AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

Department of Electronics
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LEDs FOR GENERAL AND HORTICULTURAL LIGHTING

Espoo 07.06.2012

Final Project

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SCHOOL OF ELECTRICAL ENGINEERING **Abstract of the Final Project**

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Abstract text

The work begins with an introductory part about Light Emitting Diode (or LEDs) and how these devices work. This report also shows an overview of different artificial light sources such as incandescent lamps, fluorescents tube and high-intensity discharge (HID) lamps. The LED lighting is more energy-efficient than other artificial lighting, since they require less energy to operate. The following part of the work reports LEDs for General Lighting that describes some basic concepts such as spectrum, wavelength, Color Rendering Index (CRI), and Correlated Color Temperature (CCT); in order to establish and acquire the best possible lighting for people. The rest of the document is referred to LED lighting for horticulture applications.

The Sun is an important energy source for humanity and plants. Its energy is capable of originating the photosynthesis process in plants. Nevertheless, the Scandinavian countries (such as Finland, Norway, Sweden, and Denmark) have problems to see the sun in autumn and winter season; therefore, they need to utilize artificial lighting to generate a huge variety of vegetation in greenhouses. LEDs are used in plant growth, since these devices supply good-quality lighting. Experimental measurements are also taken to combine the spectrum of various colors and to acquire the best light source with these blends, using *Microsoft Office Excel 2010* software. Finally, it is possible to learn how to mix colors in order to achieve the best combination for plants and people.

Keywords: *color rendering index, color temperature, general lighting, horticultural lighting, light-emitting diode, plant growth, solid-state lighting*

Preface

This report for my Final Project has been conducted at Lighting Unit of Aalto University (School of Electrical Engineering).

Firstly, I would like to dedicate this work to my family, especially to my parents and my sister, Eva. My deepest thanks go to them, since I would not have been able to do my Final Project abroad, and they have permitted me to live this new experience in my life.

Dad, mum, Eva…Thank you!!!

My friends also have a special role for this Project. Thanks to them, it has been possible to reach my goals in my life, since they have been with me for the good and bad moments. You are really friends.

Antonio, Hugo, Javi, Mercedes, Nacho, Fran…Thank you!!!

I would not like to forget of my Erasmus friends. We have been able to create a little family during these five months. Thank you for those wonderful moments in Finland.

Alvaro, Ana, Attila, Bruno, Elodie, Gianluca, Raúl, Sandra, Tim…Thank you!!!

I am especially grateful to my flatmates, Zbynek and Samuel, for your support and happiness during all this time. You know it, but you have a house in Spain to visit me when you want to.

Samuel, Zbynek…Thank you!!!

Finally, I would also like to thank to all personnel of Lighting Unit of Aalto University for giving this opportunity to make my Final Project here, especially to Paulo Pinho (my instructor) and Liisa Halonen (my supervisor).

To all of you…Thank you!!!

Espoo [07.06.2012] Emilio Girón González

List of Abbreviations

Abbreviations

CCT	Correlated Color Temperature
CIE	International Commission on Illuminations
CRI	Color Rendering Index
HID	High Intensity Discharge
Hz	Herzt
ipRGC	intrinsically photoreceptive Retinal Ganglion Cell
IR	Infrared
K	Kelvin Temperature
LED	Light-Emitting Diodes
nm	Nanometer
OLED	Organic Light-Emitting Diode
PAR	Photosynthetically Available Radiation
PE	Polyethylene
PLED	Polymer Light-Emitting Diode
PPF	Photosynthetic Photon Flux
PPFD	Photosynthetic Photon Flux Density
RGB	Red-Green-Blue
SED	Spectral Energy Distribution
SI	International System of Units
SPD	Spectral Power Distribution
SSL	Solid State Lighting
UV	Ultraviolet

List of Symbols

Symbols

$\mathbf{CO_2}$	Carbon dioxide
$\mathbf{C_6H_{12}O_6}$	Glucose (Carbohydrates)
$\mathbf{E}$	Illuminance (or Illumination)
$\mathbf{E}$	Irradiance
$\mathbf{F}$	Luminous Flux
$\mathbf{H_2O}$	Water
$\mathbf{I}$	Luminous Intensity
$\mathbf{I_e}$	Radiant Intensity
$\mathbf{L}$	Luminance
$\mathbf{O_2}$	Oxygen
$\mathbf{R_a}$	General Color Rendering Index
$\mathbf{R_i}$	Special Color Rendering Index
$\mathbf{XYZ}$	Color matching functions
$\mathbf{x}$	Chromaticity Coordinate
$\mathbf{y}$	Chromaticity Coordinate
ϕ_e	Radiant flux
AE_i	Color Difference

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1 Introduction

1.1 Theoretical Foundations: Light Emitting Diode (LED)

1.1.1 Introduction to LED

LEDs, or light-emitting diodes, were discovered in 1907 by the British inventor H.J. Round. A LED can be compared with a diode because it represents a device or chip, made with semiconducting materials that are doped to form a p-n junction [1].

LEDs are very reliable technologies. Although, it is possible that their output lights slowly degrade over time. At some phase the amount of light produced by the LED becomes insufficient for the intended application; therefore, it will be necessary to replace it. The life of an LED should be based on the amount of time that the device can produce sufficient light for the planned application.

Currently, manufacturers can design LEDs in different colors, shape and size. The size and shape of LEDs is shown in Figure 1.1. LEDs are used as indicator lamps in some devices; therefore, the interest in using LEDs for display and illumination applications has been steadily growing over the past few years. [2]

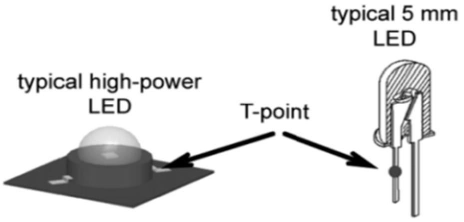


Figure 1.1: Example of two different types of LEDs [2]

1.1.2 LED Operation

A LED is a type of diode which operates as a semiconductor device. It is possible to consider the evolution of the LED from a diode because the role of a LED is to emit light through its p-n junction and other dopant materials to create the junction. The dopant in the n-area provides negative charge known as electrons; whereas the dopant in the p-area provides positive charges referred to as holes. The light-emitting diode is capable of converting electricity to light, when a voltage is applied to the p–n junction from the p-area to the n-area. [3]

When a light-emitting diode is on, electrons are able to recombine with electron holes within the device. An electron releases energy when it drops from a higher orbital to a lower one. This energy is freed in the form of a photon: a carrier of electromagnetic radiation of all wavelengths. The color of LED depends on the band gap energy of materials utilized to create p-n junction, since that band gap is dependent on the emitted wavelength. [3]

The current of LEDs flows from the p-side of a semiconductor to its n-side, but not in the reverse direction. The p-side is referred to as the anode while the n-side is referred to as the cathode as shown in Figure 1.2. [4]

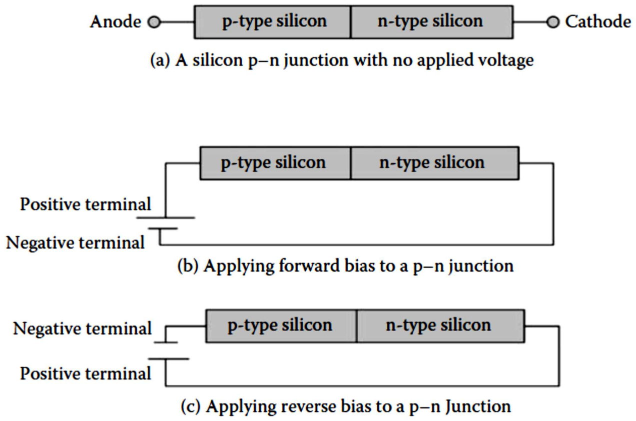


Figure 1.2: The p-n semiconductor junction [4]

Figure 1.2 shows three different combinations for diode operations. The first is when there is *no applied voltage*, which causes a depletion zone, as shown in Figure 1.3. The depletion area is created because the electrically charged carriers in the n-type silicon (referred to as electrons) and p-type silicon (referred to as holes) are attracted and then eliminated in a process called recombination [4]. However, to remove the depletion zone, electrons need to move from n-area to p-area, while holes go in the opposite direction. Thus, when the voltage difference is high between the positive and negative electrodes, electrons in the depletion zone are expelled from their holes so that they begin to move. After this process, the depletion zone disappears and new current flows across the p-n junction.

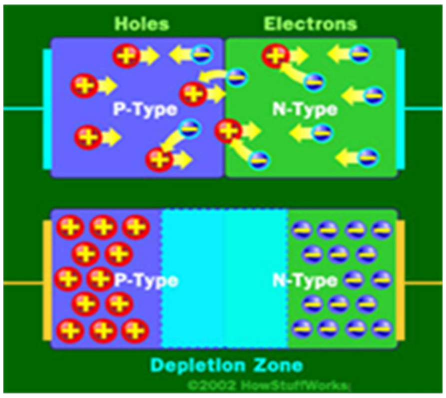


Figure 1.3: Formation of depletion zone

The second case is when the positive terminal is connected to the anode, allowing a *forward bias***.** This case reduces the width of the depletion zone, pushing the holes in the p-area and the electrons in the n-area toward the junction. Moreover, the negative charge applied to the n-type silicon repels electrons from the p-side silicon; whereas, the positive charge applied to the p-type silicon likewise refuses the holes from the n-type silicon [4]. Thus, an effect is created with the positive and negative terminal connections to force electrons and hole toward the p-n junction, reducing the width of the depletion zone to cross this zone through a tunnel created by increasing the forward bias voltage.

The last case is called *reverse-bias* because the polarity of terminal battery is inverted. For this case, the p-zone is connected to the negative terminal of a supply source, and the n-zone is connected to the positive terminal of the same supply source. These actions generate an increase at the width of the depletion zone, since it produces a growth of the potential for the electric current in this zone. Therefore, it is necessary to utilize a reverse-bias connection to minimize this potential in the p-n junction. This last case is typically used in Zener diodes. [1] [4]

There are no large differences of operation between diodes or LEDs, because they work in the same way. However, it is possible to find some dissimilarity between the two: an LED emits light in proportion to the forward current flowing through it while the diode exists in different ways of operation. [4]

1.2 Lighting Technology overview

Conventional lighting consists of three different types: fluorescent, incandescent, and high-intensity discharge (HID). Using these artificial lightings, it is possible to produce a huge variety of vegetation in the greenhouses. However, LEDs currently have more importance than these kinds of devices. [5]

1.2.1 Fluorescent

A fluorescent lamp or fluorescent tube is a gas-discharge lamp filled with partial atmosphere of rare gas (normally argon) and small amount of mercury. This lamp uses electricity to excite mercury vapor. The atoms of mercury are excited to produce short-wave ultraviolet light that causes a phosphor to radiate, producing visible light. To regulate this electrical current, a ballast is required to provide control to electrical impedance and to transform electric power into light. [5] [6]

The flicker of fluorescent lamps is generated when they operate with 60 Hz line voltage. However, this problem can be solved by utilizing high frequency electronic ballast which eliminates this flicker. [5]

This kind of lamp uses approximately 50 to 80% less energy than incandescent bulbs and their average lifespan is around 7,500-10,000 hours. [7]

1.2.2 Incandescent

Incandescent lighting is capable of generating light by resistive heating of a thin tungsten filament. The filament literally glows white hot and generates much more heat than light. Incandescent lamps do not provide an acceptable quality of light; nevertheless, they are frequently utilized everywhere. [6]

A halogen lamp is a special type of incandescent lamp which contains a halogen additive that drives a virtuous chemical cycle whereby tungsten from the filament is removed from the outer wall of the bulb and re-deposited on the hot filament [6]. A transformer is usually used for conversion to low voltage. This is necessary in some applications to produce a more concentrated source of light for optical coupling with a reflector. These lamps produce only 10% of light, while the rest (90%) is consumed as heat. The average lifespan of an incandescent bulb is between 2,500-4,000 hours. [5] [7]

1.2.3 High-intensity discharge (HID)

High-intensity discharge (HID) lamps typically contain multiple atmospheres of mercury pressure at operating conditions, which produces light by means of an electric arc between tungsten electrodes housed inside a translucent or transparent fused quartz or fused alumina arc tube. This tube contains metal salts and gas. When the arc is formed, then it heats and evaporates the metal salts forming plasma, obtaining a notable light [5]. This kind of lighting also needs to use a ballast, as occurs with fluorescent lamps.

Low pressure sodium lamps offer very high efficacy, but with poor color rendering and an unpleasant yellow color [5]. The average lifespan of an HID is between 20,000-25,000 hours [7].

