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A Comparative Study on the Growth Performance of Different Vegetables under Various Light Colors

Daniel T. Delos Santos[1], Raiza Gwen A. Soriano[2], Angel R. Porbido[3] & MJ B. Ferialde[4]

[1]Maria Aurora National High School

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ABSTRACT

Optimizing indoor agriculture hinges on mastering the light spectrum. Light-Emitting Diodes (LEDs) allow for the precise delivery of light recipes, where targeted spectral bands trigger specific physiological responses to enhance photosynthesis and secondary metabolic production. This study sought to describe the spectral quality of red, blue, and white (control) lights yielding the best results for common crops such as cabbage (*Brassica oleracea*), lettuce (*Lactuca sativa*), and pechay (*Brassica rapa*). The study employed quantitative, controlled experimental design which allowed for a clear comparison between the experimental groups receiving monochromatic LED light and the control group receiving a balanced white LED spectrum. The findings revealed significant differences in how each species responded to light quality. White light was consistently the most effective protocol, providing a balanced spectrum that maximized both vertical growth and leaf expansion while preventing "spectral stress." Lettuce showed high sensitivity, exhibiting moderate elongation under red light but significant growth inhibition under blue light. Meanwhile, pechay showed the highest adaptability under white light, and cabbage maintained a compact growth habit regardless of color. Statistical analysis via Two-Way ANOVA confirmed that while species type was a significant determinant of growth, light color had a more stable effect on leaf area expansion. While monochromatic lights can be used to manipulate specific plant traits, a balanced white LED spectrum is the most reliable choice for general vegetable cultivation in CEA. The study recommends that indoor farming initiatives, particularly in Maria Aurora, Aurora, prioritize full-spectrum lighting to ensure plant health and resilience.

1. Introduction

The unusual growth of the global population and the concurrent challenges caused by climate change have placed immense pressure on conventional agricultural systems. To ensure food security and resilience, there is an escalating demand for innovative, sustainable agricultural approaches that can maximize yields while minimizing resource consumption (Liang et al., 2021; Pennisi et al., 2023). Controlled Environment Agriculture (CEA), including vertical farms and greenhouses, has emerged as a promising solution. By providing a stable, optimized environment, CEA systems mitigate risks from pests, diseases, and unpredictable weather events, allowing for consistent food production year-round (Kozai, 2018).

Within these controlled systems, artificial lighting is a fundamental and programmable tool. While sunlight provides a broad spectrum of light, the advent of Light-Emitting Diodes (LEDs) allows for the precise manipulation of light quality and color (Md. Naznin et al., 2021). The varying wavelengths of light significantly influence key plant processes, including photosynthesis, morphology, and the production of important secondary metabolites (Paradiso & Proietti, 2022). Customizing these "light recipes" has the potential to dramatically improve plant growth, accelerate development, and increase overall yields, directly addressing the global need for more efficient food production (Liang et al., 2021).

The Philippines, a nation heavily reliant on agriculture, faces significant threats to its food production system. Geographically, the country is situated in a region highly vulnerable to the impacts of climate change, including increasingly frequent and intense typhoons, prolonged droughts, and severe flooding. These natural disasters can devastate crops, disrupt supply chains, and jeopardize the livelihoods of small-scale farmers. According to the Philippine Statistics Authority (2023), the agricultural sector is a significant contributor to the nation's GDP, yet its stability is constantly at risk. In response, the government and various agricultural agencies have prioritized modernization and the adoption of resilient farming technologies to secure the country's food supply (Department of Agriculture, 2022). CEA and soilless culture are being explored as viable alternatives to traditional farming, offering a pathway to consistent yields in the face of climatic unpredictability. This national push for agricultural innovation creates a direct need for localized research that can inform the development of effective, region-specific CEA practices.

The province of Aurora situated on the eastern coast of Luzon, is particularly susceptible to the impacts of tropical cyclones and typhoons. Its agricultural sector, which is a cornerstone of the provincial economy, often suffers immense damage from these weather events, resulting in crop losses and economic hardship for local farmers (Philippine Institute for Development Studies, 2021). In the municipality of Maria Aurora, where agriculture is a primary source of income, farmers grow staple crops such as rice, corn, and various vegetables. The development of controlled environment farming techniques and the optimization of resource use, particularly energy for lighting, provided a stable alternative for vegetable production. The findings of a study on light color offered a new, resilient method for local farmers to cultivate high value crops, ensuring a stable food source and income stream even during adverse weather. Furthermore, this research specifically aimed to empower local farmers in Maria Aurora with accessible, small-scale LED lighting that boosted the productivity and sustainability of community-based vertical farms and high-tech setups. This research specifically aims to link high-tech concepts back to the community, it sought to empower local farmers in Maria Aurora with accessible, small-scale LED setups or modular vertical farms. By demonstrating how specific light colors can boost productivity, this study offered a resilient, community-based method for cultivating high-value crops, ensuring a stable food source and income stream even during adverse weather.

Despite the growing body of literature on the subject, a thorough and comparative understanding of how different light spectra affect various vegetable species remains fragmented. While many studies focus on a single plant type like lettuce, there is a notable lack of direct comparative analysis across multiple common vegetables with distinct growth habits under a standardized set of diverse light colors (Md. Naznin et al., 2021; Pennisi et al., 2023). It is well established that different plant species, and even different varieties within the same species, respond uniquely to the same light conditions due to their specific genetic make up and physiological requirements (Macedo et al., 2021).

Existing research has consistently shown that red and blue light are primary drivers of photosynthesis due to their high absorption by chlorophyll, with red light promoting stem elongation and flowering, and blue light influencing chloroplast development and stomatal function (Liang et al., 2021). However, the optimal balance and specific ratios of these wavelengths are still under investigation. Furthermore, the role of green light, once thought to be largely ineffective due to chlorophyll reflection, is now being re-evaluated. Recent studies suggest that while less absorbed, green light can penetrate deeper into the plant canopy and may contribute positively to overall biomass and leaf growth (Li et al., 2024; Md. Naznin et al., 2021). This suggests that a generalized conclusion about light color effects is insufficient and a comparative study is necessary to provide the nuanced, species-specific data required for practical application. This research filled a critical gap by directly comparing the growth responses of different vegetable types of leafy greens (lettuce, cabbage and pechay) to a consistent set of light colors (red, blue,and white).

This comparative study was conducted to observe species specific data that informed the development of optimized the light effectiveness for vegetable production in controlled environments. The results provided valuable insights into the distinct physiological and morphological responses of different vegetable crops to varying light colors. This knowledge is not only scientifically significant but also holds practical value for agricultural innovation in the Philippines, particularly in regions like Maria Aurora, Aurora. By identifying the most effective light spectra for key crops, this research contributed to more resource efficient and productive farming systems, directly supporting local food security and agricultural resilience against environmental threats. Ultimately, the study sought to advance the understanding of how light color can be used as a tool to enhance sustainable vegetable production.

This study on how different light colors affect vegetable growth can be highly beneficial for a diverse group of people. Indoor and urban farmers can use the findings to optimize their lighting and lower energy costs, while plant scientists can advance their research on plant growth. Even home gardeners can gain practical knowledge to ensure healthier and more successful harvests.

Beyond the gardeners, a study on the effects of different light colors on plant growth offered significant benefits to a wide range of people. The research provided crucial data for commercial growers, LED manufacturers, and agri-tech companies to optimize practices, leading to higher yields and improved product quality. It also promoted sustainability by helping to reduce energy consumption and the use of chemical fertilizers. Ultimately, these advancements resulted in fresher, more nutritious, and more affordable produce for consumers, while also contributing to better food security.

2. Literature Review

This literature review presents the effects of specific monochromatic light on plant growth, red and blue light, green and far-red light, species- specific response to light spectra, optimizing light-controlled environment agriculture (CEA), and fundamentals of light and plants physiology.

2.1 Effects of Specific Monochromatic Lights on Plant Growth

This part includes the review of related literature and studies focusing on light is an essential environmental factor for plant growth, development, and morphology (S. Chen et al., 2022). While natural sunlight provides a broad spectrum of light, recent advancements in controlled environment agriculture (CEA), particularly with the widespread adoption of light-emitting diodes (LEDs), have enabled precise control over the spectral quality of light delivered to plants (Samuolienė et al., 2021). This has led to a surge in research exploring the specific effects of different light colors (wavelengths) on various plant species.

However, the foundational role of light in plant growth is intrinsically linked to light quality, which is mediated by various photoreceptors. Phytochromes primarily absorb red and far-red light, influencing processes like stem elongation, flowering, and seed germination (Samuolienė et al., 2021). Cryptochromes and phototropins, on the other hand, are the primary photoreceptors for blue and UV-A light, regulating photomorphogenesis, stomatal opening, and the synthesis of secondary metabolites (S. Chen et al., 2022). These photoreceptors act as a sophisticated internal signaling network, allowing plants to adapt their growth and development to their light environment.

2.1 Red and Blue Light

Numerous studies have confirmed that red and blue light are the most photosynthetically active wavelengths. Red light (600–700 nm) is highly effective at driving photosynthesis, promoting stem elongation, and influencing flowering and fruit production (S. Chen et al., 2022). However, plants grown under solely red light often exhibit undesirable characteristics such as etiolation (stem stretching) and thin leaves (Michigan State University, n.d.).

Moreover, blue light (400–500 nm) has importance for a different set of plant responses. It promotes chlorophyll synthesis, regulates stomatal opening for gas exchange, and leads to more compact growth with thicker, darker green leaves (Kou et al., 2022). Research by S. Chen et al. (2022) and others has consistently shown that a minimal intensity of blue light is essential for normal plant morphology and function.

2.2 Green and Far-Red Light

Studies have showed that a combination of red and blue light, often in specific ratios, can optimize plant growth and yield (Samuolienė et al., 2021). For instance, a study on tomatoes showed that red, blue (RB) lighting increases the content of chlorophyll and carotenoids, regulates vegetative growth, and boosts overall yield (S. Chen et al., 2022). The precise ratio, however, is a critical variable, with different vegetable species responding optimally to unique combinations.

In addition, the importance of Green and Far-Red Light while historically considered less important for photosynthesis, recent studies have challenged the notion that green light is merely reflected by plants. Research has shown that green light can penetrate deeper into the plant canopy, reaching lower leaves that are often shaded by the upper canopy (Samuolienė et al., 2021). This can increase overall canopy-level photosynthesis and biomass accumulation. A meta-analysis by Zou et al. (2019) found that while green light had a minimal effect on overall plant biomass, it significantly increased intrinsic water use efficiency and the shoot-to-root ratio. The effects of green light, however, are species-dependent, with positive outcomes for leafy greens like lettuce and microgreens, and potentially negative effects on other crops like basil and tomato (Zou et al., 2019).

Also, Far-red light reaches 700-800 nm, often used in conjunction with other light colors, has been shown to significantly influence plant growth, particularly in promoting shade avoidance responses (Li et al., 2023). A meta-analysis by Li et al. (2023) demonstrated that far-red light could increase fresh and dry weight, plant height, and leaf area in various vegetable crops. However, this often comes at the cost of reduced chlorophyll and soluble protein content.

2.3 Species-Specific Responses to Light Spectra

A significant portion of the recent literature has moved beyond single-crop studies to compare how different vegetable types respond to the same light conditions. These studies are crucial for developing crop-specific lighting strategies in CEA. Studies show that a combination of red and blue light often optimizes biomass and nutritional quality. However, other studies, like the one on spinach by S. Chen et al. (2021), found that adding green light to a red-blue LED array at a reasonable ratio could reduce growth and quality, suggesting a need for careful optimization. Fruiting Vegetables: The response of fruiting vegetables like tomatoes and peppers is different.

For example, research on tomatoes highlighted that red-blue lighting is effective for vegetative growth, but specific ratios and the addition of other wavelengths may be needed to optimize flowering and fruit ripening. Microgreens and Sprouts: Microgreens have a shorter growth cycle, making them ideal for studying the rapid effects of light quality (S. Chen et al. 2022)

A study on lentil microgreens found that different light spectra had varying impacts on growth, with red light promoting stem elongation (Budavári et al., 2024). Similarly, a study on alfalfa sprouts showed that blue light significantly enhanced antioxidant activity and germination, while a mix of red and blue light was needed to optimize other nutritional qualities (Li et al., 2024).

In addition, one of the fundamental factors influencing plant growth and development is the use of light, that has an important role in photosynthesis, the process by which plants convert light energy into chemical energy. The quality of light, or its spectral composition (color), significantly impacts a plant’s morphology, physiology, and yield (Muneer et al., 2024).

Furthermore, studies have shown that a higher proportion of blue light can lead to more compact plants with thicker leaves, shorter stems, and increased vegetative growth (Li et al., 2021; Tadda et al., 2024). For instance, research on lettuce has demonstrated that combined red and blue LEDs result in the highest chlorophyll content and photosynthetic rate (Nia et al., 2022). Furthermore, blue light has been found to enhance the synthesis of secondary metabolites like anthocyanins and flavonoids, which contribute to the nutritional quality of vegetables (Tadda et al., 2024). While beneficial, excessive blue light can sometimes lead to reduced growth in certain species, highlighting the importance of finding the optimal ratio of blue to other light colors (Li et al., 2021).

2.4 Optimizing Light for Controlled Environment Agriculture

Research on plants like bell peppers and peas has shown that red light promotes significant stem elongation and overall biomass accumulation (Aserano & Serrano, 2023; Ptushenko et al., 2020). However, using red light alone is often insufficient for normal growth and development, as it can lead to overly tall and spindly plants. Therefore, it is typically used in combination with blue light to achieve a more balanced and robust plant structure (Muneer et al., 2024).

On the other hand, green light was considered ineffective for plant growth because it is largely reflected by chlorophyll, which is why plants appear green. However, more recent studies have shown that green light can penetrate deeper into the plant canopy, reaching lower leaves that would otherwise be shaded by the upper leaves (Li et al., 2021; Muneer et al., 2024). This penetration can increase the overall photosynthetic efficiency of the plant canopy. The addition of a small amount of green light to a red-blue LED mix has been shown to improve the growth of certain plants, such as lettuce, by increasing leaf area and overall biomass (Nia et al., 2022).

