

Chapter 3

Artificial Lighting Systems for Plant Growth and Development in Indoor Farming



Munirah Hayati Hamidon and Tofael Ahamed

Abstract Due to the increasing demand for food from the growing global population, indoor farms have received attention from farmers because of their ability to produce more food as a supplement to the conventional farming system. In a highly controlled indoor environment, the application of artificial lighting is essential in replacing the function of natural sunlight. The primary purpose of artificial light sources is to promote plant growth. However, the operational requirements of indoor plants vary widely and uniquely, and thus artificial lighting systems become more complex. The light used for indoor farms must satisfactorily address a variety of performance to ensure the optimum plant growth and development. Therefore, this chapter discussed the key factors involved in the specific lighting parameters such as light quality, quantity, and duration for compliance to meet the growing requirements of indoor cultivation. Furthermore, several types of artificial lights also have been reviewed to understand which light type is reliable for indoor farms.

Keywords Indoor farming · Artificial lighting · Light quality · Light intensity · Light duration

3.1 Introduction

The land resources for agriculture have been decreasing as more areas are urbanized to accommodate other sectors, such as industry, manufacturing, and housing development. However, the global population is increasing rapidly each year and is projected to increase to 9.6 billion by 2050; thus, more food must be produced to feed this population. Hence, urban agriculture (UA) is one of the growing food security solutions to address the issues of global population and urbanization that are

M. H. Hamidon

Graduate School of Science and Technology, University of Tsukuba, Tsukuba, Ibaraki, Japan

T. Ahamed (✉)

Faculty of Life & Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

e-mail: tofael.ahamed.gp@u.tsukuba.ac.jp

rapidly increasing. UA is defined as the production, processing, and distribution of food produced in cities for local consumption. Vertical or indoor farming is one developing form of urban agriculture that is currently booming and has been explored specifically by developed countries.

Farmers are increasingly adopting indoor farming due to the possibility of regulating environmental conditions such as light and temperature in accordance with the plant types and environmental requirements. Indoor farming typically provides a much higher yield than traditional farming methods and has the potential to supplement food provided by existing agriculture practices. It allows farmers to produce their crops year-round without being affected by the increasing trend in global warming and extreme climate changes. Moreover, this advanced agricultural model has enabled crops to be grown without the need for clearing additional land.

Generally, several main factors must be considered when setting up and maintaining an indoor farm: location, type of cultivation system, crops, and technology used (Wong et al., 2020). Indoor farms range in size from small shipping containers to large vertical multi-layered buildings, enabling them to be built not only in rural areas but also in cities. Regarding the cultivation type, the soilless culture system is the most suitable cultivation practice for indoor farming, as it frees plant from soil-related issues. Leafy vegetables, small fruits such as tomatoes and strawberries, herbs, flowers, and microgreens are some of the common types of crops that are suitable to grow in indoor farms. Currently, green vegetables dominate the highest percentage of plants grown in indoor farming worldwide due to their high nutrition per calorie compared to other foods. Moreover, they are also rich in vitamins, minerals, fiber, and antioxidants (Wong et al., 2020).

The use of technology is frequently the determining factor in the success of an indoor farm. Technological advancements such as light emitting diode (LED) lighting, sensors, and automation have made indoor farming more efficient and customized for producing certain crops. The growth and development of plants grown indoors rely entirely on artificial lighting systems (Fig. 3.1). Understanding what type of light is required and how much it is required is the key to effectively and successfully growing plants indoors. Plants require an energy supply from light for photosynthesis. Photosynthesis is a process when energy from light sources converts carbon dioxide (CO_2) and water into carbohydrates and oxygen with the aid of chlorophyll pigments in the leaves. Different plants grow differentially when they receive different light qualities, intensities, and durations.

3.2 Light for Plant Growth

Light is composed of particles called photons, which are bundles of the electromagnetic field that contain a specific amount of energy. Electromagnetic radiation is one type of wave that is expressed by speed (c), wavelength (λ), and frequency (ν).

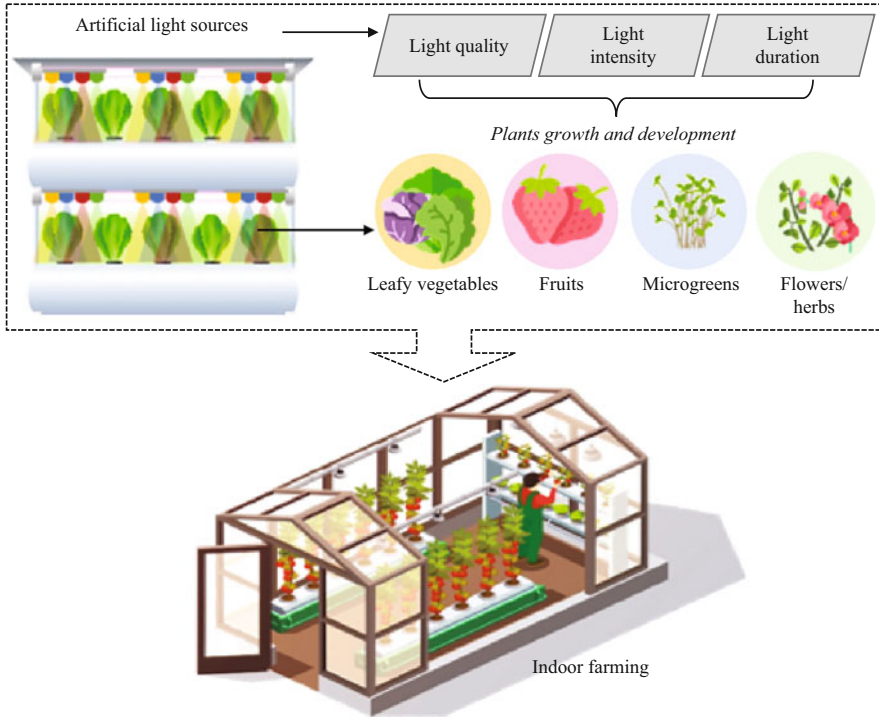


Fig. 3.1 Artificial lighting for indoor farming

$$\lambda = c/\nu \quad (3.1)$$

Equation (3.1) shows that the light wavelength is inversely proportional to the frequency. An increase in frequency will decrease the light wavelength with a corresponding increase in the energy of the photons that produce the light. These photons produce light when a charged particle shifts from a higher energy level to a lower energy level (Xu et al., 2016) (Fig. 3.2). The energy of a photon is determined using the Planck–Einstein equation:

$$E = h\nu = hc/\lambda \quad (3.2)$$

where h is the Planck constant.