1.2.4 Solid-State Lighting (SSL) Technology

1.2.4.1 Introduction to SSL

Semiconductor light-emitting diodes (LEDs), organic light-emitting diodes (OLED), or polymer light-emitting diodes (PLED) are types of lighting within *solid-state lighting*. The term “solid state” is defined as light emitted by solid-state electroluminescence, without referring to incandescent bulbs or fluorescent tubes. [8]

It is important to address the argument for SSL as an energy saving technology and to examine the larger issue of environmental impact. SSL comparison with existing incandescent and discharge light sources should consider total life cycle costs, not just energy efficiency during product use. It is widely reported that solid state lighting has the potential to substantially reduce energy consumption on a significant global scale. The main challenges of SSL are [5]:

- **Minimum cost.**
- **Better quality of light.**
- **Improve efficiency of light generation and light extraction.**

1.2.4.2 Inorganic LEDs (LEDs)

High-performance inorganic LEDs are now available that produce light spanning the visible spectrum. LEDs generate more efficient light than incandescent lamps and enable feasible a wide variety of applications [8]. Moreover, light-emitting diodes have considerable advantages, particularly for monochromatic applications. They are durable and provide very long life [5]. This lifetime is roughly of 50,000 hours, as shown in Figure 1.4, which is at least 20 times more the lifetime of an incandescent bulb. [5]

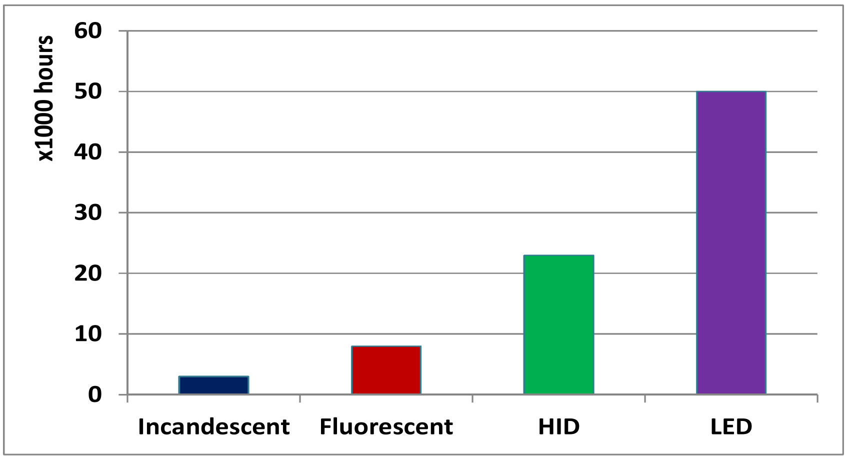


Figure 1.4: Lifetimes for existing lighting sources [5]

LED devices are currently viable choices for a variety of applications requiring monochromatic light. LEDs produce better light quality than incandescent lamp, since LEDs are durable, cool, mercury-free, and more efficient. Thus, the progress in LED efficiency over time, compared to conventional light source development, is shown in Figure 1.5.

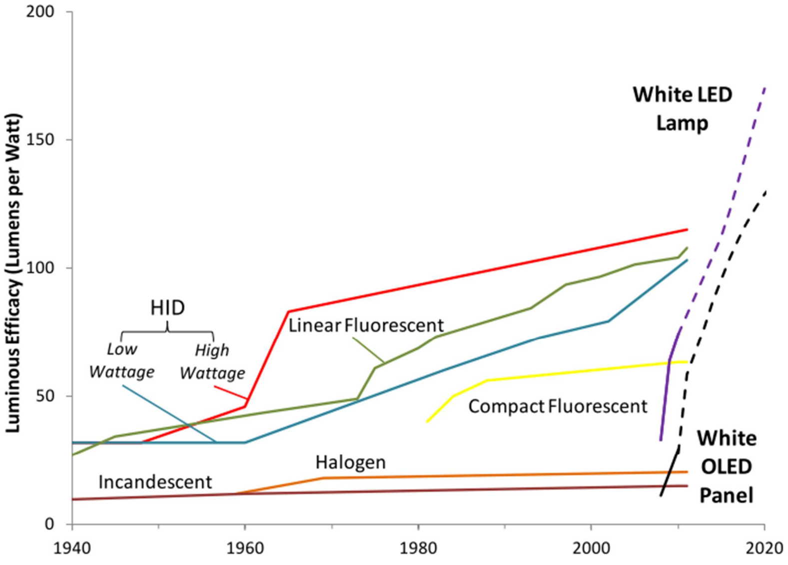


Figure 1.5: Evolution of luminous efficacy performance of white light sources [9]

1.2.4.3 Organic LEDs (OLEDs)

Organic LEDs are semiconductor diodes which emit light. They consist of organic materials instead of inorganic crystals [5]. OLEDs are commonly categorized intro two categories of “small molecules” and “polymers” [10]. Small molecule OLEDs are vapor deposited onto either a glass or plastic substrate, while polymer OLEDs are quite efficient.

OLEDs have considerable characteristics in comparison with LEDs; the first, it is possible to obtain more colors (even black); the second, they utilize less energy, but are more expensive to manufacture. However, this kind of technology has not been used in many applications yet. [11]

2 LEDs for General Lighting

2.1 Lighting Units and Quantities

There are many units to measure light, but it is necessary to introduce one more fundamental unit, and the SI system uses the *Candela*. This one and other units are shown in Table 2.1. [1]

Table 2.1: The measurement of light [1]

Quantity	Symbol	Unit	Definition
Luminous Intensity	**I**	**Candela (Cd)**	The luminous intensity of a 555,016 mm (or 540 x 10^{12} Hz) source which has a radiant intensity in a given direction of 1/683 W/sr, when measurement in that direction.
Luminance	**L**	**Candela per square meter (Cd/m^2)**	The intensity of a source in a given direction divided by its orthogonally projected area in that direction
Luminous Flux	**F**	**Lumen (lm)**	An isotropic point source of intensity one Candela produce a total luminous flux of 4:π lumens
Iluminance (Illumination)	**E**	**Lux (lx)**	The concentration of luminous flux falling on a surface
Radiant Intensity	I_e	**Watts per steradian (W/sr)**	Radiant power emitted by a point source in a given direction.
Radiance		**Watts per steradian per square meter ($W/sr.m^2$)**	The radiant intensity of a source in a given direction, divided by its orthogonally projected are in that direction
Radiant Flux	ϕ_e	**Watts (W)**	Radiant power of a source at all wavelengths
Irradiance	**E**	**watts per square meter (W/m^2)**	Radiant power incident on a surface

It is possible to appreciate some effect of a light such as the **brightness**. The brightness is not an official term of the lighting trade and this effect is defined by its luminance.

Nevertheless, this concept is essential to understand visual quality, especially in relation to contrast and glare. [1]

2.2 Light Spectrum

Light is represented as a form of energy capable of showing itself as electromagnetic radiation and is visible to the human eye [12]. The *electromagnetic spectrum* is all possible frequencies of the electromagnetic radiation that are within a specific range. The electromagnetic spectrum of an object is the characteristic distribution of the electromagnetic radiation emitted or absorbed by the particular object. Using this radiation, it is possible to interact with the world: radio waves provide TV and radio; microwaves are used in radar communications; X-rays allow obtaining information about internal organs; and other different usages [13].

A spectrum is obtained when the electromagnetic radiation is distributed according to its wavelength. The visible spectrum is only a small part of the whole electromagnetic spectrum, since this spectrum is roughly comprised between 380 and 720 nanometers [12]. The electromagnetic spectrum is divided into five major types of radiation. These waves (including microwaves), light (including ultraviolet, visible, and infrared), heat radiation, X-rays, and gamma rays are shown in Figure 2.1 [14].

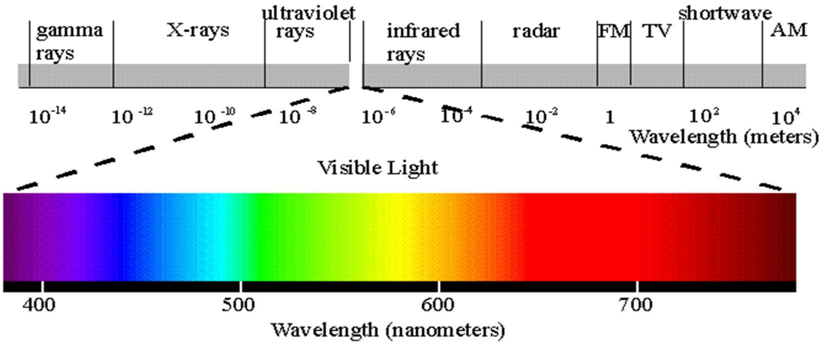


Figure 2.1: Visible spectrum for the human eye [15]

The visible spectrum is the portion of the electromagnetic spectrum that is visible to the human eye [12]. A light-adapted eye generally has its maximum sensitivity at around 555 nm, between green and yellow regions of the optical spectrum.

2.2.1 White light and color

The waves generated in the electromagnetic radiation are comparable with the waves produced on the surface of water. The distance from the peak of a wave to the next peak is the wavelength of the electromagnetic radiation, as shown in Figure 2.2. [13]

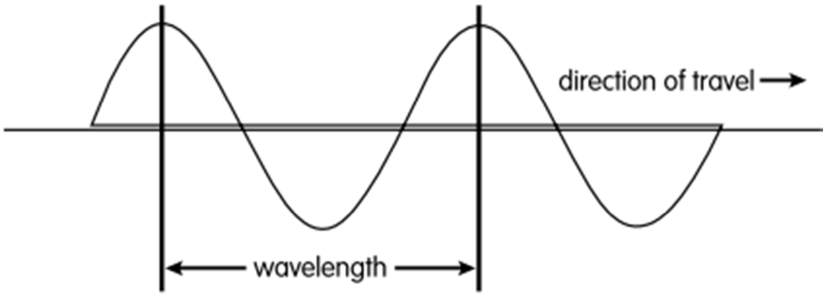


Figure 2.2: The wavelength of electromagnetic radiation [14]

All electromagnetic waves can be also described by their frequency. This frequency is defined as the number of whole waves (or cycles) that pass by a point per unit time.

Lamps emit white light, namely, what appears to the eyes as “white” is actually a combination of different wavelengths in the visible portion of the electromagnetic spectrum [13].

The white light can be achieved through LEDs with two main processes:

1) ***Phosphor conversion***, in which a blue or near-ultraviolet (UV) chip is coated with phosphor to emit white light. When blue LED is combined with a yellow phosphor, the light will appear white to the human eye [15] [16].
2) ***Color-mixing***, in which light from multiple monochromatic LEDs (red, green and blue) are mixed, obtaining white light [15].

The main role is to determine the potential of LED technology to generate high-quality white light. A representation about how to obtain this light is shown in Figure 2.3:

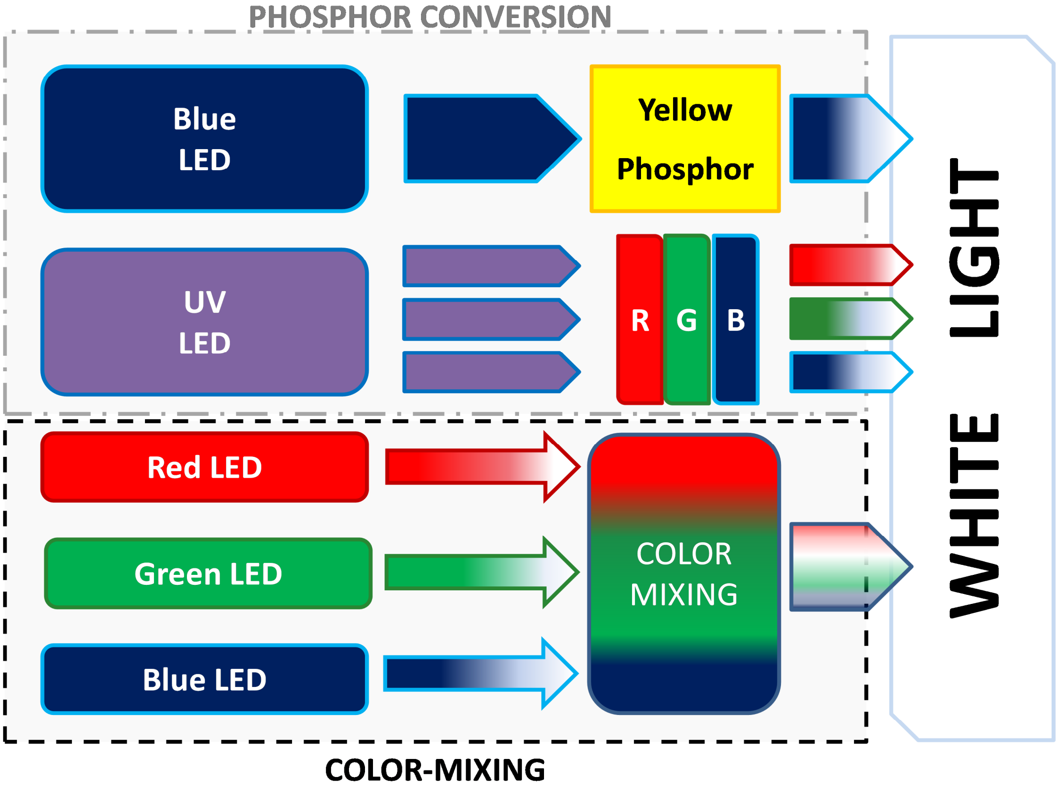


Figure 2.3: General methods to create white light from LEDs

Moreover, there is a third option to acquire white light. This new approach is still developing and consists in combining the phosphor conversion and color mixed approaches, obtaining *Hybrid Method LED*, as shown in Figure 2.4: [9]

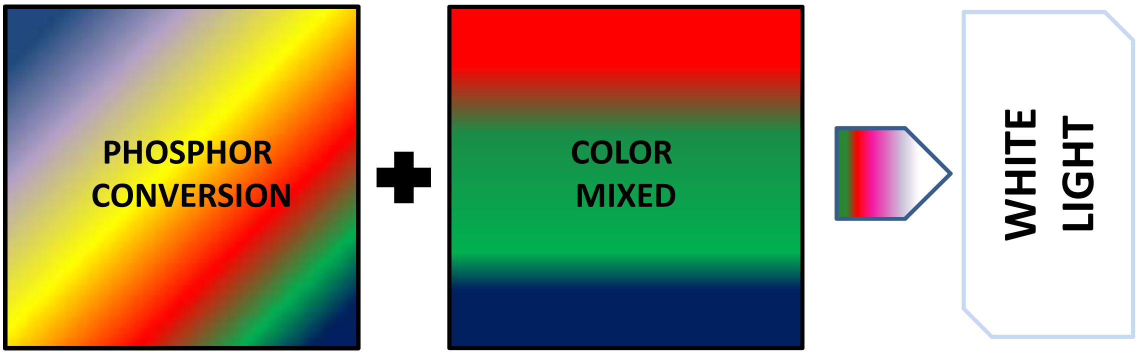


Figure 2.4: Hybrid Method LED to create white light

Hybrid Method LED technology is capable of acquiring good-quality color and efficacy, saving until 75% of energy.

