A Review-The Influence of Light Quality and Quantity on Photosynthesis and Photobiological Processes

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Photosynthesis, a fundamental process of life on Earth, uses sunlight, water, and carbon dioxide to harvest chemical energy in addition to oxygen. Improving photosynthetic efficiency has been identified as a possible strategy for enhancing crop yields under realistic farming situations. The light reactions of photosynthesis have been thoroughly investigated, including their components, structure, and regulatory mechanisms, leading to proposed solutions for improving the process. These tactics range from focused changes to specific components to comprehensive redesigns of the entire process, with scales ranging from individual cells to entire canopies. This article looks at ways to increase light utilization per leaf, including pigment reduction, overexpression of photosynthetic proteins, extending the lifetime of photosynthetic equipment, and incorporating nanomaterial. Furthermore, options for optimizing photosynthetic adaptation to environmental changes are examined, such as systems to disperse excess excitation energy or lower power. Schemes for improving acclimation are also introduced, which are stimulated through natural or laboratory-tempted adaptations. However, these attempts are in the experimental phase or have yet to provide the expected results, owing to the complicated integration of photosynthesis within networks of cellular and metabolic processes that differ between species and cultivars. Integrated, systems-wide techniques are necessary to achieve substantial advances in crop production enhancement.

Keywords: Photosynthesis, synthetic biology, photobiology, Light quality, Photosynthetic efficiency, Photo biological processes, Acclimation.

1. Introduction

Joseph Priestley and Jan Ingenhousz discovered the light-dependent emission of oxygen by plants in the 1770s. According to a study, photosynthesis is a crucial process that sustains all life on Earth by converting carbon dioxide (CO_2) and water (H_2O) into organic compounds using photons as a source of biologically active energy (X. G. Zhu et al., 2022). Photosynthetic organisms, including cyanobacteria, algae, and plants, are responsible for producing the food we consume, the oxygen we breathe, and the majority of our energy resources. Since then, other innovators including Calvin, Bassham, and Benson (Caferri & Bassi, 2022), have made substantial contributions to characterizing the enzyme-catalyzed route of carbon assimilation in photosynthesis. They established the groundwork for further research and exploration in this area. The primary components involved in photosynthesis across diverse systems, as well as the underlying regulatory processes, have gradually been revealed over time. Countless researchers' combined efforts have resulted in a complete understanding of the complexities of this critical process.

Photosynthesis is a fundamental process that utilizes sunlight, water, and CO2 (carbon dioxide) to produce the chemical energy necessary for the synthesis of organic matter. Cyanobacteria, algae, and plants, as photosynthetic organisms, play a crucial role in sustaining ecological food chains and generating the oxygen vital in respiratory metabolic processes. They directly or indirectly form the foundation of human nutrition through the consumption of animal-derived products.

Given the pivotal role of photosynthesis in crop plants, enhancing its efficiency holds immense potential for increasing agricultural productivity. The rate of photosynthesis directly influences crop yield (Ort et al., 2015), making it a primary target for research and improvement (Long et al., 2006). However, it is important to recognize that our cultivated crop plants have evolved from free-living dynasties that reformed natural ecological conditions and competed with neighbouring plants. Consequently, despite extensive refinement efforts, current crop varieties have not yet fully optimized their capacity (Slattery & Ort, 2021) to maximize biomass production in dense canopies.

This knowledge gap highlights the need for further research aimed at improving the photosynthetic efficiency of crop plants. By gaining a deeper understanding of the underlying mechanisms and limitations, we can develop targeted strategies to enhance photosynthetic performance and ultimately increase agricultural productivity. Such advancements are essential for meeting the demands of a growing global population and ensuring food security in a sustainable manner.

Photosynthetic reactions (Bellasio, 2019) can be categorized into two phases including light-dependent reactions and dark reactions. The light-dependent reactions occur in photosynthetic membranes and involve the absorption of photons by chlorophyll molecules associated with antenna proteins. This energy is then transferred to reaction centers, leading to the stabilization of energy through secondary processes that generate high-energy bonds in adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH). These molecules serve as energy sources for carbon dioxide fixation, which occurs in the cytoplasm of single-cell organisms or in the stroma of chloroplasts in higher plants. Carbon dioxide fixation involves three subsequent reactions: carboxylation, reduction, and regeneration. The most abundant enzyme on Earth, ribulose-1, 5-bisphosphate carboxylase/oxygenase (RuBisCO), catalyses the fixation of carbon dioxide to ribulose-1, 5-bisphosphate (RuBP), generating 3-phosphoglyceric acid (PGA). Subsequently, PGA is reduced using NADPH and ATP, forming triose phosphate. The majority of triose phosphate is recycled back to regenerate RuBP, while the remaining portion is either converted to starch within the chloroplast stroma or exported to the cytoplasm, where it is transformed into sucrose. The overall process of photosynthesis can be represented by the equation that summarizes the conversion of carbon dioxide, water, and light energy into glucose and oxygen as below (Thornton et al., 2023).

