensity and spectrum of the illumination remained a challenge until the development of high-power LEDs. With today's LED luminaires the complete set of environmental parameters can be kept under control. Indoor farms, Plant Factories, Vertical Farms with artificial lighting enable basil to be cultivated while minimizing the interaction with external climate. The notion of lighting control in agriculture is drifting from setting photosynthetic photon flux density (PPFD) and Daily Light Integral (DLI) levels towards manipulating the spectral distribution and intensity of the irradiance throughout the cultivation period (Marondedze et al., 2018).

The Daily Light Integral (DLI) is often used by professional horticulturists. In horticulture the DLI definition of Faust and Logan (2018) is widely accepted, i.e., the DLI describes the daily accumulated photosynthetically available number of photons delivered to a given area over the course of one day. However, DLI is mostly estimated from averaged solar radiation values instead of calculating it directly from spectrally resolved photon spectra or field spectrometric data. Most DLI models assume that 45% of the solar radiations is in the range of 400 to 700 nm (PAR). There are also different conversation practices to calculate photons from radiometric units. Otherwise, recent developments in field or terrestrial spectroscopy, earth observation and radiative transfer models opened new perspectives to calculate photon flux with high temporal, spatial and spectral resolution (Yang et al 2020). Using a miniature spectroradiometer for a spectral range of 350 to 1000 nm with

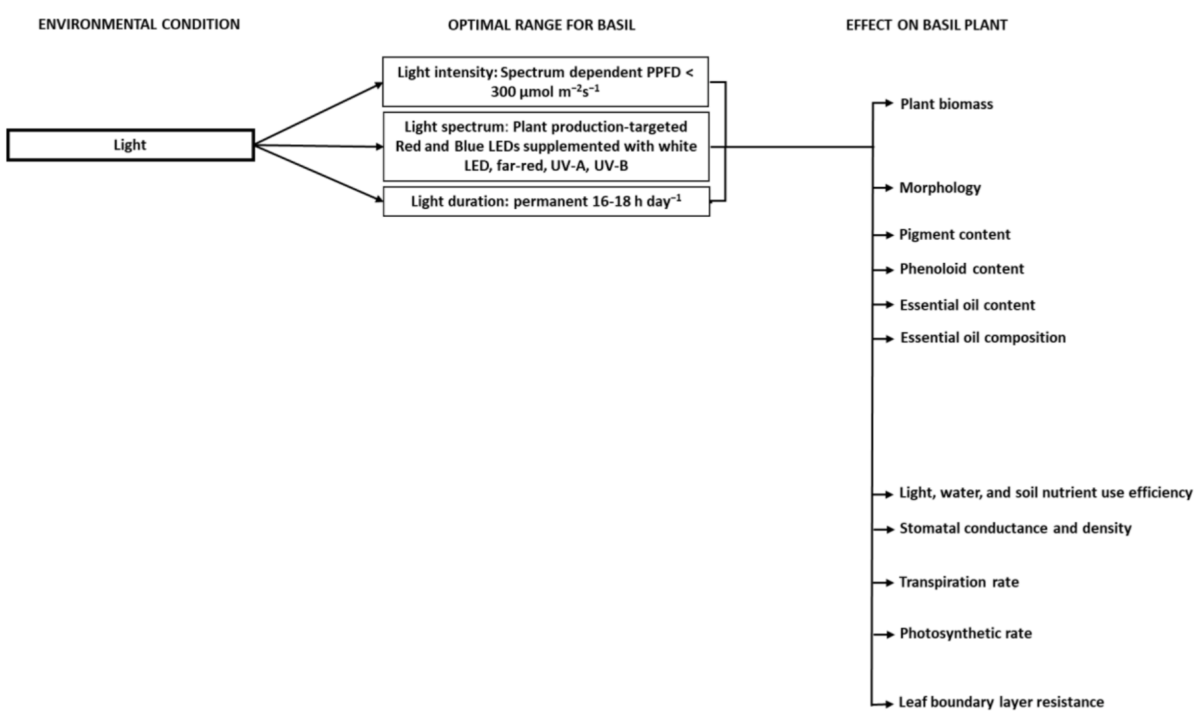

Fig. 1. Optimal light parameters for basil in a controlled artificial lighting system (based on Ahmed et al. 2020). Optimal parameters within provided ranges depend on phenology, variety and aim of production.