2.3 Chromaticity Coordinates

LEDs, or any other light source, can produce white light. The white light must correctly show all the color of illuminated objects. The color is represented by the *International Commission on Illumination (CIE)* colorimetry system. *XYZ color matching functions* is used to weight the spectrum of a given light. From the resultant three weighted integral values the *chromaticity coordinate x,y* is calculated by the following expressions (1) and (2). [17]

$$\boldsymbol{x} = \frac{\boldsymbol{X}}{(\boldsymbol{X}+\boldsymbol{Y}+\boldsymbol{Z})} \tag{1}$$

$$\boldsymbol{y} = \frac{\boldsymbol{Y}}{(\boldsymbol{X}+\boldsymbol{Y}+\boldsymbol{Z})} \tag{2}$$

Any color can be expressed by the chromaticity coordinate (x,y) on the *CIE 1931 (x,y) chromaticity diagram*, as shown in Figure 2.5.

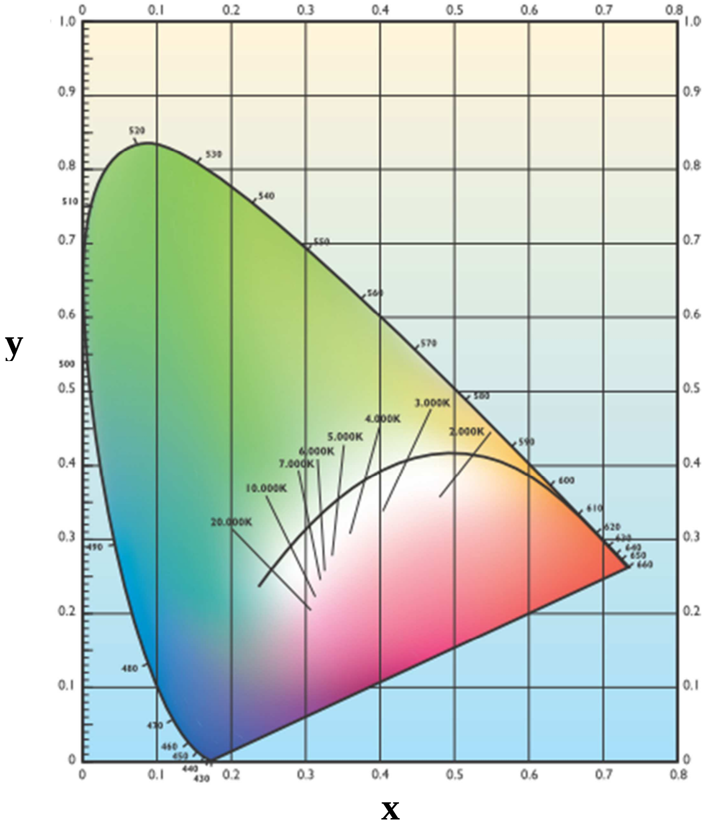


Figure 2.5: CIE chromaticity diagram [12]

2.4 Correlated Color Temperature (CCT)

Correlated Color temperature (CCT) is the color on the Planckian locus, defined by the blackbody temperature in Kelvin degrees [17]. Colors around Planckian locus are from 2,500 to 20,000 K. However, the CCT of most traditional lamps for general lighting is basically included in the range from 2,850 K (warm white) to 6,500 K (cool white).

Color temperature is a quality of the white light which varies depending on the source. The typical color of an incandescent lamp is labeled as *"Illuminant A"* and the typical color of day is labeled as *"Illuminant 65"*. All these labels are standardized by CIE.

Correlated Color Temperature is used instead of color coordinate, because the color temperature cannot be used for the color coordinate (x,y) of the Plackian locus. [18]

2.5 Color Rendering Index (CRI)

The *Color Rendering Index*, or *CRI*, is the most important characteristics of light sources for general lighting. CRI is a property which allows checking whether object colors are correct under the given illumination. If there is a poor light source, so CRI value will be very low; therefore, it would be necessary to utilize a better quality lighting to supply a higher CRI value. [19]

The procedure for this method consists in selecting fourteen samples of different colors: the first eight samples are medium saturated colors; while, the last six are highly saturated, as shown in Figure 2.6. Thus, there is to calculate the color difference ΔE_i of these color samples when illuminated by a reference illuminant and when illuminated by a given illumination. This color difference (uniform color space), now obsolete, is shown in expression (3). [18] [19]

$$AE_i = 1964\, W * U * V \tag{3}$$

Figure 2.6: Color Rendering Index Test Colors [20]

Moreover, the *Special Color Rendering Index* R_i for each color sample is calculated using the expression (4).

$$R_i = 100 - 4{,}6\Delta E_i \; ; \qquad (i=1,\ldots,14) \tag{4}$$

This expression (4) shows the R_i value as an indicator of the color rendering for each particular color. When the average of R_i for the first eight color samples is calculated, then it is possible to obtain the *General Color Rendering Index* R_a, as shown in expression (5). The maximum value for R_a is 100.

$$R_a = \sum_{i=1}^{8} R_i/8 \tag{5}$$

Table 2.2 illustrates examples of CRI. Clearly the fact that different reference sources can be used to determine CRI means that user must know which reference has been utilized for each described application.

Table 2.2: The CIE Color Rendering Index [1]

CIE - CRI	**Typical Application**
>90	Where accurate color matching is required; e.g. print inspection
80-90	Where good color judgment is required, or where appearance is important; e.g. retail display

60-80	Where moderate color rendering is required; e.g. commercial premises
40-60	Where color rendering is not important but where a marked distortion of color is unacceptable; e.g. warehouses
20-40	Where color rendering is of no importance, and a marked distortion of color is acceptable; e.g. some road lighting

2.5.1 CRI and LEDs

Some scientific researches have shown that the white light produced by LEDs is preferred over halogen and incandescent light resources, even those with higher CRI value. [21]

The Color Rendering Index (CRI) has been previously used to compare fluorescent and HIP lamps for over 40 years. However, the International Commission on Illumination does not recommend its usage with white light LEDs, because these present a particular wavelengths do not perform such as incandescent on the eight sample CRI color. This recommendation is based on a survey of numerous academic studies that consider both phosphor-coated white light LEDs and red-green-blue (RGB) LEDs clusters. [22]

Nevertheless, there are some recommendations for CRI and LEDs from CIE. These advices should not be used to make product selections in the absence of in-person and on site-evaluations. [22]

1. *Identification of visual tasks to be performed under the light source. If color fidelity under different light sources is critically important, CRI values may be a useful metric for rating LED products.*
2. *CRI could use CCT to compare light sources. This applies to all light sources, not only LEDs.*
3. *Color appearance more important than color fidelity. Do not exclude white light LEDs solely on the basis of relatively low CRI values.*
4. *Evaluation LED system in person.*

2.5.2 Quality of Light aspects

A light source does not only must supply high-quality light, but there are other important factors such as visual comfort and physical or physiological aspects. [16]

A good lighting can be described according to the level of well-being and performance required for each application. Moreover, eyes must adapt the visual environment to execute the activity at the workplace. [16]

Lighting quality is also a financial issue. For example, in an office environment, poor lighting conditions can easily result in losses in the productivity of the employees and the resulting high production costs of them.

2.5.2.1 Psychological aspects

Everybody perceives and receives the information of environment through their eyes, analyzing these data by means of their brains [16]. Variation of luminance and colors can transmit emotions, attractiveness and different sensations in the human body.

Normally, a lighting installation that does not meet the expectation of the users can be considered unacceptable. An insufficient lighting produces impact and lack of motivation for people.

2.5.2.2 Visual aspects

The most important visual aspects are to ensure adequate and acceptable light levels and create a good-quality light and visual environment. If this quality lighting is obtained, the visual task will be correctly executed; there is to avoid visual discomfort.

The correlated color temperature (CCT) and the general color rendering index (CRI) are used to describe the color characteristics of light in space through the spectral power distribution (SPD), indicating the power in the light at each wavelength. [16]

Glare is caused by high or excessive luminance in the visual field. This effect produces discomfort in human eyes. LEDs also produce glare because they are small point sources with high intensities that can form luminaires with diverse shapes and sizes.

On the other hand, light also presents effects that are fully or partly separated from the visual system. These are called the *non-visual effect* of light. This effect of the light is the *intrinsically photoreceptive retinal ganglion cell* (ipRGC) which is a factor very important in non-visual aspects. The ipRGC has been noticed for entraining humans to the environmental light/dark cycle. Light is thought as of an external cue that entrains the internal clock to work properly. Nevertheless, this aspect is not in development yet, because it still lacks quite researching to know what their effects are for the humans. [23]

To obtain an acceptable light, it is necessary to account for different aspects and characteristics, as shown in Figure 2.7.

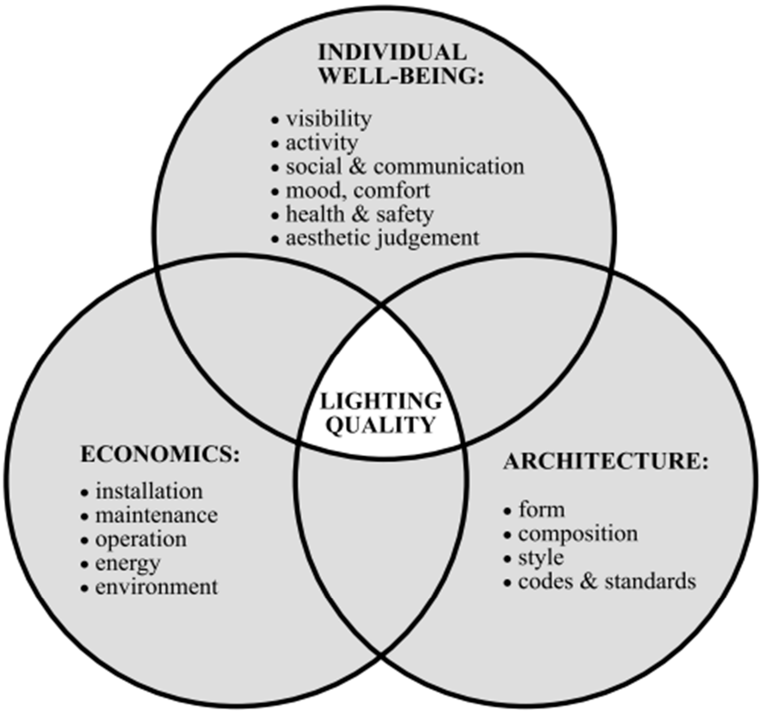


Figure 2.7: Some aspects to acquire quality lighting [24]

2.6 Advantages and disadvantages of LEDs

The main **advantages** for LEDs are: [25]

- **Reduced Energy Consumption:** LED devices can offer a more energy efficient by means of producing light, particularly when it is compared to incandescent sources.
- **Long Operation Life:** Commercial and industrial specifies are generally interested in using a light source that is reliable and lasts a long time. In this way, there will be a huge saving in maintenance and a more safe system.

- **Good physical robustness and durability:** Due to its structure and operation, LED has got more resistant to shattering or impact damage in these applications.
- **Safety improvements:** Led luminaries are made of multiple diodes, and are less likely to fail simultaneously.
- **Color maintenance:** Monochromatic LED for colored light applications allows the elimination of filters and hence better color control and color life than conventional technologies.
- **Smaller package size:** Due to their compact size, LED device are an excellent option, since size or weight will not be a problem. New technologies also allow these structures and sizes.
- **Adjustable color:** LEDs can easily modify the intensity and color of the LED light to augment particular colors in the products.
- **Contain no mercury.**
- **Light pollutions reduction:** The directional quality of street or road LEDs and different areas, reducing light pollution.

