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REVIEW ARTICLE

LED farming – An innovative technique of productive and effective crop cultivation

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Abstract

The United Nations conference on Trade and Development has projected that by 2050, two-thirds of the global population will reside in urban areas. In response to the growing demand for food in urban settings, indoor farming-particularly through Controlled Plant Production Systems-offers a viable solution. Among the critical factors influencing indoor cultivation, light availability and quality are especially limiting. The intensity and spectral composition of light are essential for maximizing crop productivity per unit area. Light Emitting Diodes (LEDs) have emerged as a transformative tool in indoor cultivation, serving as an efficient and highly effective light source. The National Aeronautics and Space Administration (NASA) used LED lights to grow plants in space during the 1960s. Later, in the 1980s, Japan began utilizing LEDs for high quality vegetable and fruit production. In addition, LED lights in horticultural crops have been applied intensively, providing specific wavelengths of light to meet the crop demand. LED technology offers numerous advantages including, lower heat generation, higher energy efficiency and reduced power consumption, making it a sustainable choice for indoor farming. Red and blue LED lights, in particular, are more efficient and promote higher photosynthetic rate, flowering , bioactive compound production and overall crop yield. LED light consumes only 25 % of the energy used in conventional lighting systems, which significantly reduces operational costs. The paper reviews the significance of LED farming and its effects on crop growth, crop quality and yield. It also explores the application of LEDs in speedy breeding and algal photobioreactors. Further, it underscore LEDs potential to revolutionize urban agriculture and highlights the need for future research focused on optimizing spectral combinations and improving cost-efficiency.

Keywords: food; indoor cultivation; light; light emitting diode

Introduction

The global population is rapidly increasing and is projected to reach approximately 9.7 billion by 2050. It is estimated that around 68 % of this growing population will reside in urban areas (1). Currently, the urban population accounts for 51.1 % in developing nations and 80.5 % in developed nations, respectively. Meanwhile, cultivable land is shrinking significantly due to rapid urbanization and is further affected by the adverse effects of climate change, including rising global temperatures, erratic monsoon rainfall, droughts, etc. These factors, coupled with the escalating demand for food in urban areas, present significant challenges to ensuring food security in the future.

Meeting this rising demand through conventional farming methods is increasingly difficult due to numerous limitations. Controlled Environment Agriculture (CEA), commonly referred to as indoor farming, is emerging as a sustainable and innovative approach to address these issues. It allows crops to be cultivated under optimized and controlled conditions, thereby enhancing productivity per unit area and ensuring profitability. By integrating advanced technologies and precision farming techniques, indoor farming offers immense potential to secure future food supplies and meet the nutritional needs of the growing urban population.

Light is a critical factor in indoor farming, as its intensity, spectral quality and photoperiod significantly influence plant growth and development. These parameters can be precisely managed through artificial lighting systems. However, traditional lighting technologies such as fluorescent, incandescent and high-pressure sodium (HPS) lamps are often energy-intensive and inefficient (2). Advancements in lighting technology have led to the development of LEDs as a superior alternative. LEDs are semiconductor devices that consume significantly less energy while offering high luminous efficacy, ranging from 80 to 150 lm/W (3).

In controlled environment agriculture, LED farming employs LEDs as the primary light source. LEDs can emit specific wavelengths at desired intensities, effectively targeting plant photoreceptors and meeting their exact light requirements. This capability enables optimal plant growth, maximizes photosynthetic efficiency and enhances flowering and fruiting. Additionally, LEDs produce minimal heat, making them ideal for inter-canopy lighting, which improves light penetration and photon absorption, leading to uniform growth and increased yields.

Moreover, LED farming supports the year-round cultivation of healthy and nutritious crops-particularly leafy greens and vegetables-regardless of external weather conditions. As such, LED farming represents a cutting-edge, sustainable solution to meet the world's growing food demand by maximizing productivity, promoting resource efficiency and addressing environmental constraints.

Principle of LED

Oleg Vladimirovich Losev, a Russian scientist developed the first LED; however, his work was overlooked at that time. Eventually, Nick Holonyak in 1962 developed the first visible spectrum LED and considered as the father of LED. LED is a semiconductor device that operates under forward bias condition and consists of a P-N junction, which is fabricated by the semiconductor material. The P-type region consists of holes and N-type have free electrons. When a forward voltage is applied, holes and free electrons move towards each other, resulting in recombination. During recombination process, an electron falls to a lower energy level, releasing energy in the form of a photon. The wavelength of light produced on LED is determined by the energy band gap of the material utilized for semiconductor (4).