$$6\,CO_2 + 6\,H_2O = \text{light} \rightarrow C_6H_{12}O_6 + 6\,O_2 \qquad (1)$$

Several factors, especially the quality as well as quantity of light, influence photosynthetic efficiency. The spectral makeup or specific wavelengths of light are referred to as light quality, whilst the intensity or overall amount of light is referred to as light quantity. Both factors have a significant impact on plant photosynthetic machinery and photobiological activities.

Light quality has a large impact on photosynthetic pigments, particularly chlorophylls, which absorb light energy. Light of various wavelengths, such as blue, red, green, and far-red, has diverse powers to induce photosynthesis. The absorption spectra of different pigments, as well as the activation of certain photoreceptor proteins responsible for light perception and signal transduction, cause this difference. Aside from light quality, light quantity is also important in photosynthesis (Trivellini et al., 2023). Inadequate light restricts the availability of energy for photosynthetic activities, but much light can cause damage by producing reactive oxygen species. Light intensity and duration have a direct impact on photosynthetic rates and overall plant productivity. Plants have evolved a variety of adaptive strategies to optimize light use, such as changing the number and distribution of chloroplasts, modulating photosynthetic pigment concentrations, and regulating stomatal opening.

Understanding the impact of light quality and quantity on photosynthesis and photobiological processes is critical for basic research as well as practical applications. Researchers can develop techniques to improve photosynthetic efficiency, crop yields, and artificial lighting systems in controlled situations, and promote sustainable agriculture by unraveling the complicated mechanisms behind plant reactions to light. The purpose of this study is to look at the unique impacts of light quality and quantity on photosynthesis and related photobiological processes. We hope to improve our understanding of the underlying mechanisms and provide significant insights for optimizing plant growth, productivity, and adaptation to changing environmental conditions by exploring the interaction between light and photosynthetic efficiency.

Optimizing a master transcription factor's activity

The nucleus-encoded GOLDEN2-LIKE (GLK) (X. Zhu et al., 2018) transcription factors play an important role in stimulating the expression of photosynthesis-related genes in the first scenario. Chl biosynthesis, light harvesting, soluble electron carriers, and photosystem reaction-center proteins are all controlled by these genes. GLK overexpression has different consequences based on the promoter and target species used. Overexpression of maize GLKs regulated by the maize ubiquitin promoter in rice, for example, resulted in seed yields comparable to the wild type under near-field conditions. Similarly, overexpression of A. thaliana GLK1 with particular promoters boosted seed oil content in A. thaliana. Recent research (X. Li et al., 2020) found that harnessing the maize ubiquitin promoter to overexpress maize GLK genes in rice improved photosynthesis and crop yield in the field. Increased levels of photosynthetic pigments, proteins, stomatal conductance, intercellular CO2 concentrations, photosynthetic yields, carbohydrate buildup, and enhanced photoprotection were observed in these transgenic lines. Under diverse circumstances, D1 protein levels were also elevated in the transgenic lines. Another study (Yeh et al., 2022) corroborated similar findings by overexpressing both maize GLK genes in rice under their promoters at the same time, yielding the maximum grain yields.

Optimizing the specific photosynthetic protein levels

Cumulative levels of specific endogenous or exogenous soluble electron transporters involved in photosynthesis, such as ferredoxin, plastocyanin, flavodoxin, and cytochrome c6, have been shown to promote growth and enhance photosynthetic yields (Leister, 2019). Overexpressing certain genes, like CAO, in plants can lead to an increased abundance of light-harvesting proteins with further thylakoid proteins, resulting in improved dry matter accumulation, electron transport, and enhanced photosynthesis under high as well as low light conditions. However, the effect of CAO overexpression on photosynthesis is not consistent across all plant species, as overexpressing CAO in Arabidopsis does not enhance photosynthesis and can be detrimental under high light conditions. Additionally, overexpression of RuBisCO, (Suganami et al., 2021), has been found to increase photosynthesis and biomass accumulation, with or without Rubisco activase. However, such approaches are effective only when sufficient nitrogen fertilization is provided, considering the high abundance of RuBisCO protein.