These devices are developed very quickly and they will provide many advantages in the near future.

On the other hand, they can present some **disadvantages** too: [25]

- **Lack of standardization.**
- **High price:** Currently, LEDs are more expensive than conventional lighting technologies.
- **Spectrum:** The spectrum of some white LEDs significantly differs from a blackbody radiator, such as the sun or an incandescent light. This problem can cause the color of object to be differently perceived under LED illumination than sunlight or incandescent sources.
- **Color Rendering Index:** CRI can sometimes be low, and it does not acquire a correct measurement. If a LED has got a poor CRI, this light will not be very useful and comfortable.
- **Risk of glare:** As result of small lamp size can produced this effect unpleasant.
- **Ambient operation:** The ambient temperature is an important factor in LEDs. These may result overheating and a bad operation. This is important because LEDs are used in many applications and are required a good reliability.

- **No uniform illumination:** After a long time in usage, LEDs can modify their brightness and illumination.

2.7 Applications of LEDs for General Lighting

Currently, LEDs are almost irreplaceable as signs of status and importance in the field electric and electronic equipment. LEDs are very useful in other areas, such as marker and orientation lighting, or illumination of architectural. Some main general applications of LEDs are:

- **Lighting for orientation:** in huge buildings, garages, shopping center …
- **Safety signs for emergency routes.**
- **Illumination in general:** in workplace, housing, external lighting (outside)…

All these applications have benefited from LEDs for different reasons: with LEDs surpassing traditional technologies in at least one aspect for the application. For example, small size, energy efficiency, and low light output requirements have been a great boon for LEDs in decorative lighting. Outdoor area and parking lot lighting with LEDs is becoming more commonplace because LEDs can provide better light pollution control, color rendering, and subjective preference than traditional high pressure sodium lighting [26]. Furthermore, it can be found more applications but for specific applications: such as automotive industry, illumination of signal (traffic light), advertising, and other applications.

3 LEDs for Horticultural Lighting

3.1 Units for horticultural lighting

The Photosynthetic Photon Flux Density (PPFD) measures the number of photons in the range of 400-700 nm falling at a surface per unit area per unit time [27]. PPFD is a measure of Photosynthetically Available Radiation abbreviated as PAR [28]. Hence the units of PPFD are $micromoles \cdot m^{-2} \cdot s^{-1}$. Thus, a PPFD of one micromole corresponds to 6,022 x 10^{17} photons falling on a one meter square per second. However, the term photosynthetic photon flux (PPF) is also frequently used in some occasion to refer to the same quantity [27].

3.2 The importance of the light for plants

The light is necessary to produce food for trees and plants by a process called *photosynthesis.* Photosynthesis is the most important biological process on Earth because it traps the energy of sunlight and stores it as chemical energy [29]. Thus, all the energy used by life on Earth is almost produced from sunlight by photosynthesis and is passed through the food chain to organisms which cannot photosynthesize.

The light is an important element for people and especially for the organism. It is difficult which a plant can grow without light; therefore, it is necessary to research in different field and conditions to acquire a correct lighting. Thus, LEDs are used to procure this growing in plants, since these devices permit to develop a correct atmosphere in the greenhouses. [30] [31]

The amount of light entering the greenhouse depends on the shape, structure, and material of the house; while the amount light absorption depends on the distribution and orientation of plant leaves. Apart from natural light, artificial light is increasingly used to supplement or substitute sunlight in greenhouses.

The Scandinavian countries (such as Finland, Norway, Denmark and Sweden) have a cold climate and few hours of sun. For this reason, it is necessary to utilize artificial lighting. Finland is about 1,100 km long from south to north, and the climatic conditions considerably vary. In southern the growing season is 170 days, but in the north it is only 100 days. [32]

3.2.1 Photosynthesis

Photosynthesis is the synthesis of sugar from light, carbon dioxide and water, with oxygen as a waste product or by-product. This process is an extremely complex, since it requires the coordination of many biochemical reactions [29]. It occurs in higher plants, algae, some bacteria, and some organisms collectively referred to as photoautotrophs. Photosynthesis requires light energy which is absorbed by special pigments, most notably chlorophyll. This pigment is the most important light-absorbing on the plants [29]. Photoperiodism, phototropism, and photomorphogenesis are also different processes which together with photosynthesis are necessaries [27]. The following expression, (6), shows the simplified chemical equation for photosynthesis.

$$6CO_2 + 6H_2O + light\ energy \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \textbf{(6)}$$

The carbohydrates, such as sugar glucose ($C_6H_{12}O_6$) and oxygen (O_2), are the main products of the photosynthesis process. These are obtained through carbon dioxide (CO_2), water (H_2O), and using the light energy. This process is possible to execute it by the activities of photosynthetic pigments, such as the chlorophyll that converts this energy generated into chemical energy. Moreover, the chlorophyll has maximum sensitivities in the blue and red regions, around 300-400 nm and 600-700 nm, respectively. [31]

3.2.2 Photoperiod effects

Photoperiod, also called light periodicity or light duration, is the amount of light and darkness in a daily cycle of 24 hours. [33]

The photoperiod response is stimulated when some changes are originated in a protein called phytochrome, produced by the light received [34]. This molecule is capable of absorbing red light or far-red light. Normally, there are more red lights during the daytime and more far-red lights at dusk, dawn, and night period. In this way, the plant can sense whether it is night or day.

The most of plants are very sensitive to small amounts of red and far red light, as shown in Figure 3.1; artificial manipulation of photoperiod responses can be accomplished using relatively small amounts of artificial light, such as LEDs.

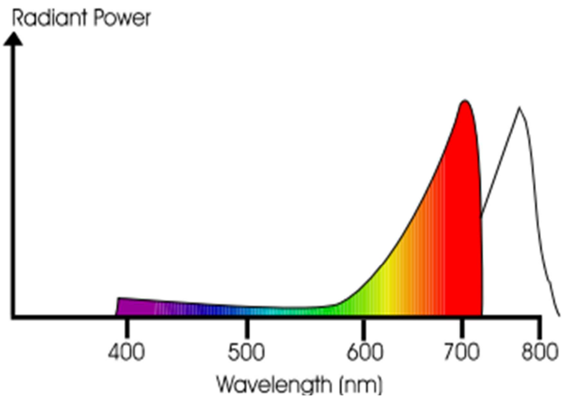


Figure 3.1: Photoperiod response [34]

Therefore, the photoperiod response can be divided into three types, as shown in Figure 3.2:

- **Short day plants:** flowering in responds to long periods of night.
- **Long day plants:** flowering in responds to short periods of night.
- **Neutral day plants:** flowering without regard to the length of the night, however if there is short period of night the flowering is faster.

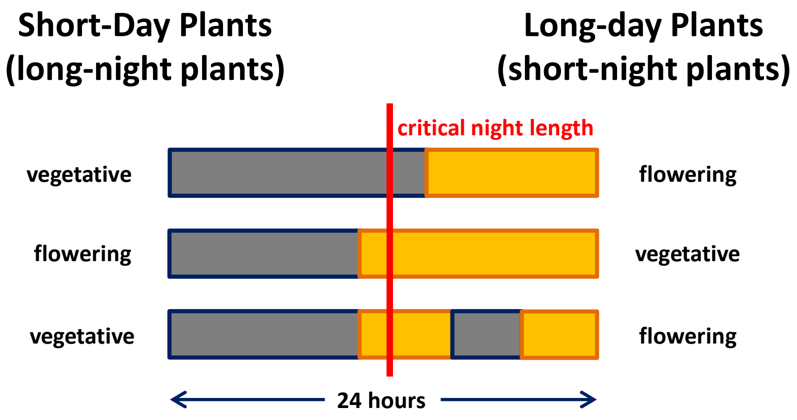


Figure 3.2: Photoperiod and flowering [35]

In Figure 3.2 the left side represents *short-day* plants flower with uninterrupted long nights; while the right side shows *long-day* plants flower with short nights or interrupted long nights.

3.2.3 Phototropism

Phototropism is the movement executed by the plants towards light [30]. Sunflowers are also called because they turn their heads to follow the sun each day. Phototropism can cause deformities in plant growth if the lighting is uneven or unequal. Some plants are so sensitive that they are capable of responding, through phototropism, to moonlight.

3.3 Importance of LEDs in horticulture

3.3.1 Solid-state Lighting in horticultural lighting

Solid-state lighting (SSL) is a technology in which conventional incandescent and fluorescent lamps for horticultural lighting have been replaced by light-emitting diodes [36]. LEDs are one of the biggest advancements in decades. The first time that LEDs were utilized as a light source for plants occurred in 1980s, as shown in Figure 3.3. Nowadays, LEDs continue to move towards becoming economically feasible for even large-scale horticultural lighting applications.

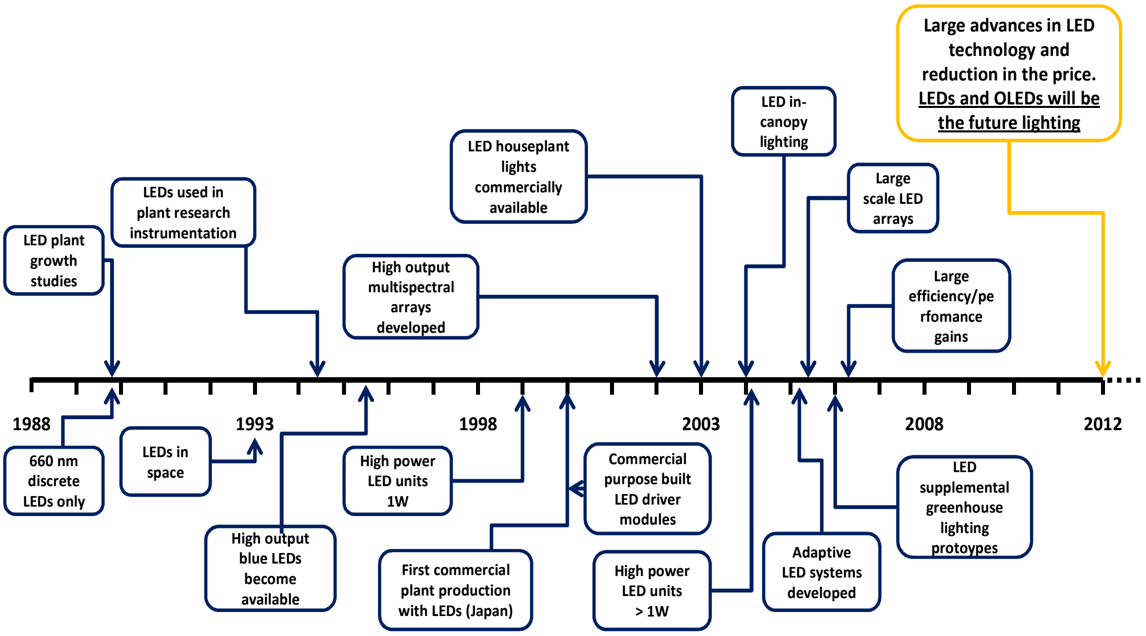


Figure 3.3: Timeline of developments impacting the use of light-emitting diode lighting in horticulture [36]

LED lighting systems have considerable advantages over existing horticultural lighting; since they can control spectral composition, produce high-quality light, and work during a long time without failure. LED color combination generates important profit for the plants, increasing their growths and productions in the horticulture field [37].

3.3.2 Light quality

Light quality consists in finding that wavelength is better to generate the photosynthesis process and a correct plant growth. [38]

The ultraviolet wavelength (UV), visible light, and infrared (IR) are very important in photobiology field. Some scientific researches have demonstrated wavelengths between 300 nm to 900 nm are capable of affecting plant growth. Nevertheless, the light quality does not play a significant role for plants, because there are other necessary properties such as intensity, light duration, and climatic factor. [39]

Humans perceive light in different way than plants. The human eye has the strongest response to light in the green/yellow part of the spectrum. Plants respond better to their growth with blue and red light, as shown in Figure 3.4. Chlorophyll does not absorb light in the green region of the spectrum, since it is reflected [34]. For this reason, the chlorophyll and plants are green.

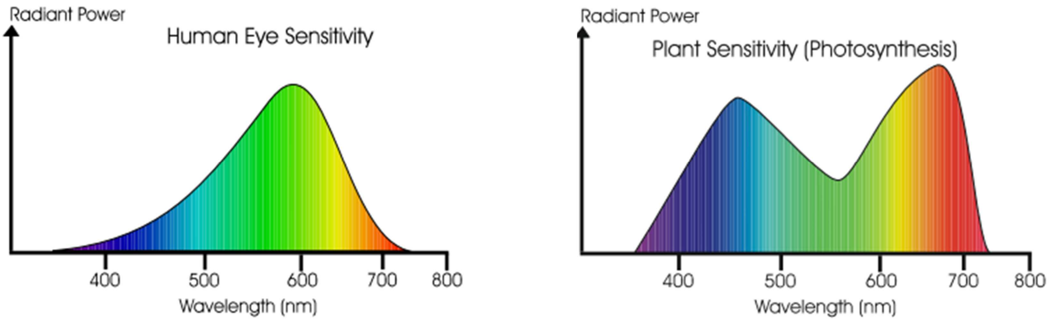


Figure 3.4: Visible spectrum between humans vs. plants [34]

In Figure 3.4, the absorption of light by chlorophyll is at a maximum at two points on the graph roughly in 430 and 660 nm. The rate of photosynthesis at the different wavelengths of visible light likewise shows two peaks which roughly correspond to the absorption peaks of chlorophyll [34]. Plants do not depend only on chlorophyll, but also have other pigments which absorb light of other wavelengths. The rest of the wavelength values, to know how to affect plant growth, are shown in Table 3.1.