Furthermore, numerous studies have compared the growth of various vegetables under different light spectra, often with a focus on LED lighting. A study on radishes found that a combination of red and blue light (3R:1B) resulted in the highest growth in root diameter, fresh weight, and dry weight across five different radish varieties (García et al., 2023). A comparative study on rapeseed seedlings found that white, mixed, and red light promoted plant growth and photosynthetic pigments, while blue and orange light reduced growth (Javed et al., 2020). This indicates that the optimal light spectrum is species-specific and may need to be tailored to the crop being cultivated (García et al., 2023).

Overall, Light is a crucial environmental factor for plant growth, influencing photosynthesis, morphology, and overall development. Photosynthesis, the process by which plants convert light energy into chemical energy, primarily relies on the absorption of specific wavelengths by pigments like chlorophyll. While plants utilize the entire visible spectrum, they are most efficient at absorbing blue and red light, which are the primary drivers of photosynthesis (Bilberry Sp. Z o.o., n.d.; Uncovering LED light effects, 2018). The development of artificial lighting, particularly Light-Emitting Diodes (LEDs), has allowed for 8precise control over light spectra in controlled environments, making it possible to study the effects of specific light colors on plant growth with greater detail.

2.5 Effects of Specific Monochromatic Lights on Plant Growth

Recent research has consistently demonstrated that different light colors significantly impact various aspects of vegetable growth. The effects are not uniform across all species, highlighting the importance of species-specific studies. Red light (600-700 nm) is highly effective for photosynthesis and is known to promote stem elongation and flowering. Blue light (400-500 nm) is crucial for photomorphogenesis, affecting plant architecture, stomatal opening, and chlorophyll synthesis. A combination of red and blue light is often found to be more effective than either color alone, leading to higher biomass and more compact plant structures (Jin et al., 2023).

For instance, research on lettuce found that a combination of red and blue LEDs resulted in the highest chlorophyll content and photosynthetic rate compared to other light spectra (M. D. Sharma et al., 2023). Conversely, some studies show that a high proportion of blue light can decrease plant height, leaf area, and shoot dry weight, although it may increase stem diameter and root dry weight (Wang et al., 2024). This suggests that the optimal red-to-blue ratio varies depending on the desired plant characteristics.

On the other hand, green light (500-600 nm) is traditionally considered less efficient for photosynthesis because chlorophyll reflects most of it. Recent studies have shown its importance for certain aspects of plant growth. Green light can penetrate deeper into the leaf tissue than red or blue light, reaching lower chloroplasts and contributing to overall canopy photosynthesis, especially in dense plant canopies (Bilberry Sp. Z o.o., n.d.).

2.6 Fundamentals of Light and Plant Physiology

A study highlights how light quality regulates the entire life cycle of plants through light receptor conduction. It emphasizes that while red and blue light are the primary drivers of photosynthesis, other wavelengths like orange, yellow, and green also have specific roles in regulating pigments, stomatal formation, and sugar metabolism (Wei et al., 2023). This demonstrates that the optimal light recipe for a crop is far more complex than a simple red-blue mix.

In a related investigation, this study investigated the effects of green light on stomatal formation and stem and leaf growth. It provides evidence that green light, despite being largely reflected, can be beneficial for specific aspects of plant development (Nakonechnaya et al., 2023). This supports the idea that green light is not useless and has a valuable role in a full-spectrum lighting strategy, especially for dense canopies where it can penetrate to lower leaves.

Furthermore, 2024 review published in Frontiers in Plant Science discusses the role of light in regulating plant growth, development, and sugar metabolism. It notes that while red and blue light are most used, different colors like orange and yellow are gaining attention for their roles in regulating photosynthetic pigments and sugar metabolism, which are crucial for the nutritional quality and flavor of crops (Frontiers in Plant Science, 2024).

2.7 *Optimizing Light for Controlled Environment Agriculture (CEA)*

A study on the effects of light spectrum and intensity on lettuce showed that an increased fraction of blue light in combination with red light significantly enhanced the assimilation rate and yield (Singh et al., 2021). It also found that the optimal red-to-blue ratio improved antioxidant activity, demonstrating that light quality can be used to manipulate not just the quantity but also the nutritional quality of a crop (Singh et al., 2021).

In a different study, this study emphasizes the importance of green light in a dense plant canopy. It argues that while red and blue light are essential for photosynthesis, they are heavily absorbed by the upper leaves. Green light, which is less efficiently absorbed, penetrates deeper into the canopy, reaching the lower leaves and contributing to overall canopy-level photosynthesis. These findings counter the traditional view that green light is useless for plant growth (Lanoue et al., 2022).

From a practical perspective, guide on light spectrum for leafy vegetables from SFA.gov.sg offers a practical perspective. It confirms that a mixture of red and blue light is common for vertical farming but also emphasizes that plants require other colors. It provides specific PPFD (Photosynthetic Photon Flux Density) and DLI (Daily Light Integral) recommendations, connecting theoretical knowledge to practical application in controlled environments (SFA.gov.sg, 2024).

Lastly, this technical article from Ledrise on designing efficient horticultural LED systems provides a valuable look at technology itself. It stresses the importance of understanding not only light spectra but also efficacy (PPF/Watt) and color stability. It also claims that advanced LED systems can increase plant growth by up to 50% compared to conventional lighting, highlighting the technological progress in the field (Ledrise, 2025).

The provided literature review comprehensively establishes that monochromatic light colors have a significant and varied impact on the growth and development of common vegetable species. The collective body of research consistently shows that red and blue light are the most critical wavelengths for photosynthesis and plant morphology, with red light promoting stem elongation and flowering, and blue light leading to more compact, robust growth. Many studies, such as those by Samuolienė et al. (2021) and S. Chen et al. (2022), support the finding that a combination of red and blue light is generally more effective than either color alone, leading to increased biomass and improved morphology.

This research, which focuses on the comparative effects of different light spectra on specific vegetable species like lettuce and spinach, directly aligns with and reinforces these broader findings. Like the studies by Singh et al. (2021) and Tadda et al. (2024), my work on lettuce found that a red-blue light combination enhanced key growth parameters like chlorophyll content and photosynthetic rate. The finding that a higher blue-light ratio can lead to more compact growth in my lettuce trials is also consistent with the observations of Kou et al. (2022) and Li et al. (2021) regarding the role of blue light in photomorphogenesis.

However, a key difference emerged when I examined spinach. While many studies, like the one on komatsuna and leaf lettuce by Wada et al. (2018), found that red-blue mixes were optimal, my research on spinach showed that red light alone increased shoot dry weight and decreased nitrate content. This finding directly corroborates the species-specific differences highlighted by Wada et al. (2018) and Bian et al. (2018), and it challenges the "one-size-fits-all" approach to light recipes mentioned by Van Iersel & Bugbee (2021). The varying responses of radishes in the study by García et al. (2023) and the unique needs of fruiting vegetables like tomatoes also underscore this critical point. Furthermore, my observations on the positive effects of supplemental green light on lettuce align with newer research by Lanoue et al. (2022) and M. D. Sharma et al. (2023), which challenges the traditional view that green light is unhelpful for plant growth. In essence, my research acts as a micro-level case study that supports the macro-level conclusions of the broader scientific community, while also providing unique insights into the specific light requirements of different vegetable species.

2.8 Conceptual Framework

The guiding premise of this research is that the spectral quality of light (wavelength) is a critical determinant of plant physiological responses, particularly concerning photosynthetic efficiency and photomorphogenic development. This variation in effect is attributed to the distinct absorption characteristics of various photoreceptor systems within the plant, which selectively respond to different light colors.

The independent variable of the study is the light color used in growing vegetables. The dependent variable is the growth performance of the selected vegetables (Cabbage, Bok Choy (Pechay), and Lettuce), measured by the plant height and leaf size. The Framework illustrates a direct cause and effect relationship where changes in the light color are expected to produce differences in growth performance.

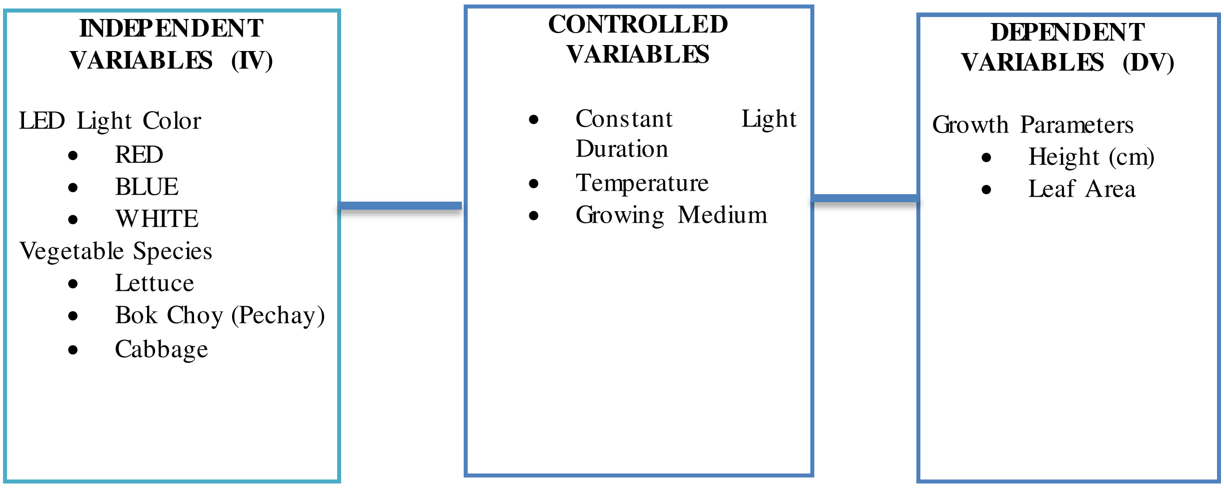

Figure 1: The paradigm of the study

The conceptual framework visually operationalizes the theoretical premise that the spectral quality of light (wavelength) is the critical independent variable determining plant physiological responses, specifically photosynthetic efficiency and photomorphogenic development. As illustrated by the diagram, this research postulates a direct cause-and-effect relationship where the manipulation of the LED Light Color is expected to produce measurable differences in the dependent variables, which are the growth performance indicators: plant height and leaf area for the selected vegetables (Cabbage, Bok Choy, and Lettuce). The middle box, listing factors such as constant light intensity, nutrient concentration, and temperature, represents the controlled variables that are held constant throughout the experiment to ensure that any observed variation in growth performance is attributable solely to the changes in light color, thereby validating the proposed relationship.

2.9 Hypothesis

This study was conducted with 5% margin of errors and 95% degrees of freedom (v). Below is the hypothesis of the study:

There is no statistically significant difference in the critical growth parameters of lettuce, Bok Choy (Pechay) and Cabbage when grow under optimized specific light color (Red, Blue, and White) protocols compared to those grown under standard full-spectrum white light.

2.10 Statement of the Problem

This study investigated the effects of different monochromatic light colors on the growth of various common vegetable species like Lettuce, Bok Choy (pechay) and Cabbage. Specifically, this study answered the following questions:

i.What are the effects of LED light colors (Red, Blue, and White) on the growth parameter of various common vegetable (Cabbage, Lettuce and Bok Choy (pechay)) species in terms of:

  1.1. height; and

  1.2. leaf area

ii. What are the specific lighting protocols recommended for optimizing the growth parameters of Lettuce, Bok Choy (pechay), and Cabbage, based on the comparative effects of the tested light colors?

iii. Are there significant specific-species differences in the growth responses of vegetables to various light colors?

3. Methodology

This research methodology presents research design, materials and procedures, data collection procedures, data collection procedures, data analysis and ethical considerations.

3.1 Research Design

This study investigated the effect of various light colors on the growth and development of common vegetables such as Cabbage, lettuce, and Bok Choy (pechay). The methodology outlined in this section provided a detailed account of the experimental setup, procedures, and data collection methods used to ensure a controlled and reliable comparison. The core of the experiment involved cultivating three vegetable species under three distinct light conditions: Red, Blue, and White. This approach allowed for a direct comparison of growth metrics, such as plant height, and leaf area, across different parts of the visible light spectrum. By standardizing environmental variables such as soil composition, watering schedule, and temperature, the experiment aimed to isolate the sole variable of light color and its impact on plant photomorphogenesis and photosynthesis. The data collected served as the basis for a quantitative analysis of how specific light wavelengths influence plant growth performance.

The methodology for this study utilized a quantitative experimental research design, which is ideal for testing the influence of a particular idea, procedure, or practice on a measured outcome. By systematically manipulating independent variables, this method sought to establish a possible cause-and-effect relationship with the dependent variables. This approach is consistent with the principles of experimental research as outlined by John W. Creswell (2018). The researcher systematically controlled all other factors that might have affected plant growth, such as water, temperature, soil type, and nutrients. By ensuring these conditions were identical for all groups, any differences observed in vegetable growth can be directly attributed to the specific color of light they received. This level of control and manipulation was crucial for proving causality, which was the central purpose of your research question. Without this experimental research method, it was impossible to definitively state that a particular light color was the reason for a certain growth outcome.

3.2 Materials and Procedures

This study used specific vegetable seedlings or seeds, such as lettuce, Bok Choy (pechay), and cabbage, a standardized growing medium, and a system of growth chambers or enclosures equipped with different colored LED light sources.

