Review Article

Enhancing Plant Growth: Harnessing the Effectiveness of Artificial Light

ABSTRACT

This extensive analysis reveals the significant influence of artificial light, especially light-emitting diodes (LEDs), on enhancing plant growth for sustainable agriculture and horticulture optimization. The production of seedlings is an essential component of contemporary agriculture. While study is conducted on the complex relationships between plants and artificial light sources.Controlled light conditions in growth chambers and vertical farming systems are excellent solutions that enable year-round and space-efficient seedling production. It is possible to draw the conclusion that using artificial light can result in increased biomass, faster growth rates, and better crop quality. This review highlights the effects of various light spectra, intensities, and durations on critical physiological processes involved in seed germination, vegetative growth, and overall seedling development during propagation.Apart from that, the new study looksinto the complexity of photosynthesis, photomorphogenesis, and photoperiodic reactions, providing useful insights for customising light conditions for different crops and developmental stages.

Keywords: *Plant growth, artificial light, spectrum, intensity, duration and plant response*

1. INTRODUCTION:

When it comes to contemporary agriculture and horticulture, the search for plant propagation methods that are both effective and environmentally friendly is of the utmost importance in order to guarantee both food security and crop output [1]. The conventional method of plant propagation has undergone a substantial transformation as a result of technological breakthroughs, notably in the field of artificial lighting. Throughout the course of human history, the major source of energy for photosynthesis and the development of plants has been natural sunshine. On the other hand, researchers and cultivators have been forced to look for alternate solutions because of the constraints that are imposed by seasonal changes, geographical locations, and the amount of daylight readily available [2]. In order to circumvent these limitations, artificial light has evolved as a strong tool that provides exact control over the light spectrum, intensity, and duration. An in-depth examination of the complex relationship that exists between light and plant physiology is required in order to make progress in the direction of comprehending and using the efficacy of artificial light for the proliferation of plants [3]. The influence of artificial light on essential processes like photosynthesis and photomorphogenesis is significant, ranging from the germination of seeds to the development of an organism's vegetative growth and beyond. As a result of their low energy consumption and spectral tuning capabilities, light-emitting diodes have emerged as a crucial component in this paradigm shift [4]. They make it possible to customize the light conditions, which provides the opportunity to imitate and even improve the spectrum of natural sunshine. The optimization of growth parameters and the acceleration of the production of high-quality seedlings are both significantly impacted by this degree of control, which has far-reaching ramifications. The use of artificial light goes beyond the confines of the laboratory and other controlled environments to a wide variety of situations, such as greenhouses, vertical farms, and even urban agricultural projects [5]. With the help of these technologies, it will be possible to propagate plants throughout the whole year in a space-efficient manner, which would guarantee a steady and dependable supply of seedlings regardless of the external environmental circumstances. Within the framework of this ever-changing environment, the purpose of this research is to investigate and analyse the available information and insights into the exploitation of artificial light for the purpose of effective plant multiplication. In order to make a contribution to the continuing conversation about using technology for agriculture that is both sustainable and productive, this paper will investigate the present level of research, practical uses, and possible advancements. The use of artificial light is not only a technical improvement; rather, it signifies a paradigm change in the manner in which we approach and improve the basic processes of plant growth [6]. This provides a view into the future of precision agriculture and horticulture. This paradigm shift towards artificial light in plant propagation signifies a departure from conventional agricultural norms. The nuanced interplay between light and plant physiology becomes particularly pronounced when considering the versatility of LEDs [7]. These compact, energy-efficient devices not only allow for the manipulation of the light spectrum but also present opportunities for energy savings and resource optimization. In the context of seed germination, artificial light offers a means to extend photoperiods, ensuring consistent conditions conducive to uniform and timely sprouting. The controlled provision of light during this crucial phase not only accelerates the germination process but also contributes to the development of vigorous seedlings with enhanced disease resistance [8]. Moving beyond germination, artificial light becomes a key determinant in steering the trajectory of vegetative growth. The ability to tailor light spectra to the specific needs of different plant species opens avenues for optimizing biomass accumulation and nutrient assimilation [9]. Researchers and growers alike are exploring the potential of spectral manipulation to induce desirable traits such as increased branching, compact growth, and enhanced photosynthetic efficiency. Practical applications of artificial light in controlled environments, such as greenhouses, extend these benefits. The integration of LEDs allows for the creation of growth chambers where light, temperature, and humidity can be precisely regulated. This level of control not only facilitates year-round propagation but also addresses the challenges posed by limited arable land, enabling cultivation in non-traditional spaces. Vertical farming, an innovative approach gaining prominence, leverages artificial light to optimize space utilization further [10]. Stacked layers of crops receive targeted light exposure, allowing for increased productivity within confined urban environments. This vertical integration aligns with the growing emphasis on sustainable agriculture practices and local food production. However, the transition towards artificial light in propagation is not without challenges. Energy consumption, cost implications, and the ecological footprint of manufacturing light technologies warrant careful consideration [11]. Striking a balance between technological advancements and sustainable practices remains a focal point in the ongoing discourse surrounding artificial light in agriculture. As we navigate the changing world of artificial light in plant propagation, this review attempts to summarise existing knowledge, highlight obstacles, and pave the way for future breakthroughs.By shedding light on the transformative capabilities of LEDs and their integration into diverse agricultural settings, we contribute to the collective understanding of how technology can propel the efficiency and sustainability of plant propagation in the 21st century.