Stay-green parameters: Optimising life of photosynthetic apparatus

Promoting enhanced photosynthesis for a set length of time may produce similar outcomes to maintaining regular photosynthesis levels for a longer period. Maximizing grain filling can be accomplished by utilizing "stay-green" genotypes (Carmo-Silva et al., 2017), which are characterized by prolonged flag-leaf longevity. Similarly, the stay-green trait is a valuable breeding target for sorghum, wheat, rice, maize, and barley in hot climates with limited water supply. However, the underlying physiological mechanisms of natural variation in stay-green qualities across cultivars, as well as the specific genes contributing to stay-green quantitative trait loci (Kamal et al., 2019), persist mainly unidentified. Nonetheless, based on mutants exhibiting delayed senescence, specific genes driving the "stay-green" feature have been discovered. While some alterations may delay senescence, they may not preserve complete photosynthetic potential. In rice, mutants lacking effective stay-green features frequently have deficiencies in Chl b reductase NYC1 or NYC3, the alpha/beta hydrolase-fold family protein, both of which play critical roles in Chl metabolism. Genetic studies (Yamatani et al., 2022) involving proteins such as Balance of Metabolism (BCM) 1 and 2, Stay-Green (SGR) 1 and 2, and the observation that overexpression of GLK genes leads to delayed senescence all point to a link between Chl metabolism and GLK-mediated gene expression regulation. Other mutations linked to the stay-green feature have been found in genes involved in hormone and proteasomal control in a variety of plant species. Thorough genome-scale research in maize (Sekhon et al., 2019) identified eight capable candidates for "stay-green" properties, counting a NAC transcription factor, trehalose-6-phosphate synthase, and two xylan biosynthesis enzymes.

Nanomaterials for Photosynthesis Optimization

The most recent approach to using nanomaterials to improve photosynthesis involves using compounds absorbing solar emission in less effective photosynthesis spectral regions, such as UV as well as green light, and then releasing the light of greater wavelengths such as blue or red light to motivate photosynthesis as shown in the (figure1). The figure illustrates that Conjugated polymers (CPs) have been employed in some organisms to facilitate photosynthesis. These CPs, such as poly boron-dipyrromethene-co-fluorene (PBF), can absorb green light and emit light in the red region.