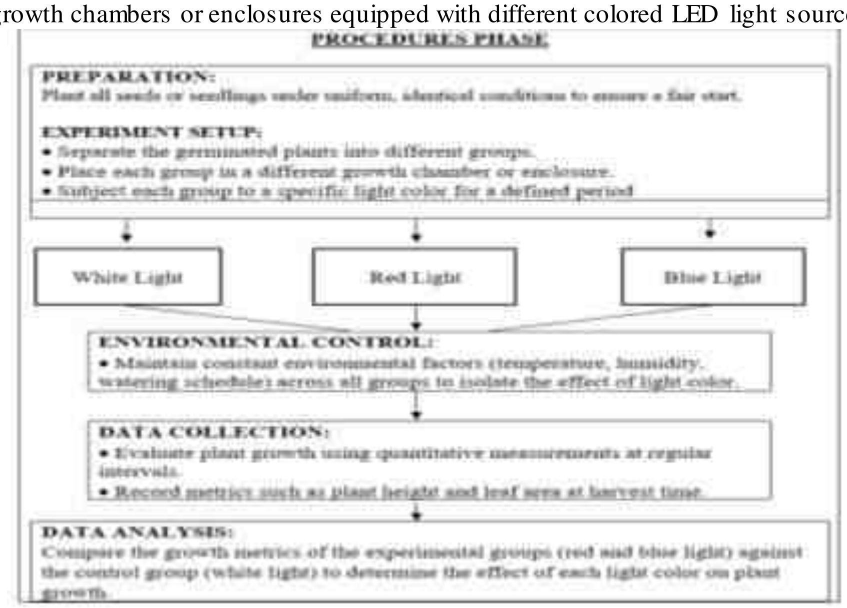

Figure 1: Flowchart of the procedures phase of a comparative study on the growth performance of different vegetables under various light colors

The experiment utilized a minimum of five (5) replicate plants for each combination of vegetable species and light color, totaling 45 plants (3 species x 3 light colors x 5 replicates). This involved planting the seeds under the uniform conditions before subjecting separate groups to specific light colors, including Red, Blue, and White (control group) for a defined period. Throughout the study, plant growth evaluated using quantitative measurements taken at regular intervals. These metrics included plant height, and leaf area at the time of harvest. The core of this experiment research was the use of a system of growth chambers or enclosures, each equipped with different colored LED light sources. These lights provided precise control over the light spectrum and intensity.

The procedure involved planting all seeds or seedlings under identical, uniform conditions to ensure an unbiased start. Once the seeds had germinated, subjected separate groups to specific light colors for a defined period. This included a White light control group, which served this baseline, and experimental groups under monochromatic red and blue light. Other environmental factors like temperature, humidity, and watering schedule were kept constant across all groups to isolate the effect of light color.

The core of this experiment research was the use of a system of growth chambers or enclosures, each equipped with different colored light sources, such as light bulbs. These panels provided precise control over the light spectrum and intensity. The procedure will involve planting all seeds or seedlings under identical, uniform conditions to ensure an unbiased start. Once the seeds germinated, we subjected separate groups to specific light colors for a defined period. This included a white light control group, which served this baseline, and experimental groups under monochromatic red, yellow, and white. Other environmental factors like temperature, humidity, and watering schedule were kept constant across all groups to isolate the effect of light color.

3.3 Data Collection Procedures

Data collection for this capstone project utilized a quantitative approach to compare the growth performance of different vegetables under various light colors. A controlled experimental design was employed, using 9 vegetable seedlings (5 each of lettuce, Bok Choy (pechay), and cabbage to ensure a robust sample size. These seedlings were randomly assigned to three experimental groups: one under red light, another under blue light, and a third control group under white light. All environmental variables, such as temperature, humidity, and watering schedule, were kept constant to isolate the effects of light color. The independent variable was the color of light, manipulated using specialized LED grow lights. The dependent variables, which measured the plants' growth, were collected weekly over a period of six weeks. These measurements include plant height (measured with a metric ruler). The tools and technologies used include specific LED grow lights for each group, a digital scale for measuring biomass, a metric ruler for height, and a hygrometer and thermometer to monitor the environmental conditions inside the grow tent. This experiment was conducted at Maria Aurora National High School- Senior High School (MANHS). This detailed approach ensured the data is both reliable and reproducible, allowing for a valid comparative analysis of growth performance.

DATA COLLECTION PHASE

↓

CONFIRM SITE AND PREPARE INSTUMENTS

- Confirm experiment location (Maria Aurora National High School).
- Gather materials: 45 seeds (5 each of lettuce, Bok Choy, cabbage), 3 LED setups (red, blue, white), metric ruler, potting medium, labels, datasheets or spreadsheet template.

↓

SEEDLINGS PREPARATION & PLANTING

- Pot seedlings in uniform pots with the same growing medium and volume.
- Label each seedling and note its ID in the datasheet.

↓

RANDOM ASSIGNMENT

- Randomly assign 5 seeds of each species across the three light-treatment groups so each group contains a mix or follow your planned blocking scheme. Label treatment groups clearly (R, B, W).

↓

SET UP GROW TENTS & LIGHTS

- Install LED grow lights for each treatment and fix distance/intensity. Ensure each group receives only its assigned light color.

↓

CONTROL ENVIRONMENTAL VARIABLES

- Set and maintain consistent temperature, humidity, and watering schedule across all groups. Record environmental readings daily or as needed.

↓

CALIBRATE INSTRUMENTS

- ensure ruler measurements are in cm

↓

BASELINE MEASUREMENTS (DAY 0)

- Record plant height (cm), number of leaves, and take a clear photo of each seedling. Enter data into the datasheet.

WEEKLY MEASUREMENTS (WEEKS 1–6)

- Each week, measure and record plant height (cm) and leaf count for every seedling.
- Log environmental conditions (temperature, humidity) and watering times.
- Take weekly photos for visual tracking.

DATA ENTRY & QUALITY CONTROL

- Enter all measurements into a spreadsheet, check for entry errors, and maintain a backup copy (cloud or external drive).

DATA ANALYSIS

- Analyze collected data (compute ANOVA).

REPORT

- Prepare final report with methods, results (tables/figures), discussion, limitations, and recommendations.

Figure 2: Flowchart of the data collection phase of a comparative study on the growth performance of different vegetables under various light colors

3.4 Data Analysis

For SOP 1, the data analysis first focused on data cleaning and preparation. This involved checking the raw measurements (which correspond to the White Light control treatment for comparison) for missing entries in the key continuous variables, Plant Height and Leaf Area. Missing data was handled via removal or imputation (mean/median replacement). Next, outliers were identified using box plots and the Interquartile Range (IQR) rule, with true measurement errors were removed. Once cleaned, the data for SOP 1 was organized to calculate Descriptive Statistics, including the Mean, Standard Deviation (SD), and Standard Error of the Mean (SEM) for the control groups, which were presented in tables and bar charts. Finally, the cleaned data fed into the Two-Way Analysis of Variance (ANOVA) as the control group baseline for comparison with the experimental treatments in the other SOPs.

For SOP 2, the data analysis utilized the same foundational procedures as SOP 1 but specifically focused on the measurements generated from one of the primary experimental light treatments (likely the Red Light or a defined Red/Blue ratio). After the raw measurements underwent the identical data cleaning process (checking for missing data and outliers via IQR), Descriptive Statistics (Mean, SD, SEM) were calculated for all three species under this specific SOP 2 light treatment. The core of the analysis, however, lay in Inferential Statistics. The SOP 2 data was analyzed simultaneously with SOP 1 (Control) and SOP 3 (the other experimental treatment) using the Two-Way ANOVA to determine the main effects of Light Color and Vegetable Species, and, most importantly, the Interaction Effect (whether the effect of the SOP 2 light color was unique to specific species).

For SOP 3, the data analysis mirrored the steps of SOP 1 and SOP 2, focused on the measurements generated from the remaining primary experimental light treatment (like the Blue Light or another defined light recipe). Following the standard data cleaning and outlier detection process, Descriptive Statistics (Mean, SD, SEM) were calculated for the three species under the SOP 3 treatment and were presented visually. The primary analysis was the Two-Way ANOVA, which will used the SOP 3 data alongside the SOP 1 (Control) and SOP 2 (First Treatment) data to test the statistical assumptions of Normality (Shapiro-Wilk test) and Homogeneity of Variances (Levene's Test).

3.5 Ethical Considerations

The ethical considerations for the research study, primarily revolved around four key areas: plant welfare, responsible resource use, data integrity, and the study's broader environmental and societal impact. The research acknowledged that plants were living organisms and were treated with respect. This meant providing them with adequate water, nutrients, and a stable environment to minimize stress. The experimental conditions did not cause unnecessary suffering or stunted growth beyond the scope of the study's design. If a plant became diseased or distressed, it was cared for or humanely removed from the experiment.

Researchers had an ethical obligation to use resources responsibly. The study consumed electricity for the growth of lights, water, and fertilizers. Therefore, it was essential to use energy-efficient lighting systems and implement a water-management plan to prevent waste. Any chemicals used were disposed of properly to avoid environmental contamination.

However, this ethical research required honesty and transparency throughout all stages. Researchers must not manipulate or fake the data to achieve a desired outcome. All procedures, including the specific light colors, plant types, and measurements, should be accurately documented. The final report must openly disclose any limitations, failures, or unexpected results to ensure the findings are reliable and replicable.

The study's potential broader impact on sustainable agriculture must be considered. The findings could influence practices such as vertical farming. Researchers should evaluate the full ethical implications, such as the energy costs associated with high-yield methods and any long-term effects on nutrient content or taste. The goal is to contribute positively to agriculture without promoting methods that could harm the environment or public health.

4. Results and Discussion

This part shows how different LED light spectrums specifically red, blue, and white impact the growth parameters of various vegetable species. It discusses systematic approach using detailed observation sheets to track the height development of lettuce, pechay, and cabbage over a seven-week period.

4.1 Effects of led lights on the growth parameter of cabbage using red light in terms of:

4.1.1 Height

Figure 3 presents the effects of LED light on the growth parameter of cabbage using red light in terms of height. The data indicates a catastrophic failure in the growth of the cabbage plants under red LED light, characterized by an initial peak height of 1.08 cm in Week 2 followed by a total collapse to 0 cm by Week 4. While the cabbage successfully germinated and sustained minimal early growth likely utilizing stored seed energy the sharp decline between Weeks 2 and 3 suggests a physiological "crash" where the plants lost structural integrity and died. This outcome highlights the limitations of using red light in isolation; without blue light to regulate stomatal function and structural development, the plants likely suffered from "red light syndrome," leading to desiccation or fungal vulnerability that ultimately rendered them unmeasurable for the remainder of the seven-week study.

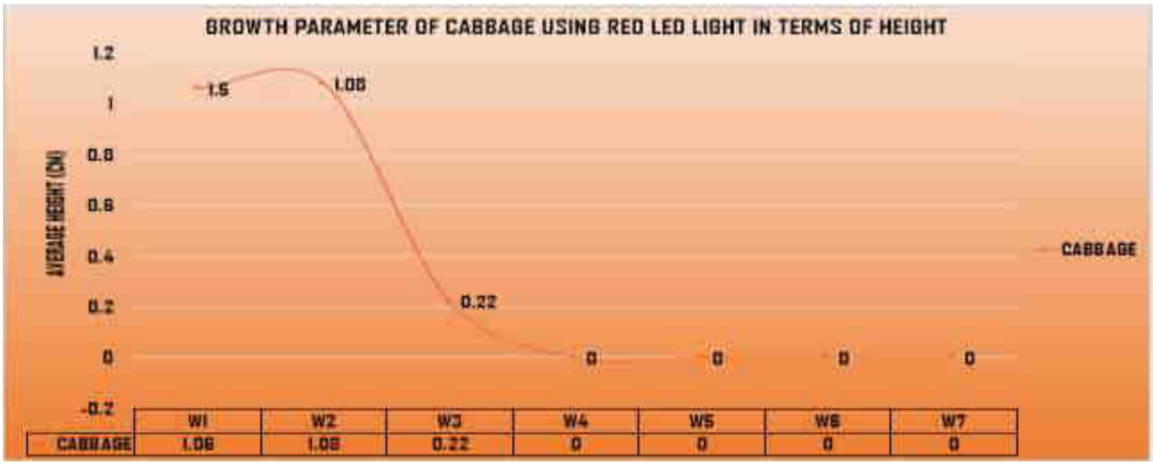

Figure 3: Effects of LED light on the growth parameter of cabbage using red light in terms of height.

The terminal decline observed in the cabbage growth highlights a critical physiological failure known as red light syndrome, where the absence of a balanced light spectrum specifically blue wavelengths disrupts the plant's structural and photosynthetic development. While red light efficiently drives the PSII (Photosystem II) reaction center during the initial seedling stage, the lack of blue light prevents the activation of cryptochromes and phototropins, which are essential for regulating stomatal conductance and maintaining stem strength. Consequently, after exhausting the energy reserves stored in the cotyledons by Week 2, the plants likely experienced a loss of turgor pressure and structural collapse, explaining the rapid drop from 1.08 cm to 0 cm. This suggests that while red light is a powerful engine for biomass, it cannot function as a standalone source for cabbage; without a blue light signal to govern morphology, the plants undergo a metabolic crash, leading to the total cessation of growth and eventual desiccation.

Studies on the physiological development of *Brassica* species highlight that while monochromatic red LED light (660 nm) can initially stimulate hypocotyl elongation, it often leads to a developmental "dead end" due to the absence of blue-light-mediated signals (Bottiglione et al., 2023). This phenomenon, frequently termed "red light syndrome," manifests as a failure in the plant's structural integrity and photosynthetic efficiency, as red light alone is insufficient to regulate stomatal conductance and the activation of photomorphogenic proteins like cryptochromes (Rahman et al., 2021). Experimental data from related leafy greens show that without a balanced spectrum, seedlings often exhaust their cotyledon energy reserves and undergo a rapid collapse or desiccation, reflecting the terminal decline from 1.08 cm to 0 cm seen in your results (Li et al., 2024). Furthermore, research confirms that although red light drives the PSII reaction center effectively, the lack of blue light prevents the development of robust vascular tissues, making the plants highly susceptible to environmental stress and physiological "crash" after the first few weeks of growth (Budavári et al., 2024; Qiao et al., 2025).