Three key aspects of light influence how plants grow and develop: quantity or intensity, quality, and duration (Fig. 3.3) (Runkle, 2017). Light quantity refers to the intensity or concentration produced by a light source. Light quality, on the other hand, reflects the color or wavelength reaching the plant surface. Light duration, also known as the photoperiod, is defined as the amount of time a plant needs to be exposed to a light source.

Fig. 3.2 Photons produced from changes in the energy level to emit light

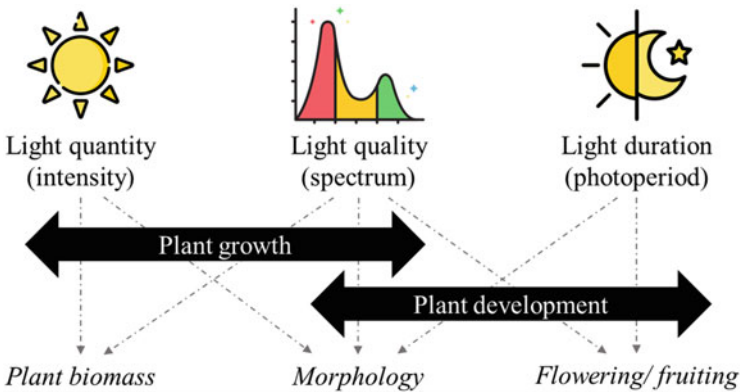
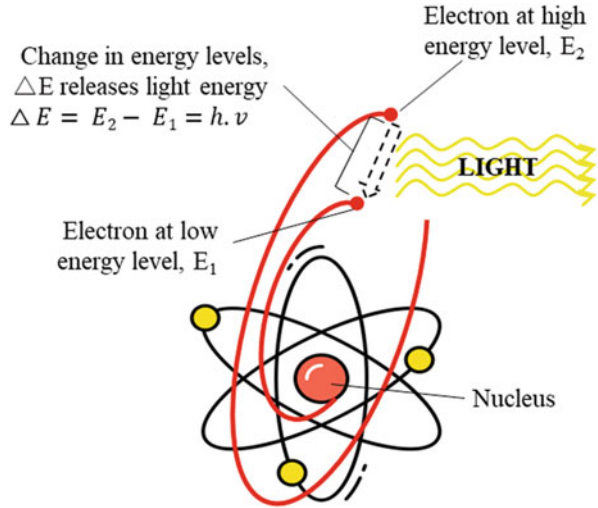


Fig. 3.3 The principles of light and its importance for plant growth and development

3.3 Light Quantity

The light quantity needed by each plant differs. Some plants may require a very minimal light intensity, but others may need a high light intensity to grow. Plants perform the photosynthesis process within the radiation spectrum between 400 and 700 nm, which is known as photosynthetically active radiation (PAR).

Numerous studies have been conducted and have shown that the light quantity is important for promoting plant growth and development. Under certain conditions and in different plant types, a higher light intensity leads to high yields. However, excess light may damage plants, and too little light will inhibit growth (Barber & Andersson, 1992). This difference is because light intensity is one of the most critical elements influencing the photosynthesis process in plants. Photosynthesis is defined

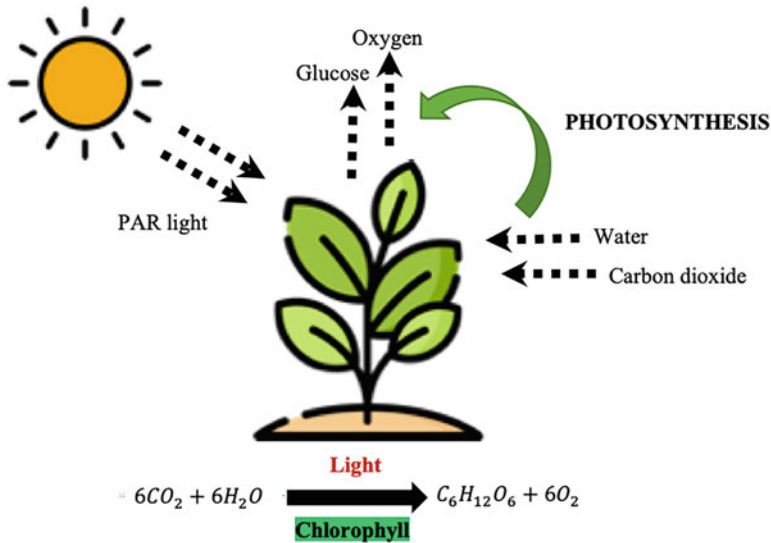


Fig. 3.4 The photosynthesis process

as the process by which green plants use light to synthesize nutrients from carbon dioxide and water to produce carbohydrates and oxygen (Fig. 3.4).

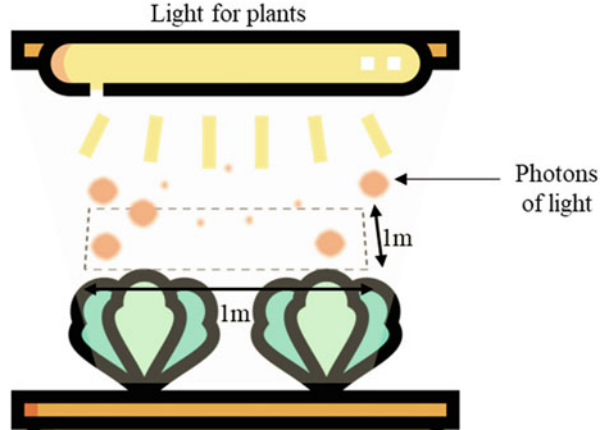
Plants store and use the carbohydrates produced during photosynthesis as their nutrient source. Every plant begins its photosynthesis process differently, depending on the energy levels of the light sources, which is known as the light compensation point. This threshold is reached when the amount of light energy available for the photosynthetic process is sufficient to create more oxygen than the plant needs for respiration. Similarly, the CO_2 released by the plants through respiration should not be greater than the amount of CO_2 consumed by the plant during photosynthesis, resulting in null or negative net photosynthesis.

Light falls to the ground as tiny particles known as photons. The photons encompass various energy quantities, depending on the light frequency. However, photosynthesis is mainly related to the number of photons rather than to their energy level. The light quantity reaching the plant varies according to the distance between the plants and the light source. The light quantity is determined by calculating the photosynthetic photon flux density (PPFD). The PPFD is measured by calculating the number of photons in the PAR region that reach a certain area at a constant distance (Fig. 3.5). It is typically reported in $\mu\text{mol m}^{-2}\text{s}^{-1}$, where μmol is a unit of counting based on Avogadro's number:

$$1 \mu\text{mol m}^{-2}\text{s}^{-1} = 6.022 \times 10^{23} \times 10^{-6} \times (10^9)^2 = 0.6022 \text{ nm}^{-2} \text{ s}^{-1} \quad (3.3)$$

By calculating the PPFD, we can understand the exact amount of light that is received by or reached the plants for photosynthesis.