2. ARTIFICIAL LIGHT TECHNOLOGY: Artificial light technology is the use of man-made light sources, such as electric bulbs or LEDs, to illuminate both indoor and outdoor areas. It includes a variety of technologies and methods for producing and controlling artificial light, which contributes to improved visibility, safety, and aesthetic appeal in a wide range of applications, including residential, commercial, industrial, and public contexts [12].

2.1Importance of Artificial Light technology:

Plant culture and growth rely heavily on artificial light, especially in indoor environments or places with low sunshine. Artificial illumination encourages photosynthesis, which is required by plants to create energy and thrive [13]. This regulated light environment also enables year-round cultivation, avoiding the limitations of seasonal fluctuations in lighting. Furthermore, artificial light allows producers to optimise and alter light conditions, resulting in faster growth rates, healthier plants, and higher agricultural yields. It increases agricultural output in areas with bad weather conditions or limited access to natural sunshine With technological breakthroughs such as LED lighting, energy-efficient and cost-effective artificial lighting choices in agriculture are becoming more widely available, providing long-term solutions for improving plant growth. Overall, artificial light makes a big contribution to global food security by allowing for consistent growing of healthy crops in a variety of conditions [14]. Artificial light may considerably improve plant development by providing a steady, regulated light source for photosynthesis. However, it is critical to ensure that the light spectrum, intensity, and duration are ideal for the individual plant species in order to avoid detrimental effects on growth or energy waste.

Table 1: Effect of artificial light on plant growth enhancement.

Research description	Results	Reference
"Impact of Light Quality on Plant Growth"	Red and blue light promote photosynthesis and growth in plants	[15]
"Effects of Light Intensity on Plant Development"	Higher light intensity can enhance growth in certain species	[16]
"Role of Light Duration in Crop Yield"	Extended light duration may increase yield in some crops	[17]
"Wavelength-specific Effects on Flowering Plants"	Different wavelengths affect flowering and fruiting	[18]

"LED Lighting for Sustainable Crop Production"	LED lighting systems can be energy-efficient and promote growth	[19]

2.1.1 LED (light-emitting diode) technology

The incorporation of LED (light-emitting diode) technology into the realm of plant growth has ushered in a transformative era, reshaping traditional approaches to cultivating crops and nurturing plant development. Distinguished by its energy efficiency, longevity, and customizable light spectra, LED technology offers a nuanced solution to enhance fundamental physiological processes such as photosynthesis and photomorphogenesis [20]. Departing from conventional lighting methods, LEDs provide a spectrum that can be tailored to meet the specific needs of plants at various growth stages, from seed germination to flowering. The advantages of LED technology for plant growth are multifaceted. Their energy efficiency stands out, enabling the production of light with significantly lower energy consumption compared to traditional sources [21]. With an extended lifespan, LEDs contribute to long-term cost savings and reduced environmental impact. The capacity to adjust light spectra is an important feature since it allows gardeners to optimise conditions for different plant species and growth stages. Additionally, the minimal heat emission of LEDs is advantageous in maintaining controlled environments, preventing temperature fluctuations that could impede plant growth. The compact design and flexibility of LED fixtures facilitate strategic placement, maximising light exposure in diverse cultivation settings [22].