LEDs offers numerous advantages over conventional lighting sources, including smaller size, lower power consumption, higher luminous efficacy and reduced heat generation. These attributes make LEDs highly suitable for applications such as indoor crop cultivation, where efficient and controlled lighting is essential (5).

Science of LED farming

Light, air, water and nutrients are the essential growth factors for all plants. It is crucial to regulate these factors at optimal levels to achieve the maximum potential of the plant (6). LED farming provides an innovative solution, allowing precise control over these elements. It enables the plants to thrive in a perfectly optimized setting by customizing light intensity and spectrum, ensuring a balanced supply of water and nutrients and maintaining ideal environmental conditions. The method not only enhances the growth efficiency but also ensures the production of healthy, nutrient-rich greens and vegetables, paving the way for sustainable and high-quality food supply.

LEDs and plant production

In the 1990s, research findings revealed that red LED light alone was sufficient for crop growth and the completion of the plant life cycle. However, subsequent studies demonstrated that the combination of blue light with red LEDs significantly enhanced crop growth and development (7). When chlorophyll molecules absorb light energy, it triggers photosynthetic activities, converting light energy into chemical energy to produce carbohydrates by utilizing carbon dioxide and water under light conditions. Red and blue light are particularly effective in being absorbed by chlorophyll, thus accelerating the photosynthetic process (8, 9). Red light was found to be 25-35 % more efficient than blue light in driving photosynthetic activities. This difference is attributed to the fact that blue light is partially absorbed by accessory pigments and non-photosynthetic pigments, which reduces the efficiency of energy transfer to the photosynthetic reaction centers (10, 11). However, both red and blue light are absorbed at different levels by chlorophyll a and chlorophyll b, contributing to enhanced photosynthesis.

In addition, plant photoreceptors play a critical role in regulating growth and development. For instance, phytochrome, a key photoreceptor, responds to red and far-red light, mediating processes such as flowering and seed germination. Meanwhile, the internal clock of plants is regulated by cryptochrome, which absorbs ultra-violet, blue and green spectra. Further, phototropin is a photoreceptor that absorbs blue light and influences stomatal opening, as well as the arrangement of photosynthetic pigments, optimizing light capture (12). The combination of red and blue light promotes optimal plant growth and development. However, achieving the ideal ratio of these wavelengths in indoor cultivation remains challenging for various crops. The broad spectrum of light often leads to energy wastage, whereas LEDs offer an advantage as they can emit specific spectral compositions, thus reducing power consumption.

The combined irradiance of red and blue LED light can trigger desirable plant responses; however, the optimal red to blue light ratio varies significantly among different crops (13). By utilizing LED technology, growers can tailor light spectra to meet specific crop requirements, enhancing productivity and sustainability while minimizing energy usage. This highlights the importance of continued research to optimize light quality for various crops.

Effects of LED lighting on crops

Light plays a dual role in plant development : it serves both as an essential energy source for driving photosynthesis and as a crucial signaling mechanism that regulates photomorphogenesis. Crop development can be optimized by providing plants with the required quality and intensity of light. LED lights have emerged as a highly effective tool for achieving these conditions, offering precise control over spectral composition, light intensity and photoperiod. Plants exhibited improved photosynthetic efficiency, biomass accumulation and bioactive compound production and achieved higher yields under LED lighting conditions.

Crop growth and development

LED lighting substantially promotes leaf area, chlorophyll content, net photosynthetic rate and biomass production, particularly under red and blue LED lights, which directly enhance crop yield attributes and overall productivity. Plants achieve maximum photosynthetic efficiency when the wavelength of LED light closely aligns with the absorption peaks of chlorophyll. The effects of different LED lights including, red LED, blue LED, red-blue LED and white LED on various vegetables, flowers and medicinal plants has been investigated (14). Findings revealed that a red-blue LED combination in 70:30 ratio offered the most significant benefits, such as increased photosynthesis rates and fresh weight, compared to other light treatments.

An earlier study evaluated the use of red LEDs as radiation sources for growing lettuce and compared the results with those under fluorescent and incandescent lamps (15). The results demonstrated that plant characteristics such as fresh weight, dry weight and stem length were notably enhanced under red LED lighting. Similarly, a combination of red-blue-far-red LEDs resulted in increased plant height and fresh weight in sweet basil (*Ocimum basilicum* L.) compared to red-blue and white LED treatments (16).