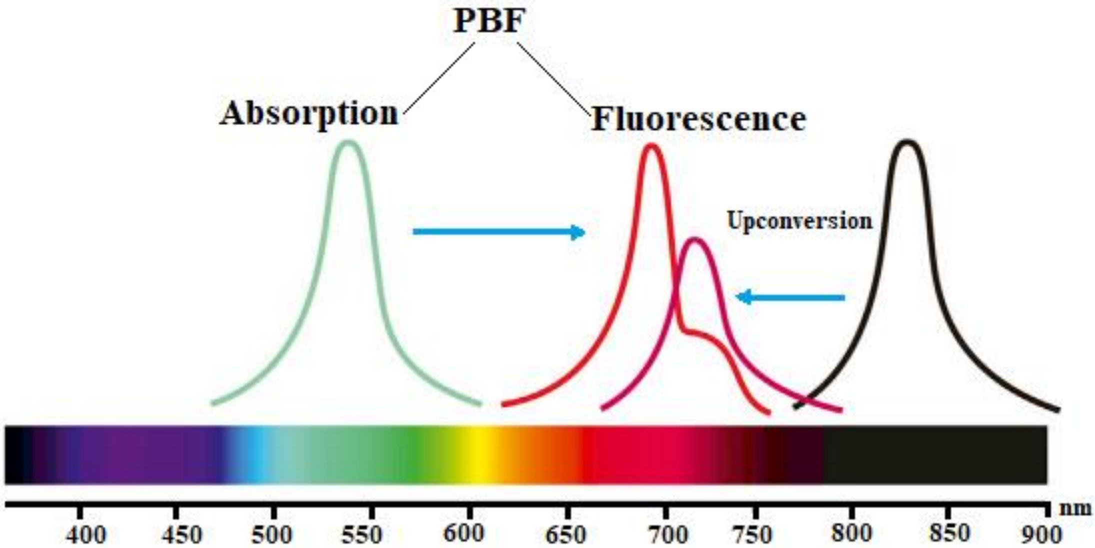

Figure 1: Nanoparticles for extending photosynthesis solar light energy spectrum

The figure also illustrates another approach involving up-conversion, where far-red light, unsuitable for driving photosystems II and I (PSII and PSI), can be converted into visible light. Additionally, the conversion of infrared light IR into visible light is demonstrated in cyanobacterial cells assorted with NPs (nanoparticles) encumbered with the Rose Bengal photosensitizer (Huo et al., 2021). Various nanomaterials have been explored for their potential to augment photosynthesis, together with aggregation-induced emission materials, quantum nanodots, and CPs. These nanomaterials exhibit different fluorescence quantum yields, with values ranging from up to 14% for upconversion materials, 33% for aggregation-induced emission materials, and up to 68% for CPs (Bai et al., 2021). Derivatives of tetraphenylethylene and triphenylamine (TPE-PPO, TPA-TPO) have been conjugated to spinach chloroplasts, resulting in the conversion of UV light (300–400 nm) into blue (400–500 nm) light (PEP) and the absorption of green light (525–600 nm) (PFBT) followed by red fluorescence emission, respectively. The conjugated chloroplasts exhibited enhanced photosynthesis, as indicated by 2, 6-dichlorophenolindophenol (DCPIP) decrease and ATP creation.

Small nanoparticles like Carbon quantum dots with lower diameters than 10 nm have also shown promise in enhancing photosynthesis. These dots can enter chloroplasts converting UV light to photosynthetically dynamic radiation, leading to improved photosynthetic electron transport and growth when applied to rice leaves (Y. Li et al., 2021). CPs are utilized at diverse levels, including remote chloroplasts to whole plants, for the enhancement of photosynthesis. Chloroplasts coated with CP-containing nanoparticles, such as poly-fluorene-phenylene (PFP) with poly-fluorene-benzothiadiazole (PFBT), demonstrated broader absorption spectra and increased light harvesting compared to uncoated chloroplasts. These coated chloroplasts exhibited enhanced photosynthesis, as evidenced by reduced DCPIP and ATP production. Similarly, PFP nanoparticles were applied to enhance photosynthesis in the cyanobacterium Synechococcus PCC7942, resulting in increased NADPH, O2, and ATP production, and quicker growth at lower concentrations of PFP (Zeng et al., 2021). In the flowering plant A. thaliana and unicellular green alga Chlorella pyrenoidosa, the CP PBF, which captivates green light and emits fluorescence in the range of 570-800 nm, was found to enhance growth and increase the production of ATP, NADPH, and O2. PBF was taken up by the roots in A. thaliana and associated with improved growth, particularly at lower concentrations (Zhou et al., 2022).

Hence, nanomaterials hold the potential for expanding the range of solar energy utilized in photosynthesis, especially in terms of converting far-red light into visible light. This approach could be particularly applicable for organisms that exhibit a "green gap" in their action spectra of photosynthesis, such as Nannochloropsis oculata, Acaryochloris marina, and Synechocystis PCC 6803. However, for plants with relatively flat action spectra, the conversion of green into red light may not be practical. Interestingly, previous studies have demonstrated that green light more effectively drives leaf photosynthesis than red light under intense white light conditions (Lanoue et al., 2022).

