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Role of LED (Light Emitting Diode) Light Illumination on the Growth of Plants in Greenhouse Farming-Hydroponics: IOT Technology

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Abstract

This review paper of literature highlights role of Light Emitting Diode (LED) on the growth of plants under controlled conditions of greenhouse farming particularly hydroponics. “Internet of Things (IOT)” is a system of interconnected computing devices, sensors, objects, microcontrollers, and cloud servers that can transmit data across a network and control other devices remotely without human intervention. Light Emitting Diode (LED) is a more efficient, versatile, lasts longer, highly energy-efficient, directional, narrow light spectrum, low power consumption, and little heat production. Common LED colors include amber, red, green, and blue. Hydroponic grow lights are designed to mimic the natural light that plants need for photosynthesis. Plants can only use the spectrum of visible light to produce photosynthesis, and this narrow spectrum (400 to 700 nanometer) is recognized as the **Photosynthetically Active Radiation** (**PAR**). The development and growth of diverse plant species can be influenced differently by a variety of colored LED lights. LED illumination provides an efficient way to improve yield and modify plant properties. Therefore, LED systems plays an important role in controlling morphological, genetic, physiological, chemical properties, increasing the synthesis of a variety of beneficial secondary metabolites, and optobiological interactions of plants in greenhouse farming. In general, red and blue light is essential for maximizing the photosynthesis process due to their strong absorption by the plant chlorophyll molecules. LED illumination sources are increasingly being utilized to enhance the growth rate of vegetables and herbs cultivated in greenhouses worldwide. LED illumination spectrum manipulation could enable significant morphological adaptations, and identification of the wavelength ranges is required to increase the plant photosynthesis process.

Keywords: Greenhouse farming; Hydroponics; Illumination; IOT technology, Light Emitting Diode (LED); Photosynthetically Active Radiation (PAR); Vertical farming

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1. Introduction

Hydroponics is the art of growing plants without a soil but with using nutrient solution under hi-tech greenhouse controlled conditions in urban area [1-100]. Because of the precise regulation of watering and feeding the plant, this method is superior to the traditional method 1-243]. Hydroponic systems are designed to provide plants with the right amount of water, nutrients, and oxygen for optimal growth [1, 4, 224-226]. They are used in both commercial and private settings to cultivate various plants, including vegetables, fruits, herbs, and flowers. Hydroponics is influenced by many factors such as, light, oxygen level, carbon di-oxide (CO_2), nutrients supply, pH and electrical conductivity (EC), water and humidity, temperature, human labor, maintenance of the machinery, electricity, and water supply[1-243]. However, carbon foot print of hydroponic vertical farming is very high. In many cases, vertical farm production methods contribute more to greenhouse gas (GHG) emissions than products grown in the field and shipped long distances to market [1-243]. Hydroponic systems are classified into different types, vary in the pattern of their water/nutrition supply, among which Deep Water Culture, Dutch Bucket method, Wick System, Ebb and Flow (or Flood and Drain), Nutrient Film Technique (NFT), Vertical farming, Aeroponics, Aquaponics, Fogoponics, Kratky, and Drip irrigation system are the most popular hydroponics systems [1-176-184-223-243]. The hydroponic method is successfully used for fast-growing leafy vegetables and commercial crops, such as lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), potato (*Solanum tuberosum* L.), tomato (*Solanum lycopersicum* L.), Kale (*Brassica alboglabra* L.), pepper (*Capsicum annuum* L.), Cucumber (*Cucumis sativus* L.), and Strawberry (*Fragaria ananassa)* [1-184-223-232-238-240]. Some of the more common techniques used in greenhouse production include drip irrigation, hydroponics and aeroponics [1-176-184-223-243].

Hydroponics makes it possible to harvest several crops throughout the year, without chaotic discharges of either pesticides or fertilizers to the environment [1-184]. Hydroponics uses less land and water than traditional open-field agriculture [1-184-223-243]. Indeed, by using smart greenhouses equipped with several computer based technologies to control critical parameters for healthy plant physiology [1-243, 395-397]. Furthermore hydroponic optimizes the use of water and chemicals to eliminate potentially hazardous waste and residuals [1-180]. Large-scale hydroponics facilities operate under controlled conditions of climate, lighting, and irrigation, rendered by numerous sensors, web platforms, software (IOT applications), and now a days mobile applications available[15, 43, 55-59, 62, 66 ,73, 92, 118, 125, 134, 176-183, 395-397]. Due to such technological advancements, the hydroponics' market is expected to grow significantly from 2021 to 2028, at a compound annual growth rate (CAGR) of 20.7% from 2021 to 2028 [1-180].

Internet of Things (IOT) technologies has been used through Artificial Intelligence (AI) [395-397], machine learning-based energy, water-saving measures, automated farm operations, and mechanization to resolve crop monitoring challenges in a controlled urban hydroponics [1, 4,15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183, 395-397]. Hydroponics, a cultivation technique without soil, facilitates the growth of organic vegetation while concurrently minimizing water use and eliminating the necessity for pesticides [1-243]. In order to achieve effective cultivation of hydroponic plants, it is essential to maintain a controlled environment that encompasses essential factors such as temperature, carbon dioxide (CO_2) levels, oxygen availability, and appropriate lighting conditions [1- 176-183-243]. Additionally, it is crucial to ensure the provision of vital nutrients to maximize output and productivity [1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183]. Due to the demanding nature of a hydroponic farmer's schedule, it is necessary to minimize the amount of time dedicated to nutrient management, as well as pH and EC adjustments [1- 176-183-243]. Therefore, smart greenhouses can aid farmers in raising the yield of their crops[1- 176-183-243]. The sensors capture the data inside and outside the greenhouse and automatically transmit them to a central cloud server for storing and archiving [1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183]. These data can be accessed by end-users devices and benefit from the generated knowledge of their crops, suitable harvesting time, and energy consumption [1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183]. Additionally, cloud edge points can be used for storing the data for more rapid processing [1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183]. The implementation of intelligent agriculture, Artificial Intelligence (AI), big data, robotics, and IOT in agriculture accelerated the transition from Agriculture 3.0 to Agriculture 4.0 [1, 160-178, 346, 395-397]. Smart farming (represented in Agriculture 4.0) provides a path to sustainability by applying information and communication technology (ICT) with technologies like cloud computing [1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183]. IOT, AI, and robotics technologies in the cyber-physical cycle of farm management has been applied[1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183, 395-397]. The evolving Internet of Things (IOT) technologies, including smart sensors, devices, network topologies, big data analytics, and intelligent decision-making, are thought to be the solution for automating greenhouse farming parameters like internal atmosphere control, irrigation control, crop and growth monitoring [1, 15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183, 395-397].

Hydroponic systems are a combination of several technologies and include a specific set of system models [1-176-243]. These systems enable growers to obtain higher yields with each harvest and eliminate the need for pesticides and herbicides as compared to traditional cultivation methods. Exotic vegetables, cabbage, peas, and salad vegetables grow well using hydroponics[1-176-243]. Crops such as tomatoes, exotic vegetables, cabbage, peas, and salad vegetables required proper care and continuous maintenance[1-176-243]. In the following section, the LED light applications, role of LED lighting illumination on the growth of plants has been reviewed and discussed.

2. Hydroponics :History

The term "hydroponics" was first introduced by American scientist Dr. William Gericke in 1937 to describe all methods of growing plants in liquid media for commercial purposes [1, 4, 8, 214-224]. Dr. William F. Gericke is attributed with being the father of modern hydroponics [4, 8]. Born on a Nebraska farm August 30th, 1882 [4, 8]. Educated at Ohio State, Johns Hopkins, California [4, 8]. He was a professor and plant physiologist at UC Berkeley, USA [8]. Before 1937, scientist were using soilless cultivation as a tool for plant nutrition studies [1, 4, 8, 214-225]. In 1860, two scientists, Knop and Sachs, prepared the first standardized nutrient solution by adding various inorganic salts to water, then using them for plant growth [214-224] Later, scientists started using an aggregate medium to provide support and aeration to the root system [1, 4, 214-225]. Quartz sand and gravel were the most popular aggregate mediums used in soilless cultivation at that time [4, 214-225]. In the late 1960s, Scandinavian and Dutch greenhouse growers tested rockwool plates as a soil substitute, which resulted in revolutionary expansion of rock wool-grown crops in many countries [4, 214-225]. Today, many alternative porous materials are used as growing media in hydroponics, including organic medias like coconut coir, peat, pine bark and inorganic mediums such as mineral wool, grow stone, perlite and sand [4, 214-225]. The famous Hanging Garden's of Babylon were rumoured to have used hydroponics to create the incredible famous for lush growth [4, 8]. However modern historians doubt that Similarly, ancient Egyptian hieroglyphics dating back to several hundred years BC depict the growing of plants along the Nile River without soil, as do the floating gardens of the Chinese, as described by Marco Polo in his famous journal [4, 8]. The Aztec "chinampas" were a form of hydroponics, floating rafts of reeds loaded up with sediment from the lake bottom8]. Roots of the plants grew through the reeds allowing constant water source and root oxygenation. Some chinampas were up to 60 metres long [4, 8].