Investigations into different red-blue LED ratios in tomato plantlets revealed that a 10:1 red-to-blue ratio yielded higher survival rates, pigment concentrations and growth parameters, including leaf area, shoot number, root length and dry weight (17). Additionally, blue LEDs (465-470 nm) significantly increased seedling weight and chlorophyll content in pea seedlings compared to red LEDs (18). Blue light also promotes stomatal opening, thereby facilitating CO_2 uptake and enhancing photosynthesis.

Various photoreceptors respond effectively to red, far-red and blue light under targeted spectral compositions at optimal intensities (Table 1). These findings underscores the potential of LED lighting as a sustainable and efficient light source for controlled environment agriculture, enabling improved plant growth, productivity and resource efficiency.

Flowering

In the floriculture sector, LED lighting is predominantly favored for two main purposes *viz.* stimulating plant growth rate and improving the quality of cut flower production and manipulating flowering time by adjusting day length to ensure flowering at predetermined dates, thereby maximizing income potential. This is achieved through the precise control of light spectra, particularly in the red and far-red wavelengths, which influence photoreceptors such as phytochromes. Phytochrome is a critical photoreceptor that governs flowering in plants which exists in two interconvertible forms such as Pr and Pfr. Red light (660 nm) converts Pr into its active form (Pfr), during daylight conditions, promoting flowering and vegetative responses. Conversely, far-red light (730 nm) converts Pfr back to Pr, thereby regulating flowering responses and photoperiodic behaviors in crops (26).

Spectral control using red and far-red light *via* LEDs effectively manipulate pythochrome levels in crops, directly influencing critical day length and optimizing flowering time. LEDs are also favoured for their low power consumption, minimal heat output and long operational lifespan, making them efficient for floriculture sector. Several studies have documented the significant impacts of LED lighting on flowering behavior. For instance, flower crops such as marigold and treasure flowers under red-blue LED lighting in greenhouse conditions exhibited a 50 % increase in flower production and a reduction in time to first flowering by half compared to conventional condition (27). These findings highlights the potential of LEDs to enhance both the speed and yield of floral production.

Furthermore, LED lighting is widely employed to accelerate plant propagation, notably reducing the rooting period by 2-3 days. Red LEDs are particularly effective in improving photosynthetic activity and manipulating flowering time through phytochrome-mediated responses (28). Far-red LEDs are also utilized to modulate flowering, complementing the function of red LEDs in optimizing photoperiodic and developmental responses. By leveraging the precision and adaptability of LED technology, the floriculture industry can achieve enhanced productivity, high quality flower production and improved profitability through efficient light management.

Bioactive compound production

Bioactive compounds, including both primary and secondary metabolites, are essential in determining the flavor, aroma and taste of crop produce. Secondary metabolites, in particular, play a vital role in protecting plants against oxidative damage and various environmental stress. Light-responsive photoreceptor such as phytochrome and cryptochrome are integral to the biosynthesis of these compounds. Phytochromes and cryptochromes act as molecular switches detect light signals and trigger a cascade of biochemical events that ultimately leads to the production of various bioactive compounds. Phytochrome primarily regulate the synthesis of phenolic compounds, while cryptochrome facilitates the synthesis of pigments such as carotenoids, chlorophyll and anthocyanins (Table 2). This regulation is achieved by influencing transcription factors and gene expression pathways associated with bioactive compound biosynthesis.

Table 1. Effect of LED lighting on the growth of various crops

Light source or/and lighting conditions	Crops	Effect on crop growth	References
Red-blue LEDs (70:30 and 45 µmol m^{-2} s^{-1})	Micro propagated strawberry plants	Increased root and shoot fresh weight	19
Red-blue LEDs	Radish and Lettuce	Higher leaf area with enhanced photosynthetic rate	20
Red-blue LEDs (1:1 and 70 µmol m^{-2} s^{-1})	Lillium	Increased bulblet fresh and dry weight	21
Red LEDs (638 nm, 300 µmol m^{-2} s^{-1}) with HPS lamp (90 µmol m^{-2} s^{-1})	Red leaf, green leaf and light green leaf lettuces (*Lactuca sativa* L.)	NO_3 concentration increased by 12.5% in light green lettuce but decreased by 56.2% and 20% in red and green leaf lettuce respectively	22
Red LEDs (640 nm, 270 µmol m^{-2} s^{-1}) with blue LEDs (440 nm, 30 µmol m^{-2} s^{-1})	Red leaf lettuce (*Lactuca sativa* L.)	More leaf expansion	23
Blue LEDs with red and green LEDs (Total PPF maintained at 300 µmol m^{-2} s^{-1})	Cherry tomato seedling	Stomatal number and net rate of photosynthesis increased	24
Blue LEDs (460 nm) with red LEDs (660 nm) with total PPF of 80 µmol m^{-2} s^{-1}	Chinese cabbage (*Brassica camprestis* L.)	Increased chlorophyll content	25