Fig. 3.5 The measurement of light energy required for plants



$$\text{PPFD} = \frac{\text{Photons of light}}{\text{area} \times \text{time}} \quad (3.4)$$

3.3.1 Plant Photosynthesis in Response to Light

In general, the photosynthesis rate is substantially influenced by the light intensity. Initially, the photosynthesis rate increases as the light intensity increases. However, after reaching the light saturation point, the rate eventually approaches its maximum value. The light saturation point is defined as the point when light intensity no longer affects the rate of photosynthesis. The photosynthesis rate curve or light response curve (LRC) becomes flat when it reaches this saturation point (Fig. 3.6).

The LRC model quantifies the relationship between photosynthesis and light intensity (Herrmann et al., 2020; Wan et al., 2018). The model is diversified and has been determined using several empirical models: (1) a rectangular hyperbola model, (2) a modified model of the rectangular hyperbola, (3) a nonrectangular hyperbola model, and (4) an exponential function model (Wan et al., 2018).

1. Rectangular Hyperbola Model

The rectangular hyperbola model is calculated as follows:

$$P_n(I) = \frac{\alpha P_{\max}}{\alpha I + P_{\max}} - R_d \quad (3.5)$$

where $P_n(I)$ is the net photosynthesis rate, I is the photosynthesis photon flux density, α is the initial gradient of the light response curve, P_{\max} is the maximum net photosynthetic rate and R_d is the dark respiration rate. P_{\max} is determined as:

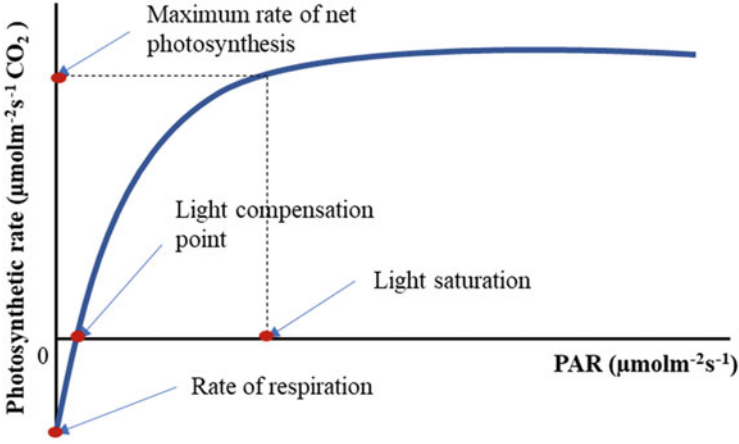


Fig. 3.6 Change of photosynthesis rate with the light intensity

$$P_{\max} = \alpha \left(\frac{\sqrt{\beta + \gamma} - \sqrt{\beta}}{\gamma} \right)^2 - R_d \quad (3.6)$$

where β is the humidity coefficient and γ is the temperature coefficient.

2. Modified Model of the Rectangular Hyperbola

The mathematical expression of the modified model of the rectangular hyperbola is described as follows:

$$P_n(I) = \alpha \frac{1 - \beta I}{1 - \gamma I} I - R_d \quad (3.7)$$

where α is the initial gradient of the light response curve, β and γ are the humidity and temperature coefficients, respectively, I is the photosynthesis photon flux density, and R_d is the dark respiration.

3. Nonrectangular Hyperbola

The following equation is used to calculate the nonrectangular hyperbola model:

$$P_n(I) = \frac{\alpha I + P_{\max} - \sqrt{(\alpha I + P_{\max})^2 - 4\theta \alpha I P_{\max}}}{2\theta} - R_d \quad (3.8)$$

where $P_n(I)$ is the net photosynthesis rate, I is the photosynthesis photon flux density, θ is the curve curvature, and α is the gradient of the plant photosynthesis to the light response curve when $I = 0$, namely, the initial gradient of the light response curve, which is also called the initial quantum efficiency. P_{\max} is the maximum net photosynthetic rate, and R_d is the dark respiration rate.

4. Exponential Function Model

The exponential function model that been used to determine the light response of plant photosynthesis is calculated as follows:

$$P_n(I) = P_{\max} \left(1 - e^{-aI/P_{\max}} \right) - R_d \tag{3.9}$$

In this equation, the definitions of all parameters are the same as those described in Eqs. (3.5) to (3.8).

3.4 Light Quality

Light quality indicates the light wavelength or spectrum. The wavelengths emitted by the sun range from 280 to 2800 nm, which is 97% of the total spectral distribution (Kozai et al., 2015). They are classified as ultraviolet, visible light, and infrared. The lowest wavelengths have the highest energy, indicating that ultraviolet radiation has higher energy than infrared radiation. The wavelengths visible to humans range from 380 to 770 nm, which are referred to as visible light. The visible light is split into violet (380–430 nm), blue (430–500 nm), green (500–570 nm), yellow (570–590 nm), orange (590–630 nm), and red (630–770 nm).

Two prominent types of effective radiation for plants are known as (1) photosynthetically active radiation (PAR) and (2) physiologically active radiation. The physiologically active radiation is divided into five wavebands: Ultraviolet (UV) 300–400 nm, blue light (B) 400–500 nm, green light (G) 500–600 nm, red light (R) 600–700 nm, and far-red light (FR) 700–800 nm. Meanwhile, the waveband of PAR ranges from 400 to 700 nm (Fig. 3.7) (Tazawa, 1999; McCree, 1981).

The green pigment in plants that absorbs PAR, chlorophyll, has two absorption peaks: red and blue light. Plants usually absorb only a small amount of green light and reflect it back, which is the reason most plants appear green to humans (Fig. 3.8).