3. Hydroponics: Light Emitting Diode (LED)

LED is defined as Light Emitting Diode, a new technology which produce light more efficiently than incandescent light bulbs [4, 244-264]. LED lighting differs from incandescent and fluorescent in several ways [4, 244-264]. LED lighting is more efficient, versatile, and lasts longer. In 1962, Nick Holonyak, Jr, invented the first LED that could produce visible red light [244-264]. He invented these red diodes during his employment with General Electric. For his achievement, Holonyak has earned the title of "Father of the Light-Emitting Diode" [4, 244-264]. On August 8th of 1962, the two engineers filed a patent for "Semiconductor Radiant Diode" based on their work, which the U.S. Patent Office granted for their GaAs infrared light-emitting diode, under U.S. Patent No. 3, 293, 513 [4, 244-264]. The work from Texas Instruments was expanded upon by Hewlett-Packard (HP) to create cost effective LEDs for the commercial market 244-264]. LED is a highly energy-efficient lighting technology, and has the potential to change the future of lighting throughout the world [244-264]. The useful life of LED lighting products is defined differently than that of other light sources, such as incandescent or compact fluorescent lighting (CFL) [244-264]. LEDs typically do not "burn out" or fail. Instead, they experience 'lumen depreciation. This means brightness of the LED dims slowly over time [244-264]. LEDs are "directional" light sources, which means they emit light in a specific direction, unlike incandescent and CFL, which emit light and heat in all directions [1-244-264-280]. Hence LEDs are able to use light and energy more efficiently in a multitude of applications [244-264]. LEDs use heat sinks to absorb the heat produced by the LED and dissipate it into the surrounding environment. This keeps LEDs from overheating and burning out [244-264-265-335-392]. Thermal management is generally the single most important factor in the successful performance of an LED over its lifetime [244-264]. Common LED colors include amber, red, green, and blue [244-264-265-335-392]. To produce white light, different color LEDs are combined or covered with a phosphor material that converts the color of the light to a familiar "white" light used in homes [1, 4, 244-264-265-335-393]. Phosphor is a yellowish material that covers some LEDs [244-264]. Colored LEDs are widely used as signal lights and indicator lights, like the power button on a computer[244-264].

A light-emitting diode is a semiconductor device that emits visible light when an electrical current passes through it. It is essentially the opposite of a photovoltaic cell (a device that converts visible light into electrical current) [244-264]. A diode is an electrical device or component with two electrodes (an anode and a cathode) through which electricity flows - characteristically in only one direction (in through the anode and out through the cathode) [244-264]. Diodes are generally made from semi-conductive materials such as silicon or selenium - substances that conduct electricity in some circumstances and not in others (e.g. at certain voltages, current levels, or light intensities) [244-264]. LEDs are composed of two types of semiconducting material (a p-type and an n-type) [244-264]. Both the p-type and n-type materials, also called astringent materials, have been doped (dipped into a substance called a “doping agent”) so as to slightly alter their electrical properties from their pure, unaltered, or “intrinsic” form (i-type) [244-264]. When a light-emitting diode (LED) has a voltage source connected with the positive side on the anode and the negative side on the cathode, current will flow[244-264].

LED lighting is very different from other lighting types such as incandescent and CFL. Key differences include: Light Source: LEDs are the size of a fleck of pepper, and can emit light in a range of colors [244-264]. A mixture of red, green, and blue LEDs is sometimes used to make white light [244-264]. Direction: LEDs emit light in a specific direction, reducing the need for reflectors and diffusers that can trap light [244-264]. This feature makes LEDs more efficient for many uses such as recessed down lights and task lighting [244-264]. With other types of lighting, the light must be reflected to the desired direction and more than half of the light may never leave the fixture [244-264]. Heat: LEDs emit very little heat [244-264]. In comparison, incandescent bulbs release 90% of their energy as heat and CFLs release about 80% of their energy as heat[244-264]. Lifetime: LED lighting products typically last much longer than other lighting types [244-264]. A good quality LED bulb can last 3 to 5 times longer than a CFL and 30 times longer than an incandescent bulb[244-264]. The high efficiency and directional nature of LEDs makes them ideal for many industrial uses [244-264-265-335-392]. LEDs are increasingly common in street lights, parking garage lighting, walkway and other outdoor area lighting, refrigerated case lighting, modular lighting, and task lighting [244-264].

4. LED Light Measurement: Lumens

The brightness of all types of LED lights is measured in Lumens [244-264]. More Lumens means a brighter bulb. Traditional incandescent bulb brightness is measured in watts [244-264]. Because LEDs use far less energy than incandescents, a better way to gauge the brightness of LED bulbs is to compare Lumens [244-264]. For example, a traditional 60-watt light bulb will emit around 700-Lumens [244-264-265-335-392]. An LED bulb with comparable Lumens uses less than 10-watts of electricity [244-264]. Lumens = the amount of light the bulb gives off. Wattage = the amount of energy a bulb uses. The greater the Lumens-to-watts ratio a bulb has, the more energy-efficient it is [244-264].

Light intensity is how much light is reaching a surface [244-264]. The most common unit of measurement for light intensity is Lux (lx) [244-264]. One Lux is equivalent to the amount of light cast from a candle on a squared meter surface one meter away [244-264]. It is one Lumen of light per square meter [244-264]. For plants, the ideal light intensity depends on the type of plant, and its growth stage [244-264-265-335-393]. For example, hydronic vegetables like lettuce prefer light with an even wavelength of 400 to 700 micromoles of intensity [244-264]. While other plants, like tomatoes, prefer a full spectrum light with heavy on red and 800-900 micromoles of intensity [244-264]. Hence one can easily measure the intensity of light with a Lux-meter [244-264]. Most Lux meters have a sensor that measures the amount of light in a specific area and then displays the results in Lux (lx) [244-264].

5. Hydroponic Gardening: LED Light

Light is one of the most essential factors in growing plants [1, 4, 244-264-265-335-393]. In fact, plants can only grow and produce food through photosynthesis, which uses artificial or natural sunlight to convert water and carbon dioxide into the things plants need to survive: oxygen and glucose [1, 4, 244-264-265-335-392]. This is especially true for hydroponic gardening [1, 4, 244-264-265-335-392]. The right kind of light will help plants to grow strong and healthy, while the wrong kind of light can cause them to weaken and become sickly [4, 244-264-265-335-392]. But with so many different types of hydroponic grow lights on the market, it can be tough to decide which is right for hydroponic setup[244-264-265-335-392]. Light is a vital element for plant growth[1, 4, 244-264-265-335-392].

While all plants need light to grow, not all plants require the same amount or type of light [4, 244-264-265-335-392]. For example, tomatoes and pepper plants are high-intensity-light plants, which means they need a lot of light to produce fruit[4, 244-264-265-335-392]. On the other hand, lettuce and spinach are low-intensity-light plants, which means they can grow with less light[4, 244-264-265-335-392]. Hydroponic grow lights are designed to mimic the natural light that plants need for photosynthesis[4, 244-264-265-335-392]. This means they provide a light source with the right mix of light wavelengths and intensities that plants need to grow [4, 244-264-265-335-392]. This includes day length, light color, and light intensity [4, 244-264-265-335-392]. Both daytime and night time cycles are considered when designing hydroponic grow lights and are equally crucial for plants[4, 244-264-265-335-392]. Light contains different wavelengths. These wavelengths determine the color of the light and the energy level [4, 244-264-265-335-392]. For example, blue light has a shorter wavelength than red light, which means it has more energy[4, 244-264-265-335-392].

The shorter the wavelength, the higher the energy. The longer the wavelength, the lower the energy[4, 244-264-265-335-392].

When it comes to plant growth, different colors of light have different effects[4, 244-264-265-335-392]. For example, blue light is typically used for vegetative growth, while red light is used for flowering and fruiting [244-264-265-335-392]. However, it is important to note that plants do not just use one wavelength of light. Instead, they use a mix of all the different colors of light in the visible spectrum [244-264-265-335-392]. Therefore, hydroponic grow lights are designed to mimic the sunlight that plants need for optimal growth of plants [4, 244-264-265-335-392]. Although a lux meter may provide some guidance on light intensity[244-264]. While lux is only concerned with the amount of light humans can see (lumens), plants also take in light beyond this range [244-264]. This is called Photosynthetically Active Radiation (PAR) [244-264-265-335-392]. PAR meters measure the amount of PAR light, which is the light that is used for photosynthesis. This is the light in the visible spectrums 400 to 700 nanometer [4, 244-264-265-335-393].