Table 3.1: How the light spectrum affects plant growth

Wavelength (nm)	Description
200-280	UVC ultraviolet range which is extremely harmful to plants because it is highly toxic.
280-315	Includes harmful UVB ultraviolet light which causes plants color to fade.
315-380	Range of UVA ultraviolet light which is neither harmful nor beneficial to plant.
380-400	Start of visible light spectrum. Process of chlorophyll absorption begins.
400-520	This range includes violet, blue, and green bands. Peak absorption by chlorophyll occurs, and a strong influence on photosynthesis (promote vegetative growth).
520-610	This range includes green, yellow, and orange bands and has less absorption by pigments.
610-720	This is the red band. Large amount of absorption by chlorophyll occurs.
720-1000	There is little absorption by chlorophyll here. Flowering and germination is influenced.
+ 1000	Totally infrared range. All energy absorbed at this point is converted to heat.

Analyzing spectrum, from shortest to longest wavelengths, the visible light corresponds to the color violet, blue, green, yellow, orange and red. These colors are used as standards in describing rainbow and light quality.

The first color analyzed is *blue light*. The blue color is utilized to stimulate and regulate growth processes in plants, since it is essentially for the photosynthesis process. This color promotes the formation of chlorophyll on leaf surfaces to absorb energy and to convert into chemical energy. Moreover, processes such as stomata opening or increasing the photomorphogenetic response are developed by blue light. [40]

The second is *red light*. Red light is absorbed by vegetation; however, it also transmits far-red light. Both red and far-red light can be converted to the other. The red light spectrum allows stimulating plant growth and also contributes to the plant photosynthesis. [40]

Previous studies have demonstrated that the mixture between blue and red light is the most effective for the crop growth. This combination has been examined in many areas of photobiological research, including photosynthesis and chlorophyll synthesis, obtaining good quality in the vegetables growth [41].

The third color analyzed is *green light*. Normally, the role of green color consists in the regulation of vegetative development, photoperiodic flowering, stem growth modulation, and stomatal opening [41]. This spectral region also affects chlorophyll and carotenoid synthesis, improving the color of leaves [42]. Furthermore, effects produced in plants by green light are completely opposite of effects with red and blue lights. However, blue and red lights are sometimes mixed with green light to enrich the development and plant growth.

The fourth spectral region is *UV light*. If this light is utilized in large amounts, it is dangerous for the flora. Nevertheless, the near-UV light can be beneficial for plants whether its usage is not abusive. The main role for this wavelength is to provide tastes, aromas, and plant colors [42].

The last one is *infrared radiation*. This radiation only participates in photosynthesis process and other plant reactions [43]. It is absorbed by plant cells; however, the energy contained is quite low to excite electrons; therefore, this energy is converted into heat.

3.3.3 Light quantity

Light quantity or light intensity is a different term from light quality because this refers to the amount of light that plants receive, without accounting for wavelength or color.

This term is usually measured by the units of *lux* and *footcandle*. Units footcandle and lux are merely based on visual sensitivity and do not provide information about photon contents in the light source.

If there is an increase in the light intensity, it will result to an increase in the rate of photosynthesis and will likewise reduce the number of hours that the plant must receive every day. On the other hand, deficient light intensities tend to reduce plant growth due to a low amount of solar energy restricts the rate of photosynthesis. In this way, excessive light intensity should be avoided because it can scorch the leaves and reduce crop yields. [35]

3.4 Greenhouses and phytotrons

Greenhouses and horticulture are terms very related. Horticulture is opposite of agriculture. Horticulture is done on a much smaller scale, since horticulture is used to conduct research and study different plants, their growth, their cultivation and breeding, their crop yield, and how to improve their quality [37]. However, agriculture is something developed in the great outdoors; but, some of it is done indoors. When done indoors (i.e. greenhouses), it is very important to know the exact quantity of sunlight necessary for plant growth.

A greenhouse is a man-made system to simulate an appropriate ecosystem in order to grow crops. At the beginning, these kinds of “houses” were property of rich people, since they wanted to obtain out-of-season fruit and vegetables. [44]

Nowadays, greenhouses fulfill important functions in the horticulture world. The main role is to save money and produce products. A greenhouse has to meet economic and environmental requirements, acquiring important benefit in the crops. [45]

Controlling the climate in the greenhouse allows protecting the vegetables from external climate (such as raining, snowing or sudden changes in temperature), in order to favor the growth. Greenhouses are built by transparent or translucent material structure. This material usually is glass or polyethylene (PE), but the most used is usually the PE [44]. The polyethylene is a material capable of blocking ultraviolet rays, but not the infrared radiation. This material presents a short durability; hence, this must be frequently changed.

On the other hand, a phytotron is an enclosed research greenhouse used to study interactions between plants and atmosphere. Phytotrons can regulate some growth parameters such as humidity, temperature, carbon dioxide (CO_2) concentration, and other environmental conditions. A phytotron is relatively expensive; but this is very useful in the evaluation of the crop quality, controlling the necessary lighting at each moment. [46]

3.5 Horticultural applications

LEDs can develop important functions in horticultural lighting [36]. These can control the production lighting in controlled environments and photoperiod lighting in greenhouses. There are three general LED configurations that can be applied to horticultural lighting: point source, planar array, and vertical array.

The first is to utilize LEDs as a *point source* that eliminates many of their inherent advantages as horticultural lighting. Current “bulb type” LED systems have been marketed for house plants [36]. Nevertheless, their output light at the canopy level is generally too low for most commercial horticulture applications [36]. For this reason, the bulbs need to be moved away from the plant canopy to procure broad enough area coverage, resulting in a rapid decrease of light levels.

The second configuration is p*lanar arrays* that are contiguous units of LEDs or configured as rails or bars; while *vertical arrays* are fabricated from similar configurations but operated within the plant canopy. [36]

4 Measurements and Results

This chapter is divided into four parts: the first consists in explaining main problems with the LED technology to acquire the best lighting for horticultural applications and applications for people (such as lighting at the workplace). The second one is about describing objectives and laboratory instruments that have been used to execute these measurements. Experimental measurements obtained are indicated in the third section. Finally, the conclusions about these results are shown at the end of this fourth chapter.

4.1 Problems

LEDs are devices of monochromatic light (except for white light spectrum); namely, they only provide a light color. These need to be mixed with other colors to supply high-quality growth for plants. Nevertheless, plants require acceptable intensity light to develop the photosynthesis process. One LED cannot generate this process; since plants demand a considerable number of LEDs to absorb adequate light levels through pigments, as the chlorophyll.

The horticultural lighting is quite difficult to identify the best combination for plants, since there are different valid mixtures. According to the vegetable or plant used will be better to utilize one kind of color combination or another one. Thus, this combination is capable of providing the best growth and development for them. This blend consists of merging blue and red color, and some other color can be also added to enrich and accelerate the plant growth.

On the other hand, LEDs also present problems when are utilized for general lighting. People need to sense well-being in their work environment or in any other situation. This light quality is mainly measured through color rendering index (CRI). This factor will be used in the next sections to measure and acquire a correct light for people and to avoid an uncomfortable lighting.

4.2 Objectives

The main role of LEDs, when they are used in horticulture and other applications for people, is to obtain the best lighting to acquire a satisfactory plant growth and a comfortable environment.

Several laboratory instruments are utilized to measure the quality light: various color LEDs; a spectrometer (*Ocean Optics HR4000*) and an optic fiber to transmit the color spectrum; a special black box to execute the color mixture and acquire its spectrum; a laptop; and software to represent the spectrum obtained through spectrometer and optic fiber. Some of these instruments used are shown in Figure 4.1.

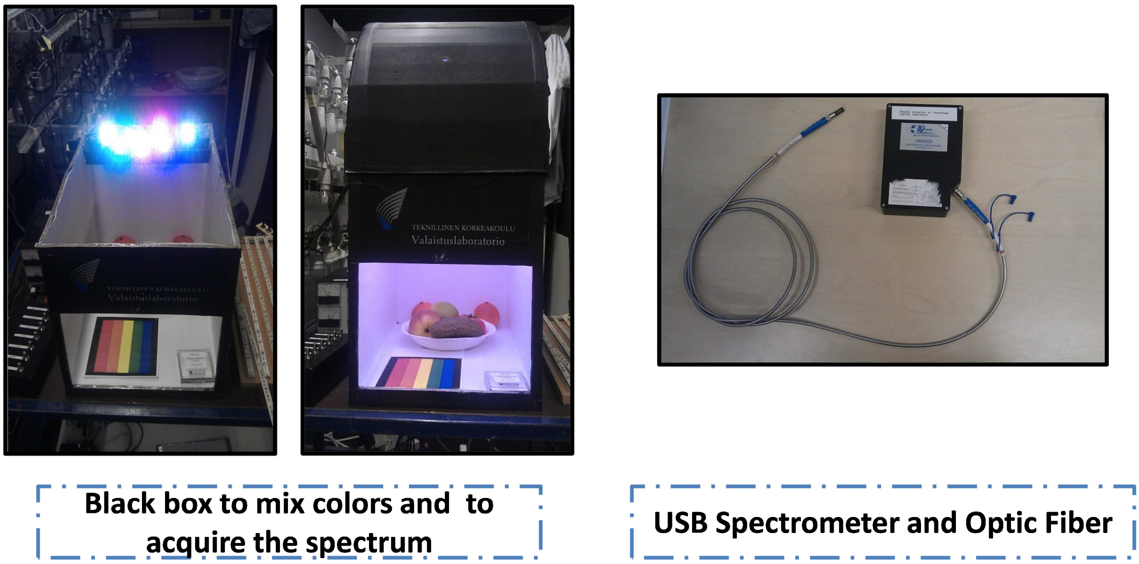


Figure 4.1: Some instruments used for experimental measurements

Colors, such as amber, blue, cool white, cyan, green (524 nm), green (532 nm), infrared, red (630 nm), red (670 nm), warm white, and yellow, are acquired in the lab-room. Microsoft *Office Excel 2010* software and a special application developed to Excel are used to combine these colors, acquiring the best possible CRI value to provide a notable lighting for people. This application allows playing with colors and knowing what percentages used are for each combination.

4.3 Results

This section shows measures and results obtained for different combinations of color LEDs. There are various kinds of combinations for fixed percentage and variable percentage. Firstly, when the best possible combination for plants is acquired, this same mixture is utilized to procure the most comfortable lighting for people (white light), adding new colors to this blend.

4.3.1 Combination of color LEDs for horticultural lighting and for general lighting (fixed percentage)

In this section, the percentages for plants are fixed to provide the best lighting for people. Namely, a new color mixture will be produced for applications in general lighting, keeping the same basic percentage used for horticultural lighting.

4.3.1.1 Blue and Red (670 nm) LEDs

Blue and red colors are the best blend for plants and vegetables. This composition allows acquiring an excellent plant growth in horticulture field.

According to the most recent researches, the combination roughly of 23% blue color and 77% red color provide good results for an optimum plant growth. The spectrum obtained presents two peaks around 450 nm (blue zone) and 670 nm (red zone), as shown in Figure 4.2.