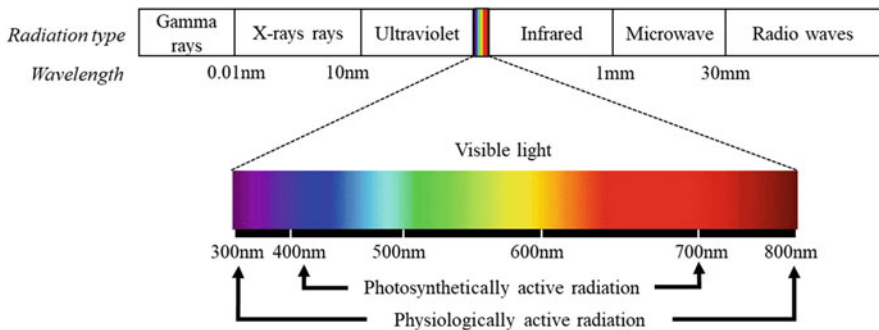


Fig. 3.7 The visible light spectrum distributions

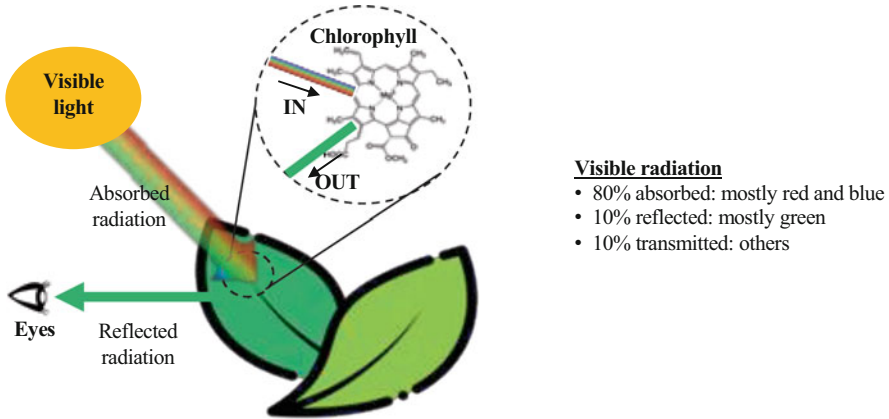


Fig. 3.8 Spectrum of plant absorption, reflection, and transmission

The functions of light for food production should be to promote rapid seedling growth, improve branching density, support the developing leaf size, and enhance the flowering/fruiting cycle irrespective of the season to maximize production quality and quantity. An understanding of the effects of different wavelengths of the light spectrum on plant growth is essential to provide a proper artificial light system for cultivating vegetables in indoor environments. Light quality not only affects the growth and morphology of plants but also regulates metabolite accumulation (phytochemicals) in plants (Fig. 3.9) (Paradiso & Proietti, 2021; Wong et al., 2020).

3.4.1 Light Energy Use Efficiency of Lamps (LUE_L) and Plant Community (LUE_P)

When estimating the photosynthesis rate or production of plants in indoor farms, all the essential resources for plant growth, such as water, light, CO_2 , and temperature, are connected (Fig. 3.10) (Kozai, 2011). Among these resources, the usage of artificial light in indoor farming is the most costly. Hence, evaluating the light energy use efficiency of lamps (LUE_L) and plant communities (LUE_P) is the primary concern in plant production for indoor farms (Kozai, 2013).

The LUE_L and LUE_P are determined using the as following equations:

$$LUE_L = fD/PAR_L \quad (3.10)$$

$$LUE_P = fD/PAR_P \quad (3.11)$$

In these equations, f is the conversion factor from dry mass to chemical energy fixed in dry mass (approximately 20 MJ kg^{-1}), D is the increase in the dry mass of

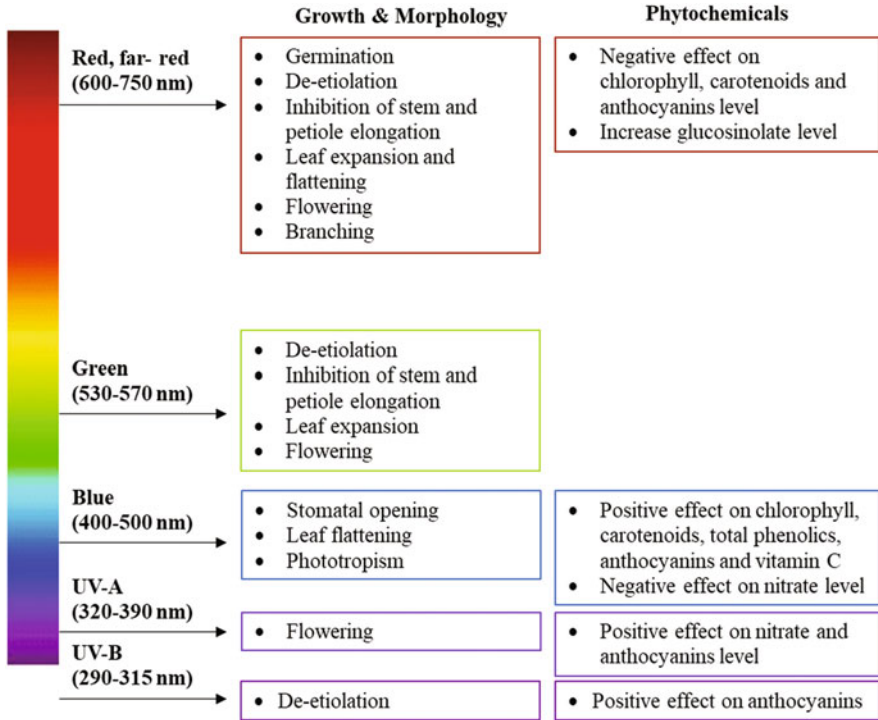


Fig. 3.9 The effect of the light spectrum on plant growth and development

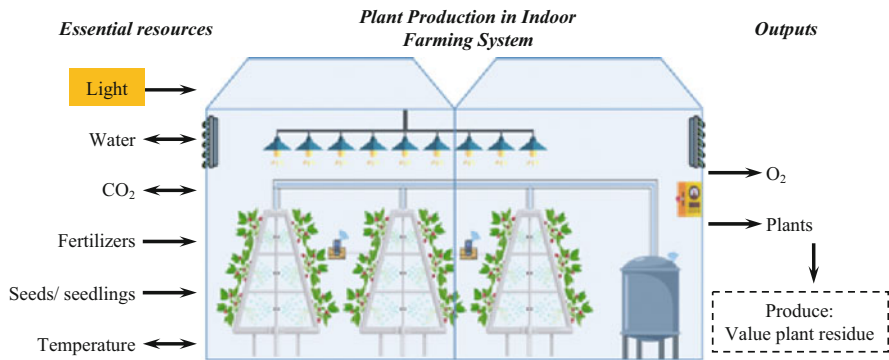


Fig. 3.10 Essential resources for plants grown in indoor farms

whole plants or salable parts of plants in the closed plant production system (CPPS) ($\text{kg m}^{-2} \text{h}^{-1}$), PAR_L is the photosynthetically active radiation (PAR) emitted from lamps, and PAR_P is PAR received at the plant community surface in the CPPS ($\text{MJ m}^{-2} \text{h}^{-1}$). Alternatively, LUE_L and LUE_P have also been calculated using the following equations:

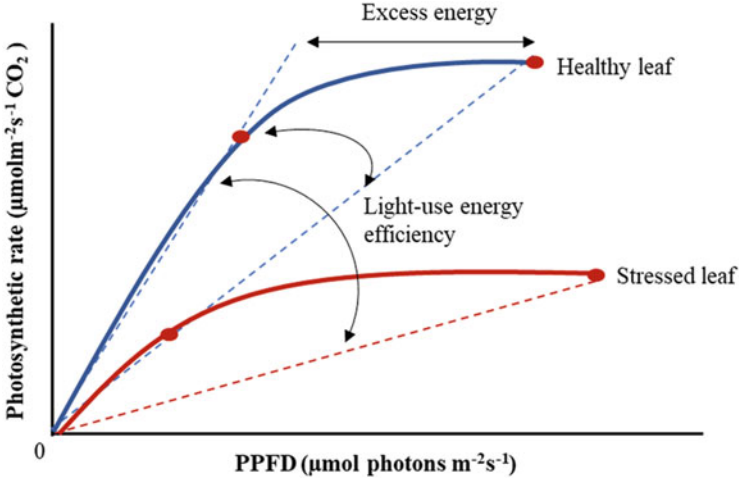


Fig. 3.11 Light use efficiency (LUE) concept for estimating the photosynthesis rate

$$LUE_L = bC_P / PAR_L \tag{3.12}$$

$$LUE_P = bC_P / PAR_P \tag{3.13}$$

where b is the minimum PAR energy to fix 1 mol of CO₂ in plants (0.475 MJ mol⁻¹) and C_P is the net photosynthetic rate of plants (mol m⁻² h⁻¹). The ratio of PAR_P to PAR_L is known as the “utilization factor” in illumination engineering. The LUE models have become valuable tools for estimating vegetation productivity (Fig. 3.11) (Gamon, 2015).

3.5 Light Duration or Photoperiod

The quantity of daily daylight hours exerts a direct effect on the growth and flowering of many plant species. Therefore, the manipulation of daylight hours is important for scheduling the amount of light needed for certain plants growing indoors. A photoperiod is defined as the light duration within a specific time span, usually a 24-h period. Photoperiod control is essential for indoor farming, especially for the flowering process, as every plant responds differently to the relative length of the light and dark periods (Boyle, 1992). Plants are categorized into three classes according to the light duration needed to trigger blooming or flowering.

1. Day-Neutral Plants (DNP)

The flowering time for day-neutral plants may be any duration of the day. Normally, they bloom after achieving specified developmental phases. Examples include tomatoes, cucumber, hydrangea, sunflower, and pepper.

2. Short-Day Plants (SDP)

These plants only require a short period of daylight (approximately 8–10 h). The flowering process only occurs when the photoperiod is less than a critical day length (Fig. 3.12). For SDP, flower blooms occur either in early spring or fall. When the day length surpasses a certain threshold, plants discontinue flowering and begin the vegetative phase. Examples include potato, zinnia, soybean, cosmos, poinsettia, and chrysanthemum.

3. Long-Day Plants (LDP)

LDP require a relatively longer time of daylight than night to bloom (usually 14–16 h). The plants only bloom when the photoperiod surpasses the critical day length (Fig. 3.12). Late spring to early summer is the usual flowering season for LDP. Examples include hibiscus, radish, cabbage, spinach, and lettuce.

By understanding how daylength affects plant development, we can further manipulate the photoperiod of indoor farming to promote different stages of

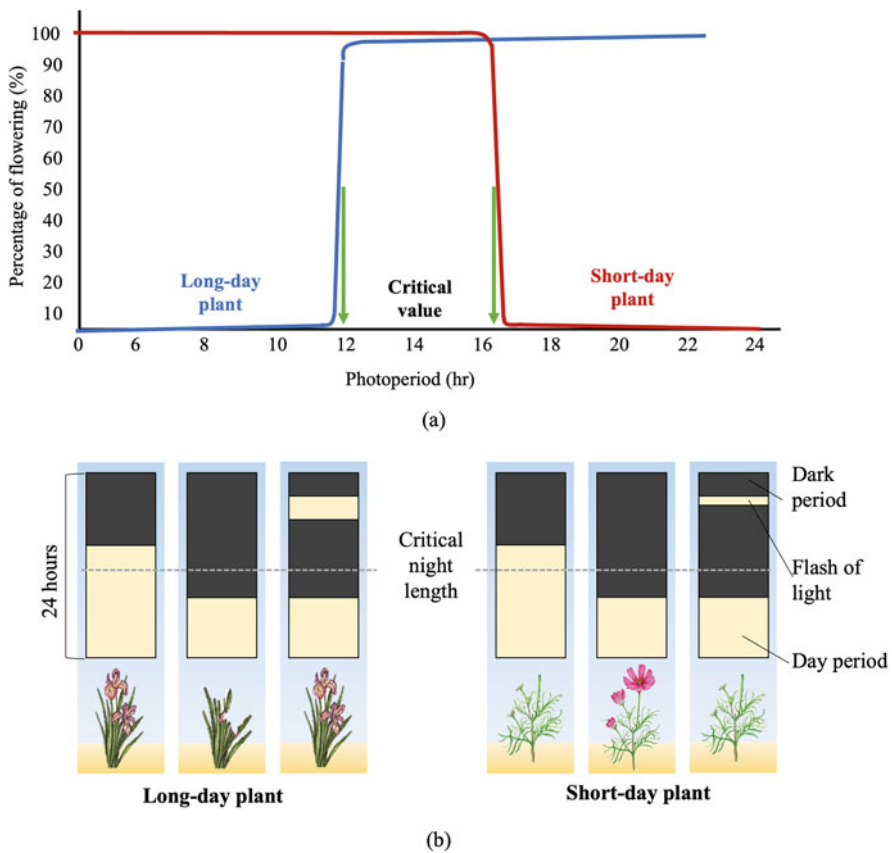


Fig. 3.12 (a) The photoperiodic response in long- and short-day plants. (b) The photoperiodic regulation of flowering in long- and short-day plants

development in photoperiod-responsive crops. Furthermore, flowering in plants is more responsive to dark periods than to light periods. Thus, manipulation of the photoperiod benefits growers in planning the flowering process for their plants and ensuring that they produce the flower even if it is not during their flowering period. If growers need the LDP to bloom, they can extend the light period into the night, which is known as night interruption control.