1 nm spectral resolution, it is relatively simple to derive the photon flux curve and its integrative results for enhanced and more accurate DLI series and maps. For future LED horticulturists spectroradiometers will be helpful devices to map LED spectrum quality, monitor light recipes or even construct own spectral light libraries in a vertical farm. These devices are able to outperform present derived DLI estimates and would significantly increase light measurement accuracy not only for the PAR but also for the extended ranges, from UV to NIR. For hemispherical or field light conditions atmospheric radiative transfer models could be used, similarly to the solar power plants, to effectively calculate solar irradiation at a given surface. The radiometric transfer models are available (Antonanzas-Torres et al. 2019) with high spectral, temporal and spatial resolution to serve future horticulturists both under LED, non-LED or mixed environments.

Several publications highlight the effect of light on basil. Light treatments or light recipes define both quantitative parameters (light intensity and photoperiod) and qualitative parameters (spectral power distribution) which affect plant growth and physiology. The use of 435 nm and 665 nm radiation in a ratio matching the absorbance of basil photopigments improved physiological parameters and increased growth and yield (Rihan et al., 2020). Growers may choose the light recipe according to market preferences. Keeping blue content relatively low compared to red (B:R=1:4.75), the weight of the fresh produce can be maximized. However, the taste and flavor proved to be significantly better in case of higher blue content (B:R=1:1.9) (Yelton et al., 2017). The effect of light interacts with other environmental parameters therefore light recipes vary significantly if cultivation parameters are changed. NPK fertilizer along with a special LED light combination (B:R=3:1) produced the highest basil weight in another experiment (Barbi et al., 2021). Shelf life and tolerance towards cold was increased by green:red (1:4) light treatment (Jensen et al., 2018), however the presence of the trace element selenium without light treatment can also extend shelf-life of basil (Puccinelli et al., 2020). Given the large number of parameters affecting basil growth the chase for a single best cultivation technology may be a futile effort. The growing conditions however could be optimized for a specific controlled environment.

Fig. 2 illustrates the operational principle of a smart greenhouse lighting system. In order to maintain uniform temporal and spatial irradiance distribution across the crop supplemental lighting is mounted at relatively high location above the plants. Sensors measure the local photon flux densities at various points of the greenhouse. The photon flux density is the sum of the photon flux density from artificial lighting and the contribution of the natural daylight. The controller automatically adjusts the light output of luminaires according to the signals received from sensors (Nicole et al., 2021).

In a simple implementation of the smart system utilizing fixed spectrum lighting, sensors are quantum sensors measuring photosynthetic photon flux density (PPFD) in the 400-700 nm range. The supplemental lighting is dimmed or brightened to counterbalance the variations in daylight intensity.

In climates with excessive natural light shades can be employed to control spectral distribution and intensity of the incident sunlight (Castronuovo et al., 2019).

In a more sophisticated implementation of the smart lighting system color sensitive sensors or simple spectrometers monitor spectral power distribution of the total irradiance at various locations of the greenhouse (Durmus, 2020).

The color tunable luminaires adapt to the local intensity and spectral changes of the natural daylight. In this way the desired spectral irradiance levels and color ratios can be set with maximum utilization of natural sunlight (Jiang et al., 2020, Paradiso and Proietti, 2021).

Fig. 3 depicts the concept of spectral tailoring in a greenhouse. The luminaires comprising a multitude of LEDs cover the wavelength range from UV to far-red allowing the real time customization of the emission spectrum. Though narrow band LEDs allow fine tuning of the spectrum, for the sake of simplicity manufacturers tend to report photon flux data in a 100 nm wide bins: UV < 400 nm, Blue (B) 400-500 nm, Green (G) 500-600 nm, Red (R) 600-700 nm and Far-red (FR) 700-800 nm (DLC,