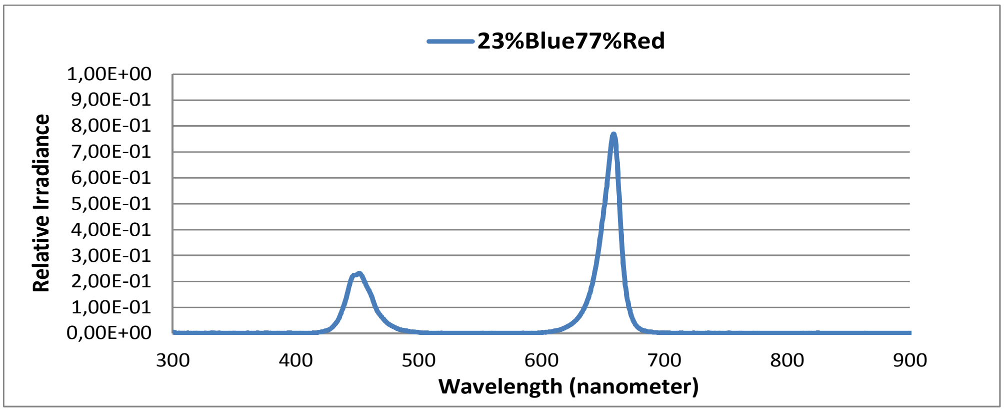
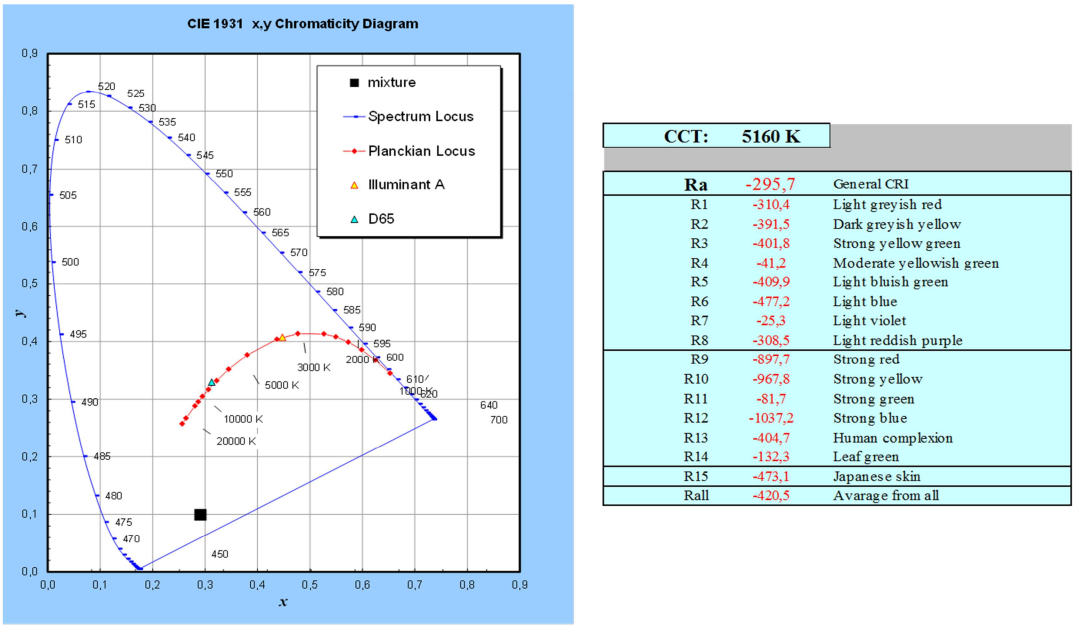


Figure 4.2: Spectrum obtained through blue and red color combination

These peaks correspond to the visible spectrum in plants. If this figure is compared with Figure 3.4, it will check that their waveforms are basically the same in both cases. For this reason, this color combination is the best one for plants.

If this result is represented in *CIE 1931 x,y Chromaticity Diagram*, it will checked that CRI is very poor value, as shown in Figure 4.3, because of this color combination is not usually used as lighting for people. Moreover, CRI method does not provide information for horticultural lighting, just for general lighting.

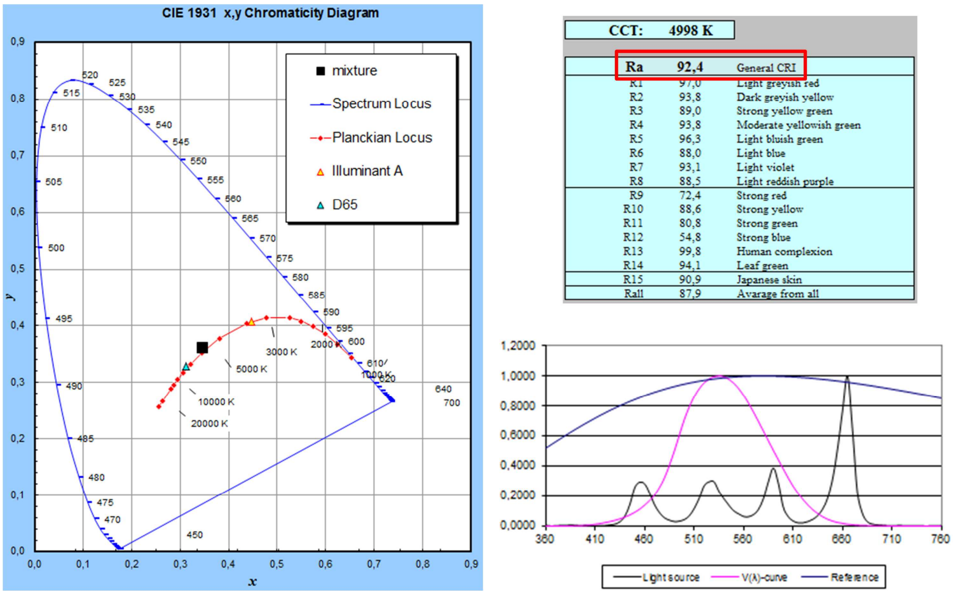


CCT:	5160 K	
Ra	-295,7	General CRI
R1	-310,4	Light greyish red
R2	-391,5	Dark greyish yellow
R3	-401,8	Strong yellow green
R4	-41,2	Moderate yellowish green
R5	-409,9	Light bluish green
R6	-477,2	Light blue
R7	-25,3	Light violet
R8	-308,5	Light reddish purple
R9	-897,7	Strong red
R10	-967,8	Strong yellow
R11	-81,7	Strong green
R12	-1037,2	Strong blue
R13	-404,7	Human complexion
R14	-132,3	Leaf green
R15	-473,1	Japanese skin
Rall	-420,5	Avarage from all

Figure 4.3: CIE 1931 x, y Chromaticity Diagram for combination blue and red LEDs

The main role consists of situating the black square above the red line, or technically called Planckian locus, to reach correct value for CRI. CCT also is checked, but this has less importance than CRI value because CCT only indicates whether the light is nearer cool white or warm white.

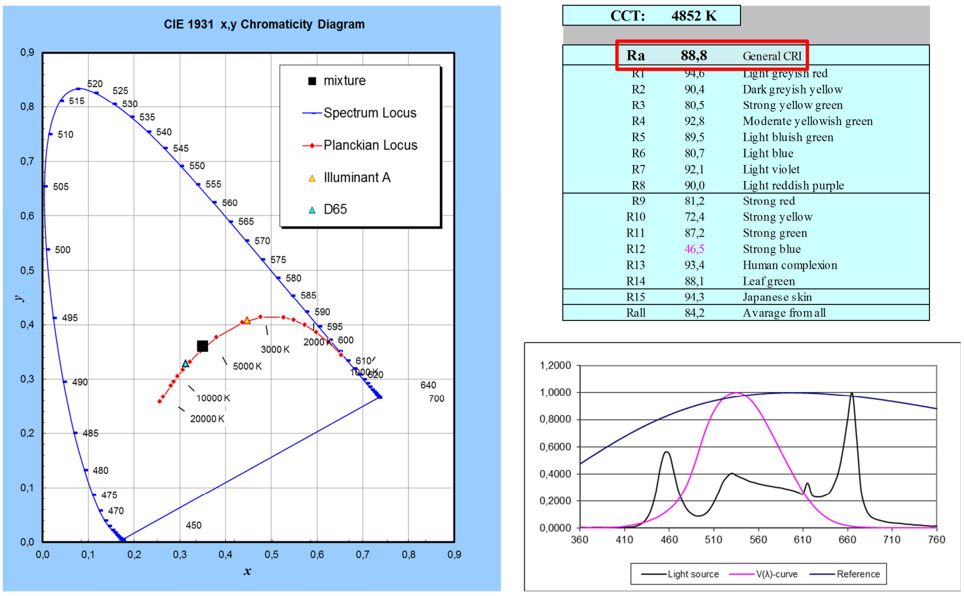
Various colors are tested to change the position of that square. Some colors such as yellow, amber or green are used. The amber color is rejected because CRI value is quite poor when this color is utilized. Therefore, yellow and green colors are selected, resulting in an exceptional color rendering (around 93) and CCT near cool white, as shown in Figure 4.4. The color percentage for this combination is 65% Blue-Red + 15% Green + 20% Yellow.



CCT:	4998 K	
Ra	**92,4**	General CRI
R1	97,0	Light greyish red
R2	93,8	Dark greyish yellow
R3	89,0	Strong yellow green
R4	93,8	Moderate yellowish green
R5	96,3	Light bluish green
R6	88,0	Light blue
R7	93,1	Light violet
R8	88,5	Light reddish purple
R9	72,4	Strong red
R10	88,6	Strong yellow
R11	80,8	Strong green
R12	54,8	Strong blue
R13	99,8	Human complexion
R14	94,1	Leaf green
R15	90,9	Japanese skin
Rall	87,9	Avarage from all

Figure 4.4: Result of combining blue-red, green, and yellow color

Moreover, other combinations are also possible to acquire a good-quality light with other different colors. In this case, colors used are blue and red color, green color, and cool white color. Thus, CRI slightly decrease its value because the blend contains a large amount of red color, as shown in Figure 4.5. However, CRI is still high value (88,8). The percentage for each color is 70% Blue-Red + 20% Cool White + 10% Green.



CCT:	4852 K	
Ra	**88,8**	General CRI
R1	94,6	Light greyish red
R2	90,4	Dark greyish yellow
R3	80,5	Strong yellow green
R4	92,8	Moderate yellowish green
R5	89,5	Light bluish green
R6	80,7	Light blue
R7	92,1	Light violet
R8	90,0	Light reddish purple
R9	81,2	Strong red
R10	72,4	Strong yellow
R11	87,2	Strong green
R12	46,5	Strong blue
R13	93,4	Human complexion
R14	88,1	Leaf green
R15	94,3	Japanese skin
Rall	84,2	Avarage from all

Figure 4.5: Result of combining blue-red, green, cool white, and yellow color

4.3.1.2 Blue, Red (670 nm), and Infrared LEDs

Infrared (IR) light effects are experienced in different ways. IR light positively affects plant bloom, excessive infrared light damage its growth and scientists utilize infrared in scanning techniques to monitor its development. [43]

Infrared color must combine in small amounts between red and blue color to obtain a right combination and to develop a notable plant growth. A good percentage is 22% Blue + 75% Red + 3% Infrared. The spectrum obtained for this percentage is shown in Figure 4.6.

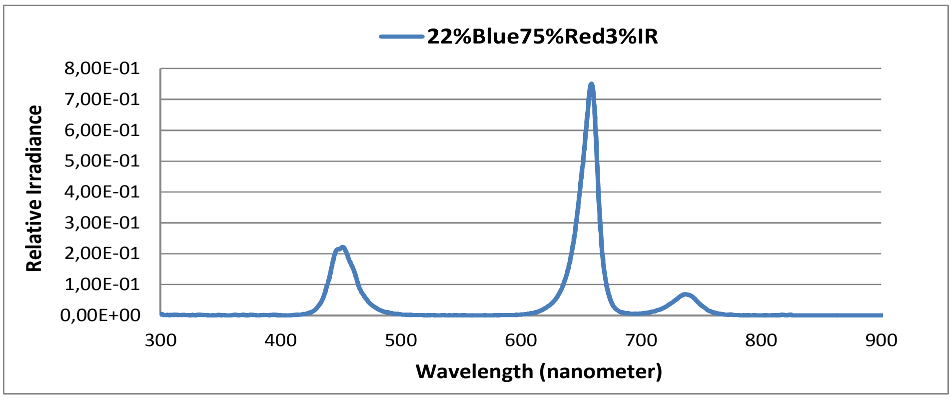
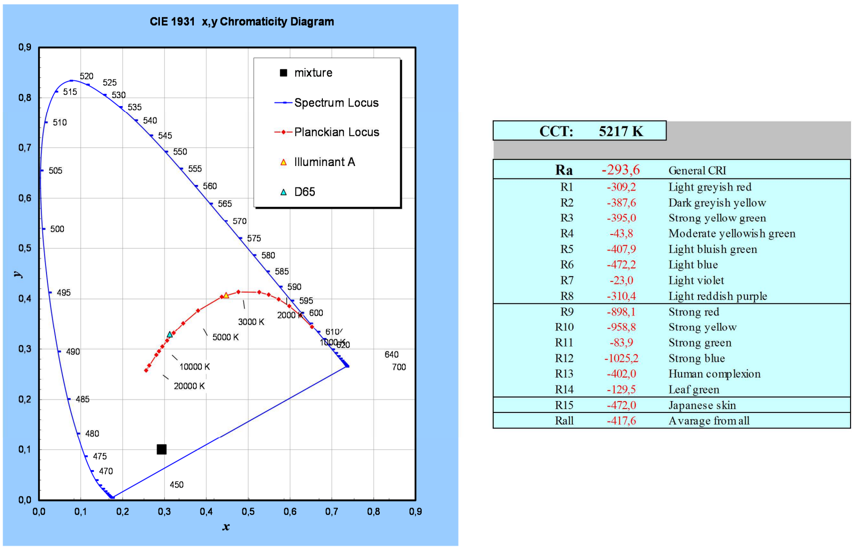


Figure 4.6: Spectrum obtained through blue, red and infrared color combination

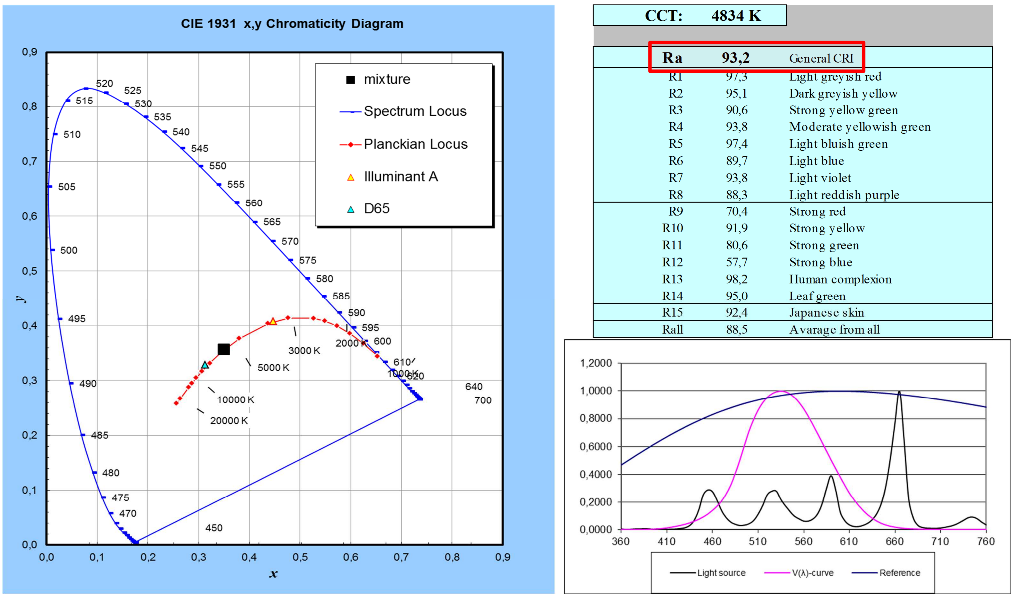
Similarly to the previous case, this percentage is represented in CIE 1931 x,y Chromaticity chart, as shown in Figure 4.7.