There are several different types of hydroponic lights available in the market, each with its own set of advantages and disadvantages [4, 244-264-265-335-392]. Therefore, choice of the hydroponic light will ultimately depend on specific grow operation [244-264-265-335-392]. HID Lights : High-intensity discharge (HID) lights are some of the most popular grow lights in the market [244-264]. Commercial hydroponic growers often use them because they are very efficient and produce a lot of light [244-264]. HID lights come in three different varieties: Metal halide (MH), Ceramic Metal Halide (CMH), and High-pressure sodium (HPS) [244-264-265-335-392]. Metal halide (MH) lights emit a blue light spectrum ideal for vegetative growth, while High-pressure sodium (HPS) lights emit a red light spectrum ideal for flowering plants [244-264]. Ceramic Metal Halide (CMH), and Metal halide (MH) lamps can be used for both vegetative growth and flowering, while an HPS light should only be used during the flowering stage [244-264]. ID lights also produce a lot of heat, so they need to be used in conjunction with a cooling system, like an air-cooled reflector or inline fan. Fluorescent Grow Lights: Fluorescent lights are another popular type of grow light, especially among home growers [244-264]. They are very energy-efficient and emit very little heat, making them ideal for small growth operations [244-264]. Fluorescent light is best for vegetative growth and can be used with an HID grow light for flowering [244-264]. Fluorescent lights come in two varieties: Compact fluorescent lights (CFLs) and T5 fluorescent lights [244-264]. Compact fluorescent lights (CFLs) are smaller and do not produce as much light. Moreover, T5 fluorescent lights are often used in commercial grow operations because they are very efficient and produce a lot of light [244-264-265-335-392]. LED grow lighting is becoming a gold standard in the grow light industry because of its many advantages [4, 244-264]. For example, LEDs are long-lasting, very energy-efficient, and emit very little heat [4, 244-264-265-335-392]. An LED fixture can last up to 50,000 hours, which is much longer than an HID or fluorescent lamp[4, 244-264]. One of the biggest advantages of an LED light is that it can be tuned to specific wavelengths of light [4, 244-264-265-335-392]. This means one can get a LED grow light that emits specific wavelengths of light for plants need for optimal growth [4, 244-264]. LED grow lights can be customized to specific grow operation, from red/blue to full-spectrum light [244-264-265-335-392].

6. Hydroponic Grow Lights: Main Parts

Hydroponic grow lights consist of three main parts: Ballast – The grow light ballast is the component that regulates the voltage and current going to the light bulb [244-264]. Reflector –The reflector is responsible for gathering as much light as possible and reflecting it onto the plants [244-264]. Lamp – The lamp (commonly but erroneously called a "bulb") is where all the action happens [244-264]. This is the part of the grow light that produces the different wavelengths of light that plants need for photosynthesis [244-264]. Timer – The timer is an optional component that can be used to automate the grow light cycle [244-264].

7. Hydroponics: Applications of LED light

One of the greatest challenges of modern agriculture is to produce more healthier, and safer food under sustainable systems [1, 4, 244-264-265-335-392]. This includes a focus on increasing the efficiency of water, nutrients and increasing the sustainable productivity of crops under innovative systems with LED lights on soilless cultures [1, 4, 359]. Light emitting diodes (LEDs) offers advantages of narrow light spectrum, low power consumption, and little heat production [4, 358]. With the LED technology, commercial production and research have increased involving the use of LED in the growth process [4, 244-264-265-335-392]. Various research investigations have examined crop production under different color LEDs, varying color fluorescent lights, and diverse combinations of these two lighting sources [4, 244-264-265-335-392]. LED lighting has become allied to these systems, as they are energy efficient and can have a specific spectrum for each agricultural need [4, 244-264-265-335-393]. However, it has been shown that not only the development and growth of the plants is solved by this system, but also the crops suffer changes, improvements, or damages that cause the increase or decrease of nutritional compounds in the crops [4, 244-264-265-335-393]. The combined effect of LED lighting through vertical farming systems is an alternative to increase the nutritional parameters, productivity of vegetables crops, optimizing the raw resource use, such as water and energy [1, 4, 244-264-265-335-393]. As a growing light, the LED is a growing technology compared to conventional lighting sources such as high-pressure sodium lights (HPS) or fluorescent lights [1, 4, 244-264-265-335-392]. The benefits of LEDs include optimizing illumination spectrums to the particular wavelengths required by crops, reducing energy saved in the conversion of energy to photon energy, minimum thermal emission, and longer life [1, 4, 244-264-265-335-392]. In addition, the luminous efficiency of LED-based solid-state lighting is still being improved, and significant gains are provided with a novel color-mixed solid-state lighting technology [1, 4, 244-264-265-335-392]. LED technology has been evolving effectively to improve the efficiency of electricity conversion to light for photosynthesis [1, 244-264-265-335-393]. There are increasing studies indicated that the device's overall efficiency is highly dependent on the lighting strategy [1, 4, 244-264-265-335-393]. Many studies have been conducted to investigate the use of various color LEDs to accelerate plant growth compared to plants grown in normal solar irradiance [1, 4, 244-264-265-335-392]. In literature, red and blue light are used in current LED-based artificial lights for agricultural production because these spectra efficiently stimulate leaf photosynthesis [1, 4, 244-264-265-335-393].

LED lighting is very famous for its pure monochromatic light [4, 335]. Therefore, LED is recognized as the new technology source of light for greenhouse farming [1, 4, 244-264-265-335-392]. On the basis of literature survey it is found that light quality (spectral arrangement) and quantity (photoperiod and intensity) influence plant growth, metabolism, and also interact with several factors including environmental parameters in defining the plant behavior[4, 244-264-265-335-392]. The Light Emitting Diode (LED) lights are extensively utilized in the cultivation of several plant species, especially greenhouse farming due to their lower power consumption and higher luminous efficiency compared to the conventional fluorescent lights [4,244-264-265-335-392]. LED light influences performance of enzyme, gene expression, cell wall formation, plant defense and postharvest quality [1, 4, 244-264-265-335-392].

LEDs may be used in a variety of lighting applications, such as tissue culture lighting, controlled environment research lighting, supplementary lighting, and photoperiod lighting for greenhouses [1, 4, 244-264-265-335-392]. The photomorphogenesis development of a plant can be altered by the characteristics of LED light, which has a major effect on development and growth of plants [4, 244-264-265-335-392]. LEDs offer enormous potential as supplementary or primary sources of lighting systems in the field of greenhouse farming particularly hydroponic vertical farming [4, 244-264-265-335-392]. LEDs provide a number of benefits. LEDs are more ideal for plants because of their long life, low emission temperature, small in size, and ability to choose various particular wavelengths [4, 244-264-265-335-392]. LEDs are growing further to become cost-effective for even large-scale horticulture lighting applications as light output increases and decrees in the device expenditures [4, 244-264-265-335-392]. On the basis of literature survey it is confirmed that LED lighting is also well known for many advantages in terms of precision and customization, allowing for tailored lighting conditions that can optimize development and growth of plants[4, 244-264-265-335-392]. LED lights have gained significant popularity in various applications such as cultivation facility for plants, plant production, and plant tissue culture [4, 244-264-265-335-392]. However, traditional bulbs are gradually being replaced with LEDs, and the rapid advancements in LED technology offer immense opportunities for the advancement of greenhouse farming lighting [1, 4, 244-264-265-335-392].

Plants need adequate photoperiodic sunlight to synthesize photosynthesis [1, 4, 244-264-265-335-392]. Natural light, on the other hand, is often insufficient for optimum plant development in nature due to the effect of clouds, rain, and other climate factors [1, 4, 244-264-265-335-392]. So, artificial lighting is used in plant-growing facilities because all light sources are not created equal. For plant photosynthesis, the primary energy source is light, whether it is a natural source or artificial source[1, 4, 244-264-265-335-392]. Instead of using traditional light for *in vitro* plant growth, LEDs were used because it has several unique advantages, the light wavelength is adjustable, low energy consumption, eliminates energy efficiency, and long life [4, 244-264-265-335-392]. Therefore, LEDs are used *in vitro* plant growth to solve the difficulties faced in conventional light sources, such HPS and fluorescent lamps which have high energy consumption and luminous efficiency [4, 244-264-265-335-392]. In nature, plants use the sunlight as source of light and plants have developed physiological adaptations to cope with the fluctuations in solar intensity and spectrum [1, 4, 244-264-265-335-392].Therefore, plants possess inherent capacity and adaptability, enabling them to thrive and flourish across diverse environmental settings [1, 4, 244-264-265-335-392]. Plants have the inherent property, the ability to adjust and acclimate to artificial lighting conditions[4, 335]. Therefore, LED systems plays an important role in controlling morphological, physiological, chemical properties of plants in greenhouse farming [1, 4, 244-264-265-335-392]. Hence capabilities of LEDs rely on a precise understanding of photobiological, physiological, and technological aspects to ensure optimal operation [4, 244-264-265-335-392]. Another advantage is that LED lights are cool, they do not burn plants when they light up on plants close to them [4, 244-264-265-335-392]. This means that more space can be used in the same amount of time. The primary impacts of light colors on plant performance are shown by the spectrum effects of LEDs as an independent source of light, together with the diverse sensitivity of many plant species and alternatives [1, 4, 244-264-265-335-393].