LED technology finds diverse applications in plant growth, starting with its pivotal role in seed germination and seedling development. The controlled provision of light ensures uniform conditions, fostering the production of healthy and robust seedlings [23]. During the vegetative growth phase, the tunable spectra of LEDs influence factors such as branching, leaf expansion, and overall biomass accumulation. In the flowering and fruit development stages, precise control over the light spectrum enhances reproductive processes, leading to increased flower production, improved fruit quality, and optimised yields [9]. Controlled Environment Agriculture (CEA) systems, including vertical farming and greenhouse cultivation, leverage LED technology to create tailored light conditions, maximising productivity and resource efficiency. Moreover, LED technology is indispensable in plant research and experimentation, facilitating studies on the impact of specific wavelengths on plant responses and contributing to a deeper understanding of plant physiology [24]. While LED technology offers numerous advantages, there are considerations and challenges to navigate. The initial cost of high-quality LED fixtures may be a barrier for some growers, despite long-term cost savings. Standardisation metrics for assessing LED performance in horticulture remain a challenge. Heat management may still be required for large-scale LED installations to prevent localised temperature variations [25]. Successful implementation also requires a nuanced understanding of plant responses to specific light spectra, highlighting the importance of staying informed about the latest research findings. Looking ahead, the future of LED technology in plant growth holds promising directions and innovations. Ongoing research into plant responses to different light spectra is expected to guide the development of tailored LED solutions [26]. Integration with smart technologies, including sensors and automation systems, is anticipated to enhance precision agriculture practices. Continued advancements may lead to increased affordability, making LED technology more accessible to a broader range of growers. Customised solutions for specific crops and growth stages are likely to emerge, optimising light conditions based on the unique requirements of each plant species [27]. In conclusion, the integration of LED technology in plant growth signifies a dynamic and promising frontier in modern agriculture, offering sustainable and efficient solutions for crop cultivation.

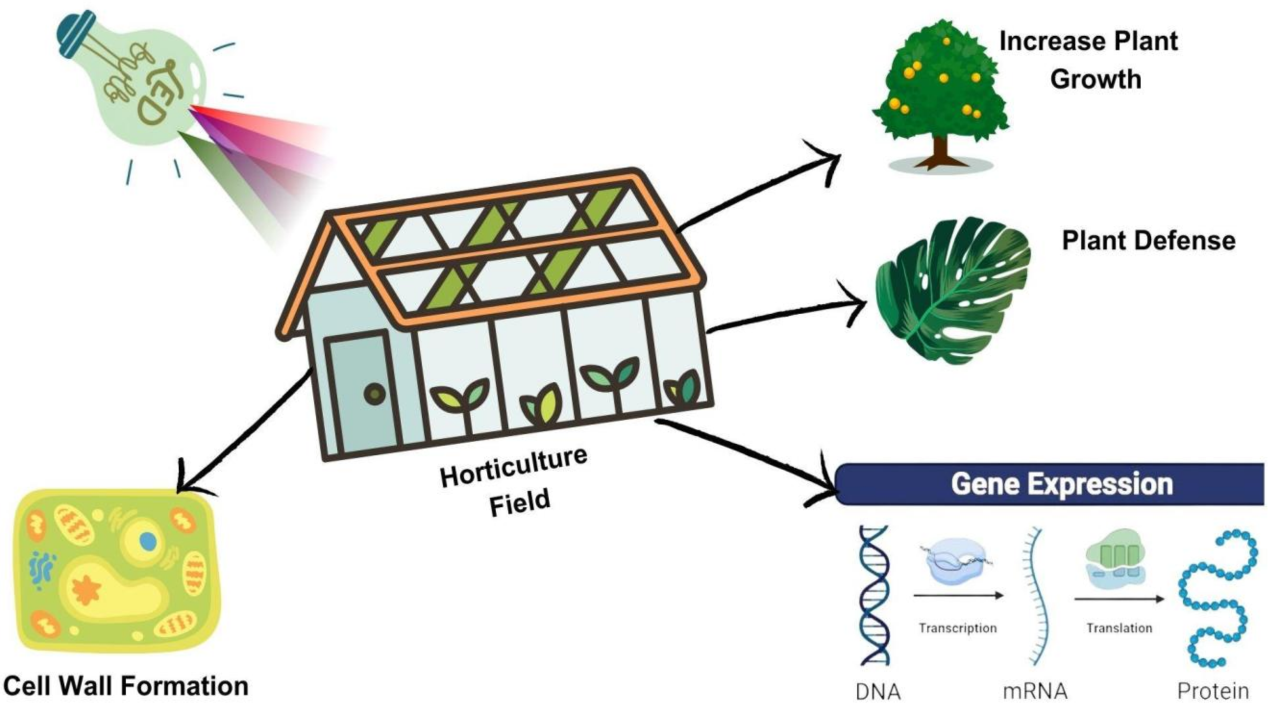

Fig 1. Light emitting diode (LED) lights for the improvement of plant performance and production.