CCT:	5217 K	
Ra	-293,6	General CRI
R1	-309,2	Light greyish red
R2	-387,6	Dark greyish yellow
R3	-395,0	Strong yellow green
R4	-43,8	Moderate yellowish green
R5	-407,9	Light bluish green
R6	-472,2	Light blue
R7	-23,0	Light violet
R8	-310,4	Light reddish purple
R9	-898,1	Strong red
R10	-958,8	Strong yellow
R11	-83,9	Strong green
R12	-1025,2	Strong blue
R13	-402,0	Human complexion
R14	-129,5	Leaf green
R15	-472,0	Japanese skin
Rall	-417,6	Avarage from all

Figure 4.7: Spectrum obtained through blue, red, and infrared LEDs

Knowing the black square position, colors such as green and yellow can be deployed to check whether the lighting obtained is close to white light. Thus, the mixture is started with these colors and the fixed percentage of blue, red, and IR. This blend is altered until obtaining the best possible white light. The correct combination is 66%Blue-Red-IR + 20% Yellow + 14% Green, as shown in Figure 4.8:



CCT:	4834 K	
Ra	**93,2**	General CRI
R1	97,3	Light greyish red
R2	95,1	Dark greyish yellow
R3	90,6	Strong yellow green
R4	93,8	Moderate yellowish green
R5	97,4	Light bluish green
R6	89,7	Light blue
R7	93,8	Light violet
R8	88,3	Light reddish purple
R9	70,4	Strong red
R10	91,9	Strong yellow
R11	80,6	Strong green
R12	57,7	Strong blue
R13	98,2	Human complexion
R14	95,0	Leaf green
R15	92,4	Japanese skin
Rall	88,5	Avarage from all

Figure 4.8: Result of combining blue, red, IR, yellow, and green color

Figure 4.8 shows a fine CRI (93,2) value. Moreover, its CCT is nearby cool white. For this reason, this lighting can be considered outstanding for its usage in many applications.

4.3.1.3 Red (670 nm) and Cool White LEDs

Some studies have demonstrated that the combination between red and cool white generate a satisfactory growth for plants. Nevertheless, this combination is not better than the combination of red and blue color. Blue and red colors in plants are capable of providing notable properties to augment and improve its growth and development.

The percentage to acquire a correct lighting in horticulture field is 84% Red + 16% Cool White. This combination is shown in Figure 4.9:

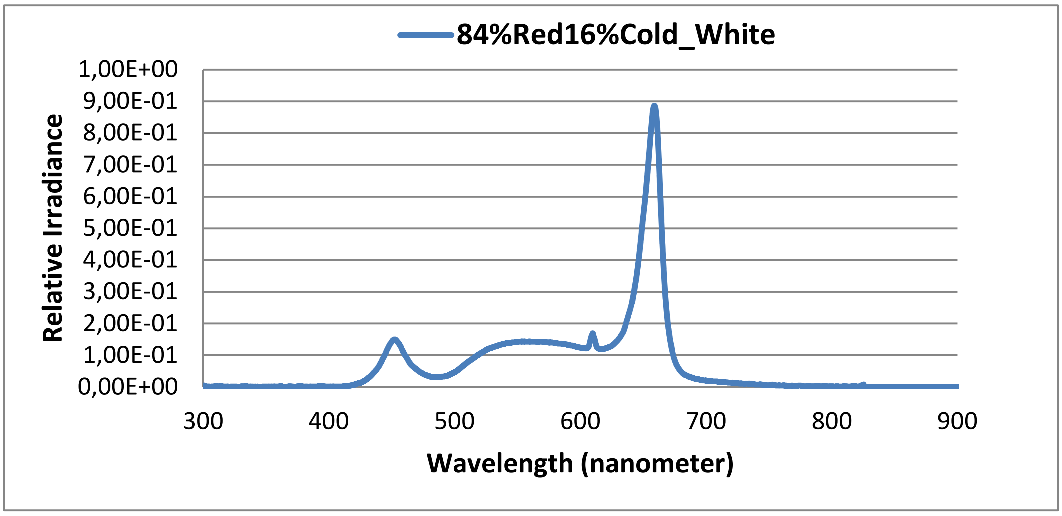
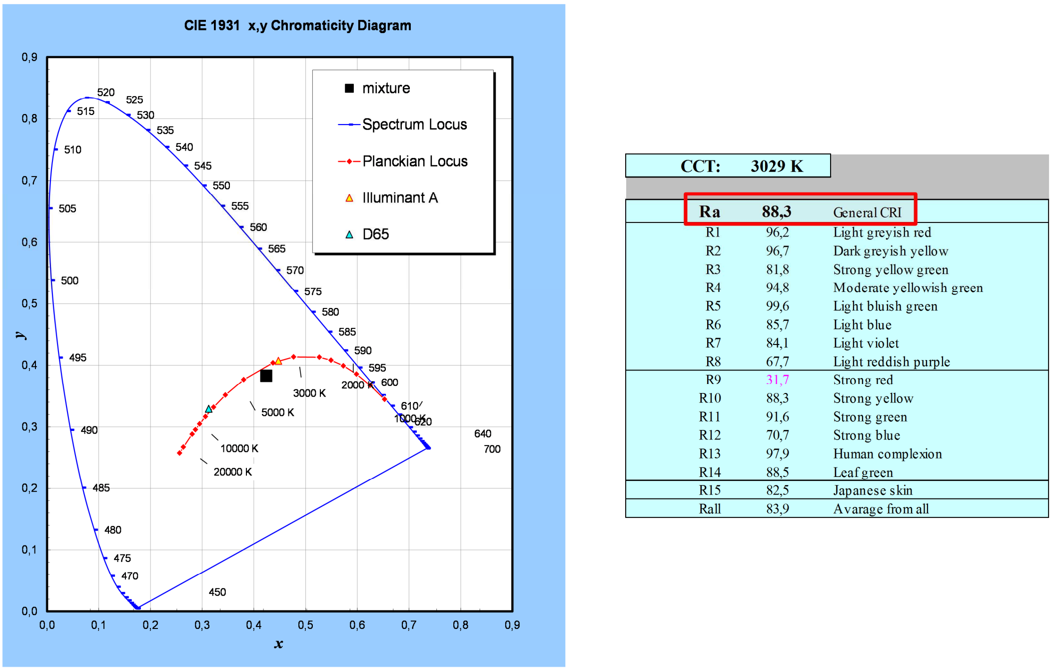


Figure 4.9: Spectrum obtained through red and cool white combination

Figure 4.9 illustrates the importance of this combination for plant growths, since this presents peaks around 450 nm and 660-670 nm. Therefore, this percentage provides a acceptable light for horticulture.

On the other hand, this same percentage is represented in chromaticity diagram, as shown in Figure 4.10:



CCT:	3029 K	
Ra	**88,3**	General CRI
R1	96,2	Light greyish red
R2	96,7	Dark greyish yellow
R3	81,8	Strong yellow green
R4	94,8	Moderate yellowish green
R5	99,6	Light bluish green
R6	85,7	Light blue
R7	84,1	Light violet
R8	67,7	Light reddish purple
R9	31,7	Strong red
R10	88,3	Strong yellow
R11	91,6	Strong green
R12	70,7	Strong blue
R13	97,9	Human complexion
R14	88,5	Leaf green
R15	82,5	Japanese skin
Rall	83,9	Avarage from all

Figure 4.10: Result of combining red and cool white

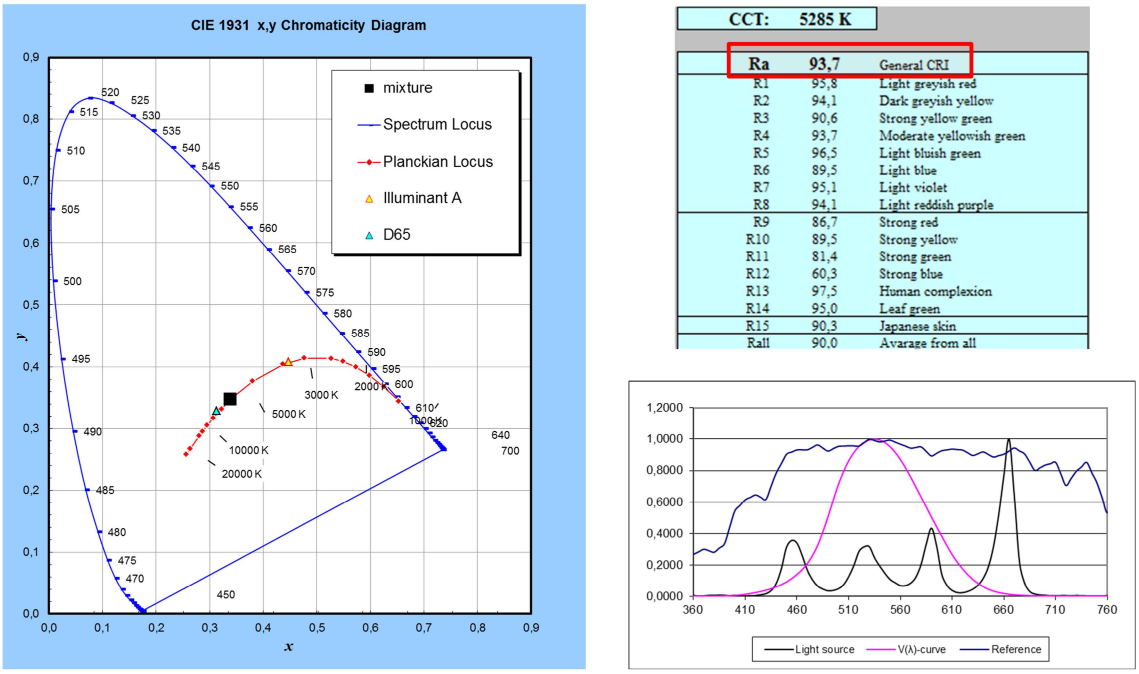
This mixture generates a fine light in horticulture lighting, and the same blend also creates an fair lighting for people. The CRI value is almost ideal (near 90); for this reason, this lighting can be utilized in horticultural lighting and general lighting, at the same time.

4.3.2 Combinations of color LEDs for general lighting (independent percentages)

For this new case, percentages are completely independent for each color. Namely, the combination is directly executed with different random colors to acquire the best white light.