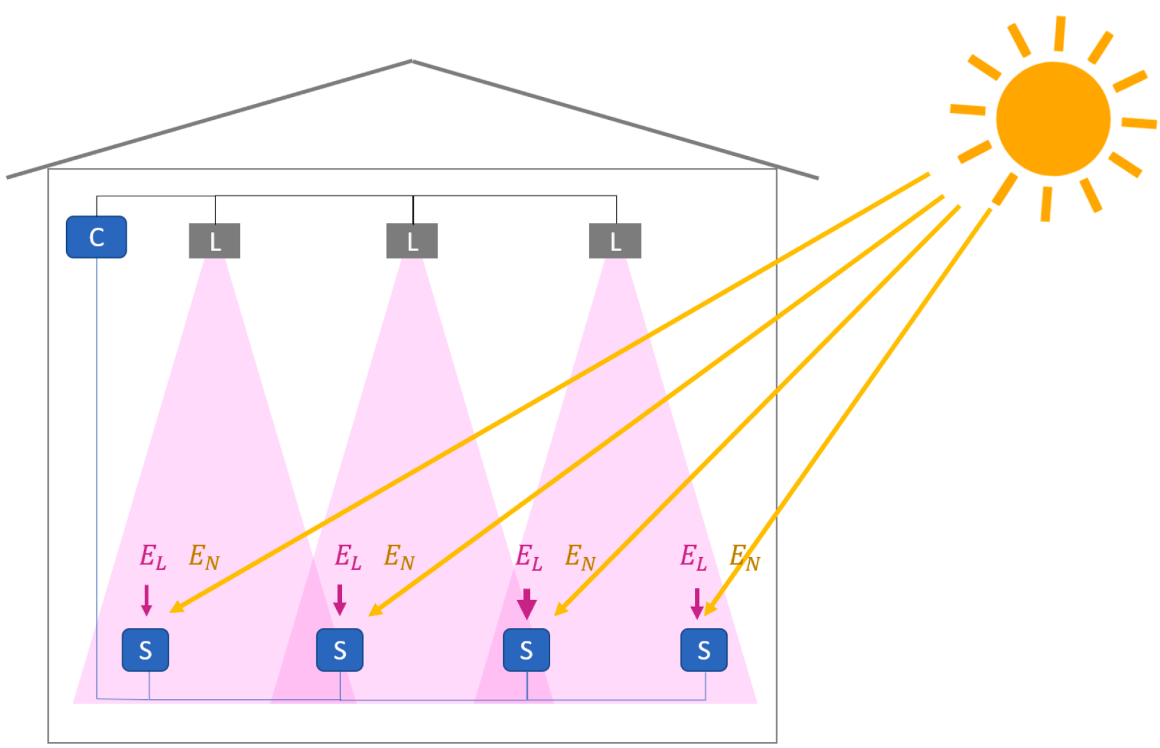

Fig. 2. Operation principle of a smart greenhouse lighting system. The controllable light sources (L) are used to supplement natural daylight. The local photon flux density measured by sensors (S) is the sum of the artificial light coming from the luminaires (E_L) and the photon flux density contribution from the sun (E_N). The controller receives signal from sensors (S) and adjusts the output of the light sources individually to supplement natural daylight according to a control algorithm. In this way the predetermined irradiance across the entire crop can be maintained.

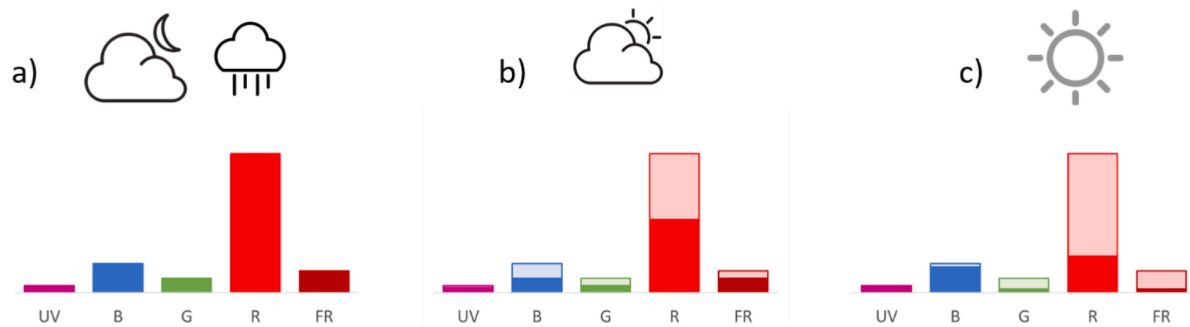

Fig. 3. Illustration of spectral tailoring of greenhouse supplemental lighting. The objective is to maintain constant spectral irradiance over the illuminated surface indicated by the frames representing photon flux densities in UV, Blue (B) Green (G), Red (R) and Fa-red (FR) wavelength bins. If natural daylight is scarce (a) the luminaire operates at full power in each wavelength bins. In case of overcast day (b) or clear sky (c) significant amount of sunlight is utilized and only the gap to the predetermined photon flux density values is supplemented by artificial light in each bin (full bars).