8. Photosynthetically Active Radiation (PAR)

Light is an important factor for plant development and protection, since the required energy is obtained through the photosynthesis process [1, 4, 244-264-265-335-392]. Photosynthetic efficiency is the measure of the ability of plants to convert light energy into chemical energy via the process of photosynthesis [1, 4, 244-264-265-267-335-393]. Light is also one of the sensory signals that enable plants to adapt to external stimuli [1, 4, 244-264-265-335-392]. Several essential crops have a higher-than-average photosynthetic efficiency, enabling them to produce substantial yields. LEDs provide many advantages that make them an ideal solid-state lighting alternative for greenhouses due to their high energy efficiency for photosynthesis, easy spectral composition control, low radiant heat output, and easy light intensity adaptation to plant photoreceptors [1, 4, 244-264-265-267-335-393]. Over the past two decades, several researchers have worked to make LEDs an energy-efficient lighting option to increase greenhouse plant flowering and photosynthetic efficiency [1, 4, 244-264-265-267-335-392]. Although there is a wide range of terrestrial sunlight, plants can only use the spectrum of visible light to produce photosynthesis, and this narrow spectrum is recognized as the Photosynthetically Active Radiation (PAR) [1, 4, 244-264-265-335-393]. Photosynthetically Active Radiation (PAR) is a light of wavelengths in the range 400~700 nm. The photosynthesis of plants utilizes this portion of the light spectrum [1-244-264-265-335-392]. Light-emitting diodes (LED) illumination provides PAR that the plants uses for photosynthesis [1, 4, 244-264-265-267-335-392]. Therefore, PAR plays a significant role in plant morphogenesis [335]. Between 400 and 700 nm is assumed to be the photosynthetic active radiation (PAR) region, which is favourable to plants [1, 244-264-265-267-335-392]. To produce energy, plant chloroplasts may take in and use electromagnetic light in the PAR range, which is necessary for photosynthesis [1, 4, 244-264-265-267-335-392]. Additionally, plants may detect electromagnetic radiation using receptors other than PAR. Between 360 and 760 nm, pigments respond to photosynthesis [1, 244-264-265-267-335-392]. Throughout this wide range, incoming photons provide various levels of energy for photosynthesis [1, 4, 244-264-265-267-335]. The suggested advantageous photon flux, which provides information on both light intensity and wavelength usefulness for plants might be used [4, 267-335-392]. Accordingly, photons between 600 and 630 nm are 20 to 30 percent more advantageous to plants than those between 400 and 540 nm [1, 4, 244-264-265-267-335-392]. In addition, broad-spectrum sources can not be readily controlled in terms of their spectral output. It is possible to match and adjust the LED lighting system's spectrum output to the photoreceptors of plants in order to maximize productivity while minimizing energy waste[1, 4, 244-264-265-267-335-392].

Furthermore, the use of LEDs for greenhouse illumination has significantly improved plant quality, especially in geographic regions (Finland, Norway and Sweden) with reduced sunlight during winter seasons [1,4, 244-264-265-267-335-392]. This also increases plant productivity in terms of high yield due to the efficiency of LEDs. LEDs emits wavelengths over a broad spectrum [1, 244-264-265-267-335-392]. The use of LEDs can also optimize the illumination spectrum for specific plants, resulting in maximizing the yield and nutritional quality of the vegetables and herbs [4, 265-267-335-392]. LED manipulation plays an important role for maximizing the yield of vegetables and herbs [4, 265-267-335-392]. There are many ongoing experimental research using several light spectra trialed for enhancing the yields of vegetables and herbs grown in greenhouse agriculture [1, 4, 244-264-265-267-335-392]. In all the experimental greenhouse research projects, the effects of photosynthetic photon flux density (PPFD) on the LED illumination spectrum has been investigated [4, 244-264-265-267-335-392]. The Fraction of Photosynthetically Active Radiation (FPAR), is used as an index for evaluating yields and biomass production [4, 244-264-265-267-335-392]. On the basis of literature survey it is found that different LED manipulation across different plant species in greenhouse experiments have noticed wide morphological diversity and developmental patterns to specific wavelength manipulations [4, 244-264-265-267-335-392]. However, a comprehensive analysis of the impact of LED manipulation on plant growth must also include a quantitative assessment of the whole range of the PAR [4, 244-264-265-267-335-392]. Additionally, an LED may be readily coupled with sensors and digital controllers to adjust smart lighting programs for plant photosynthesis by altering the emission ratio of blue to red LEDs, frequency, and intensity for plant species and development phase [4, 244-264-265-267-335-392]. Recently, GAN-based LEDs have been shown to perform better than traditional lighting sources in enhancing plant growth efficiency [244-264-265-267-335-392].

Light is energy source for photosynthesis and photo morphogenesis (quality of light), photoperiodism (length of night and day) [4, 244-264-265-267-335-392]. The electromagnetic energy of light is very sensitive to human eyes because the radiation wavelength is between 400 and 700 nm [1, 4, 244-264-265-267-335-392]. For photosynthetic plants, light is especially needed for carrying out physiological functions as well as for plant growth [4, 244-264-265-267-335-392]. Light controls about 90 % of plant genes for stimulating plant growth in greenhouse agriculture. In the greenhouse sector, energy is a significant cost element, accounting for around 20–30 % of overall production expenses [1, 4, 244-264-265-267-335-392]. It is very important for greenhouses to have the right lighting for crops, especially in areas where the seasonal photoperiod (day length) changes and there is not enough light for plants to grow properly[1, 4, 244-264-265-267-335-392]. In LED lights the output of different wavelength ranges of the emitted light by the lamp is controllable rather than the commercial light source which was traditionally used earlier in greenhouse farming [4, 244-264-265-267-335-392]. LEDs are utilized in the context of plant growth, high yield and are also easily controlled by the spectral output because it matched with the plant photoreceptor [4, 244-264-265-267-335-392]. LEDs exhibit a high concentration of monochromatic light sources, and their wavelengths correlated to the same wavelength spectrum associated with plant development [4, 244-264-265-267-335-392]. The capacity to modify the spectrum quality of plant display lights is also of important to plant growth and development [1, 4, 244-264-265-267-335-392]. The capacity to dynamically modify the spectrum output may potentially be utilized to impact plant morphology in a number of different ways. Spectra's output may also be adjusted according to the length of a photoperiod or growth cycle, allowing it to be customized for certain crops or production processes[4, 244-264-265-267-335-392]. Additionally, the luminous spectrum of LEDs, which are made from quantum dot (QD) materials, is developed and optimized based on the Photosynthetic action spectrum (PAS) of plants, taking into consideration both their photosynthetic and visual capabilities [244-264-265-267-335-392].

9. Hydroponics: LED Light Set Up

Another important factor is uniformity in LED illumination [4, 335]. This will prevent the spread of the photons and thus reducing the wasted electricity [335]. Therefore, first step is to set up the LED light source before illuminating the plant with LED sources[1-265-335-392]. In other words, the distribution of a constant photosynthetic photon flux (PPF) will solve the problem and ensure uniform light [1-265-335-392]. Moreover, the power consumption tends to increase with greenhouse size due to the inadequate arrangement of the LED lighting system [335]. This results in non-uniform photosynthetic photon flux (PPF) distribution or a smaller plant growth area under the fixture, thus leading to wasted radiation (i.e., electricity) [1-265-335-392]. Once the LED lighting system's positioning has been optimized, the next important step is to determine the essential wavelength ranges that affect the plant growth rate and understand their interaction with the plant biology system[1-265-335-392]. Plant cell system is characterized by the primary photoreceptors, phytochromes (PHY), phototropin (PHOTO), and cryptochromes (CRY) [1-265-335-392]. Phytochromes (PHYs) typically capture light effectively in the red (600~700 nm) and far-red (700–800 nm) ranges [1-265-335-392]. In contrast, the phototropin (PHOTOs), cryptochromes (CRYs) and zeitlupe (ZLT) photoreceptors perceive light actively in the blue (400~500 nm) and the UV-A (315~400 nm) regions [1-265-335-392]. On the other hand, the UVB-Resistance locus 8 (UVR8) photoreceptors absorb light strongly in the UV-B (280~315 nm) regions[1-265-335-392]. Therefore, plant photoreceptors and their absorption in the LED illumination spectrum, must be carefully considered for optimal plant growth in greenhouse environments [1-265-335-392].

The quantification of the effect of the LED illumination spectrum, the critical wavebands and their interaction with the plant system should be the next step [4, 265-335-392]. This is a very important step since requires the identification of the best wavelength ranges and the impact of photosynthetic photon flux that leads to higher productivity in the greenhouse-grown plant[1-265-335-392]. It is important to note that an LED source has a relatively narrow bandwidth (~50 nm) and specific wavelength selectivity, making it ideal for indoor farming[1-265-335-392]. For example, red LED illumination peaked at 630 nm can be applied in a horticultural application for regulating blossoming [335], whereas blue-violet LED can be used as a scheme [1-265-335-392].