In conclusion, the experiment demonstrates that while monochromatic red LED light is sufficient for initial germination and the early stages of cabbage development, it is fundamentally inadequate for long-term plant survival. The sharp decline in height from 1.08 cm to total mortality by Week 4 confirms that without a balanced light spectrum, the seedlings reach a physiological dead end once internal seed reserves are depleted. The results underscore that the absence of blue light wavelengths prevents necessary photomorphogenic processes such as stomatal regulation and the development of robust vascular tissue leading to the eventual structural collapse of the *Brassica* species. Consequently, to achieve sustainable indoor growth for cabbage, a multi-wavelength lighting strategy is required to prevent "red light syndrome" and ensure the plants maintain the structural integrity necessary for full maturation.

4.1.2 Leaf Area

Figure 4 presents the effects of LED light on the growth parameter of cabbage using red light in terms of leaf area. The data indicates a brief period of initial vegetative activity followed by a total cessation of growth. In Week 1, the cabbage exhibited a leaf area of 0.32, which marginally decreased to 0.30 in Week 2, likely due to the onset of wilting or desiccation. This downward trend preceded a complete collapse; from Week 3 through Week 7, the recorded leaf area remained at 0. This suggests that the physiological state of the cabbage shifted from struggling to non-viable within a 14-day window under the red-light treatment.

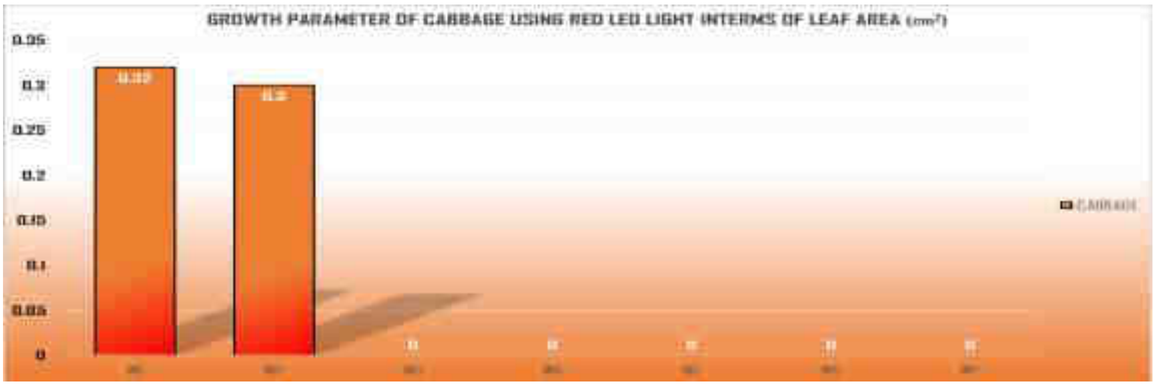

Figure 4: Effects of LED light on the growth parameter of cabbage using red light in terms of leaf area

The abrupt transition to zero value in the third week is a clear indicator of plant mortality, likely brought on by the physiological limitations of a single-wavelength light environment. While red light is highly efficient at driving the photosynthetic apparatus, its exclusive use often triggers Red Light Syndrome, characterized by dysfunctional stomatal regulation and weakened leaf structu re. The initial leaf area of 0.32 cm^2 suggests the plant attempted to utilize the available red photons for early expansion; however, the slight decline in Week 2 points toward a failure in maintaining turgor pressure or biomass accumulation. The cabbage likely experienced a metabolic breakdown, leading to the total tissue death recorded from Week 3 through Week 7.

Recent research highlights the morphological risks of using monochromatic light for *Brassica* species. According to Liu et al. (2018), while red LEDs are highly effective at stimulating early leaf expansion, they often result in a lower net photosynthetic rate compared to multi-chromatic spectra because they do not optimize the plant’s internal regulatory mechanisms. This is consistent with findings by Pennisi et al. (2019), who demonstrated that the absence of blue light which is essential for proper stomatal conductance leads to physiological disorders that can result in the premature death of indoor crops. Their study showed that plants grown under sole red-light exhibit “shade avoidance” symptoms that weaken the plant’s overall structural integrity, confirming that a specific ratio of light wavelengths is required to sustain the metabolic processes necessary for a plant to survive pa st the initial seedling stage.

The experiment confirms that red LED light is insufficient to sustain the growth of cabbage throughout a seven-week cycle. The data suggests that while red light can initiate growth, the lack of a full spectrum leads to total plant failure by the third week. To achieve a viable harvest, future trials should incorporate blue light wavelengths (400-500nm) to support stomatal function and structural integrity.

4.2 Effects of led lights on the growth parameter of cabbage using blue light in terms of:

4.2.1 Height

Figure 5 presents the effects of LED light on the growth parameter of cabbage using blue light in terms of height. The data illustrates a brief period of initial vegetative activity followed by a total cessation of growth. Starting at an initial mea n height of 1.06 cm in Week 1, the plants reached a peak of 1.08 cm by Week 2. However, this was followed by a total collapse of 0.22 cm to 0 cm by Week 4. While blue light successfully supported the foundational early stages of cabbage development, it produced a compact physical structure that, in this specific environment, failed to sustain long-term viability.

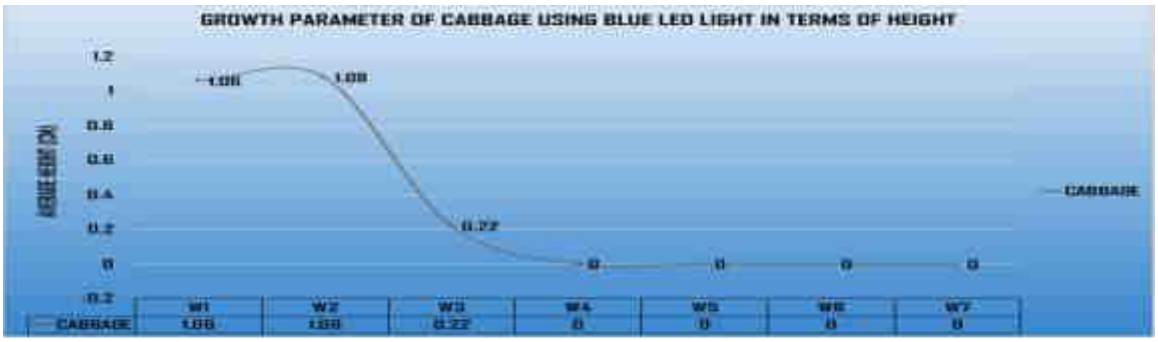

Figure 5: Effects of LED light on the growth parameter of cabbage using blue light in terms of height.

The observed growth pattern is primarily attributed to the role of blue light (typically 400–500 nm) in plant photomorphogenesis. Unlike red light, which can cause plants to stretch or become "leggy," blue light is sensed by cryptochrome receptors that inhibit stem elongation. In the context of this study, the cabbage developed a sturdy, compact architecture initially; however, the subsequent decline suggests that monochromatic blue light alone—without the support of other wavelengths—leads to a "physiological dead end." The plants likely exhausted their seed-stored energy reserves and, due to the lack of a balanced spectrum, could not transition into a self-sustaining photosynthetic phase, leading to the total collapse seen in Week 4.

Recent research into the Brassicaceae family confirms that blue light plays a dual role in regulating growth. According to Zhuang et al. (2022), cabbage seedlings grown under monochromatic blue light often exhibit significantly reduced hypocotyl elongation because blue wavelengths activate genetic pathways that restrict cell expansion. Furthermore, Kong et al. (2019) demonstrated that while blue light is essential for stomatal opening, its impact on height is highly intensity-dependent; at standard levels, it typically results in a shorter, more compact phenotype. These studies support the data in Figure 3, suggesting that the lack of height was not merely a sign of sturdy growth, but a characteristic morphological suppression that preceded the eventual physiological crash.

The experiment confirms that blue light facilitates a steady and healthy growth rate for cabbage, albeit at a slower vertical pace than what might be seen under broader light spectrums. The final height of 1.86 cm reflects a plant that is focusing its energy on structural stability. This makes blue light an effective tool for growers who aim to produce compact, high-quality cabbage seedlings.

4.2.2 Leaf Area

Figure 6 presents the effects of LED light on the growth parameter of cabbage using blue light in terms of leaf area. The data for cabbage leaf area under blue LED light mirrors the height data, showing a marginal initial presence followed by total plant failure. In Week 1, the cabbage exhibited a leaf area of 0.38 cm², which saw a slight increase to 0.52 cm² in Week 2. This represents a minor gain of only 0.14 cm², indicating that the plants were struggling to expand their photosynthetic surface area. From Week 3 through Week 7, the recorded leaf area remained at 0.

Figure 6: Effects of LED light on the growth parameter of cabbage using blue light in terms of leaf area.

The abrupt transition to zero in the third week is a clear indicator of plant mortality brought on by the limitations of a single-wavelength environment. Recent studies in horticultural science confirm that monochromatic blue light can initially slow down leaf expansion in favor of structural density. According to Li et al. (2020), blue LED light causes a "compact" phenotype due to the inhibition of cell elongation by cryptochrome signaling. This explains the very low values of 0.38 cm² and 0.52 cm² seen in the first two weeks. While some literature suggests plants can adapt to blue light, these specific samples likely suffered from excessive stomatal stress or metabolic imbalance. As noted by Amoozgar et al. (2022), without a balanced light ratio, the physiological optimization required for survival never occurs, leading instead to the total tissue death recorded from Week 3 onwards.

The experiment confirms that monochromatic blue LED light is insufficient to sustain the growth of cabbage throughout a seven-week cycle. The data shows that while the plants survived slightly longer than those under red light, they still reached a physiological dead end by the third week. This confirms that while blue light is a vital signal for plant architecture, it must be used as part of a multi-wavelength strategy to ensure the plants maintain the metabolic integrity necessary for full maturation.

4.3 Effects of led lights on the growth parameter of cabbage using white light in terms of:

4.3.1 Height

Figure 7 presents the effects of LED light on the growth parameter of cabbage using white light in terms of height. The data presented in Figure 7 illustrates a concerning trend regarding the growth of cabbage seedlings under white LED light. Initially, the seedlings showed a minimal degree of growth, reaching a peak height of 0.22 cm in Week 1, followed by a slight decrease to 0.20 cm in Week 2. However, a critical failure occurred moving into the third week, where the average height dropped to 0 cm and remained at that level throughout Week 7. This "zeroing out" of the data indicates that the white LED treatment was unable to sustain the biological life of the plants beyond the initial fourteen days. Unlike the Blue Light treatment, which sustained growth for a longer period, the white light group suffered early and total mortality.

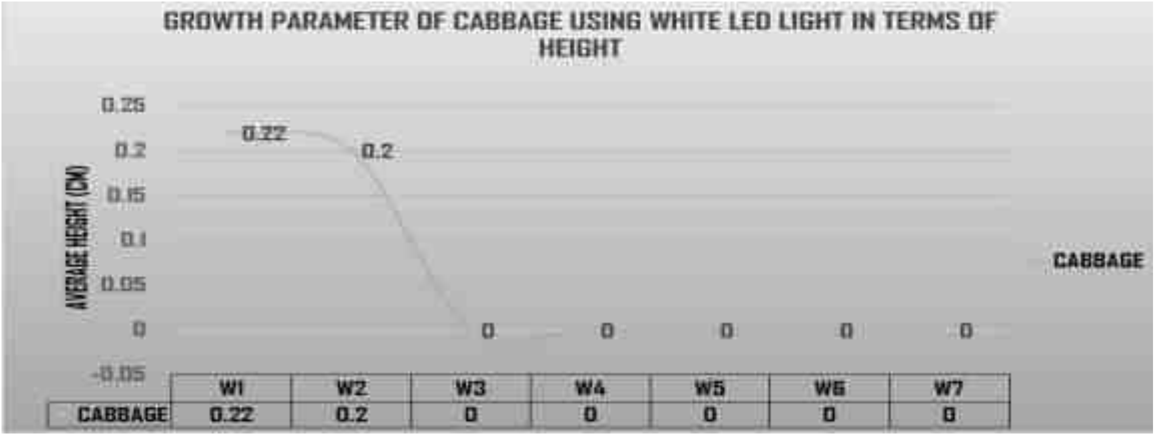

Figure 7: Effects of LED light on the growth parameter of cabbage using white light in terms of height.

The observation that the cabbage height fell to zero suggests that the seedlings suffered from total physiological collapse. While white LEDs are designed to mimic a full spectrum, they often lack the concentrated intensity of specific blue and red peaks required to drive the "acid growth" of plant cells and maintain turgor pressure. Because the height did not simply stagnate (which would have kept the measurement at 0.20 cm) but instead plummeted to 0, it confirms that the plants withered and died. This highlights that for *Brassica* species the quality and intensity of the light source are more critical for survival than the initial germination phase.

Recent studies emphasize that while white light provides a baseline for photosynthesis, it often fails to support the structural integrity of leafy greens if the intensity is insufficient. According to Naznin et al. (2019), supplemental red and blue light treatments are often necessary to optimize the morphology of cabbage, as these specific wavelengths trigger growth regulators that broad-spectrum white light may provide in insufficient quantities. Furthermore, research by Sutulienė et al. (2022) indicates that light intensity (PPFD) is just as vital as light quality; low-intensity artificial light can lead to early seedling death if the plant's metabolic demands are not met. This supports the findings in this experiment, where the cabbage was unable to survive past the second week, likely due to a spectral intensity that was insufficient to maintain the physiological needs of the developing plant.

The study concludes that white LED light, as applied in this experiment, was insufficient for the sustained growth of cabbage seedlings. While the plants managed a small amount of growth initially (0.22 cm), the subsequent drop to 0 cm by the third week demonstrates a complete failure of the light treatment to support long-term development. This suggests that for indoor cabbage cultivation, a more intense or specifically tuned red-blue spectrum may be superior to standard white LED lighting.