2.2 Fluorescent Lighting.

Lighting has long been an essential component in our field of plant development. It serves as a cost-effective and energy-efficient alternative to standard incandescent sources. This versatile technology, known for its affordability and broad light spectrum, has found widespread use in various horticultural settings, especially in indoor gardening and greenhouse environments [28]. Its role in addressing the challenges posed by insufficient natural light in indoor spaces has made it a popular choice among growers. The advantages of fluorescent lighting in plant growth are evident in its energy efficiency, characterised by minimal heat emission. This efficiency ensures that a significant portion of the energy consumed contributes to photosynthesis rather than being wasted as heat. The broad spectrum emitted by fluorescent bulbs covers wavelengths suitable for different stages of plant growth, making them suitable for supporting plants throughout their entire lifecycle [29]. Additionally, the affordability of fluorescent lighting fixtures has contributed to their accessibility, making them suitable for both small-scale and commercial cultivation setups.

Fluorescent lights are particularly effective during seed germination and early growth, providing the necessary light intensity for uniform sprouting and supporting the healthy development of seedlings [30]. They are conducive to vegetative growth, influencing factors such as leaf expansion, stem development, and overall biomass accumulation. Furthermore, fluorescent lighting serves as an excellent source of supplemental lighting, complementing natural sunlight or other primary light sources, particularly in regions with limited sunlight or during the winter months [31]. However, certain considerations and challenges come with the use of fluorescent lighting in plant growth. These include limited light penetration, requiring careful positioning for uniform coverage, and the lower light intensity compared to some other technologies, which may impact the growth of light-demanding plants [32]. Additionally, the lifespan and lumen depreciation of fluorescent bulbs necessitate periodic replacement to maintain optimal light levels, impacting long-term operational costs. Looking ahead, the future of fluorescent lighting in plant growth may involve advancements in technology to address limitations such as light intensity and lumen depreciation. Integration with other lighting technologies, such as LEDs, is an area of exploration, potentially combining the strengths of both to create more versatile and efficient lighting solutions [33]. Sustainability initiatives may also play a role in enhancing the eco-friendliness of fluorescent lighting systems, considering factors such as recyclability and energy-efficient manufacturing processes. In conclusion, fluorescent lighting continues to be a significant player in modern horticulture, offering a reliable and accessible solution for various cultivation scenarios. Recent studies and potential advances indicate that this lighting option will continue to play an essential role in the evolving landscape of plant development.

2.3 High-Pressure Sodium (HPS) Lamps.

High-Pressure Sodium (HPS) lamps have emerged as a prominent lighting technology in the plant growth, presenting distinctive characteristics that cater to the specific needs of cultivated vegetation known for their high-intensity light output and efficiency, HPS lamps have found widespread application in various horticultural settings, contributing significantly to indoor gardening, greenhouse cultivation, and supplemental lighting strategies [34].

The primary advantage of HPS lamps lies in their ability to provide a high-intensity, warm-coloured light that closely mimics the spectrum of natural sunlight. This characteristic is particularly beneficial during the flowering and fruiting stages of plant growth, as it promotes robust reproductive processes and enhances overall yield. The efficiency of HPS lamps, both in terms of light output and energy consumption, makes them a preferred choice for growers seeking to optimize resource use in commercial and large-scale cultivation setups [35]. HPS lamps play a pivotal role in supporting the entire lifecycle of plants, from seed germination to vegetative growth and eventual flowering. The warm spectrum emitted by these lamps facilitates the expansion of leaves, stem development, and the accumulation of biomass during the vegetative phase. Moreover, their influence on the photoperiod is advantageous in maintaining consistent and extended light cycles, fostering uniform growth patterns and minimizing stress on the plants. While HPS lamps offer several advantages, considerations and challenges are inherent in their use. Notably, the heat generated by these lamps necessitates proper ventilation and heat management in cultivation spaces to prevent elevated temperatures that could adversely affect plant health. Additionally, the spectrum emitted by HPS lamps is not as versatile or tunable as some other lighting technologies, limiting their application in certain growth scenarios [36]. Looking toward the future, advancements in HPS lamp technology may focus on addressing heat management concerns and expanding the versatility of the emitted light spectrum. Integration with other lighting technologies, such as LEDs, may offer a hybrid approach, harnessing the strengths of each to create more adaptable and efficient lighting solutions [37]. As the horticultural landscape evolves, HPS lamps continue to be a reliable choice for growers seeking high-intensity lighting solutions that support robust plant growth throughout various stages of cultivation.