Table 2. Production of bioactive compounds in response to LED lightning

Light source or/and lighting conditions	Crop	Effects	References
Red LEDs (660 nm, 50 μ mol m^{-2} s^{-1})	Red leaf cabbage	Promotes anthocyanin content	40
Red LEDs (640 nm)	*Brassica oleracea* L. (Khale plants)	Increases lutein accumulation	13
Far red (730 nm, 20 μmol m^{-2} s^{-1}) with red (640 nm, 300 μmol m^{-2} s^{-1})	Red leaf lettuce (*Lactuca sativa* L.)	Decreases antioxidant potential and anthocyanin content	41
LED Light (638 nm, 170 μmol m^{-2} s^{-1})	*Lactuca sativa*	Improves free radical scavenging activity, tocopherol content and phenolic compound	42
Blue LEDs alone (468 nm) or with red LEDs (655 nm)	Red leaf lettuce seedlings	Promotes antioxidant activity and polyphenols	43

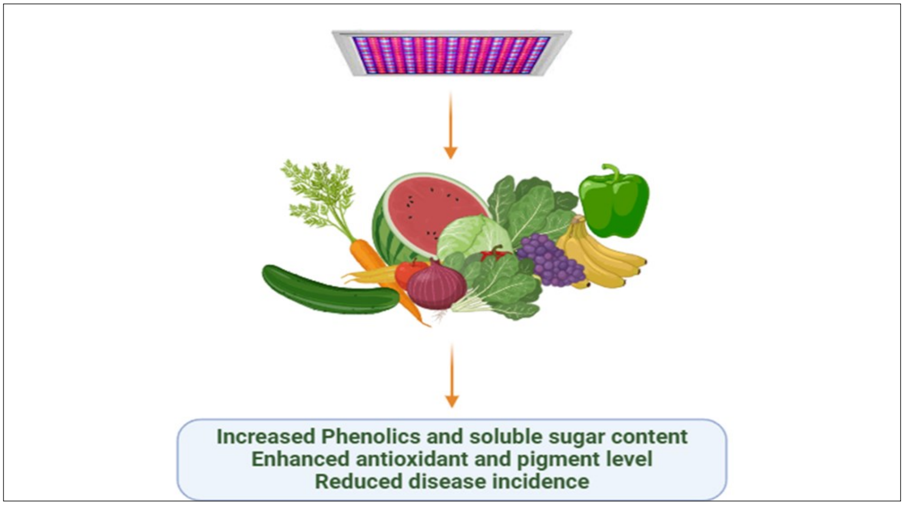

Fig. 1. Influence of LED light source on production of bioactive compounds in crops.

Recent advancements in agricultural research have highlighted the potential of LED to enhance the production of bioactive compounds and improving crop quality (29, 30) (Fig. 1). LEDs with specific wavelengths and intensities, such as red, blue and red-blue combinations, have been shown to significantly influence the accumulation of bioactive compounds. The activity of enzymes critical to secondary metabolite production, such as phenylalanine ammonia-lyase, chalcone synthase, chalcone isomerase, flavanol synthase and stilbene synthase, are also significantly upregulated under LED lighting.

Studies indicated that the combination of red and blue LEDs is mainly effective in increasing chlorophyll, carotenoid content and antioxidant levels in crops such as lettuce, kale, spinach, basil and sweet peppers. The red-blue LED combination is superior over red LEDs alone in enhancing antioxidant activity, with its effectiveness varying among crops (17). In pea seedlings, red LEDs (625–630 nm) promoted β-carotene synthesis and overall antioxidant activities (18). Red LEDs also increase phenolic compound levels in buckwheat sprouts (31), while blue LEDs enhance carotenoid content in strawberries and tocopherol concentration in lettuce (32, 33). Moreover, high-intensity blue LEDs have been shown to significantly elevate antioxidant activity in vegetables by enhancing the scavenging capacity for reactive oxygen species and free radicals (34). LEDs with mixed spectra, such as red-blue-green, further improved nutritional quality by improving the nitrogen, magnesium, zinc and other micronutrient levels in crops such as lettuce, tomatoes and radish (34, 35).