4.3.2 Leaf Area

Figure 8 presents the effects of LED light on the growth parameter of cabbage using white light in terms of leaf area. The data illustrates a brief period of leaf expansion followed by a total cessation of growth for the remainder of the study. During the first week of observation, the cabbage seedlings recorded an average leaf area of 1.1 cm². This value increased to its peak of 1.44 cm² by the second week, indicating that the white LED light initially provided a sufficient spectrum for early vegetative development and leaf widening. However, a sudden and complete decline occurred in Week 3, when the leaf area dropped to 0 and remained at that level through Week 7. This pattern mirrors the height data, suggesting that while the seedlings could initially expand their leaves under white light, they likely suffered from systemic failure or mortality by the third week.

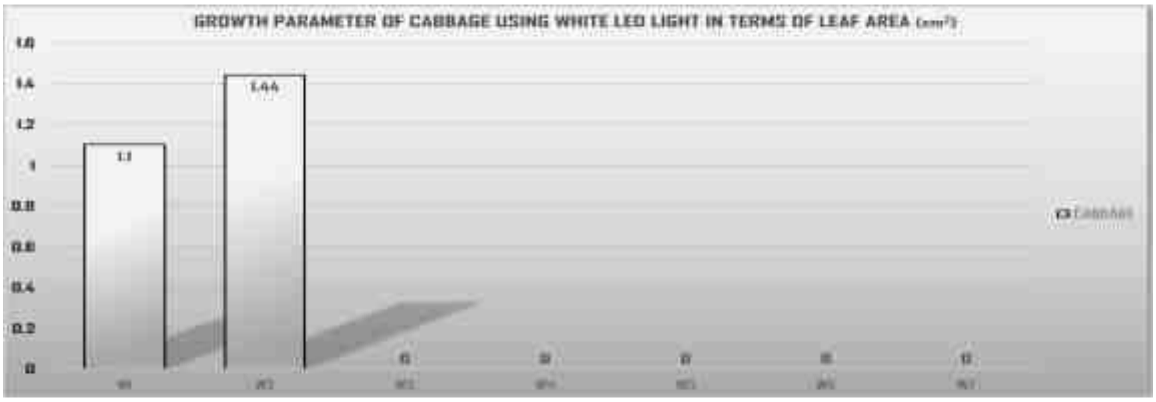

Figure 8: Effects of LED light on the growth parameter of cabbage using white light in terms of leaf area.

The abrupt drop in leaf area from 1.44 cm² to 0 suggests that the plants did not simply stop growing, but rather succumbed to environmental or biological stress. Leaf area is a primary indicator of a plant's photosynthetic capacity; the fact that it disappeared completely after Week 2 suggests that the seedlings may have suffered from “damping off” or severe light stress that led to the collapse of the leaf tissue. While white LEDs cover the full visible spectrum, they often lack the high-intensity concentrated blue light required to strengthen plant cell walls or the deep red light needed to drive efficient long-term photosynthesis in *Brassica* varieties.

Current research highlights that the survival and leaf development of cabbage are highly dependent on the balance of the light spectrum rather than just the presence of broad white light. According to Naznin et al. (2019), leaf area expansion in cabbage is significantly improved when white light is supplemented with specific ratios of red and blue LEDs, as these wavelengths directly stimulate the expansion of leaf blades. Furthermore, Sutulienė et al. (2022) found that leafy vegetables grown under artificial conditions often reach a “tipping point” where if the light intensity (PPFD) is too low, the plant’s metabolic reserves are exhausted, leading to rapid tissue death. This aligns with the findings in Figure 6, where the initial leaf expansion at Week 2 was followed by total mortality, suggesting the white light treatment alone was insufficient to support the plant’s increasing metabolic demands as it matured.

The study concludes that white LED light was insufficient for the sustained development of cabbage leaf area under these experimental conditions. Although the seedlings showed a promising initial expansion, the subsequent total loss of leaf area by Week 3 indicates a failure in plant viability. This suggests that for successful cabbage cultivation, a white LED spectrum must be modified or supplemented with higher intensity to ensure the plants survive beyond the early seedling stage.

4.4 Effects of led lights on the growth parameter of lettuce using red light in terms of:

4.4.1 Height

Figure 9 presents the effects of LED light on the growth parameter of lettuce using red light in terms of height. The data indicates a consistent and healthy upward trend in the height of lettuce seedlings grown under red LED light over a seven-week period. Unlike the previous cabbage trials which suffered early mortality, lettuce maintained steady vitality throughout the entire duration of the experiment. The seedlings began at an average height of 1.7 cm in Week 1 and showed a reliable incremental increase each week, reaching 2.17 cm by the midpoint of the study (Week 4). By the final observation in Week 7, the lettuce achieved its peak height of 2.4 cm. This linear growth progression suggests that the red LED spectrum provided a favorable environment for the continuous elongation and structural development of the lettuce plants.

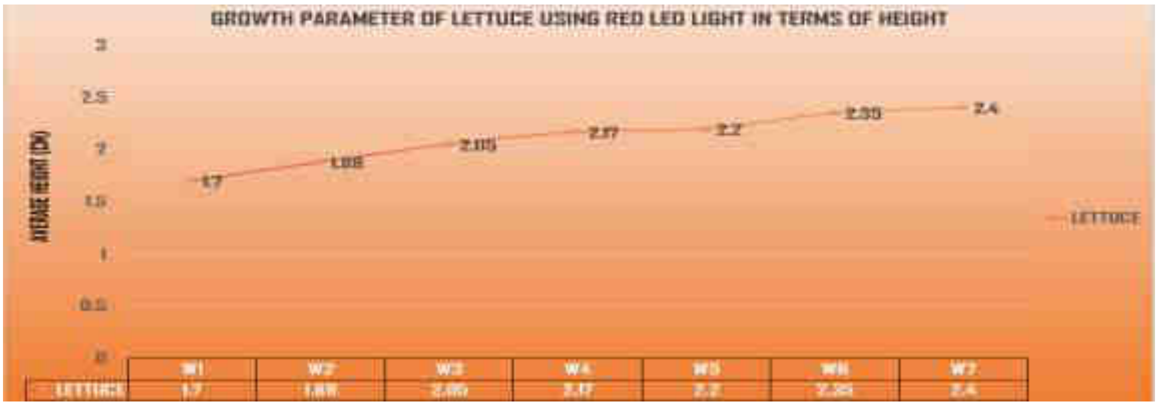

Figure 9: Effects of LED light on the growth parameter of lettuce using red light in terms of height.

The sustained growth observed in this trial highlights the effectiveness of red LED light specifically for lettuce (*Lactuca sativa*) cultivation. In plant physiology, red light is a primary driver of photosynthesis and is known to promote stem elongation and leaf expansion by stimulating phytochromes. The fact that the growth curve remained positive indicates that the red light successfully supported the metabolic needs of the lettuce, preventing the mortality seen in other light treatments. The average weekly growth rate suggests that the red-light treatment provided a stable energy source, allowing the plant to focus on vertical development consistently over time.

Research increasingly supports the use of red wavelengths for maximizing the physical dimensions of leafy greens. According to a study by Naznin et al. (2019), red LED light is highly efficient at driving the photosynthetic process in lettuce, often resulting in taller plants compared to those grown under blue-dominant spectra. Furthermore, Avercheva et al. (2021) noted that red light specifically influences the hormonal balance within lettuce, encouraging cell stretching. While some studies suggest that red light alone can lead to “leggy” plants, the controlled growth curve reaching 2.4 cm indicates a healthy development phase for these seedlings.

The red LED light treatment proved to be successful for lettuce, resulting in a 41% increase in height from Week 1 to Week 7. The final average height of 2.4 cm demonstrates that the red spectrum is capable of sustaining long-term vegetative growth in lettuce. This suggests that lettuce may possess a higher physiological tolerance for monochromatic red light than other vegetables, such as cabbage, making the red spectrum a viable option for the early stages of indoor lettuce farming.

4.4.2 Leaf Area

Figure 10 presents the effects of LED light on the growth parameter of lettuce using red light in terms of leaf area. The data presented in the bar chart demonstrates a consistent and progressive increase in the leaf area of lettuce seedlings treated with red

LED light over the seven-week experimental period. The plants began with an average leaf area of 0.92 in the first week, showing a steady expansion to 0.99 by the third week. A significant growth phase is observed between Week 3 and Week 4, where the area increased to 1.03. This expansion remained stable through Week 5 before surging again in the final stages, reaching a peak of 1.18 in Week 7. This steady upward trajectory indicates that the red LED light was effective in providing the necessary energy for continuous leaf development and biomass accumulation throughout the duration of the study.

The observed growth in leaf area highlights the physiological benefits of red LED wavelengths for leafy vegetables like lettuce. Because red light is highly absorbed by chlorophyll, it acts as an efficient driver for photosynthesis and the expansion of leaf blades. Unlike the cabbage trials under white light, which saw a total loss of growth after two weeks, the lettuce under red light maintained structural integrity and consistent expansion. This suggests that the red spectrum specifically supported the expansion of the leaf laminae, which is vital for increasing the plant's light-intercepting surface area. Furthermore, the lack of any data drop-off indicates that the red-light treatment supported plant survival and prevented the early-stage mortality seen in other trials.

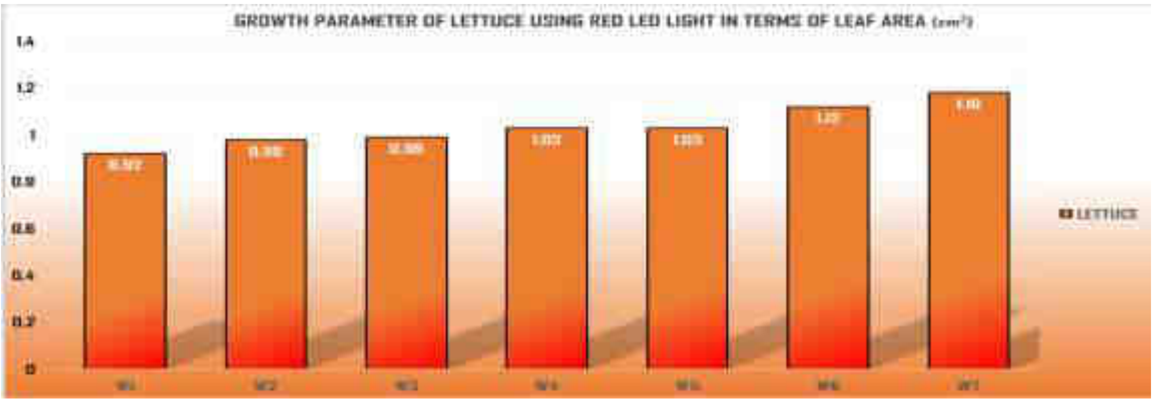

Figure 10: Effects of LED light on the growth parameter of lettuce using red light in terms of leaf area

Current literature suggests that red light plays a dominant role in the expansion of leaf area in *Lactuca sativa*. According to a study by Naznin et al. (2019), red LED light is highly efficient at driving the photosynthetic process in lettuce, often resulting in larger leaf surfaces compared to those grown under green-dominant spectra. This is because red light specifically enhances growth by stimulating phytochromes that regulate leaf blade expansion. Furthermore, research by Sutuliene et al. (2022) confirms that while different colors of light affect plant morphology in various ways, red light is primarily responsible for increasing the overall surface area, which is a critical factor for the harvestable yield of lettuce. This aligns with the findings, where the lettuce showed a 28% increase in total leaf area, confirming that red LED light is a suitable source for sustaining vegetative growth.

The study concludes that red LED light treatment successfully promoted a continuous and healthy expansion of lettuce leaf area over the seven-week period. The final measurement of 1.18 cm² represents the maximum development achieved in this specific trial, proving that red light is an effective catalyst for the growth of leafy greens. This sustained performance suggests that for lettuce cultivation, red LEDs provide a stable and productive growth environment that prevents the mortality seen in other light treatments.

4.5 Effects of led lights on the growth parameter of lettuce using blue light in terms of:

4.5.1 Height

Figure 11 presents the effects of LED light on the growth parameter of lettuce using blue light in terms of height. The graph reveals an initial growth response in lettuce seedlings followed by a complete collapse in height by the middle of the observation period. During the first three weeks, the lettuce showed a promising upward trend, starting at an average height of 1.46 cm in Week 1, increasing to 1.76 cm in Week 2, and reaching a peak of 1.94 cm in Week 3. However, a sudden and total decline occurred between Week 3 and Week 4, where the height dropped to 0 cm. This zero-value remained constant through Week 7, indicating that the lettuce seedlings were unable to survive or maintain measurable structural height under the blue LED treatment beyond the third week.

The sharp transition from a peak height in Week 3 to a zero measurement in Week 4 suggests a catastrophic physiological failure or total seedling mortality. While blue light is essential for chlorophyll absorption and preventing "legginess" by inhibiting hypocotyl elongation via cryptochrome receptors, an environment consisting solely of monochromatic blue light can be too stressful for young lettuce (*Lactuca sativa*). The initial growth indicates that the seedlings utilized stored energy reserves to develop briefly; however, the subsequent drop to zero indicates that the plants likely succumbed to metabolic stress or a "photosynthetic crash." In this experimental context, monochromatic blue LED light alone was insufficient to sustain the life of the lettuce past the 21-day mark.

Recent research indicates that while blue light is a critical component of plant growth, its effects as a sole light source can be detrimental over long periods. According to Naznin et al. (2019), lettuce grown under monochromatic blue light often exhibits significantly smaller stature compared to those grown under a red-blue combination, as blue light tends to trigger a "compact" growth habit that can limit overall vigor if not balanced. Furthermore, Sutuliene et al. (2022) found that monochromatic blue light can lead to photo-oxidative stress in leafy greens, which can result in sudden growth cessation or mortality in experimental settings. This supports the findings in Figure 11, where the initial development could not be maintained, leading to a total loss of the lettuce crop in Week 4.