2.4 Analysis of Different Lighting Sources

In the ever-evolving landscape of horticulture, the paradigm of plant lighting has witnessed a dynamic shift, extending beyond the realm of traditional sources like LEDs. While LEDs continue to play an important role due to their energy economy and adapted spectrum, new and improved lighting technologies are making gains in defining the future of plant development[38]. One such advancement is the emergence of Smart Lighting Systems, integrating cutting-edge technologies like sensors and automation to create dynamic, responsive lighting environments [39].These systems enable real-time adjustments based on environmental conditions and plant requirements, fostering precision agriculture practices. The interplay of data analytics and artificial intelligence further refines these systems, offering growers unprecedented insights into optimizing light conditions for diverse crops [40]. Additionally, Quantum Dot LEDs (QLEDs) have surfaced as a promising innovation. These nanotechnology-driven LEDs leverage quantum dots to fine-tune the emitted light spectrum with unparalleled precision. The result is a highly customizable and efficient lighting solution that addresses specific growth requirements of various plant species, promising enhanced photosynthetic efficiency and accelerated growth rates. Furthermore, fibre-Optic Lighting Systems are gaining attention for their potential in delivering light directly to specific areas of plant canopies. By channelling light through flexible optical fibres, these systems minimize energy loss and enable precise targeting of light, allowing for increased efficiency in resource utilization and localized stimulation of plant growth. The integration of Wireless Power Transfer (WPT) technology is another frontier, offering a wireless and energy-efficient means of delivering power to lighting fixtures [41].This not only enhances flexibility in fixture placement but also contributes to sustainability by reducing the need for extensive wiring. In this era of innovation, the synergy of diverse lighting technologies – from established LEDs to emerging solutions like Smart Lighting, QLEDs, Fibre-Optic Systems, and WPT – empowers growers with unprecedented control and adaptability. The future promises a tapestry of lighting strategies, allowing for customised approaches that optimise plant growth, minimise environmental impact, and pave the way for a sustainable and efficient future in horticulture.

3.IMPACT OF ARTIFICIAL LIGHT ON EFFICIENT PLANT GROWTH DEVELOPMENT: Plant propagation relies heavily on artificial light, especially in controlled conditions like greenhouses and indoor growing facilities. Artificial light may have a substantial impact on plant growth, which is impacted by several characteristics such as light intensity, spectrum, duration, and photoperiod [42]

3.1 Photosynthesis: Artificial light can replace natural sunlight as a source of energy for photosynthesis. Light-emitting diode (LED) grow lights, for example, provide certain wavelengths of light that plants can absorb and utilise for photosynthesis. These artificial light sources may be programmed to produce the optimal spectrum, intensity, and duration of light for each stage of plant growth. As a result, plants may grow and thrive in a regulated environment with artificial light, independent of weather or seasonality.

3.1.1 Light Intensity: -Adequate light intensity is required for photosynthesis, which converts light energy into chemical energy to power plant development (43). Insufficient light can reduce photosynthetic activity, but much light can cause photoinhibition or damage.

3.1.2 Light Spectrum:

Quality of Light: Plants react differently to different wavelengths of light. Blue light (short wavelength) is necessary for vegetative development and compact plant structure, but red light (long wavelength) is required for blooming and fruiting. By manipulating the light spectrum with LEDs or other artificial light sources, farmers may tailor the light environment to the demands of certain plants [44].