However, excessive blue LED illumination typically generates oxygen radicals and causes photo-inhibition in indoor greenhouse farming. In addition to this, the intensity and photoperiod of the LED illumination are the most important key parameters that affect plant growth and quality [1-265-335-392]. For example, supplemental LED illumination (during day and night) can also overcome inherent plant shading and provide the required photoperiod, hence promoting early blooming [1-265-335-392]. However, standard characterization is needed to optimize and control the LED illumination spectrum for maximizing the plant growth rate while maintaining high plant quality [1-265-335-392]. Thus, it is necessary to calibrate the LED illumination source with an accurate characterization method before installation [1-265-335-392].

10. Effect of LED illumination on Plant Growth and Development

On the basis of literature survey and according to Sena et al., (2024) [335], the use of LED illumination sources for increasing the growth rate of greenhouse grown vegetables and herbs is on the rise worldwide [1, 4, 265-335-392]. When it comes to controlled growth systems, artificial lights play a vital role, and LEDs are often considered to be the most effective artificial light sources [1, 4, 335]. LED light illumination has played an important role in increasing the synthesis of a variety of beneficial secondary metabolites [4, 265-335-392]. The manipulation of the light spectrum's composition is crucial when incorporating LED technology to elicit specific effects on a plant's morphology, physiology, and antioxidant content, viz. polyphenols, carotenoids, ascorbic acid, and other compounds [1-265-335-392]. The plants metabolite production is extremely dependent on the quality and availability of the required light [1-265-335-392]. Light not only controls the fundamental metabolic processes and growth patterns of plants, such as flowering, stem elongation, and physical characteristics, but it also has a significant influence on the complex system that regulates the production and accumulation of secondary metabolites [335]. This influence is exerted through the manipulation of the photosensory signaling pathway, which is governed by photoreceptors [4, 335]. This has opened a new topic of study that might impact significantly both pharmaceutical and nutraceutical industries [335].

This massive attractiveness of LED is due to the exponential increase in LED installations in greenhouses, positive changes in policies on reducing energy consumption, and its minimal negative impacts on the environment [4, 335]. Sena et al., (2024) [335], is also of the opinion that, further research is still required to fully understand the effect of the LED illumination spectrum on plant growth and the associated optobiological interactions governing the photosynthesis process [4, 335]. As more durable and cost-effective LED sources with a diverse range of wavelengths continue to emerge in the market, the adoption of LED illumination sources in greenhouses is expected to accelerate, leading to better horticultural production yields with a short cultivation cycle [4, 265-335-392]. On the basis of literature survey, it is also confirmed that the valid ranges of wavelength identified in the literature are red (640~720 nm), blue (425~490 nm), green (490~560 nm), and far-red (~720–750 nm), which are considered the most valuable wavelengths due to their direct and indirect impacts on plant growth and quality [265-335-392].

Further this literature survey predominantly covers widely used red, blue, green, and far-red LED illumination sources for greenhouse and growth chamber grown plants [4, 265-335-392]. It excludes other wavelength ranges, such as UV, yellow, and orange, which have rarely been deployed for growing vegetables and herbs [4, 335]. Overall, optimizing the LED illumination spectra in greenhouses for crop yield and quality improvement addresses food security and the cost-effectiveness of deploying LED sources in large-scale greenhouse installations [265-335-392]. However, significant hurdles remain in the widespread deployment of LED illumination and in developing efficient, cost-effective LED-based greenhouses [335-392]. Greenhouse experts are of the opinion that, significant advances will most likely emerge from multidisciplinary research and developmental activities involving close collaboration amongst LED manufacturers, greenhouse growers, researchers, and government stakeholders [4, 265-335-392].

According to Sena et al., (2024) [335], one of the challenge with LED technology is that the color combination of red and blue LED illuminating the plant surface generates a purplish hue to the human eye, which can mask the visual identification of nutritional deficiency or any physical disorders [335]. However, adding green light to a combination of red and blue LED illumination can resolve this problem[335]. In general, red and blue light is essential for maximizing the photosynthesis process due to their strong absorption by the plants chlorophyll molecules [265-335-392]. For example, the blue light is usually absorbed by cryptochrome, responsible for controlling the stomatal conductance and stem elongation [265-335-392].

Photosynthesis is the process which involves a chemical reaction between water and carbon dioxide (CO_2) in the presence of light to make food (sugars) for plants, and as a by-product, releases oxygen in the atmosphere [4, 221]. Carbon dioxide currently comprises 0.04 percent (400 parts per million) of the atmospheric volume[4, 221]. It is a colorless and odourless minor gas in the atmosphere, but has an important role for sustaining life [221]. Plants take in CO_2 through small cellular pores called stomata in the leaves during the day [4, 221]. During respiration (oxidation of stored sugars in plants producing energy and CO_2) plants take in oxygen (O_2) and give off CO_2, which complements photosynthesis when plants take in CO_2 and give off $C0_2$ [4, 221]. The CO_2 produced during respiration is always less than the amount of CO2 taken in during photosynthesis[4, 221]. So, plants are always in a CO_2 deficient condition, which limits their potential growth [4, 221].

Plants typically produce carbohydrates through a chemical reaction, commonly called photosynthetic reaction (involving carbon dioxide, water, and light), whereby the light energy converts into chemical energy [4, 265-335-392]. Thus, bioactive compounds and antioxidants synthesis in a plant could be triggered by using different LED wavebands, thus increasing the plant's nutritional quality [4, 265-335-392]. Therefore, adequate plant illumination is crucial for the greenhouse industry to maintain high-quality horticultural products [1, 4, 265-335-392]. The green lettuce displayed reduced flavonoid production under LED, while red lettuce showed increased production of flavonoids [335]. Supplemental LED illumination helps to accumulate phytochemicals in leafy vegetables [4, 265-335-392]. Further phenolic compounds are essential measures of the quality of vegetables and herbs, which a cultivation plant can stimulate under high-intensity LED illumination [1, 4, 265-335-392]. In contrast, red LED illumination improves the rosmarinic acid in basil plants [335]. However, it has no role in spinach phenols accumulation [335]. Similarly, green LED illumination negatively affects the accumulation of phenolic, flavonoid, and anthocyanin compounds in basil plants

[4, 335]. Using different supplemental LED spectra, one of the study demonstrated the increased proliferation of total phenolics in harvested Chinese cabbages [4, 335]. However, the adverse effect of red and blue light on nutrient accumulation has not been fully understood [4, 265-335-392].

Biosynthesis and accumulation of ascorbic acid mainly depend on the illumination intensity and spectrum [335]. A higher concentration of ascorbic acid in lettuce was observed with supplemental blue LED illumination or a mixture of red: blue illumination light than under red LED illumination [4, 335]. It has been reported that, besides the morphological development of the plant, LED illumination can positively impact the production of vitamins and helps to reduce harmful compounds by adding green LED illumination as a supplemental light [335]. Another research has also indicated that exposure to blue LED illumination significantly influences vitamin C concentration in cabbage [335-392]. In some cases, the effect of supplementary LED illumination on the contents of antioxidants and vitamin C is indirectly associated with the nitrate [4, 265-335-392]. Hydroponically cultured kale plants (*Brassica oleracea* L. var. acephala D.C.) were grown under specific LED wavelength treatments of 730, 640, 525, 440, and 400 nm had a maximum accumulation of chlorophyll A and chlorophyll B and lutein at the wavelength of 640 nm on a fresh mass basis rate reduction rate [1-265-335-392]. Furthermore, a remarkable increase in carotenoid concentration has been reported in cabbage with an LED illumination flux of 300~400 μmol m^{-2} s^{-1}[335]. The effects of different illumination spectra (640 nm, 450 nm, and white) vary among vegetable species and cultivars [265-335-392]. However, most leafy vegetables grown in controlled environments required a suitable range of photon flux (typically from 200 to 300 μmol m^{-2} s^{-1}) [265-335-392]. Blue or yellow LED illumination affects the rates of respiration and ethylene initiation of harvested fruits and vegetables, and this not only improves the synthesis of β-carotene, lutein, α-tocopherol, and ϒ-tocopherol but also enhances fruit ripening [265-335-392]. It has also been found that different lighting conditions and the duration of supplemental illumination can adversely affect a specific plant and its biochemical synthesis pathways [1-265-335-392]. For example, for green vegetables, short-duration treatment by supplemental red LED illumination has been less functional in enhancing antioxidants and nutritional components, resulting in decreased nutritional quality [4, 265-335-392].