The application of LEDs not only enhances crop quality but also reduces microbial contamination, increases nutrient content and modulates the post-harvest ripening process in fruits and vegetables. For instance, green, blue and red LEDs have been reported to induce systemic acquired resistance against fungal pathogens in crops (36). Further, LEDs also play a critical role in disease resistance and defense mechanisms in plants. Blue LEDs (460 nm) have been shown to enhance resistance against grey mold in tomatoes by increasing proline levels, antioxidant activity and free radical scavenging capacity (37). Similarly, red and purple LEDs suppress grey mold in tomatoes through physiological modifications and pathogen photo-inhibition (38). In lettuce, blue LEDs effectively suppress grey mold by enhancing antioxidant activity and promoting favorable morphological changes (39).

Crop yield

LED lighting, particularly in the red and blue spectra has demonstrated remarkable efficacy in promoting plant growth and enhancing crop yield (44, 45). These benefits are attributed to its role in expanding leaf area, optimizing net photosynthesis and regulating stomatal opening and closure-mechanisms that drive higher plant productivity. Additionally, LEDs influence flowering and activate plant defense mechanisms, thereby contributing to improved crop yield and quality (46, 47).

The interlighting system, an innovative application of LED technology, has proven especially beneficial for promoting fruit ripening, particularly in greenhouse cultivation environments (48-53). Among the various LED spectra, red light has emerged as the most effective in supporting superior growth, development and yield in vegetable crops. Moreover, the strategic combination of blue, green and red wavelengths further enhances crop production, underscoring the importance of tailoring light spectra to specific crop requirements.

For instance, basil plants grown under red-blue-far-red LED combination exhibited one-fold increase in yield, while blue-red LED combination resulted in a half-fold increase compared to white LED light illumination (54). Similarly, red-blue LED spectra increased the yield of Sida tomato fruits, enabling early harvest with enhanced fruit quality (55).

Other applications of LEDs in agriculture

Speedy breeding

Conventional breeding methods are inherently time-consuming and required multiple generation cycles to produce genetically stable lines. NASA pioneered the concept of speed breeding by cultivating wheat crops in space, leveraging extended photoperiods and precise temperature controls to accelerate photosynthesis and crop growth. This innovative approach inspired its adoption in terrestrial breeding programs, revolutionizing the pace of crop improvement by drastically reducing generation times. Speed breeding is achieved by extending the duration of light exposure, which promotes early seed set and enables multiple generations to be completed within a single year (56-59). Using this technique, it is possible to produce up to six generations annually in crops such as spring wheat, durum wheat, barley and bengal gram and it has also been successfully applied to rice, sorghum, amaranth and cotton (60).

The critical enabler of speed breeding is the use of LEDs as supplemental light sources to extend daylight periods. LEDs offer precise spectral control and high energy efficiency, playing a crucial role in maintaining optimal light conditions that support accelerated plant growth and development. This technology has demonstrated the ability to reduce the time required to reach anthesis by nearly half compared to crops grown under standard greenhouse conditions (61). Further, speed breeding represents a paradigm shift in plant breeding, allowing for the rapid development of crop varieties with improved traits such as yield, disease resistance and climate resilience. By combining extended photoperiods, controlled environmental conditions and advanced LEDs lighting technology, speed breeding has become an indispensable tool in addressing the challenges of global food security and sustainable agriculture.

Algal production

Microalgal production has emerged as a cost-effective and sustainable technology, particularly for bioenergy generation. Light illumination plays a critical role in optimizing algal growth, insufficient lighting reduced productivity, while excessive light intensity can lead to photo-inhibition. Algae exhibits higher photosynthetic efficiency than terrestrial plants, with chlorophyll pigments showing peak absorption of light in the blue (425 nm) and red (665 nm) regions of the spectrum. Artificial light sources are increasingly utilized, especially in controlled production system such as bioreactors, to fully harness the potential of microalgae. Furthermore, LEDs emit minimal heat, are durable, compact and highly adaptable for use in photobioreactor (62–66).