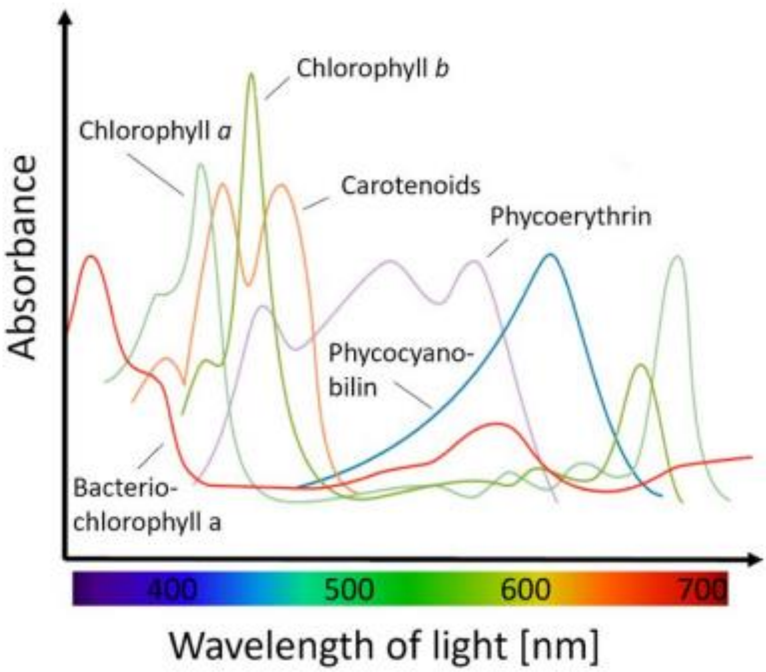

Figure 2: Different absorption spectra of pigments

The figure depicts a schematic impression of various absorption spectra of pigment families. These can spread absorption of light to wavelengths not covered by chlorophyll a. The absorbance measurements are not scaled.

Effect of light quantity on photosynthesis

Photosynthesis is highly responsive to light fluctuations, micronutrients, and water availability as well as environmental temperature. Plants have developed a range of mechanisms to adapt to changes in these parameters. Targeted approaches aim to improve plant's ability to acclimate to variations in incident light, which they encounter consistently in both field and greenhouse settings. This entails addressing two key challenges faced by plants: dissipating excess excitation energy and effectively managing unused reduction power. On the other hand, non-targeted approaches focus on promoting acclimation through natural or laboratory-induced adaptations, which may enhance plants' ability to respond to changing environmental conditions(Yin & Johnson, 2000). By understanding and utilizing these approaches, the adaptive capacity of plants can be enhanced by enabling them to thrive in diverse light conditions and effectively utilize available resources.