On the basis of literature survey it is confirmed that several experiments have been conducted over the last decade, revealing that the blue, red, far-red, and green LED illumination bands strongly affect the growth and nutritional quality of vegetables[1-265-335-392]. The development and growth of diverse plant species can be influenced differently by a variety of colored LED lights [1-265-335-392]. Although most studies have established on blue and red light 265-335-392]. To provide an example, studies have demonstrated that exposure to blue light may reduce the dry weight of shoots and leaf area in plants that belong to the *Asteraceae* family [335]. For plants in the *Solanaceae* family, it has been reported to have the reverse effect, increasing dry weight of shoots and leaf area [335]. The leaves and shoots are the leading edible parts of vegetables and herbs affected by the LED illumination [265-335-392]. For instance, wavelength-specific findings have revealed that the seedlings were first grown in blue LED illumination for 30 days (blue 460 nm, LEDs with 80 μmol m^{-2} s^{-1} and then transferred to sunlight (normal level of 350 μmol m^{-2} s^{-1}) at the 31st day and cultured for 30 days (60 days) to sunlight with 350 μmol m^{-2} s^{-1}) [4, 265-335-392]. It has been observed that blue LEDs benefit vegetative growth while red LEDs and blue plus red LEDs support reproductive growth in non-heading Chinese cabbage [4, 335].

According to Sena et al., (2024) [335], the increase in leaf area is one of the most important physiological parameters used to estimate the effective photosynthetic rates per unit area[265-335-392]. For example, it has been reported that the largest leaf area is typically produced under blue LED illumination[4, 265-335-392]. The dry mass (biomass) is typically measured after the plant is sequentially dried in a drying oven and is an indicator of plant biomass content and the quality of growth[1-265-335-392]. LED illumination has also been shown to have a positive impact on biomass build-up [265-335-392]. This biomass yield confirms the importance of the intensity and quality of illumination for satisfactory plant development[1-265-335-392]. Thus, it is evident that the blue LED illumination promotes multiple desirable plant growth factors [1-265-335-392]. Hence, it has a reasonable (and possibly under-explored) potential use in plant production, especially in greenhouse environments [1-265-335-392]. The photosynthetic pigments of plants absorb the visible light effectively, and experiments have shown that red LED illumination (red light, 600~700 nm, LEDs with 360 ± 10 μmol m^{-2} s^{-1}) to blue illumination improves the yield of tomatoes[4, 265-335-392]. Lettuce's fresh weight has been reported to increase under additional far-red LED illumination (wavelengths between 700 to 800 nm). Interestingly, a green LED has recently increased the fresh weight of lettuce, and cucumber transplants [265-335-392]. Several studies have also suggested that supplemental green LED illumination can improve the quality of tomato and sweet pepper[4, 265-335-392]. LED illumination can improve the quality of tomato and sweet pepper [265-335-392]. Similar results have confirmed that addition of green LED illumination accelerate the growth of lettuce [265-335-392]. The application of LED illumination for increasing the storage life of vegetables and herbs has attracted great interest[4, 265-335-392]. For example, it has been shown that the storage life of leafy vegetables increases with low-intensity illumination compared to storing them in a dark place. However, recently, LEDs have emerged as potential postharvest light sources. Due to their higher moisture content, vegetables and herbs typically have a short shelf life, making it challenging to store them for extended periods [265-335-392]. Vegetables and herbs are also prone to microbial degradation, which accelerates the degradation of their nutritional quality [4, 265-335-392]. It has been shown that light treatment with optimal intensity and spectrum is essential for the maximization of the shelf time of vegetables and herbs [265-335-392]. Therefore, it is essential to store vegetables and herbs using higher optical power intensities and optimum illumination spectra [265-335-392]. On the basis of literature survey it is fount that the use of supplemental LED illumination in conjunction with traditional light sources has been shown to increase the pre-harvest nutritional quality of vegetables and herbs [265-335-392]. For example, green and white LED illumination increases the chlorophyll content compared to red and blue LED illumination [265-335-392], while the vitamin C and phenolic concentrations are highest with blue and white LED illumination [265-335-392]. It is important to note that high-intensity illumination typically increases vegetables and herbs' transpiration, hence reducing their biomass and quality [4, 265-335-392]. For example, blue light illumination increases leaf transpiration [265-335-392].

The fresh and dry mass of the vegetables and herbs can be increased by increasing the intensity of red-light irradiation, which stimulates the growth of leafy vegetables [265-335-392]. On the other hand, the compactness and elongation of plants can be improved through supplemental blue illumination [4, 265-335-392]. Blue illumination contributes to several desirable factors, such as plant compactness, vegetative growth, and potentially higher pigment and concentration of vitamin C [1-265-335-392]. Thus, blue illumination is desirable in plant production[265-335-392]. On the basis of literature survey and reported results, red illumination increases the yield by decreasing the nitrate and improving plants' vitamin C [265-335-392]. These two factors are necessary for crop quality[265-335-392]. Therefore, red illumination is essential and has a significant role in improving plant quality [265-335-392]. As plant elongation and low pigment concentration are not always desirable, far-red illumination may not be crucial for increasing the plant biomass (at least for some plants) [265-335-392]. Since green illumination accelerates plant growth and increases the nutritional quality (e.g., vitamin C), thus the green wavelength is necessary for maximizing crop yield [265-335-392]. Further investigations are still needed to confirm the impact of green and far-red illumination on a plant to improve the biomass and nutrient contents of vegetables and herbs [265-335-392]. Therefore, the outcomes of different percentages of light response on plant growth and nutritional quality could be used to design the optimized lighting system for various horticultural greenhouse applications [1-265-335-392].

The control of the intensities of LED illumination spectral components enables the continuous optimization of the illumination spectrum over time, typically required in real-life scenarios [1-265-335-392]. For example, far-red can be an effective non-chemical means to control plant morphology [265-335-392]. However, with short exposure to far-red, the mechanisms responsible for increasing the plant biomass are still not well explored[265-335-392]. They may be attributed to hormonal changes and transpiration [4, 265-335-392]. One of the study indicated that the optimal illumination spectrum for plant growth is likely to change with the plant age and stage and environmental conditions [265-335-392]. In some experiments, LEDs have been used as supplemental light sources in conjunction with sunlight [1, 265-335-392]. For example, some solar spectral components might be attenuated during the day, hence insufficient for optimal plant growth [1, 265-335-392]. In most cases, larger plants intercept a relatively large portion of the sunlight, thus becoming longer than other plants [1, 4, 265-335-392]. In this case, the canopy light interception capacity can be made uniform by using supplemental LED illumination [1-265-335-392]. However, due to their high initial installation costs, LED illumination application in agricultural systems is limited to small-scale facilities [1, 265-335-392]. Research and development activities on the fabrication of cost-effective LED lighting systems have varied rapidly over the last few years [1, 265-335-392]. Thus, the cost of LED lighting systems is expected to be reduced significantly [1, 265-335-392]. For example, the efficiency of blue LED illumination sources rapidly increased from 11% in 2006 to 40% in 2011 [335], and currently, it exceeds 75% [1, 265-335-392]. On the other hand, modern greenhouses equipped with LED illumination sources and energy-efficient materials are expected to have low production costs and energy consumption [1, 265-335-392]. Ongoing LED technology development has broadened the scope of LED lighting systems in horticultural greenhouses and hygienic storage, even in developing countries [1, 4, 265-335-392].

Many researchers of the opinion that LED illumination spectrum manipulation could enable significant morphological adaptations, and identification of the wavelength ranges is required to increase the plant photosynthesis process[265-335-392]. However, far-red and green LED lighting imposes several challenges, such as illumination with more than 50% of green LED light results in a shorter plant [1-265-335-392]. In contrast, far-red light has a "shade avoidance response" since typically plants elongate in an attempt to capture the available light [265-335-392]. In some cases, an elongation response is desirable, except in the production of ornamentals [1, 4, 265-335-392]. However, studies do expose scenarios under which red LED illumination is not beneficial for specific cases [265-335-392]. For example, using red light solely is not always favourable for plant progression due to the "red light syndrome" [1, 4, 265-335-392]. However, it is reported that supplemental red LED illumination can help accumulate bioactive compounds and phenolic compounds, and antioxidant properties of the vegetables and herbs[265-335-392].

Rahman et al., (2021) [267] reported that the blue (417~450 nm) and red (630~680 nm) wavelength ranges are particularly effective for improving the photosynthesis process [267]. Interestingly, despite having lower energy (~1.82 eV), red-light wavelengths are the most effective for stimulating the photosynthetic processes [267]. Red light alone is not always favourable for plant development because of the “red light syndrome” [267]. However, these symptoms can be suppressed by adding blue light to the illumination source [4, 267]. For example, a blue-dominated LED light source with a 440 nm peak wavelength (100 μmol m^{-2} s^{-1}) has been shown to increase the pigment concentration in plants [267]. Green and far-red LED illumination can also positively impact plant growth and development among the other light spectra [1, 265-335-392]. For example, a green LED light can penetrate deeper into the leaf than blue and red LED illumination, thus increasing carbon fixation and improving the plant yield [267]. Moreover, a blue light-induced stomatal opening can be overturned using green LED illumination [267]. Similarly, far-red LED illumination has been shown to be pro-active in enhancing photosynthesis due to its synergetic effect [267]. However, by studying growth scenarios in some plants, reduction in nutrient contents has been observed when far-red light is used as a supplemental with red light [267], whereas, in other scenarios, far-red supplemental resulted in positive effects on plant growth[4, 267].