The findings revealed that red-blue LED light at an intensity of 500 lux significantly increases biomass production in *Chlorella* species compared to white or red light alone (67). Moreover, red light at an intensity of 220 lux was found to double the lipid dry weight compared to white light, demonstrating its potential for improving biofuel production from microalgae.

However, spectral requirements for optimal algal growth varied for different species, necessitates precise tuning of light wavelengths and intensities for optimal algal growth vary among species, necessitating precise tuning of light wavelengths and intensities tailored to each strain (68-71). Identifying the optimal combination of wavelength is essential to maximize both the quantity and quality of algal biomass. Red LEDs has been shown to be more effective than blue light in improving growth rates in many algal species, highlighting their potential for large-scale applications (64). By leveraging the flexibility of LED lighting, microalgal production systems can be manipulated to enhance productivity, offering a scalable solution for bioenergy and other industrial applications.

Efficiency of LED lighting

Heating and lighting are among the most significant cost factors in protected cultivation (72). Reducing these costs through energy-efficient approaches is critical for sustainable production. LED lighting has emerged as a superior alternative to traditional light sources due to higher energy efficiency and longer lifespan. LEDs require only 25 % of the energy used by conventional lamps to achieve a similar crop response or yield (73). For example, bedding plants exhibited similar flowering patterns under 150 W HPS lamps and 14 W LED light, highlighting the energy efficiency of LEDs.

LEDs can convert approximately 50 % of electrical energy into usable light, compared to only 30 % for HPS lamps. The efficiency of LED systems is determined by considering factors such as LED package efficiency under current droop, driver inefficiencies and optical losses. The most efficient HPS lamps have an efficacy of 1.7 μmol J^{-1}, while early-generation LEDs ranged from 0.8 to 1.7 μmol J^{-1}. The advancements in LED technology have significantly improved the efficacy, with modern LEDs achieving as high as 4.1 μmol J^{-1} (74, 75). The higher recorded efficacy for LEDs is 2.64 μmol J^{-1}, compared to 1.72 μmol J^{-1} for HPS lamps.

A key advantage of LED lighting is its ability to emit specific wavelengths tailored to crop growth (Fig. 2). Additional benefits include reduced electricity costs, lower maintenance requirements, steady-state operation and dimming capabilities. While the initial investment in LED systems remains relatively high, the long-term cost savings and increased profitability rationalize the expense. One study documented that using LED lighting for indoor cultivation reduces annual cost by $886.38 compared to conventional HPS lighting (76). Although the upfront cost of LED systems and installation are higher, the greater energy consumption and frequent bulb replacement associated with HPS systems significantly increase overall operational costs of indoor cultivation. Moreover, as LED technology continues to advance, both energy efficiency and purchase costs are expected to improve, making LEDs an increasingly accessible and cost-effective solution for protected cultivation (77).