3.5.1 Daily Light Integral (DLI)

Often, the light duration or photoperiod of plant growth is related to the daily light integral (DLI). The DLI is the total number of photons of PAR accumulated in a particular area received by plants in 24 h. It is an important index that combines both the light intensity and photoperiod (Xu et al., 2021). DLI exerts significant effects not only on plant growth and development but also on plant yield and quality, as it ensures that the plants perceive the optimum amount of light according to their growth cycle (Xu et al., 2021).

The DLI is a simple metric to calculate for indoor farming compared to cultivation outdoors, since light intensity and photoperiod remain constant in each stage of cultivation. In outdoor cultivation, calculating the DLI becomes trickier due to the atmosphere and seasonal changes that occur during the 24-h period. The DLI is calculated as follows:

$$\text{DLI}(\text{mol}/\text{m}^2 \text{d}) = \frac{\text{PPFD} (\mu\text{mol}/\text{m}^2 \text{s}) \times \text{Photoperiod}(\text{h}/\text{d}) \times 3600(\text{s}/\text{h})}{10^6} \quad (3.14)$$

By determining the DLI in indoor farming, growers can strategize their artificial lighting operation so that it meets the specific requirements corresponding to the plants' growth cycle and stage.

3.6 Artificial Lights for Plants Growth

A significant increase in the number of studies conducted on the use of lighting in the fields of plant and animal production has been observed during the last several decades. Different types of lighting, light wavelength ratios, and light intensities on various species of plants have been the research focus for improving plant growth, particularly in indoor horticulture fields. Studies have reported that even when equivalent light treatments are applied, the growth outcomes vary depending on the plant species.

Generally, artificial light sources are categorized into three main types according to the principle of light emission: incandescence, discharge light emission, and electroluminescence (Kozai et al., 2015; Tazawa, 1999) (Fig. 3.13).

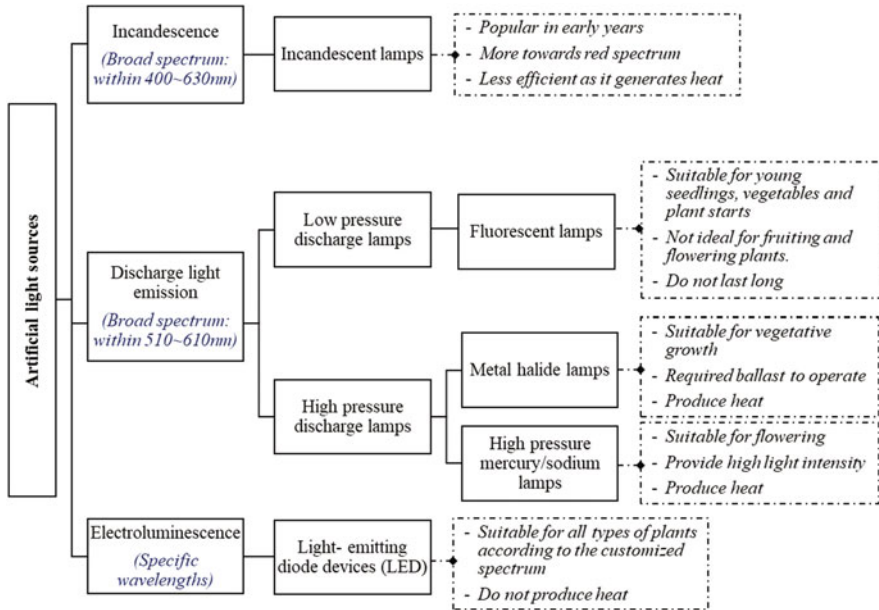


Fig. 3.13 Classification of artificial light sources

3.6.1 Incandescent Lamps

The incandescent lamp was one of the pioneering artificial light sources used for indoor farming before any other lights were developed. Incandescent light sources, as the name indicates, create light by incandescence, which is the emission of light due to heat. An incandescent light bulb is generated by placing a filament in a vacuum or inert-gas-filled container called a bulb. When an electric current is passed across the filament, it will heat up and glow with blackbody radiation and finally achieve incandescence. The filament must be placed in a bulb to prevent the metal from oxidizing and overheating. Instead of a vacuum, inert gas helps delay the evaporation of the heated filament.

In the early years, incandescent light bulbs were used as indoor lighting since they only need a power supply to operate without any supplementary equipment. The production costs are also relatively inexpensive and may operate on either alternating current (AC) or direct current (DC). However, they are very inefficient due to the intrinsic physics of blackbody radiation and are thus much less suitable for plant growth compared to other grow lights. A substantial amount of the input energy utilized to generate light is wasted as heat. When contemplating their usage to grow plants, the high heat generation of incandescent lights may be harmful to plants.

Incandescent lights are not recommended to be placed closer than 24 inch to a plant to avoid damage. However, this minimum operating distance established for safety reasons may prevent the plants from receiving proper light intensity and eventually affect their growth. Additionally, incandescent lights emit more toward

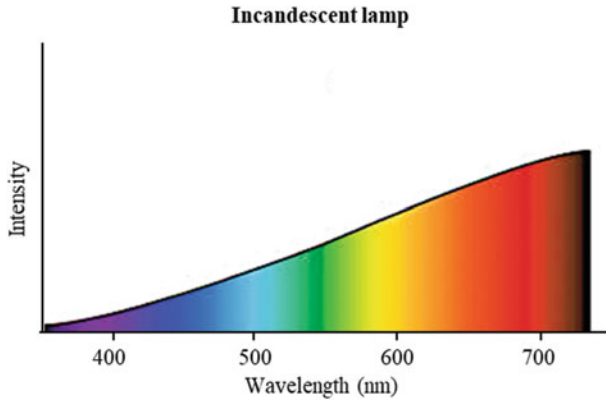


Fig. 3.14 Spectrum of the incandescent lamp

the red spectrum, depriving plants of blue light (Fig. 3.14) (Trinklein, 2016; G2V Optics Inc., n.d.).

3.6.2 *Fluorescent Lamps*

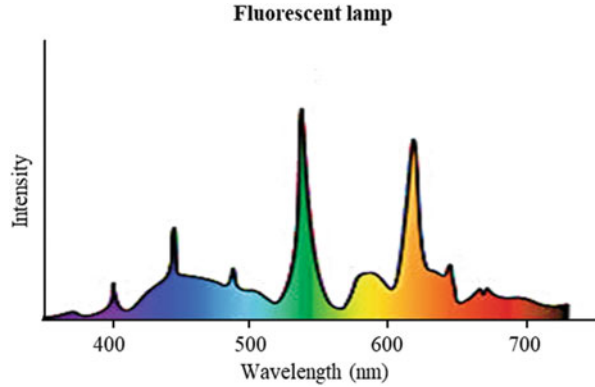
Another trendy type of lamp that is used for indoor farming is fluorescent lamps. A fluorescent lamp generates light by transferring energy via a gas contained within a tube. It generates visible light using the physical principles of optical fluorescence via a low-pressure mercury-vapor gas discharge. Fluorescence occurs when electrons return from an excited singlet state to their ground state.