2021).

Colored frames in Fig. 3 represent the predetermined photon flux densities for each wavelength bin whereas solid color bars represent the contribution of artificial lighting. Sensors in Fig. 3 measure photon flux densities in the five wavelength bins simultaneously. Depending on actual lighting conditions the controller adjusts color channels of the luminaires to achieve the predetermined photon flux densities. Only the artificial lighting provides illumination during dark periods. During the day artificial lighting automatically supplements the gap between the available natural light intensity and target photon flux density. The spectrum of the sunlight varies according to the time of day and actual weather conditions. The controller changes each color channel of the luminaire adapting in real time to the varying external lighting conditions.

The crops themselves can be improved by breeding crops for indoor circumstances. Buildings can also be made more energy efficient, for example by using the heat generated by the light for heating (Butturini and Marcelis, 2019). High-tech infrastructure including lights can create improved food quality (Piovene et al., 2015), consistent, year around production (Kozai and Niu, 2016), and employment in an otherwise highly seasonal business. It provides greater production stability due to enhanced resilience to climatic events and increasing yields compared to traditional agricultural systems (Kozai, 2016). Even though LED lamps are economical, a quarter of the costs goes to energy consumption. Much more can be produced if the efficiency of climate control technologies were improved (Butturini - Marcelis, 2019). The water-cooled LED luminaires make it possible to significantly increase the intensity of lighting without adding heat to the crop, something that was initially particularly popular in cultivations of hydroponic lettuce, herbs and cresses, where heat plays a major role. Crop management services, like LumiGrow SmartPAR™ facilitate the development of customized light programs. Growers using SmartPAR enabled LumiGrow fixtures gain unprecedented control over light ratios, photoperiods and intensities to improve specific crop features, yield, production and wasteful energy consumption (Yelton et al., 2017).

Transparent photovoltaic (PhV) solar panels (traditional photovoltaic silicon-based panels are not transparent) on a greenhouse roof can produce electricity from sunlight without affecting the plants growing underneath. This electricity from “waste” light can lower greenhouse production costs. The plastic panels with a red dye (Wavelength-Selective Photovoltaic System, WSPV) absorbs a lot of green and some blue light and sends them to thin black silicon solar cell strips run down the panels. The rest of the light goes through, made redder by the dye. The red part of the light spectrum is best for plant photosynthesis. Researchers tested the growth of twenty tomato, cucumber, lemon, lime, pepper, strawberry, and basil varieties. Around 80 percent of the crops in the magenta greenhouses were unaffected by the redder lighting, and 20 percent of the crops grew better. The panels also cost about 40 percent less per watt than conventional silicon panels (Loik et al., 2017). From the electric energy production point of view, the main factor reducing productive efficiency was the orientation of the PhV system on the roof (Minuto et al., 2009).

5. Conclusions

Optimization of basil production depends on several factors: production goals, environmental parameters (light, temperature, water supply, soil nutrient content, CO_2 concentration, relative humidity, air velocity) variety, and production system. Sweet basil (*Ocimim basilicim* L.) has been extensively studied for artificial LED lighting related to efficiency and quality improvements, including changes in both the metabolic and aromatic profiles. Plant growth and dry matter content were found to increase under rising light intensity, but only until an optimum level, after which it might be limited by other environmental factors. In addition, interaction of light quality (spectral composition) and light intensity may influence the magnitude of plant responses. Research shows that the combination of different wavelengths, light recipes and light treatments can enhance the antioxidant capacity, calcium, potassium, magnesium, and phosphorus levels, dry weight and fresh weight of basil. The high number of possible experimental light adjustment combinations leads to a combinatorial explosion; the comparison of results is possible only with limitations. Studies mostly focus on leaf or stem development; results regarding the impact of light recipes on root development, flowering and seed production are rather neglected; seed industry and gene conservation could utilize these results well. Basil is an ideal crop for vertical farming; it responds well to the climate-controlled conditions, can be grown in high density and is not taller than the average height of the shelves. The spread of smart systems can be observed as a trend in both indoor farming systems and greenhouses. With the aid of these, it is now possible to design and implement additional LED lighting that dynamically adapts to the needs of the plant and the cultivation purpose, supplementing the existing light conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2021.110486.

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