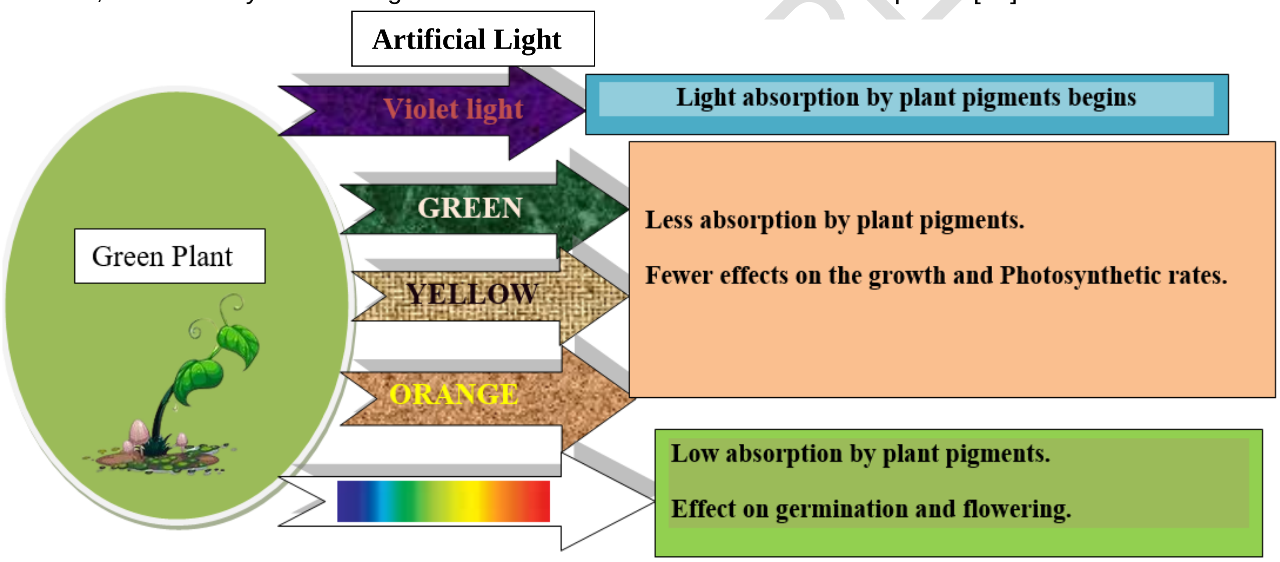

Fig 2: Effect of artificial light on plant growth enhancement.

3.1.3 Uniformity and Control:

Consistency: Artificial light creates uniform and regulated conditions for plant development, allowing producers to improve the propagation process. This control is especially useful in areas with fluctuating natural light or throughout certain seasons [45].

3.1.4 Energy Efficiency and Sustainability:LED Technology: The growth of LED (Light Emitting Diode) technology has transformed artificial lighting in agriculture. LEDs are energy-efficient and can be programmed to produce precise spectra, which promotes plant development while also saving electricity [46].

4. LIGHT SPECTRUM AND PLANT RESPONSE: The Light Spectrum refers to the electromagnetic radiation released by the sun or other light sources, which ranges from ultraviolet (UV) to infrared (IR) wavelengths. Plant Response describes how plants respond to various wavelengths of light for activities like photosynthesis, growth, and blooming [47].

4.1 Understanding Photosynthesis: The light spectrum required for photosynthesis runs from 400 to 700 nanometres, which includes blue (400-500 nm) and red (600-700 nm) light. Plants absorb blue and red wavelengths while reflecting green light, which is why they seem green[48]. Photosynthesis takes place in chloroplasts, where pigments such as chlorophyll receive light energy and transform carbon dioxide and water into glucose and oxygen via a sequence of chemical processes. This process is necessary for plant development and survival [48].

4.2 Light Spectra and Growth: During photosynthesis, plants respond to various wavelengths of light and use the visible light spectrum to produce energy. Blue light (400-500 nm) and red light (600-700 nm) play critical roles in plant growth, regulating processes such as germination, blooming, and fruiting [49]. In regulated conditions such as indoor farms and greenhouses, plant development may be optimised by using certain light spectra, such as blue light for vegetative growth and red light for blooming.

4.3 Optimising Lighting Conditions for Specific Plant Species: The light spectrum has a substantial impact on plant development, with different wavelengths influencing distinct physiological processes [50]. Blue light promotes vegetative growth and leaf development, and red light encourages blooming and fruiting. Optimising lighting conditions entails delivering the proper combination of blue and red wavelengths, changing intensity and duration based on the plant species' individual demands for photosynthesis and photomorphogenesis [51].