Fluorescent lights outperform incandescent bulbs in producing the light required for a variety of plants, particularly vegetables grown inside, since the lights are far more efficient and produce light mainly in the visible spectrum (Fig. 3.15) (Trinklein, 2016). Moreover, fluorescent lights come in a variety of colors and generate lower temperatures. Another advantage is that they typically have a long lifespan. Despite their advantages over incandescent bulbs, they require additional equipment, a ballast, which is a device that restricts the amount of current flowing through a circuit, for their operation. The ballast is needed to maintain the light at the proper voltage and current level. In addition, they also do not last very long, are delicate, bulky, and have limitations in providing a high lumen intensity.

3.6.3 *High Intensity Discharged (HID) Lamps*

HID lamps have been traditionally used to supplement indoor farm lighting that requires greater light intensities than fluorescent lighting. They are also known as

Fig. 3.15 Spectrum of the fluorescent lamp



high-pressure discharge lamps, which operate at very high pressure and temperature (Dutta Gupta & Agarwal, 2017). A series of high voltage electrical pulses are transmitted between two electrodes at the end of the tube to generate the HID light. Similar to a fluorescent lamp, an HID lamp also requires ballast, as it provides a high voltage to generate light and sustains a sufficient electrical current flow to the bulb.

Two main popular types of HID lamps are used for indoor farming: high-pressure sodium (HPS) and ceramic metal halide (MH) lamps. Both HPS and MH lamps use a gas discharge lamp with a combination of various vaporized metals, each of which has a distinct color range. The HPS lamps mostly emit a fairly monochromatic yellow–orange light, while the MH fixtures tend to produce a blue–white color of light (Fig. 3.16) (U.S. Department of Energy, 2017).

3.6.4 Light Emitting Diodes (LED)

LEDs are more robust and have longer lifespans than other traditional light sources, such as incandescent and fluorescent lamps. The color of light emitted from the LED is determined by the semiconductor material composition of an LED, which defines the total wavelength of the photon light emissions. With the currently available cutting-edge technology, LEDs can be customized to emit a certain wavelength and generate either narrow- or wide-band light that matches a specific plant requirement for maximum growth (Fig. 3.17) (Xu et al., 2016).

For instance, red and blue LEDs are frequently used because they span the spectrum where plants most efficiently absorb light. Nevertheless, some studies have shown that certain plants also utilize some parts from green and yellow regions, suggesting that grow light producers must develop LEDs with broader radiation. Additionally, some wavelengths outside the 400–700 nm range may also exert beneficial effects on plant growth. As a result, some manufacturers have modified

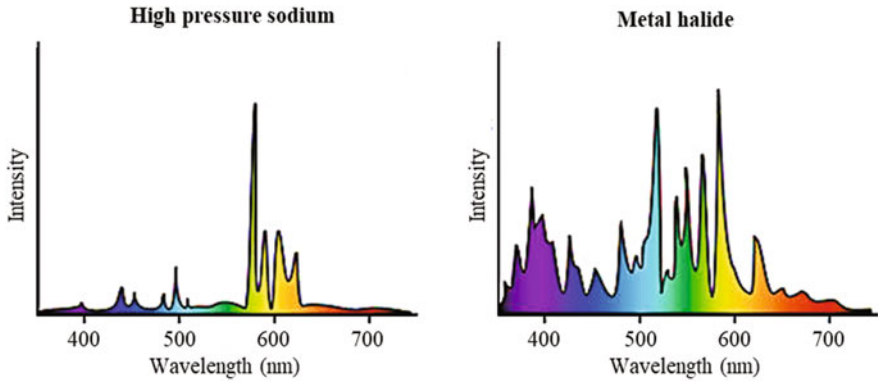


Fig. 3.16 Spectra of the HPS and MH lamps

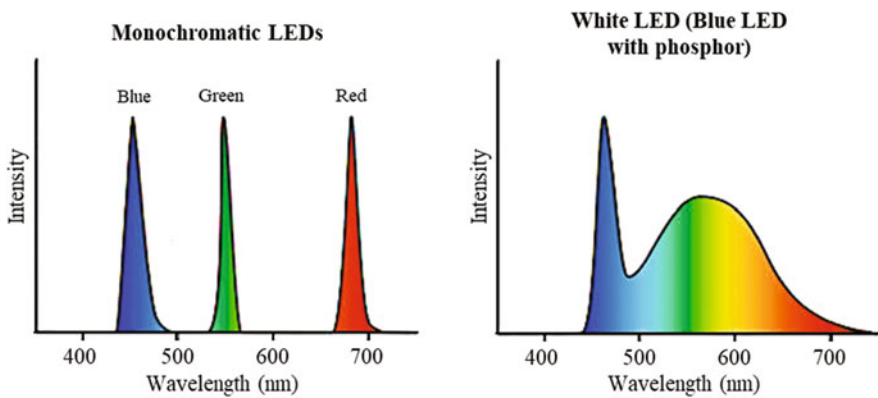


Fig. 3.17 Spectra of LEDs

LEDs such that they also deliver light that encompasses areas below 400 nm or above 700 nm.

As mentioned above, most of the grow light sources not only produce light but also produce heat, which may be harmful to the plants. Depending on the grow light types, plants may experience heat stress and localized low humidity if they are positioned too close to those lights. LED lights generate far less heat. Unlike HID, placing LEDs closer to the plants may help maximize the light intensity and spectrum received by the plants without overheating them. Additionally, LEDs are environmentally friendly, work without a ballast and have extended lamp lifetimes. Due to their effectiveness and affordability, LED grow lights are increasingly

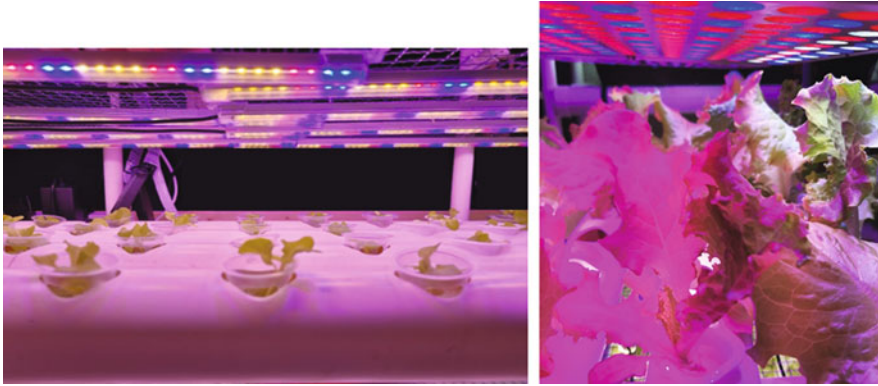


Fig. 3.18 Example of the usage of LEDs for growing lettuces indoors

replacing other grow lights, such as fluorescent lights and HIDs, in indoor farming operations (Fig. 3.18).