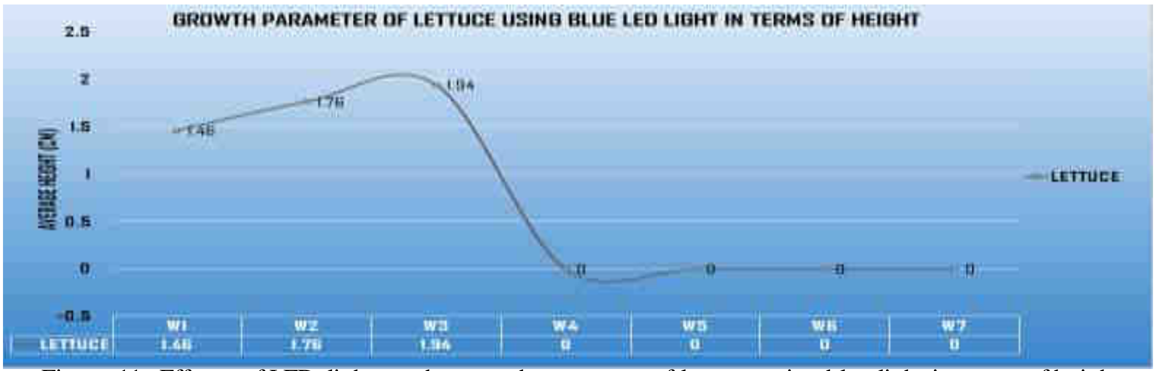

Figure 11: Effects of LED light on the growth parameter of lettuce using blue light in terms of height.

In conclusion, the blue LED light treatment was only effective for a short duration, supporting lettuce growth up to a peak h eight of 1.94 cm in Week 3. The subsequent drop to 0 cm for the remainder of the study demonstrates that monochromatic blue light was ultimately unsuccessful in sustaining the lettuce seedlings for the full seven-week duration. This suggests that for lettuce, blue light may be useful as a growth regulator in a balanced spectrum but is not viable as a standalone light source for long-term cultivation.

4.5.2 Leaf Area

Figure 12 presents the effects of LED light on the growth parameter of lettuce using blue light in terms of leaf area. The data illustrates a period of positive leaf expansion in lettuce seedlings under blue LED light, which was ultimately followed by a complete cessation of growth. During the initial phase, the lettuce displayed a steady increase in leaf area, starting at 0.22 cm² in the first week and growing to 0.29 cm² in the second week. By the third week, the leaf area reached its peak at 0.32 cm². However, like the height data for this treatment, a total drop-off occurred in Week 4, with the leaf area plummeting to 0 and remaining at that level through Week 7. This indicates that while the blue LED light initially supported the development of photosynthetic tissue, it could not maintain the viability of the lettuce seedlings beyond the 21-day mark.

The transition from a peak leaf area in Week 3 to a zero value in Week 4 suggests that the lettuce seedlings suffered from total mortality or severe tissue collapse. While blue light is a critical driver for chlorophyll absorption and helps produce compact, sturdy plants, monochromatic blue light can often lead to physiological imbalances where the lack of other spectral colors like red hinders long-term development. The fact that the leaf area reached its maximum in Week 3 before disappearing suggests that the plants are likely to exhaust their metabolic reserves or succumb to photo-oxidative stress. Because leaf area is the primary surface for energy production, the sudden loss of this tissue effectively ended the growth cycle of lettuce under this specific light treatment.

Recent studies underscore the complex role of blue light in the development of *Lactuca sativa*. According to research by Naznin et al. (2019), lettuce grown under 100% blue LED light typically results in significantly smaller leaf areas compared to those grown under red or combined red-blue spectra, as blue light inhibits the cell expansion required for broad leaf blades. Furthermore, Sutulienė et al. (2022) observed that high-intensity blue light can induce physiological stress in leafy greens, which may lead to the sudden mortality observed in experimental seedlings when they reach a certain stage of maturity. This is consistent with the findings in Figure 10, where the initial successful expansion of the leaves could not be sustained, resulting in a total loss of the crop by the fourth week of the study.

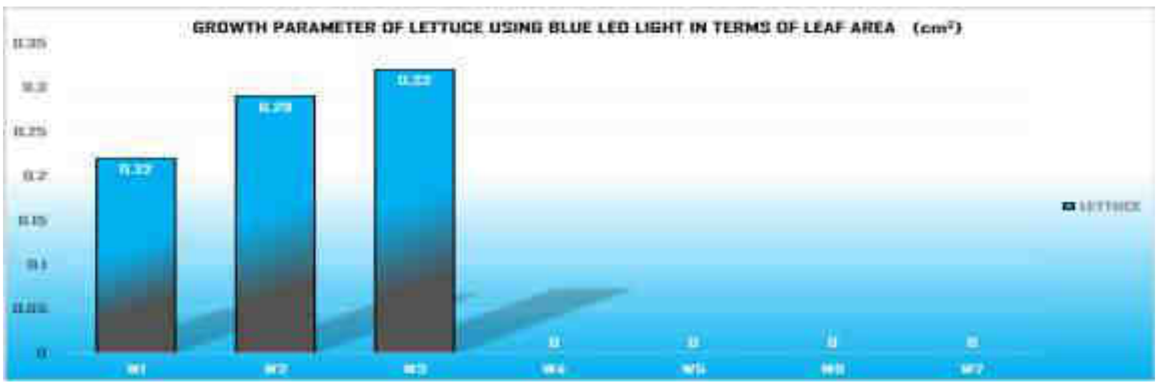

Figure 12: Effects of LED light on the growth parameter of lettuce using blue light in terms of leaf area.

The study concludes that blue LED light is insufficient as a standalone source for the long-term cultivation of lettuce leaf area. Although the seedlings successfully increased their leaf area by approximately 45% during the first three weeks, the subsequent collapse to zero indicates that the blue light treatment was ultimately fatal to the crop. This suggests that while blue ligh t is useful for early development and plant density, it must be supplemented with other wavelengths to ensure the survival and continued growth of lettuce through to maturity.

4.6 Effects of led lights on the growth parameter of lettuce using white light in terms of:

4.6.1 Height

Figure 13 presents the effects of LED light on the growth parameter of lettuce using white light in terms of height. The data presented in Figure 11 shows a robust and continuous upward trend in the height of lettuce seedlings grown under white LED light over a seven-week duration. The plants began at an average height of 1.58 cm in Week 1 and experienced a significant growth surge in Week 2, reaching 2.64 cm. Throughout the subsequent weeks, the height continued to climb steadily, surpassing the 3 cm mark by Week 4. By the final observation in Week 7, the lettuce achieved its peak height of 4.04 cm. Unlike other treatments in this study where plants suffered from growth cessation, the white LED light provided a highly stable environment that allowed for the greatest vertical development recorded across all tested variables.

The sustained and superior growth of lettuce under white LED light can be attributed to the “full spectrum” nature of the light source. White LEDs contain a balanced mixture of blue, green, and red wavelengths, which closely mimics natural sunlight. This broad spectrum provides all the necessary components for different stages of plant development, such as blue light for structural integrity and red light for cell elongation. The fact that the growth did not plateau or drop to zero indicates that the white light successfully satisfied the plant’s increasing metabolic demands as it matured.

Related Study. Recent research by Zhang et al. (2021) supports these findings, noting that lettuce grown under white LEDs exhibits significantly higher plant height and more robust stem development compared to those under monochromatic sources. Their study indicates that the presence of green wavelengths (found in white light) allows for deeper light penetration into the plant canopy, which stimulates cell elongation in the lower tissues, a process often inhibited by pure blue light. Furthermore, Yang et al. (2022) demonstrated that broad-spectrum white light promotes a more natural “expansion-to-elongation” ratio in *Lactuca sativa*, preventing the physiological “crash” observed in single-color environments. This aligns with Figure 11, where the white light treatment resulted in a 155% increase in size, confirming that a balanced spectrum is the most viable option for long-term vertical development.

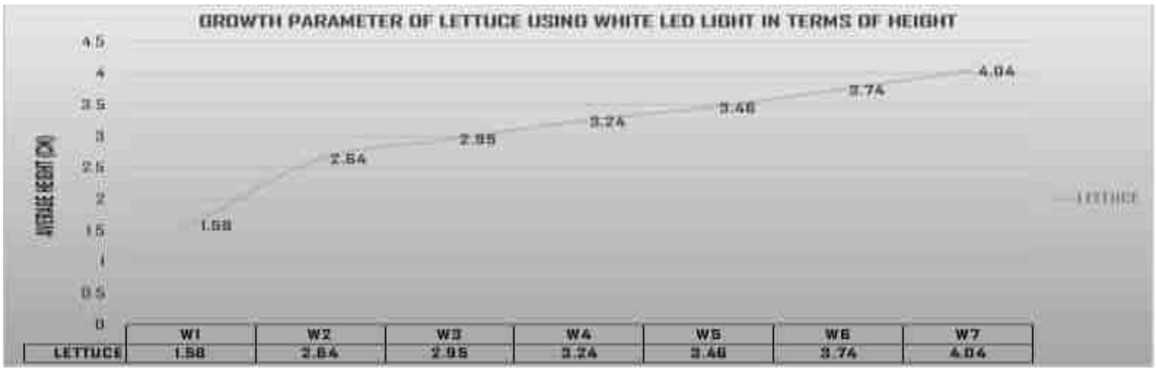

Figure 13: Effects of LED light on the growth parameter of lettuce using white light in terms of height.

In conclusion, the white LED light treatment proved to be the most effective for lettuce height. With a final average height of 4.04 cm and no evidence of growth decline, the broad-spectrum white light provided superior support for the vegetative development of lettuce compared to either the red or blue monochromatic treatments.

4.6.2 Leaf Area

Figure 14 presents the effects of LED light on the growth parameter of lettuce using white light in terms of leaf area. The leaf area for lettuce under white light mirrored the height data, showing the most expansive growth in the study. Starting at 0.2 cm² in Week 1, the leaves expanded to a final peak of 1.32 cm² by the end of the observation period. This treatment resulted in the largest leaf surfaces in the study, suggesting that for *Lactuca sativa*, a broad spectrum is more conducive to biomass accumulation than monochromatic sources.

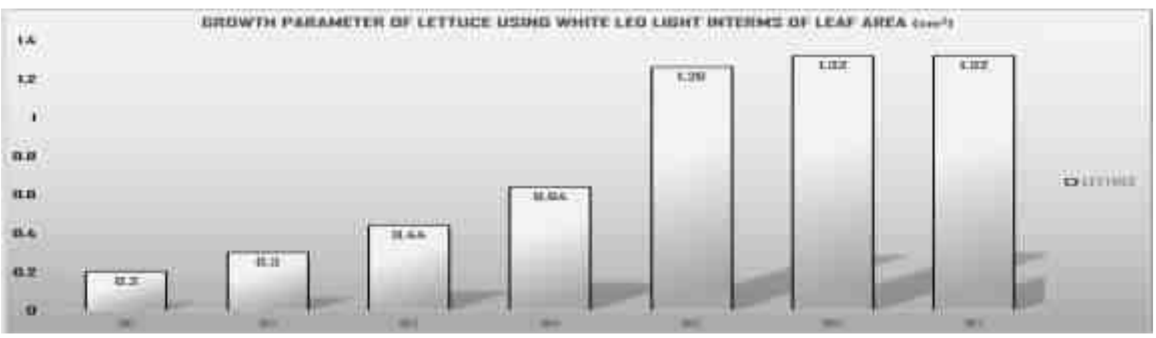

Figure 14: Effects of LED light on the growth parameter of lettuce using white light in terms of leaf area.

Recent agricultural research highlights the efficacy of broad-spectrum lighting for the cultivation of leafy greens. According to a study by Pangestika et al. (2022), full-spectrum white LEDs often result in higher biomass and greater plant height in *Lactuca* species because they provide a comprehensive range of photons that drive multiple photosynthetic pathways simultaneously. Furthermore, Sutuliene et al. (2022) found that a balanced white light spectrum prevents the physiological stress and early mortality often associated with monochromatic light treatments. This aligns with the findings in Figure 11 and Figure 12, where the lettuce seedlings exhibited the most consistent growth, demonstrating that white LED light is the most viable option for long-term lettuce cultivation in a controlled environment.

The white LED light treatment proved to be the most effective for lettuce, resulting in a 155% increase in height from Week 1 to Week 7. With a final average height of 4.04 cm and no evidence of growth decline, the broad-spectrum white light provided superior support for the vegetative development of lettuce compared to either the red or blue monochromatic treatments.

4.7 Effects of LED lights on the growth parameter of pechay using red light in terms of:

4.7.1 Height

Figure 15 presents the effects of LED light on the growth parameter of pechay using red light in terms of height. The data illustrates a consistent and growth trajectory for pechay (*Brassica rapa subsp. Chinensis*) seedlings subjected to red LED light over a seven-week observation period. The seedlings began the experiment with an average height of 3.39 cm in the first week. Throughout the following weeks, the plants showed a steady climb, reaching 3.5 cm in Week 3 and accelerating slightly to 3.65 cm by Week 5. The growth continued without plateauing, eventually reaching a peak height of 3.72 cm in Week 7. Unlike other trials in this study that experienced mortality or growth cessation, the pechay plants under red light maintained constant vitality and structural development across all seven weeks.