In Eastern countries, edible sprouts have a long-standing culinary history, where seedlings are consumed as a vital ingredient [265]. To facilitate the germination process, Light-emitting diode (LED) lamps are utilized in growth chambers, providing light with varying color characteristics, including white, red, blue, green, and their combinations [1, 265-335-392]. The impact of LED on germination growth varies based on the species [4, 265]. The use of LED technology is a promising and effective approach for producing sprouts, microgreens, and hydroponic fodder with enhanced nutritional value[1, 265-335-392]. The study conducted by Wang et al. (2023) [265] highlighted the impact of LED light intensities, including red, blue, and ultraviolet, on edible sprouts [265]. This study also showed that LED treatments with increasing light intensity enhanced the physiological and antioxidant properties of the edible sprouts, compared to the control treatment [4, 265].

The study of Wang et al. (2023) [265] evaluated the impact of LED light with red-blue-ultraviolet (6:3:1; R:B:UV) and three levels of intensity (control, 120, and 150 μmol m^{-2} s^{-1}) on five different sprout species, namely wheat, barley, mung bean, alfalfa, and soybean, after seven days of germination[265]. This research work of Wang et al., (2023) [265] investigated the effects on various parameters, including photosynthetic pigments (chlorophylls *a*, *b*, total), carotenoid, activities of antioxidant enzymes such as catalase, superoxide dismutase, and soluble proteins, soluble sugars, starch, vitamin C, and element content such as potassium, iron, and phosphorus [265]. The results of this study by Wang et al., (2023) [265] indicated that the LED treatments and increasing light intensity significantly improved the physiological and antioxidant properties of edible sprouts, with the 150 μmol m^{-2} s^{-1} treatment producing the most beneficial outcomes [4, 265]. Additionally, increasing light intensity reduces starch content while enhancing the content of photosynthetic pigments, soluble carbohydrates, vitamin C, element concentration, antioxidant enzymes, and soluble proteins [265]. Among the five species of edible sprouts, barley had the highest content of photosynthetic pigments, while soybean and mung beans had the lowest content [265]. Mung beans and alfalfa had the highest and lowest concentrations of potassium and iron, respectively [265]. In terms of phosphorus concentration, soybean and barley sprouts showed the highest and lowest concentrations, respectively [4, 265].

Light is a key environmental factor and plays an important role in plant growth, as plants cannot move and must rely on environmental adaptation mechanisms and diverse responses to changes in light impact, quality, intensity, and duration [1, 265-335-392]. This study of Wang et al., (2023) [265] investigated the effects of LED treatments and increasing light intensity on the physiological and antioxidant properties of edible sprouts, with treatment at 150 μmol/m^2s^{-1} significantly improving these traits compared to treatment at 120 μmol/m^2s^{-1}[265]. Increasing light intensity of the LED treatments enhances the content of photosynthetic pigments, soluble carbohydrates, vitamin C, element content, antioxidant enzymes, and soluble protein, while reducing the amount of starch [265]. Different types of sprouts exhibit unique physiological responses to light intensity, and increasing light intensity improves the nutritional properties and element content of all sprouts[265]. Plant tissues contain various pigments and photoactive compounds that require energy in specific wavelengths to operate, and a comprehensive understanding of the mechanisms of these optical receptors, the wavelengths received, and their effects on plant development and physiology is crucial for developing complementary optimal methods for LED lighting, with emphasis on spectral quality and enhancing secondary metabolite production[4, 265].

Another research was conducted to examine the impacts of various LED treatments, specifically white, white + red, and white + blue, on the growth, antioxidant properties, and nutritional characteristics, of wheat seedlings [335]. The study findings confirmed that all three treatments yielded similar positive effects 335]. Water spinach research also observed a significant an increase in plant height and fresh stem weight with the use of red LED treatment[335].

Vegetables and herbs play a central role in the human diet due to their low fat and calorie content and essential antioxidant, phytochemicals, and fiber [1, 4, 265-335-392]. It is well known that the manipulation of light wavelengths illuminating the crops can enhance their growth rate and nutrient contents[1,4, 265-335-392]. The study of Rahman et al., (2021) [267] confirmed that the red and blue LED illumination is more reliable and efficient than full spectrum illumination and increases the plant's biomass and nutritional value by enhancing the photosynthetic activity, antioxidant properties, phenolic, and flavonoids contents [267]. The study of Rahman et al., (2021) [267] also reported that LED illumination provides an efficient way to improve yield and modify plant properties [267]. This study also highlights the broad range of responses among species, varieties traits, and the age of plant material [267].

The development and growth of a plant is significantly influenced by the duration of light, particularly on its aboveground organs [1, 4, 265-335-392]. Crop photosynthetic rate responded well to the lighting treatment period under white fluorescent lamp [1, 265-335-392]. One of the study showed that white LED light was used to irradiate cherry tomatoes for diverse lengths of time, and the crops shoot lengths varied to varying degrees[1, 265-335-392]. However, if the exposure to light lasted for fewer than 20 days, red LED light was shown to have a statistically significant negative effect on shoot length, according to a *meta*-analysis, resulting in a decrease of 69%[335].

On the basis of literature survey it is found that light is the most essential element influencing plant development, changes in irradiance impact not just the development of plants but also their morphology, different elements of their physiology, and their overall production [1, 4, 265-335-392]. Although light quality has an impact on plants, the ramifications are more complicated [1, 265-335-392]. Plants respond differently to different types of light, but red and blue light have the greatest impact on plant development [1, 4, 265-335-392]. For artificial plant growth control, LEDs are appropriate because of their extended life, compact volume, low weight, and high photo synthetically active radiation efficiency, making LEDs a perfect light source [1, 265-335-392]. The activities of antioxidant enzymes were dramatically increased by LED lighting[1, 4, 265-335-392]. The activities of antioxidant enzymes are often triggered by an increase in ROS generation in order to prevent possible oxidative stress-related cell damage[1, 265-335-392]. The superoxide dismutase enzyme (SOD), also known as metalloenzymes, serves as the plants primary defensive mechanism against oxidative stress by converting the highly reactive superoxide radical into hydrogen peroxide and oxygen molecules [1, 265-335-392]. LEDs are considered the optimal light source for inducing organogenic and embryogenic reactions, as they can provide the specific spectrum characteristics required for these processes[1, 265-335-392]. *Arabidopsis* CRYPTOCHROME1 (CRY1) is a crucial element involved in photomorphogenesis [335].

Plants need the wavelength range of 400-520 nm. The wavelength range of 610-720 nm blue light and a red light wavelengths [1, 265-335-392]. One of the study by Promratrak (2017) [334] tested the use of LED for lighting in the plant instead of natural light. The experimental results of Promratrak (2017) [334] confirmed that the light from the LED has helped the growth of plants [334]. The test plant using natural lighting and temperature has shown the best growth of plants compared to LED lighting [334].

The shoot length of rice and petunia exhibited a notable decrease when subjected to red LED light for a duration of less than 20 days [335]. Nevertheless, given a duration above 20 days, the red LED light failed to exhibit any prominent influence on the length of the pepper shoots[335]. Similarly, shoot length was drastically decreased while using blue LED lighting lasted for fewer than 20 days [335]. However, plants exposed to more than 6 days of blue light had considerably less total chlorophyll content than the controls[335]. The relevant measures of fruit production and quality were replaced with physiological markers of crop shoot growth, which primarily focused on the length and chlorophyll content of the shoots[335].

The enhancement of wheat seedling growth is observed through various indicators such as increased leaf area, shoot fresh weight, dry weight, and plant height when exposed to white + red LED light, indicating red light have beneficial impacts on the development of wheat seedlings [1, 265-335-392]. The exposure to red light led to a significant rising in stomatal conductance in Cruciferous plants, whereas it caused a significant decrease in *Cucurbitaceae* plants [335]. Additionally, according to some research, LED lighting effects are relying upon the particular stage of a plants life cycle at which LED was used[335]. The plant *S. aureus* demonstrated the highest values for plant height, spread, leaf area, and leaf number when exposed to light intensities ranging from 1100 to 1500 lx[335]. Conversely, the plant *P. selloum* exhibited the greatest plant spread in the presence of light intensities between 700 and 1100 lx[335].

It is important to note that the influence of red and blue light on *Tritucum astivum* seedling development gradually decreased over time, suggesting a potential connection with the plant's growth stage or an acclimatization reaction to the changing lighting circumstances [335]. Five indoor ornamental species, namely *Scindapsus aureus*, *Philodendron selloum*, *Dracaena godseffiana*, *Syngonium podophyllum*, and *Schefflera arboricola*, have been found to be influenced by

LED irradiation. Adequate lighting is essential to their development and growth[335]. *Schefflera arboricola* exhibited a significant increase in length when exposed to LED illumination of 1500–1900 lx [335].