4.3.2.1 Blue, Red, Yellow, and Green LEDs

The main role is to reach a high CRI value to acquire a notable-quality light (white light). Colors such as blue, red, yellow, and green are mixed to provide white light. The percentage obtained with this color mixture is: 17% Blue + 47% Red + 21% Yellow + 15% Green. This percentage is shown in Figure 4.11:



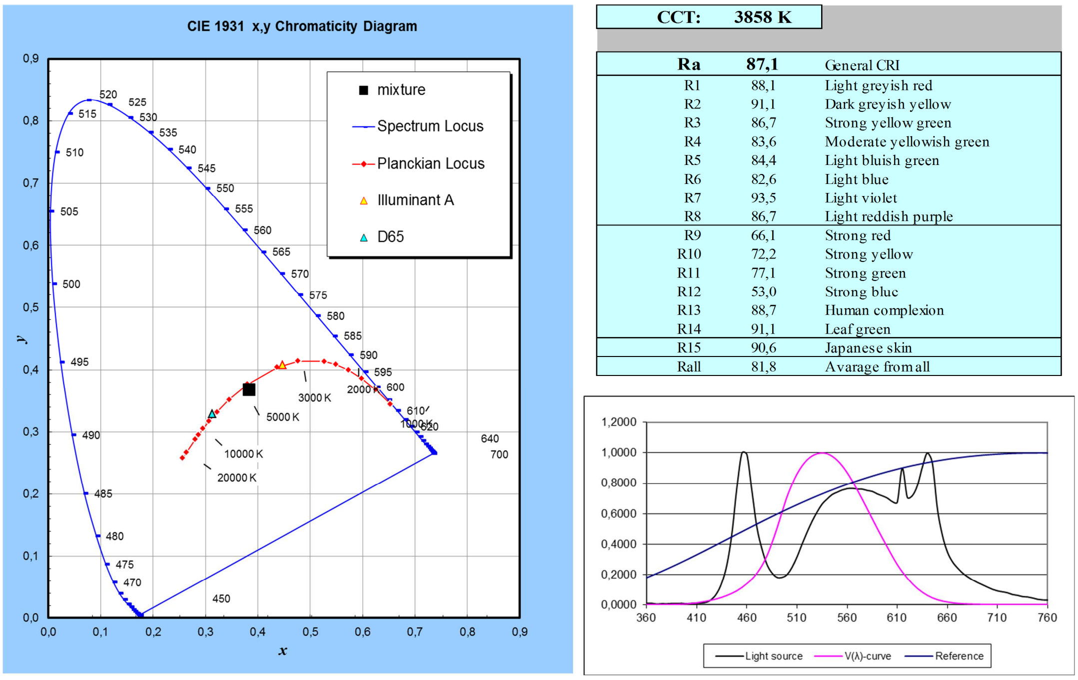
CCT:	5285 K	
Ra	93,7	General CRI
R1	95,8	Light greyish red
R2	94,1	Dark greyish yellow
R3	90,6	Strong yellow green
R4	93,7	Moderate yellowish green
R5	96,5	Light bluish green
R6	89,5	Light blue
R7	95,1	Light violet
R8	94,1	Light reddish purple
R9	86,7	Strong red
R10	89,5	Strong yellow
R11	81,4	Strong green
R12	60,3	Strong blue
R13	97,5	Human complexion
R14	95,0	Leaf green
R15	90,3	Japanese skin
Rall	90,0	Avarage from all

Figure 4.11: Result of combining blue, red, yellow, and green color

According to the Figure 4.11, this combination supplies a fine lighting for people. The CRI value is very high (around 94). Moreover, the color temperature is near cool white; therefore, this lighting would be notable choice for some applications.

4.3.2.2 Red, Cool White, and Blue LEDs

These colors have been combined to obtain an acceptable lighting for general lighting. The percentage of this mixture is 35% Red + 50% Cool White + 15% Blue. Adding a large amount of cool white is a good choice, because a satisfactory light can be acquired. Nevertheless, colors such as blue or red are necessaries to procure this adequate lighting, as shown in Figure 4.12:



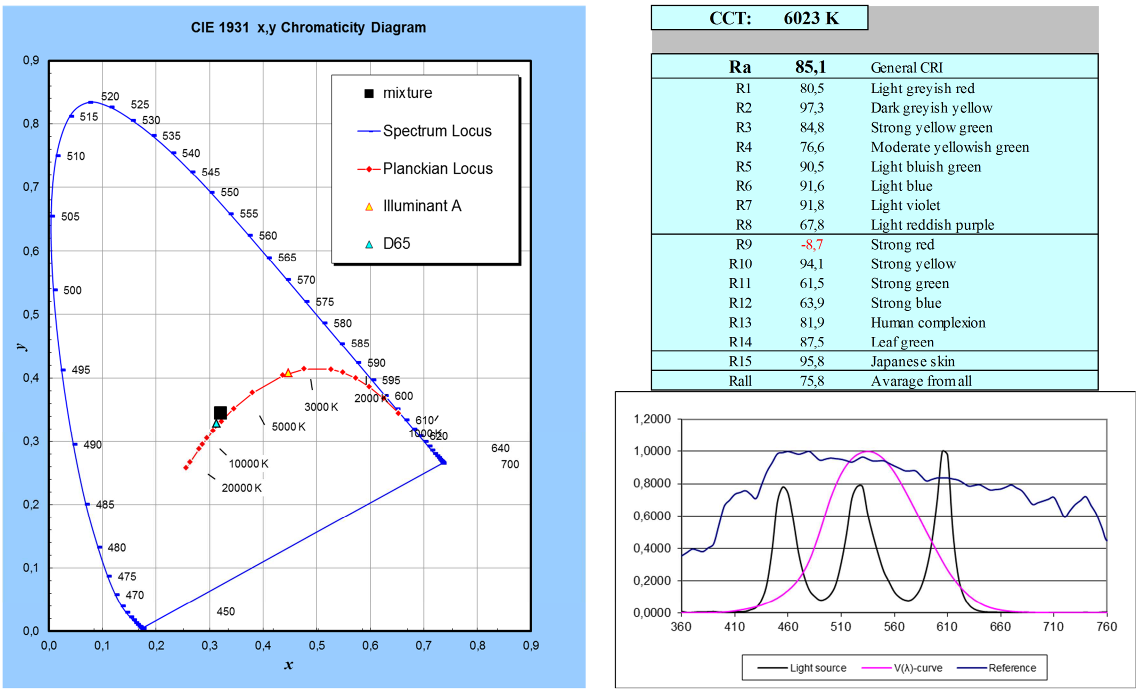
CCT:	**3858 K**	
Ra	**87,1**	General CRI
R1	88,1	Light greyish red
R2	91,1	Dark greyish yellow
R3	86,7	Strong yellow green
R4	83,6	Moderate yellowish green
R5	84,4	Light bluish green
R6	82,6	Light blue
R7	93,5	Light violet
R8	86,7	Light reddish purple
R9	66,1	Strong red
R10	72,2	Strong yellow
R11	77,1	Strong green
R12	53,0	Strong bluc
R13	88,7	Human complexion
R14	91,1	Leaf green
R15	90,6	Japanese skin
Rall	81,8	Avarage from all

Figure 4.12: Result of combining red, cool white, and blue color

The CRI is relatively high while CCT is close to warm white. This lighting obtained is acceptable for general lighting, since its color rendering is near 90; therefore, this is considered as a correct light for people.

4.3.2.3 Amber, Green, and Blue LEDs

For this last combination to analyze, colors such as amber, green and blue can also provide an acceptable light quality, as shown in Figure 4.13:



CCT:	6023 K	
Ra	**85,1**	General CRI
R1	80,5	Light greyish red
R2	97,3	Dark greyish yellow
R3	84,8	Strong yellow green
R4	76,6	Moderate yellowish green
R5	90,5	Light bluish green
R6	91,6	Light blue
R7	91,8	Light violet
R8	67,8	Light reddish purple
R9	-8,7	Strong red
R10	94,1	Strong yellow
R11	61,5	Strong green
R12	63,9	Strong blue
R13	81,9	Human complexion
R14	87,5	Leaf green
R15	95,8	Japanese skin
Rall	75,8	Avarage from all

Figure 4.13: Result of combining amber, green, and blue color

Figure 4.13 shows the combination of 40% Amber + 30% Green + 30% Blue. The result obtained is quite acceptable, because its CRI is high value (close to 86). Furthermore, its color temperature is very near cool white. In this way, this lighting would be accepted for general lighting.

4.4 Conclusions

Analyzed all cases, it is possible to obtain some comments about them. Firstly, all these measurements are simulations; therefore, these results are nearby reality. The results simulated are not exact, because there are always some errors that are obviated in these simulations.

Attending to results obtained, there is no difference between if the combination has been acquired through fixed percentage or variable percentage. Namely, good-quality lighting is obtained in both cases for horticultural lighting and general lighting.

The best mixture for plants is blue and red color; since, this blend generates a rapid growth and provides appropriate properties for the plant development and photosynthetic aspects. All these plant characteristics can be improved when some different colors are mixed with red and blue color. According to the colors added for plants, their attributes can enhance their quality for some aspects or other.

All results show notable color rendering index values, since these values are comprised from 85 to 94, supplying fine light for general lighting. However, CCT values are very variable because cool white and warm white are acquired for different combinations. Warm white or cool white can be indistinctively utilized in many applications, but depending on planned application will be more interesting to use cool white or warm white.

Finally, it is possible to procure a notable lighting for people through horticultural lighting. These light sources are very simple to obtain in simulations; nevertheless, it is sometimes possible to find little problems when these lights or combinations are executed for real cases.

5 Conclusions and Future Works

Lighting is a large growing source of energy demand, and it is necessary to seek new lighting alternatives. Most traditional lighting sources (incandescent, fluorescent, high pressure sodium) produce quite wasted energy. Nevertheless, LED lights are a fast developing technology, with a high potential for development in future years and to save energy. [47]

The main purposes of an optimum lighting design is to achieve certain appearances and, at the same time to fulfill the fundamental physiological aspects and psychological visual requirements. Nowadays, LEDs are designed with numerous shape and architectures for different lighting solutions. However, these devices still present some problems to control them: glare assessment, color rendering, and light distribution.

Light is the key element that stimulates the process of photosynthesis. By using LEDs, it is possible to tailor the growth to the specific spectrum necessary of plants. They are the green alternative to standard horticultural lighting. By utilizing state-of-the art of this technology, there is a significant opportunity to stimulate plant growth while drastically reducing energy consumption through the use of targeted lighting at 660 and 450 nanometers.

The utilization of artificial lighting in controlled or closed growth environments offer great opportunities for the cultivation of different crops or plants [31]. This artificial lighting can be controlled with control devices. Thus, it is possible to control light and color, adjusting to the necessities of the plant [48]. This means that the plants do not need the same light composition all the time; therefore, these color combinations must be changed according to the necessities that they require.

LED lamps can control the amount of light, according to the daylight entering a greenhouse. It is likely to use some control systems capable of controlling LEDs or other factors in the greenhouses. Nowadays, there are various control systems for general lighting or horticultural lighting. Some examples of control systems are: RGB dynamic color system, color temperature control systems, dimming control systems, and Dynamic Lighting Control (DLC) [49].

RGB dynamic control system is used for architectural lighting. However, color temperature control systems and dimming control systems are mainly deployed for lighting studios, minimizing energy usage. [49]

A Dynamic Lighting Control (DLC) can create several effects and moods with various color lights [50]. Some companies, such as Philips or Osram, supply this kind of control.

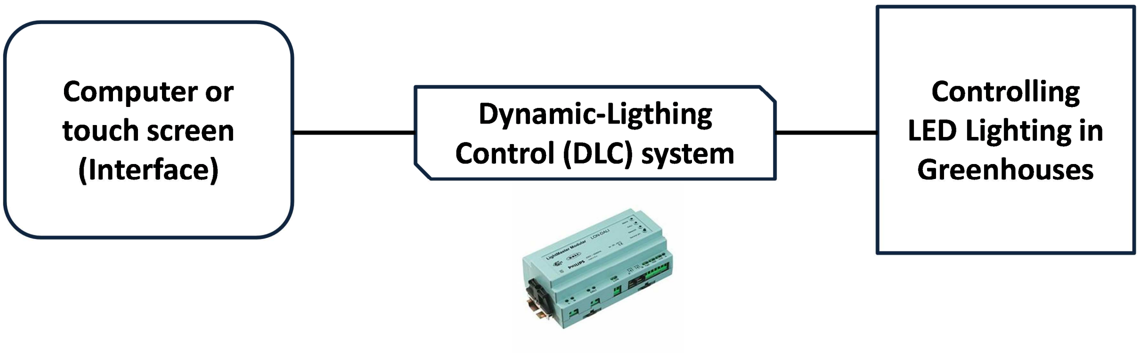


Figure 5.1: Diagram how to work a Dynamic-Lighting Control (DLC) system in greenhouses

A control device or DLC can control with large precision some aspects such as light quantity, quality, photoperiod, and combinations between LEDs. This control device may be adjusted throughout the life of a plant to potentially optimize traits of interesting such as synchronization of flowering, maintenance vegetative growth programs, control of plant stature, or acceleration of its growth [51].

Dynamic Lighting Control can also regulate the energy consumption whether the control system is connected to a daylight sensor. If the greenhouse does not receive plenty of sunlight for the plants, then it is necessary to use energy to turn on LEDs. However, if the greenhouse has got enough natural light, there is no reason to consume excessive amount of energy, since this energy would be wasted.

There are some forecasts where it is possible to anticipate that LEDs will revolutionize the lighting practices and market in the near future [16]. It is important to know that LED technology is constantly developing to obtain a better technology. According to the *US Department of Energy 2011 solid-state lighting manufacturing roadmap*, the prices of LED lamps and LEDs packages will drop around 30% from 2010 to 2015 and

10%-15% from 2015 to 2020 [49]. Therefore, LED usage will be cheaper and will increase its expansion in the horticulture field.

Nowadays, this LED technology is very useful and important for lighting world. However, there is another technology in development, such as OLEDs. They are capable of providing better lighting and color quality than LEDs; however they are still a very expensive technology. OLEDs will probably use in few years, contributing to high-efficiency.

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