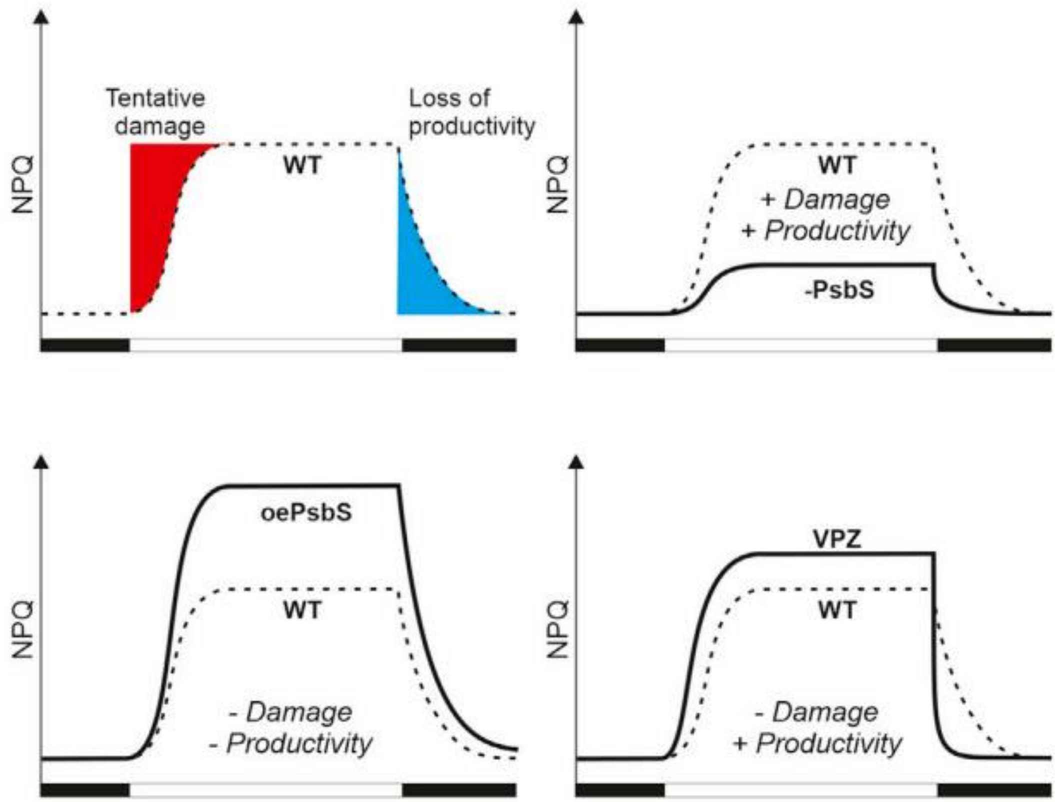

Figure 3: NPQ kinetics in terms of damage and productivity

The (figure 3) presented illustrates the kinetics of non-photochemical quenching (NPQ) under different conditions and genetic modifications in Arabidopsis, tobacco, and potato plants. NPQ serves as a protective mechanism for plants against excessive light by dissipating excess energy as heat. It involves several mechanisms, including energy-dependent quenching (qE), zeaxanthin-dependent quenching (qZ), photoinhibitory quenching (qI), sustained quenching (qH), and state transition quenching (qT). The qE mechanism relies on the presence of the PsbS protein and the interconversion of xanthophyll pigments, such as violaxanthin, antheraxanthin, and zeaxanthin. It involves the modulation of the thylakoid membrane proton gradient and the activation of quenching processes. qZ, on the other hand, is activated rapidly and may involve multiple quenching sites. The qH mechanism is subject to the plastid lipocain LCNP and needs the ROQH1 (short-chain dehydrogenase reductase) for relaxation. qI is related to photodamage and relaxes as damaged D1 proteins are replaced. qT is related to the movement of LHCII (light-harvesting complex II) from PSII to PSI upon phosphorylation. It is important to note that rising the qE amplitude by overexpression of PsbS may not essentially enhance photosynthetic efficacy. Plants lacking PsbS have been found to collect additional biomass under low-light conditions, whereas plants overexpressing PsbS show reduced biomass under the same conditions. However, PsbS overexpression can lead to increased rosette diameter in greenhouse conditions with supplemental light. Manipulating qE levels can impact singlet oxygen production, photoinhibition of PSII, the oxidation state of the plastoquinone pool, cyclic electron flow, and damage to PSI. The effects of manipulating qE can vary across different plant species. For instance, PsbS overexpression enhances crop yield in rice, while its effects on Arabidopsis and tobacco show mixed outcomes. The manipulation of qE not only affects photosynthesis but also influences the overall growth and performance of the entire plant. These effects are attributed to potential chloroplast-derived redox signals. Overall, these findings highlight the complexity of NPQ mechanisms and their role in balancing photoprotection and photosynthetic efficiency(Sahay et al., 2024). The manipulation of qE has significant impacts on plant growth and performance under varying light conditions, but its effects can vary across different plant species and growth environments.

However, crops show varying effects for different light intensities. Higher light intensity promotes increased photosynthetic rates in crops, up to a certain threshold beyond which the rates plateau or decline due to photoinhibition. Insufficient light quantity limits photosynthetic activity, leading to reduced carbon assimilation and plant growth. Optimal light quantity is essential for maximizing crop productivity, as it directly influences the availability of energy for photosynthesis.

Effect of light quality on photosynthesis.

The quality of light has a considerable impact on agricultural photosynthesis. LED lighting, with its capacity to produce a precise light spectrum, has demonstrated encouraging results in boosting greenhouse product yield, quality, and sustainability. Light wavelengths like red (R), blue (B), and green (G) have distinct effects on plant responses and physiological processes. Red light has been shown to stimulate the synthesis of pigments and active metabolites in a variety of crop species, hence improving the nutritional quality of the products. It has been demonstrated that the red-to-far-red (R:FR) ratio influences activities such as germination, plant shape, flowering, photosynthesis, and biomass accumulation. When sufficient light intensity is delivered, the interaction between red and blue light is critical for regulating plant responses, and an optimal R:B ratio can enhance photosynthetic capacity, improve growth, and increase yield(Van Brenk et al., 2024). Blue light boosts the photosynthetic process in crops by causing stomatal openings, moving chloroplasts, and increasing antioxidant and pigment formation. Greenlight contributes greatly to photosynthesis and biomass formation, particularly in the canopy's inner and lower leaf layers. It also regulates secondary metabolism and can help to regulate plant growth and shape in response to light. Despite LEDs have the potential to transform greenhouse operations through the deployment of smart lighting systems, a thorough understanding of plant responses to various light spectra, intensities, and developmental phases is required for successful use. It needs the appropriate light spectrum and intensity necessary for different crops at each phenological stage in order to maximise yield and product quality. Furthermore, for thorough characterization, it is necessary to investigate the connections between light intensity, light spectrum, and other environmental parameters. LED lighting system advancements hold promise for a variety of applications, including greenhouse cultivation, nursery production, and enrichment of plant foods with health-promoting compounds, urban vertical farming, and potential cultivation in bioregenerative life-support systems for space exploration.