5. LIGHT INTENSITY AND DURATION: Light intensity is the quantity of light energy that reaches a plant's surface, impacting photosynthesis. The duration of light exposure, or photoperiod, influences plant activities such as blooming and dormancy. Both components vary by plant species and developmental stage, which is critical for optimum development [52].

5.1Effects on Plant Morphology: Light intensity and duration influence plant shape through photosynthesis and growth patterns. Higher light intensity usually encourages compact and strong plants, while extended light durations might boost blooming. However, high light intensity or extended exposure may cause stress, which affects overall plant health and morphology[53].

5.2Time of Light Absorption and Growth Patterns: Light intensity and duration control plant development patterns, which influence morphology. While adequate intensity and duration encourage healthy development, the time of light absorption is also important. Plants absorb light at certain times, impacting activities such as photosynthesis and hormone production, which shapes growth patterns and determines total plant development [53].

5.3Photoperiodic Influence on Flowering and Fruit Set: Light duration and intensity, especially in connection with daylight hours, have a substantial impact on the blooming and development of fruit in plants [54]. Specialised day-length needs cause blossoming responses, including plants with short daylight hours blooming during prolonged night and long-day plants blossoming under shortened nights. Maintaining ideal light conditions is critical for optimising blooming and fruit-setting mechanisms in many plant species.

6.ENERGY EFFICIENT AND SUSTAINABLE PRACTICES IN ARTIFICIAL LIGHT: Balancing resource consumption is a difficulty while pursuing energy-efficient and sustainable strategies to enhance plant development. Implementing efficient lighting technology, such as LEDs, necessitates a thorough energy cost study.Integrating renewable energy sources and using smart control systems to decrease energy waste are significant problems. Developing eco-friendly solutions for optimal plant growth necessitates finding a balance between technological innovations and sustainable practices [55].

6.1 Sustainable Practices in Artificial Light Agriculture: Sustainable techniques in artificial light agriculture refer to environmentally mindful and resource-efficient methods of using artificial lighting systems for crop growing [56]. These techniques strive to reduce the environmental effect, optimise resource utilisation, and enhance long-term viability. Important aspects of sustainable practices in artificial light agriculture include:

6.1.1 Energy efficiency: To reduce power use and carbon impact, use energy-efficient lighting technology such as LED (Light-Emitting Diode) systems [57].

6.1.2 Optimised light spectrum: Customising light spectra to meet the unique demands of crops at various stages of development, encouraging effective photosynthesis and reducing energy waste.

6.1.3 Smart Lighting Controls:

Smart lighting systems with sensors and controllers may dynamically alter light levels based on crop development, natural light availability, and climatic variables [58].

6.1.4 Use renewable energy sources.

Using renewable energy sources, such as solar or wind power, to provide electricity for artificial lighting systems, reduces dependency on traditional energy infrastructure [59].

7.INTEGRATION OF SMART FARMING SYSTEMS: The adoption of smart farming systems in artificial light agriculture entails the use of modern technology and data-driven solutions [62] to optimize and improve many elements of crop production in controlled settings with artificial lighting. Smart farming systems in artificial light agriculture are implemented by incorporating modern technology like sensors, automated controls, and data analytics into controlled production settings [63]. These systems constantly monitor environmental elements such as temperature and light intensity, using real-time data to optimise conditions for plant development. These solutions provide remote monitoring and control via IOT(The incorporation of Internet of Things) connectivity, allowing farmers to make more informed decisions. Precision agriculture is also included in the integration, which ensures exact resource management and waste minimization [64]. Overall, this strategy improves productivity, resource efficiency, and sustainability in agricultural activities using artificial illumination.

7.1Greenhouse and Vertical Farming: - Greenhouse farming has become more and more popular since it has so many applications in controlled environments. Such enclosed projects offer farmers a regulated environment to optimise growing conditions for diverse crops [65]. One primary application is the extension of the growing season, which enables year-round production regardless of external weather circumstances. Furthermore, because greenhouses offer protection from pests, frost, and hot temperatures, they lessen the need for pesticides and other chemical interventions [66]. Furthermore, the controlled environment makes precise control over elements like temperature, light, and humidity possible, which raises crop yields and quality [67]. This farming method is particularly effective for high-value products when market success hinges on maintaining perfect conditions, such as exotic fruits, vegetables, and flowers. Furthermore, greenhouse farming promotes resource efficiency because it prevents soil degradation and uses less water. Applications of greenhouse farming generally promote food security in a continually changing climate and sustainable agricultural practices [68].