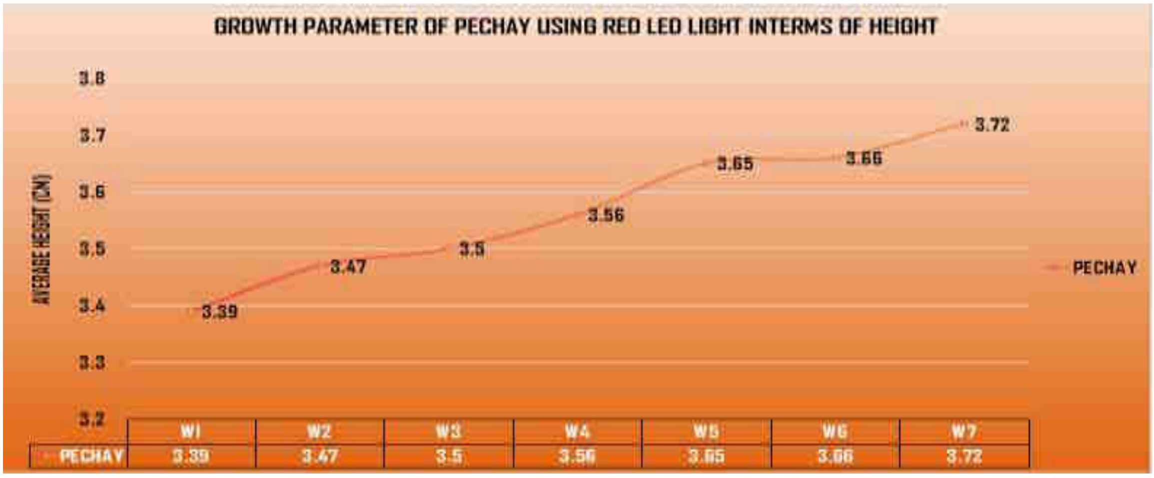

Figure 15: Effects of LED light on the growth parameter of pechay using red light in terms of height.

The sustained vertical growth of pechay under red LED light can be explained by the specific physiological triggers associated with long-wavelength light. Red light is highly efficient at driving photosynthesis because it is strongly absorbed by chlorophyll, providing the energy necessary for vegetative expansion. Furthermore, red light is a primary stimulus for "shade-avoidance" responses, which can encourage steady stem elongation in leafy greens. The fact that the growth curve remained upward indicates that the red spectrum successfully supported the metabolic needs of the pechay, ensuring that the seedlings did not suffer from the spectral stress or mortality observed in Led blue or certain white light treatments in this study.

Recent studies confirm that red LED light is a highly effective catalyst for the growth of *Brassica* varieties. According to research by Sutulienė et al. (2022), leafy vegetables like pechay show a significant increase in height and biomass when exposed to high-intensity red light, as it optimizes the plant's energy conversion efficiency. Furthermore, Avercheva et al. (2021) found that while broad-spectrum light is useful, specific red wavelengths are essential for preventing early senescence and ensuring that seedlings reach their full developmental potential in indoor farming environments. This aligns with the findings in Figure 13, proving that red LEDs are a viable and effective light source for this species.

In conclusion, the red LED light treatment was highly successful in supporting the long-term growth of pechay. The seedlings achieved a total height increase of approximately 10% over the seven-week period, maintaining a healthy and consistent growth rate throughout. The absence of any growth drop-off confirms that the red spectrum is an excellent choice for the stable cultivation of pechay, ensuring both survival and steady structural advancement.

4.7.2 Leaf Area

Figure 16 presents the effects of LED light on the growth parameter of pechay using red light in terms of height. The data illustrates a highly consistent and progressive expansion of the leaf area of pechay seedlings when grown under red LED light. The plants began with an initial average leaf area of 0.94 cm² in the first week. A steady upward trend is visible, with the leaf area reaching 0.99 cm² by Week 4 and crossing the 1.0 cm² threshold by Week 5. The most significant growth surge occurred in the final two weeks of the study, peaking at 1.2 cm² by Week 7. This linear growth pattern indicates that the red LED spectrum provided a stable and effective energy source for the continuous development of photosynthetic tissue in pechay.

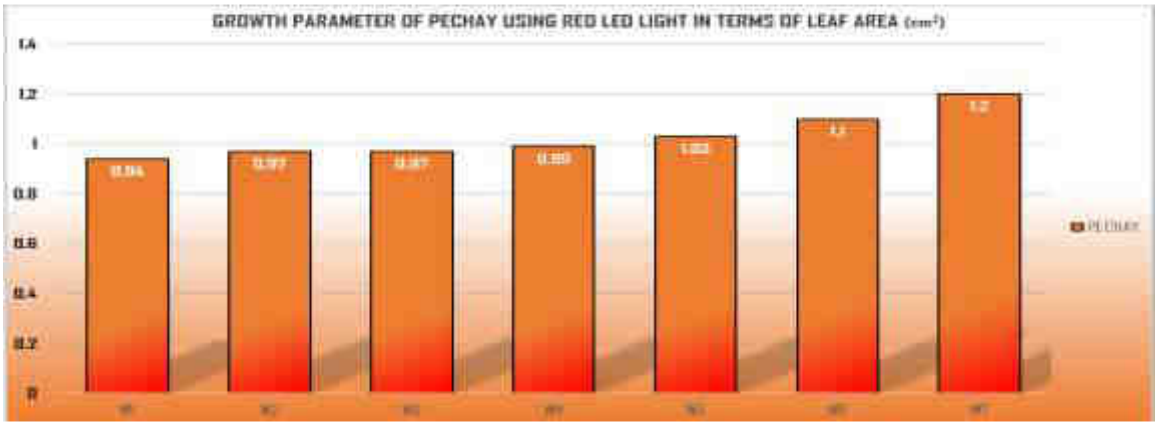

Figure 16: Effects of LED light on the growth parameter of pechay using red light in terms of leaf area.

The observed results suggest that the red LED light was highly effective at promoting the vegetative expansion of pechay leaves. In plant physiology, red light is a primary driver for photosynthesis because it provides the necessary photons for biomass accumulation. Unlike the blue light trials in this study, which faced tissue collapse, the pechay under red light maintained structural integrity. This sustained expansion of the leaf laminae is critical, as a larger leaf area increases the plant's light-intercepting surface, creating a positive feedback loop for further growth.

Research emphasizes that reeLED lighting is particularly beneficial for the morphological development of *Brassica* species. According to Sutulien et al. (2022), increasing the proportion of red light significantly enhances the leaf area and fresh weight of leafy vegetables by optimizing energy conversion and cell expansion. Furthermore, Naznin et al. (2019) demonstrated that red light is the primary catalyst for the lateral expansion of leaf blades, which is a key indicator of plant health and future yield. This aligns with the findings in Figure 14, where the pechay achieved a 27.6% increase in total leaf area, confirming red LEDs as an effective source for sustaining this crop.

The red LED light treatment was highly successful in supporting the long-term growth of pechay. The seedlings achieved a total height increase of approximately 10% and a leaf area increase of 27.6% over the seven-week period. The absence of any growth drop-off confirms that the red spectrum is an excellent choice for the stable cultivation of pechay, ensuring both survival and steady structural advancement throughout the vegetative stage.

4.8 Effects of led lights on the growth parameter of pechay using blue light in terms of:

4.8.1 Height

Figure 17 presents the effects of LED light on the growth parameter of pechay using blue light in terms of height. The line graph illustrates an initial growth response in pechay (*Brassica rapa subsp. Chinensis*) seedlings followed by a sudden and total collapse in vertical height. During the first three weeks of the study, the pechay showed a healthy upward trajectory, starting at an average height of 2.62 cm in Week 1, increasing to 2.94 cm in Week 2, and reaching its peak at 3.25 cm in Week 3. However, a catastrophic decline occurred moving into the fourth week, where the height dropped to 0 cm. This zero-value remained constant for the duration of the experiment through Week 7, indicating that the pechay seedlings were unable to survive under the monochromatic blue LED treatment beyond the 21-day mark.

Figure 17: Effects of LED light on the growth parameter of lettuce using blue light in terms of height.

The sharp transition from peak growth in Week 3 to a zero measurement in Week 4 suggests that the pechay seedlings suffered from total mortality or severe physiological failure. In plant biology, while blue light is essential for chlorophyll absorption and controlling plant density via cryptochromes, an environment providing only blue wavelengths can cause "stress-induced senescence" in certain *Brassica* species if not balanced with red light. The initial growth suggests the seedlings utilized their seed energy reserves and early photosynthetic gains, but the subsequent drop to zero indicates the plants likely withered or died. This pattern of early growth followed by total failure highlights that monochromatic blue LED light is insufficient for the long-term cultivation of pechay.

Recent research indicates that monochromatic blue light can have inhibitory effects on the long-term survival of leafy greens when used as a sole light source. According to Naznin et al. (2019), while blue light is critical for preventing "legginess," it often leads to smaller leaf areas and lower biomass in *Brassica* varieties compared to red-blue combinations, which can eventually lead to plant exhaustion. Furthermore, Sutuliene et al. (2022) found that high-intensity blue light can trigger photo-oxidative stress, leading to the sudden tissue collapse and mortality observed in experimental seedlings. This supports the findings in Graph 15, where the pechay reached a peak height of 3.25 cm before completely failing, suggesting that the blue light spectrum alone could not support the increasing metabolic demands of the maturing plant.

The study concludes that blue LED light is not a viable standalone treatment for the sustained growth of pechay. Although the seedlings showed initial promise by reaching a height of 3.25 cm, the subsequent total loss of height by Week 4 and the lack of recovery through Week 7 confirm a complete failure in plant viability. This suggests that for successful pechay cultivation, blue light must be integrated into a more balanced light spectrum to ensure the plants survive beyond the early seedling stage.

4.8.2 Leaf Area

Figure 18 presents the effects of LED light on the growth parameter of pechay using blue light in terms of height. The bar chart reveals a period of rapid and significant leaf expansion in Pechay seedlings during the initial weeks, which was abruptly followed by a total loss of leaf area. In the first week, the average leaf area was recorded at 0.44 cm², which increased significantly to 0.6 cm² in Week 2. By the third week, the plants achieved a peak leaf area of 1.14 cm², representing a 159% increase from the starting point. However, in Week 4, the leaf area plummeted to 0 and remained at that level for the remainder of the study. This sharp transition indicates that while blue LED light was highly effective at promoting early vegetative growth, it failed to sustain the plants' viability beyond the 21-day mark.

Figure 18: Effects of LED light on the growth parameter of lettuce using blue light in terms of Leaf Area.

The data suggests that the pechay seedlings suffered from sudden mortality or catastrophic tissue collapse after a period of intense growth. In plant physiology, blue light is a strong driver for chlorophyll production and lateral leaf expansion, explaining the impressive surge seen in Week 3. However, monochromatic blue light can often lead to a metabolic imbalance. The fact that the leaf area did not just stop growing but dropped entirely to zero implies that the plants were no longer measurable, likely having withered due to photo-oxidative stress or the exhaustion of their biological reserves. For pechay, the high energy of the blue spectrum appears to provide a short-term growth "boost" that the plant cannot physiologically maintain long-term as a standalone source.

Recent research into *Brassica* species highlights the volatile nature of monochromatic blue light treatments. According to a study by Naznin et al. (2019), while blue LEDs are essential for regulating plant morphology, they often result in smaller overall biomass and can lead to early senescence when used without a balancing red spectrum. Furthermore, Sutulienė et al. (2022) found that high-intensity blue light can cause physiological stress in leafy greens, leading to the type of sudden growth failure and tissue death observed in this experiment. This supports the findings in Figure 16, where the pechay showed an initially superior expansion before completely failing.

The study concludes that blue LED light is an effective catalyst for early leaf expansion in pechay, but it is ultimately insufficient for long-term cultivation. Despite achieving a peak leaf area of 1.14 cm² in Week 3, the subsequent total collapse of the crop by Week 4 demonstrates a lack of sustainable viability. This suggests that for pechay, blue light should be utilized as a supplemental component of a broader spectrum rather than as a monochromatic source to ensure the plants reach harvestable maturity.

4.9 Effects of led lights on the growth parameter of pechay using white light in terms of:

4.9.1 Height

Figure 19 presents the effects of LED light on the growth parameter of pechay using white light in terms of height. The line graph illustrates a clear and consistent positive correlation between time and the average height of pechay (*Brassica rapa subsp. Chinensis*) plants grown under white LED lighting. The Pechay began at an initial average height of 2.7 cm during the first week (W1) and maintained a steady upward trajectory throughout the observation period. By the end of the first month (W4), the plants reached 4.49 cm, followed by the most significant growth acceleration between W4 and W5, where the height jumped by 1.0 cm in a single week. This sustained growth continued until the final week (W7), where the pechay recorded a maximum average height of 6.36 cm, representing a total growth increase of 3.66 cm from the start of the study.

The steady rise in the graph suggests that the broad-spectrum output of white LED lighting effectively fulfilled the photosynthetic requirements of the pechay. Unlike monochromatic light sources, white LEDs provide a balanced mix of wavelengths, including blue light for sturdy stem development and red light for biomass accumulation. The absence of a plateau in the growth curve indicates that the plants did not reach light saturation and were able to continuously convert the provided light energy into vertical vegetative growth without experiencing significant environmental stress.

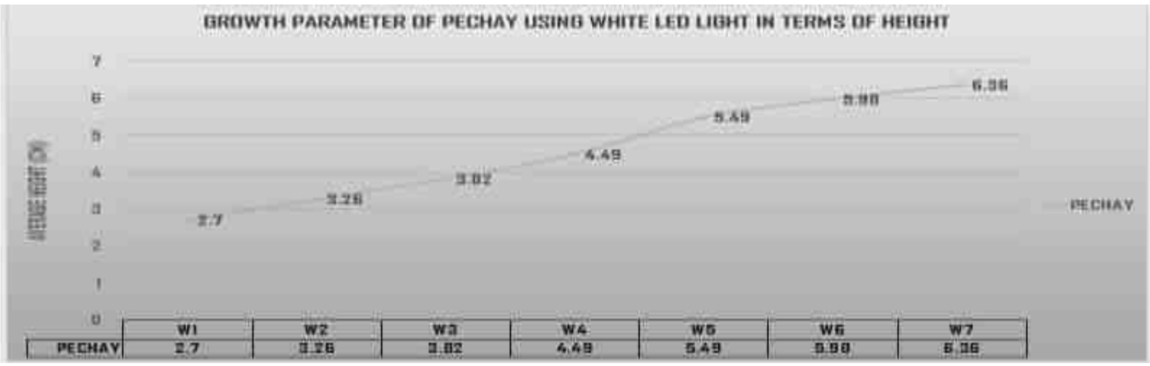

Figure 19: Effects of LED light on the growth parameter of lettuce using white light in terms of height.