Different light quality spectra, such as red, blue, and green wavelengths, have varying effects on photosynthetic rates in crops. Red light enhances photosynthetic efficiency and promotes plant growth by stimulating chlorophyll synthesis and increasing stomatal conductance. Blue light influences photomorphogenic responses, including phototropism, leaf expansion, and chloroplast development, thereby affecting photosynthesis. Green light has a lower photosynthetic efficiency compared to red and blue light, but it still contributes to overall photosynthetic activity. The ratio of different light-quality spectra affects the balance between photosynthesis and other photomorphogenic processes in crops(Liu & van Iersel, 2021).

Overall, the study leads to a better knowledge of crop productivity, sustainable resource management, and climate change adaptation, with ecological implications in terms of light influencing photosynthesis in crops. It aids in the optimization of lighting settings in controlled situations like greenhouses and indoor farms. It is feasible to improve photosynthetic rates, biomass accumulation, and, ultimately, crop yield by providing crops with the correct light spectrum and intensity. Furthermore, proper utilization of light resources can help to promote sustainable agricultural practices. Farmers can reduce resource inputs such as water and fertilizers by maximizing crop photosynthetic efficiency through suitable light quality and quantity, minimizing environmental consequences, and promoting sustainable resource management. Understanding the influence of these parameters on photosynthesis is critical for adjusting agricultural practices to changing environmental conditions since climate change influences light availability and quality. The findings of the study can be used to develop crop selection, breeding, and cultivation strategies that optimize light conditions and boost resilience to climate-induced stresses. The findings shed light on the ecological significance of differences in light quality and quantity on plant community dynamics, species interactions, and ecosystem functioning. This understanding aids in the prediction and management of the effects of changing light conditions on biodiversity, ecosystem services, and overall ecosystem health.

2. Conclusion

The study focuses on implementing a lighting system using LEDs of different spectrums. The results will demonstrate the identifications of specific LED wavelengths that demonstrate higher photosynthetic rates and overall plant growth compared to other wavelengths. The determination of an optimal combination of light quality and quantity to enhance photosynthesis and plant development. It will be helpful for crops with increased yield and resilience due to the limiting factors and experimentally tested models, similar to ways for increasing crop output. The study can observe the plants for altered leaf features, such as reduced size and increased pigmentation, allowing for denser planting and better light collection. Finally, study demonstrates that different monochromatic lights have varied effects on plant growth, photosynthesis, and chlorophyll fluorescence.

LEDs show potential as plant growth lights, but more research is needed to discover the ideal light spectrum and intensity for different crops and growth phases, as well as to understand how light interacts with other environmental conditions. These developments are critical for a variety of LED applications, including greenhouse culture, vertical farming, and space cultivation for human exploration. Finally, the findings will highlight the importance of light wavelengths in photosynthesis. Light wavelength modulation in agricultural practices, particularly indoor farming, can effectively optimize plant growth rates and increase crop production efficiency.

Future Scope

The study has considerable potential for further research and breakthroughs in plant physiology and photobiology. More research is needed to understand the underlying molecular mechanisms that influence photosynthesis and photobiological processes, such as gene expression patterns, signaling pathways, and metabolic changes associated with specific light conditions. Future research could look into how diverse plant species, especially agricultural plants and economically important plant species, respond to varied light qualities and volumes. It can reveal insights into their adaptive strategies as well as possible uses in agriculture and horticulture. Future research can focus on establishing the best light quality and quantity combinations for certain plant species, growth phases, and environmental conditions to improve cultivation practices such as indoor farming, greenhouse agriculture, and vertical farming. Future research might focus on building customized lighting systems that optimize energy efficiency and plant performance in controlled conditions using advanced lighting technologies. This review could help to design crops with more nutritional value and better health advantages. Furthermore, one promising field of future research is understanding the ecological implications of light quality and quantity on plant interactions such as competition, herbivory, and pollination. Future research can focus on the combined effects of light quality and quantity with other abiotic and biotic factors such as temperature, humidity, CO2 concentration, and nutrient availability for a more comprehensive understanding of plant responses and to facilitate the development of sustainable agricultural practices. The future scope of research on the impact of light quality and quantity on photosynthesis and photobiological processes is vast, with numerous opportunities for scientific advancements, technological innovations, and practical applications in plant biology, agriculture, and environmental sciences.

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