Vertical farmingis a cutting-edge agricultural technique that, when used in approved regions, provides innovative solutions to issues that arise in conventional farming. Crops are cultivated in vertically stacked layers or structures, typically in metropolitan settings, using cutting-edge techniques such as hydroponics, aeroponics, and controlled environment agriculture (CEA) [69]. Vertical farms'-controlled surroundings allow for exact temperature, humidity, and lighting management, which maximises plant growth and resource efficiency. This strategy tries to find solutions to a fewdifficulties, including a scarcity of arable land, variable weather patterns, and the requirement for food production that is sustainable in areas with high human density [70].

7.2 Artificial Plant Propagation Systems Artificial plant propagation systems in controlled environments refers to the use of specific, controlled circumstances to enhance and optimise the process of growing plants using various propagation methods, including tissue culture, cuttings, and seeds. These regulated habitats provide the ideal conditions for the development and growth of plants to generate more reliable and efficient results [71].

7.3 Effectiveness of Artificial Light in Extreme Climates: Artificial light during extreme weather is necessary for various reasons that enhance people's social cohesion and health [72]. Artificial light is necessary in extremely dark situations, such as underground passageways or arctic regions during the winter, to maintain normal functioning and postpone the onset of mental health problems linked to prolonged darkness. In locations like the desert or overly hot climates where daytime temperatures may be unpleasant, artificial light also allows you to work longer hours throughout the cooler periods of the day [73]. This improves flexibility in the challenging setting. Artificial light also increases security and safety during bad weather by lighting paths, aiding in emergency response, and lowering the risk of accidents [74]. Agriculture uses controlled artificial lighting systems to enhance year-round crop production and food sustainability, extending growing seasons during severe weather. All things considered, artificial light has many benefits beyond simple lighting in harsh climates, improving many elements of daily living and boosting resistance in unfavourable climatic settings.

8.CHALLENGES IN ENHANCING PLANT GROWTH WITH ARTIFICIAL LIGHT:

8.1Light Spectrum and Intensity: The spectrum and intensity of light are critical for efficient photosynthesis and plant development. Ensuring that artificial light matches the natural sunshine spectrum and intensity can be difficult, as various plants require different light conditions for maximum development.

8.2 Energy Consumption: Artificial lighting systems, particularly those based on classic incandescent or fluorescent bulbs, can be energy-intensive. Indoor agricultural and greenhouse businesses have the problem of reducing energy use while maintaining adequate lighting levels.

8.3 Heat Production: Traditional lighting sources may create a lot of heat, which is bad for plant development. Effective heat management systems are required to keep excessive heat from harming plants or increasing the demand for cooling, which can lead to increased energy usage.

8.4 Cost: The initial investment and continuing maintenance expenses of artificial lighting systems may be too expensive for small-scale farmers or regions with limited resources. Creating economical alternatives for efficient artificial lighting is critical for wider adoption.

8.5 Environmental Impact: Conventional lighting sources, such as incandescent or fluorescent bulbs, can include dangerous ingredients and are not ecologically friendly. Developing sustainable and eco-friendly alternatives is critical for mitigating the environmental effect of artificial lighting.

9. FUTURE DIRECTIONS AND INNOVATION: Future trends and breakthroughs in artificial light's efficient transmission will concentrate on optimising light distribution and transmission. Supplies, optics, and nanotechnology advancements are aimed at minimising energy losses. Intelligent lighting solutions, enabled by machine learning, offer dynamic control depending on environmental parameters and human demand. These advances promise better energy economy, versatility, and seamless interaction with developing technology, therefore influencing the future of digital lighting.

CONCLUSION: Artificial light has emerged as an effective method for increasing plant growth and production in controlled situations. Understanding the complex light systems affecting photosynthesis, photomorphogenesis, and secondary metabolism is essential for optimising artificial light usage in agriculture. To optimise the promise of artificial light in sustainable agriculture, future research should focus on generating personalised light techniques, improving energy efficiency, and upgrading sensor and control technology.

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