Techniques to intensify LED lighting efficiency in crop cultivation

The light use efficiency of LED lighting can be significantly

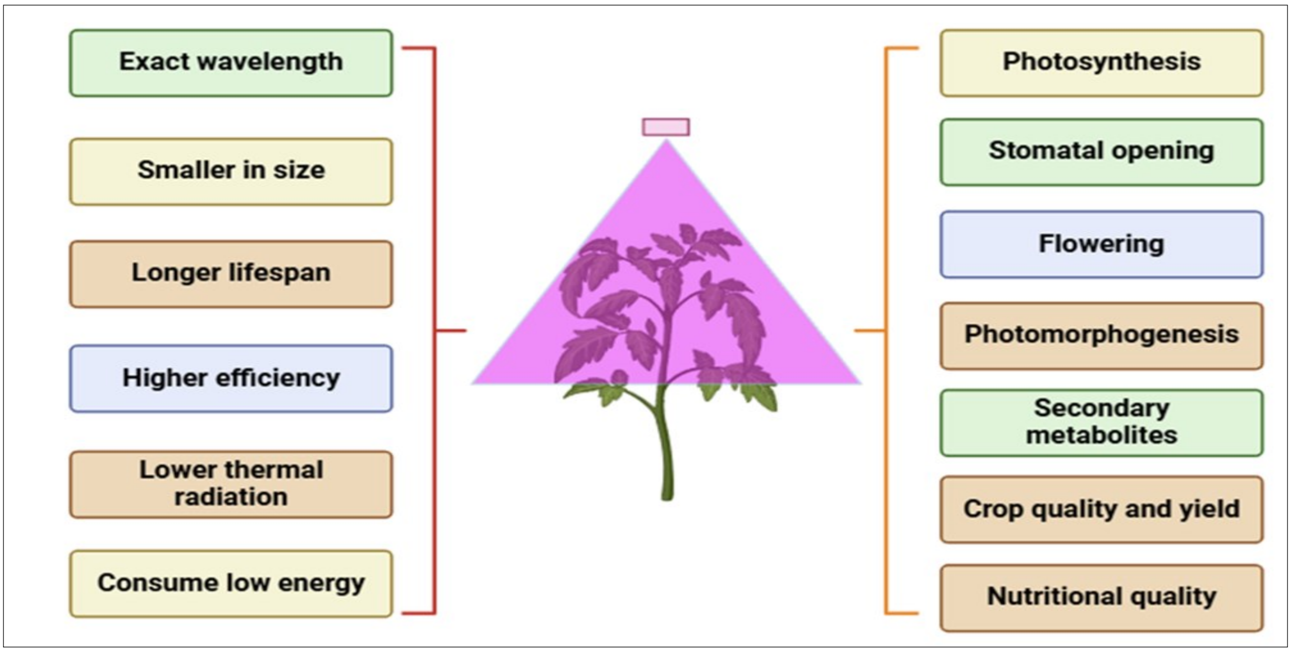

Fig. 2. Advantages of LED lightning in crop cultivation.

enhanced through various strategies such as inter-canopy lighting, targeted lighting and precise control of Photosynthetic Photon Flux (PPF). These approaches aim to maximize photons capture by plants, thereby improving both energy efficiency and plant productivity. A key advantage of LEDs is their minimal radiant heat output, which makes intercanopy lighting more feasible. By positioning lights within the plant canopy, energy requirements are reduced and desired PPF levels can be achieved with lower energy input. For example, intercanopy lighting in cowpea production achieved 50 % of the edible biomass with only 10 % of the energy input required for traditional top lighting methods (78).

Additionally, intercanopy lighting prevents premature senescence and maintains photosynthesis rates in lower leaves, which are often underutilized in conventional lighting. Targeted lighting, another efficient method, involves activating LEDs positioned directly above individual plants. This method deliver light precisely where it is needed, thereby minimizing energy waste. Targeted, close-canopy LED systems have been shown to reduce energy consumption per unit of dry mass when compared to standard LED lighting systems. It is facilitated through advanced control methods such as current control, pulse-width modulation and duty cycle control (5, 6).

By integrating intercanopy lighting and targeted lighting systems with advanced PPF controls, growers can achieve substantial energy savings while maximizing crop growth and productivity. It further makes LED-based cultivation systems, an increasingly viable solution for sustainable and efficient agricultural practices.

Conclusion

LED farming is an emerging technology that is transforming agriculture by enhancing crop productivity and quality through precise control of light spectra. Unlike conventional lighting sources such as fluorescent, incandescent or HPS lamps, LEDs provide selective light spectra along with numerous advantages, including higher energy efficiency, compact size, controlled photon flux density and exceptional durability. Although, the initial investment in LED systems is relatively high, the long-term benefits, including increased yields and energy savings, make it a cost-effective solution.

The use of LED lighting in agriculture has demonstrated numerous benefits, such as enhanced photosynthesis rates, increased leaf area, biomass production, chlorophyll content, secondary metabolite synthesis, protection against pathogens, collectively resulting in enhanced crop quality and yield. Additionally, LEDs influence key physiological processes such as the modulation of ripening and the delay of senescence, thereby extending the shelf life and enhancing the market value of crops. Different spectra ratios and light intensities produce varied responses, highlighting the need to optimize LED settings for each crop or crop variety to achieve desired outcomes.

Advancements in LED technology have led to the development of smart lighting systems integrated with wireless connectivity and software platforms. Modern LEDs are equipped with cameras and sensors that enable real-time monitoring and visual assessment of plant health, thereby supporting precision agriculture practices. These innovations facilitate better resource management, reduce energy consumption and improve crop management strategies.

The future of LED farming will depend on advancements in light spectra customization, luminous efficacy, cost-effective manufacturing and energy efficiency. As LED technology continues to evolve, its potential to manipulate crop growth and development will play a crucial role in addressing the global food and nutritional security challenges.

Authors' contributions

PP carried out the conceptualization and drafted the original manuscript. MS participated in the conceptualization, supervision, review and editing of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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