Sena et al., (2024) [335] are of the opinion that LED light has been extensively utilized to several horticultural plants [335]. However, current research scenario on LED lights is not sufficient for horticultural production [335]. Particularly, the secondary metabolite which affects the fruit and leaf quality have not been analyzed [335]. Sena et al., (2024) [335] also confirmed that there is a proof that secondary metabolites play as an essential player to combat against pests and diseases, which helps to advance their adaptation ability and also influence the quality of horticultural production [335]. Hence, a deeper study to uncover the role of LED lights on plant secondary metabolites should be investigated [335]. Sena et al., (2024) [335] also pointed that despite of several reports conducted on effect of LED lights on plants, few gaps remains unanswered [335]. In this respect, optimum intensity and light spectra required by several horticultural crops to optimize their product quality and yield need to be solved [335]. Besides, a better characterization of light spectra and intensity interactions needs to be performed [335]. LED illumination sources are increasingly being utilized to enhance the growth rate of vegetables and herbs cultivated in greenhouses worldwide [1, 265-335-392]. This surge in popularity can be attributed to the widespread adoption of LEDs in greenhouse installations, favourable energy consumption policies, and their minimal environmental impact [1, 265-335-392]. Therefore, more study is required in order to gain a comprehensive understanding of the effects of the LED illumination spectrum on plant growth and the complex **optobiological** interactions that regulate the process of photosynthesis [1, 265-335-392]. The increasing advancement of LED sources that are both long-lasting and affordable, and that provide an extensive range of wavelengths, is expected to drive the adoption of LED lighting in greenhouse environments [1, 265-335-392]. This advancement holds the potential to significantly improve horticultural production yields and shorten cultivation cycles [265-335-392]. Sena et al., (2024) [335] highlighted next-generation LED technologies that are well-suited for implementation in protected cropping facilities [335]. The objective is to enable the cost-effective attainment of high crop yields and quality [335]. Sena et al., (2024) [335] reported widely employed LED illumination sources in greenhouse and growth chamber settings, namely red, blue, green, and far-red LEDs [335]. Sena et al., (2024) [335] also are of the opinion that despite the growing popularity of LED illumination in agriculture, there are still notable challenges to overcome for the wide-scale deployment of LED-based greenhouses and the development of efficient, cost-effective systems[1, 335]. Therefore, substantial progress is expected to arise from multidisciplinary research and development efforts that foster close collaboration among LED manufacturers, greenhouse growers, and researchers [1, 265-335-392]. The capacity to perceive LED light intensity and spectrum could play a key role in the horticultural plant research particularly technological advancement on LED light-plant communications in plant kingdom [4, 335].

The study conducted by Teo et al., (2024) [358] showed that the growth of the plants is affected by different LED wavelength and power intensities of the LED [1, 4, 358]. This work adopted commercial LEDs with color variations that consist of different wavelengths [358]. The 7 white and 1 red LED showed the highest average length and width after 30 days [358]. With the help of red lights wavelength, budding process were promoted to have an early start compared to other color [1, 4, 358]. Meanwhile, having white LED lights gives a full color spectrum wavelength which includes blue light that encouraged stem and leaf development [1, 4, 358]. In the second cycle with different light power intensity, having high power will mainly promote the budding process [358]. With all spectrum color presence, the stem and leaf development of the plants was helped by high power of the LED [4, 358]. The adoption of commercial LED lights in this work contributes to the direct benefits of indoor vegetable farmers and helps to optimize the growth of the plants and improved the overall farming yield [1, 4, 358].

The study of Teo et al., (2024) [358] highlighted the effect of different light emitting diode (LED) grow light wavelength and power of the LED lights on plant growth by adopting nutrient film technique of hydroponic indoor vegetable farming [358]. Commercial LEDs are deployed in this work, and the findings benefited the farmers who rely on commercial LEDs [358]. Two phases of plant development were affected differently with different LED wavelength [358]. Color spectrum in this study involves three colors that are red, blue and white in different ratios, providing different wavelength[358]. Budding phase as well as stem and leaf development of the plant shows a great reaction with the highest average width and length of the leaf from 1 red 7 white LED wavelength[358]. Meanwhile, 2 red 3 white LED gives the early starts on the budding phase due to its red light, but the leaf development was the slowest due to the absence of blue lights [358]. The light spectrum from 1 red 7 white has included a strong blue spectrum which helps in the stem and leaf development process[358]. Different LED power with a full spectrum of LED wavelengths has shown an exceptional growth for the plants with highest power of 40 Watts [358]. With full inclusions of red, blue and white spectrum, higher power of the LED helps exponentially especially in the budding phase of the plant [4, 358].

The study of Nájera et al., (2022) [359] reported the methodology and results were analyzed over a period of 5 years using the different quality parameters of LED- lighting as the main light source[1, 359]. The main plant species studied were lettuce, cabbage, cucumber, and spinach [359]. The results of this study showed that use of 16 h light photoperiods increased nutritional compounds such as antioxidants, phenols, and total sugar concentration, but in general a moderately positive effect on plant growth and development was observed [359]. The most used light intensities were between the range of 150 and 300 μmol m^{-2} s^{-1} and the specific spectrum-LED peaks between 450–495 nm (blue) and 620–700 nm (red) [359]. Therefore, the use of LED lights on vertical farming systems as an alternative to increase the nutritional parameters of horticultural plants is a viable option as, in a short period of time and without geographical differentiation, it contributes to the production of nutraceutical compounds [1, 359]. It also contributes to a reduction of natural resource use such as water, as one hundred percent of the research was carried out on crops that utilized hydroponic systems, which have the capacity to reuse water and nutrients [1, 359].

The study conducted by Kuankid and Aurasopon (2022) [392] utilized a three LED grow light models from the manufacturer as light treatments for cultivating green leaf lettuce (*Lactuca sativa*) [392]. The results of this study showed that increased red light (RED/BLUE = 2:1) increased plant height, leaf width, and leaf length on both harvesting days (10 and 20 day after transplanting) [392]. The lettuce plant shape and size signify that the lettuces in each tier are of a good standard and comparable in size [392]. Indoor vertical hydroponics is one of the most recent agricultural technologies [392]. It is a method of growing plants in vertically stacked layers using water and nutrient solutions instead of soil [1, 392]. When cultivating such a system, utilizing and maintaining the quality of water and nutrients is critical for plant growth [1,4, 392]. Additionally, LED growth lights have a significant effect on plants[392]. Despite developments in LED lighting and Internet of Things based smart agriculture systems, there is a lack of information on LED lighting for hydroponically grown crops in vertical culture since vertical agriculture is a relatively new field of study[1,4, 392].

11. Conclusion

Hydroponics is a method of crop production in which plants are grown without soil, and nutrients required for plant growth, are supplied through liquid nutrient solution. Plant roots may or may not be supported by artificial substrate such as perlite, vermiculite, rock wool, expanded clay, coconut coir, wooden fiber or a mixture of substrates like perlite and coconut coir. Hydroponics has been recognized as a viable method of producing vegetables (tomatoes, lettuce, cucumbers and peppers) as well as ornamental crops such as herbs, roses, freesia and foliage plants. Due to the ban on methyl bromide in soil culture, the demand for hydroponically grown produce has rapidly increased in the last few years. Hydroponic agriculture offers a soilless cultivation method that can enhance crop yields and sustainability. With decreasing arable land and water availability, hydroponics is positioned to complement conventional farming approaches to support global food security.

LED is defined as Light Emitting Diode, a new technology which produce light more efficiently than incandescent light bulbs. LEDs are "directional" light sources, which means they emit light in a specific direction, unlike incandescent and CFL, which emit light and heat in all directions. LED illumination sources with IOT technology are increasingly being utilized to enhance the growth rate of vegetables and herbs cultivated in greenhouses worldwide. Furthermore, various Internet of Things (IOT) technologies communication protocols, sensors, devices, and technologies are introduced for the automatic controlling of the greenhouse farming with LED lighting. Different LED power with a full spectrum of LED wavelengths has shown an exceptional growth for the plants with highest power of 40 Watts. With full inclusions of red, blue and white spectrum, higher power of the LED helps exponentially especially in the budding phase of the plant. Increasing light intensity of the LED treatments enhances the content of photosynthetic pigments, soluble carbohydrates, vitamin C, element content, antioxidant enzymes, and soluble protein, while reducing the amount of starch. This massive attractiveness of LED is due to the exponential increase in LED installations in greenhouses, positive changes in policies on reducing energy consumption, and its minimal negative impacts on the environment. Therefore, LED red illumination is essential and has a significant role in improving plant quality. Thus, bioactive compounds and antioxidants synthesis in a plant could be triggered by using different LED wavebands, thus increasing the plant's nutritional quality. Therefore, adequate plant illumination is crucial for the greenhouse industry to maintain high-quality horticultural products. LEDs provide many advantages that make them an ideal solid-state lighting alternative for greenhouses due to their high energy efficiency for photosynthesis, easy spectral composition control, low radiant heat output, and easy light intensity adaptation to plant photoreceptors.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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