3.7 Effect of Using Artificial Light on Plants Grown Indoor

Types of plants	Plant	Light	Light duration	Effect on plants	References
Leafy vegetables	Chinese cabbage	Red + Blue + White LED ($130 \mu\text{mol m}^{-2} \text{s}^{-1}$)	18 h day^{-1}	Optimal growth of leaf length and weight.	Duc et al. (2021)
		Fluorescent lamps	14 h day^{-1}	High glucosinolate content.	
	Lettuce (“Cheongchima”)	External electrode fluorescent lamps ($150 \mu\text{mol m}^{-2} \text{s}^{-1}$)	20 h day^{-1}	Increased fresh weight, dry weight, leaf area, and daily biomass accumulation rate.	Cho et al. (2020)
	Sweet basil	Red (663 nm) + Blue (435 nm) LED	8 h day^{-1}	Increased the growth yield.	Rihan et al. (2020)
	Water spinach	Red LED ($200 \pm 15 \mu\text{mol m}^{-2} \text{s}^{-1}$)	14 h day^{-1}	Enhanced water spinach growth without causing intumescence.	Kitayama et al. (2019)
	Lettuce (“Frillice Crisp”)	Far-red (700–800 nm) + Red (600–700 nm) + Blue (400–500 nm) LED	–	Promoted the growth and increased macro- and micro-nutrient content.	Pinho et al. (2017)
Fruit vegetable/fruits	Tomato (“Dometica”)	HPS lamps + LED ($30 \text{ mol m}^{-2} \text{day}^{-1}$)	18 h day^{-1}	Increased fresh weight of fruits.	Verheul et al. (2022)
	Tomato and red pepper	Cool white LED + supplemental Far-red LED ($200 \mu\text{mol m}^{-2} \text{s}^{-1}$)	16 h day^{-1}	Increased hypocotyl length.	Hwang et al. (2020)
	Tomata (“Merlice”)	HPS lamps ($20 \mu\text{mol m}^{-2} \text{s}^{-1}$)	16 h day^{-1}	Increased leaf temperature, photosynthetic rate, transpiration rate,	Kim et al. (2019)

(continued)

Types of plants	Plant	Light	Light duration	Effect on plants	References
				and plant tissues water content.	
	Tomata ("Komeett")	Far-red (730 nm)+ Red (638 nm) + Blue (450 nm) LED	16 h day ⁻¹	Increased plant growth, accelerated flowering, and increased fruit yield.	Kalaitzoglou et al. (2019)
	Strawberry ("Machyang")	Mint-white LEDs (180 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	16 h day ⁻¹	Increased leaves number and area, top/root dry weight ratio, and number of newly formed runners/propagule.	Lee et al. (2020)
	Everbearing strawberry ("Elan")	White LED (300 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	24 h day ⁻¹	Increased yield, TSS, ascorbic acid, anthocyanin, and crop productivity.	Maeda and Ito (2020)
	Capsicum seedlings ("CAU-24")	White LED (with Red + Blue ratio) (250 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	12 h day ⁻¹	Increased seedlings biomass, chlorophyll content, and photosynthetic rate.	Liu et al. (2019)
Microgreens	Kale, Cabbage, Arugula, and Mustard	Red + Blue LED light (100–600 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	16 h day ⁻¹	Fresh and dry weight increased as light intensity increased, but decreased hypocotyl length and hue angle linearly.	Jones-Baumgardt et al. (2019)
	Soybean sprout	White fluorescence light (100 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	14 h day ⁻¹	Reduced hypocotyl length but increased the diameter of hypocotyls.	Yuan et al. (2015)
	Common buckwheat sprouts	Blue LED (12.41 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	–	Increased hypocotyl length.	Lee et al. (2014)
Flowers	Peony ("Da Fugui")	Red + Blue LED light (200–220 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	14 h day ⁻¹	Increased number of flowers, enhanced blooming rate, flower diameter, and florescence.	Wan et al. (2020)
	<i>Digitalis purpurea</i>	Red + Blue LED light (150 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	18 h day ⁻¹	Increased micro- and macro-elements as well as cardenolides accumulation.	Verma et al. (2018)

3.8 Conclusion

In conclusion, this chapter has provided adequate information on principles of light (light intensity, quality, and photoperiod) and their importance as main indicators that must be considered when using artificial lighting in indoor farms. Higher irradiance is often associated with faster development in most plants because it produces more photons to drive photosynthesis and enhance biomass accumulation. However, irradiance greater than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ may have reached the light saturation limit. As a result, photosynthetic efficiency decreases and affects the light consumption efficiency.

Despite having many diverse types of light, LEDs are currently the preferred light source for indoor farming lighting. With appropriate lighting control, they provide sufficient flexibility in altering the spectrum range of artificial lights. This approach may appropriately influence the biological and physiological attributes of a plant's growth. Furthermore, intelligent dimming may also be used to offer a seamless transition between photoperiods while achieving the required plant irradiance, depending on the time of the day.

The photoperiod is an environmental indicator that regulates flowering and has been manipulated to adjust the process of flowering for indoor ornamental crops. Photoperiod requirements will be adjusted based on plant types, mostly for flowers of either long-day or short-day plants. However, research on the effect of the photoperiod on leafy vegetables cultivated indoors is relatively less prominent. Compared to the light quantity and quality, photoperiod exerts less of an effect on the growth of and phytonutrient accumulation in leafy vegetables. The photoperiods (14–18 h light) that are normally used for leafy vegetables are currently at the optimal level. Hence, any changes in the common photoperiod of the leafy vegetables will not provide any substantial advantages for their growth.

By knowing the light information, growers using indoor cultivation can select and choose the best light intensity and light quality to achieve the preferred growth characteristics of their plants. Furthermore, this knowledge will also enable light producers to invent more ideal lighting devices, depending on the market targeted for consumption and the morphological attributes desired by indoor farming growers.

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