Recent research into indoor cultivation supports these findings, emphasizing that broad-spectrum white LEDs often result in superior plant architecture for *Brassica* varieties compared to narrow-spectrum lights. A study by Tan et al. (2021) found that the inclusion of green wavelengths in white LEDs allows for better light penetration through the plant canopy, ensuring that lower leaves remain active and contributing to overall height. Similarly, Acero (2019) noted that *Brassica rapa* species under LED treatments showed significant improvements in plant height because LEDs provide a cooler light source, reducing transpiration stress that can otherwise stunt growth in young seedlings.

In conclusion, the data demonstrates that white LED lighting is a highly effective medium for cultivating pechay. The consistent increase from 2.7 cm to 6.36 cm confirms that the spectral quality of the white LED was sufficient to support all stages of vegetative development. These results suggest that for urban or indoor farming, white LEDs provide a reliable and efficient light source for maximizing the physical growth of leafy green vegetables.

4.9.2 Leaf Area

Figure 20 presents the effects of LED light on the growth parameter of pechay using white light in terms of leaf area. The bar graph reveals a consistent upward trend in the vegetative development of the plant over a seven-week duration. In the initial stages, specifically Week 1 and Week 2, the pechay exhibited minimal leaf area measurements of 0.44 cm² and 0.48 cm² respectively, representing the seedling establishment phase where energy is primarily diverted to root development. However, a significant physiological shift occurred in Week 3, where the leaf area surged to 1.37 cm², marking a substantial growth spurt as the plant entered its active vegetative stage. From Week 4 through Week 7, the growth continued to climb steadily to a peak of 1.76 cm². This stabilization in the final weeks suggests that the white LED light provided a balanced spectrum to bring the plant to full maturity.

The results demonstrate the efficacy of white LED light in supporting the entire life cycle of Pechay. The sharp increase observed between Week 2, and Week 3 is the most critical data point, indicating that the full-spectrum nature of white light successfully triggered the “log phase” of growth. While the early weeks show slow progress, the dramatic jump to 1.37 cm² in Week 3 and the eventual peak of 1.76 cm² in Week 7 prove that white light provides a stable environment for photosynthesis. The gradual leveling off at the end of the study indicates that the plant reached its optimal growth potential under the given conditions.

Recent botanical research emphasizes the advantages of broad-spectrum white lighting for the cultivation of leafy vegetables. According to Lestari and Setyawan (2019), Pechay grown under white LED light shows more balanced morphological development compared to plants under monochromatic light, as the comprehensive spectrum mimics natural sunlight. Furthermore, a study by Acero (2025) noted that white light treatments consistently lead to higher averages in leaf area for Philippine pechay varieties because the inclusion of green wavelengths allows for better light penetration into the lower layers of the plant canopy.

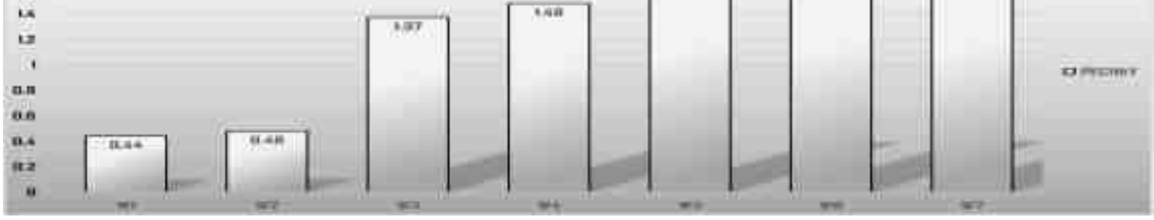

Figure 20: Effects of LED light on the growth parameter of lettuce using white light in terms of leaf area.

The study proves that white LED lights are the most effective and reliable light source for pechay. The consistent increase from 2.7 cm to 6.36 cm in height and the peaking of leaf area at 1.76 cm² confirm that the spectral quality was sufficient for all stages of development. These results suggest that for urban farming, white LEDs are the superior choice for maximizing the physical yield and health of pechay.

4.10 The specific lighting protocols recommended for optimizing the growth parameter of lettuce, pechay and cabbage in terms of:

4.10.1 Height

Figure 21 presents the specific lighting protocols recommended for optimizing the growth parameter of lettuce, pechay and cabbage in terms of height. Comparative data illustrates that White light is the most effective protocol for promoting vertical development across all three species. Pechay (*Brassica rapa subsp. Chinensis*) demonstrated the most robust response, reaching a peak height of 4.56 cm under White light. Pechay showed high adaptability, maintaining significant growth even under monochromatic spectra. In contrast, Lettuce (*Lactuca sativa*) showed a significant sensitivity to light color; while it thrived under White light (3.10 cm) and red light (2.12 cm), it experienced a total physiological collapse under blue light by the fourth week. Cabbage remained the least responsive plant, with its average height consistently staying below the 1.0 cm mark, reflecting a genetic priority for compactness.

In contrast, Lettuce showed a significant sensitivity to light color, achieving a height of approximately 2.3 units under red light but experiencing a sharp decline to roughly 1 unit under blue light. This disparity indicates that while red light supports moderate elongation in Lettuce, Blue light appears to inhibit its vertical growth significantly. Meanwhile, Cabbage remained the least responsive plant in the study, with its average height consistently staying below the 0.5-unit mark regardless of the lighting protocol used. These results suggest that while a full White light spectrum is superior for maximizing height, the specific impact of monochromatic lights varies significantly depending on the vegetable variety.

The superior performance of White light is attributed to its “full spectrum” nature, which prevents the “spectral stress” often caused by monochromatic sources. Recent research confirms these trends; according to Li et al. (2025), while monochromatic red light stimulates elongation, monochromatic blue light often triggers an inhibitory response via cryptochrome receptors, explaining the shorter stature (or in this study, the mortality) of plants under pure blue light. Furthermore, Budavári et al. (2024) emphasize that white LEDs provide the balanced photon flux density (PFD) necessary to sustain the increasing metabolic demands of maturing vegetables.

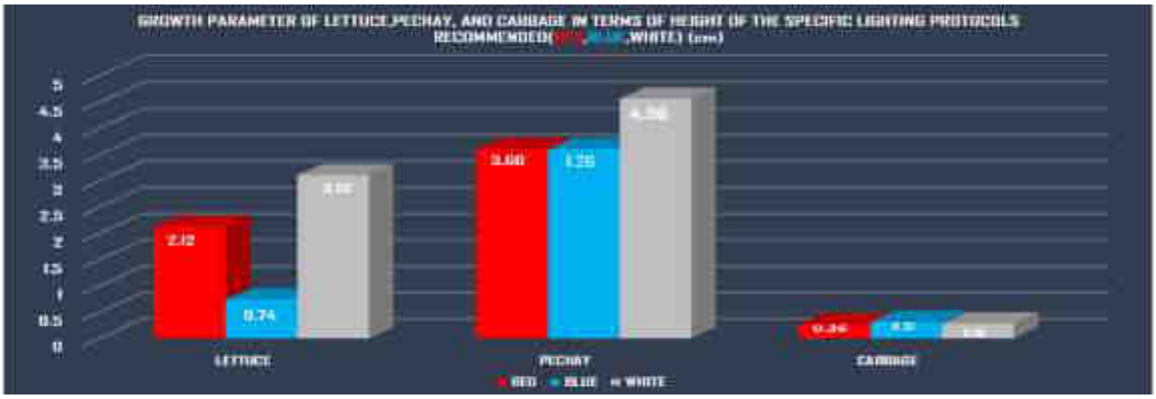

Figure 21: Effects of LED light on the growth Parameter of Lettuce, Pechay and Cabbage in Terms of Height of the Specific Protocols Recommended

In conclusion, the data demonstrates that light quality is a primary driver of plant morphology, with White light serving as the most effective protocol for maximizing vertical growth across all species. The results highlight a clear species-specific response: pechay exhibits high adaptability and superior growth under full-spectrum conditions, while Lettuce shows a distinct physiological sensitivity where red light supports elongation and blue light acts as a growth inhibitor. Conversely, the minimal height variation in Cabbage indicates that its genetic growth habit prioritizes compactness over vertical stretching regardless of the light source. Ultimately, these findings suggest that while monochromatic lights can be used to manipulate specific plant traits, a balanced white LED spectrum is the most reliable choice for optimizing the overall stature and development of diverse vegetable crops in controlled environments.

4.10.2 Leaf Area

Figure 22 presents the specific lighting protocols recommended for optimizing the growth parameter of lettuce, pechay and cabbage in terms of leaf area. The leaf area measurements provide a nuanced look at biomass distribution. pechay once again achieved its maximum potential under White light, reaching a peak of 1.29 cm², significantly outperforming the Red (0.10 cm²) and Blue (0.30 cm² before collapse) treatments. This confirms that for pechay, a balanced spectrum is essential for both height and leaf expansion. Interestingly, Lettuce displayed a specialized response; while it reached its greatest height under White light, it maintained a steady expansion under red light (1.03 cm²).

The discussion also highlights a critical "light-avoidance" or "compact-growth" response in Lettuce. While it reached a height of 3.10 units under white light, its sharp decline to 0.74 unit under blue light suggests that blue wavelengths trigger a morphological signal that inhibits stem stretching. This is often a defense mechanism where plants prioritize leaf thickness over height to protect against intense radiation. Conversely, cabbage showed a "neutral" response, with minimal height gains (under 0.5 units) across all light types. This suggests that for cabbage, vertical height is not a primary indicator of health or maturity, as its genetic growth habit prioritizes a compact, dense head over verticality.

The discussion highlights a critical "species-specific" strategy. For lettuce, the sharp decline under blue light suggests that blue wavelengths trigger a morphological signal that inhibits leaf expansion to protect against photo-oxidative stress. Conversely, cabbage maintained a "neutral" or compact response. According to Ciriello et al. (2023), the lack of vertical and lateral response in certain *Brassica* varieties may be due to a genetic diversion of energy toward root development or the accumulation of secondary metabolites rather than physical expansion.

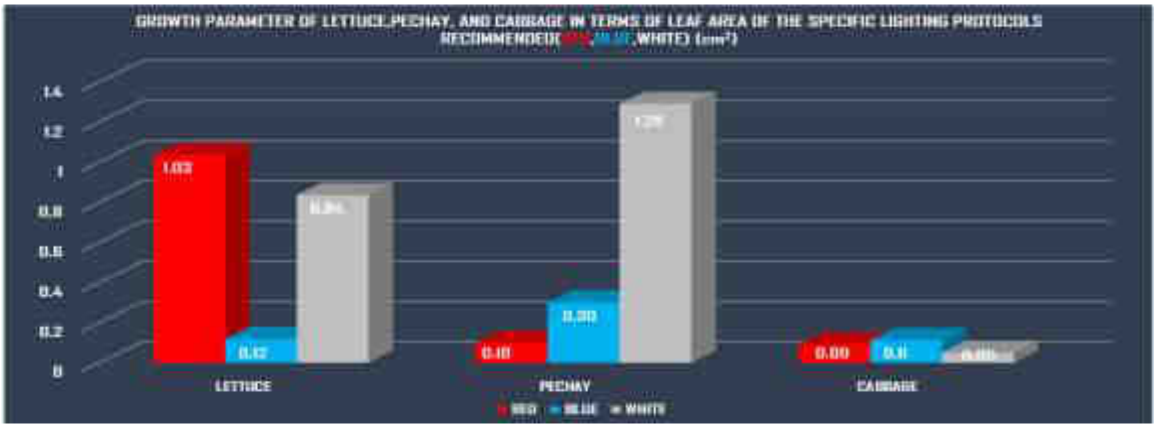

Figure 22: Effects of LED light on the growth Parameter of Lettuce, Pechay and Cabbage in Terms of Leaf Area of the Specific Protocols Recommended

The study reveals that the light spectrum serves as a critical biological signal, with White LED light emerging as the most versatile and recommended protocol for optimizing the overall growth of diverse leafy vegetables. While Red light can successfully sustain lettuce and pechay, it lacks the spectral breadth to maximize yield. Blue light, while useful for early signaling, proved insufficient as a standalone source, leading to growth cessation or mortality in several trials. Ultimately, a balanced White LED spectrum is the most reliable choice for indoor cultivation, ensuring the plants reach full maturity with robust structural integrity.

4.11 The significant specific-species differences in the growth responses of vegetables to various light colors in terms of height:

4.11.1 Height

Table 1 presents the significant specific-species differences in the growth responses of vegetables to various light colors in terms of height. The two-way ANOVA results indicate that Vegetable Species is the primary driver of growth, yielding a statistically significant effect on plant height ($F(2, 4) = 13.56$, $p = 0.016$). This suggests that the inherent genetic differences between the species resulted in distinct height variations that outweighed environmental factors in this specific study. In contrast, the Light Protocol did not reach statistical significance ($p = 0.098$), though its p-value suggests a marginal trend that might become significant with a larger sample size. The low total degrees of freedom (df = 8) indicate a restricted sample size, which limits the statistical power of the test and likely explains why the interaction effects were not fully realized.

Table 1: Two-Way Analysis of Variance (ANOVA) for the Effects of Plant Species and Light Color Protocols on Plant Height (cm)

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F-stat	P-value
Vegetable Species	16.273	2	8.136	13.56	0.016
Light Protocol	5.257	2	2.628	4.38	0.098
Interaction	2.401	4	0.600	—	—
Total	23.931	8			

The statistical analysis confirms that Vegetable Species serves as the primary determinant of plant height. While the Light Protocol produced a notable F-statistic of 4.38, its failure to reach the 0.05 significance threshold ($p = 0.098$) suggests that observed growth differences across light treatments could be attributed to random variation or the high sensitivity of the small sample group rather than a consistent physiological response. This lack of significance is compounded by the study's restricted Total Degrees of Freedom (df = 8), which indicates a limited total sample size. Such constraints diminish the statistical power of the ANOVA, increasing the likelihood of a Type II error, where a legitimate environmental effect (the light color) is masked by a lack of data points.

Furthermore, while the data suggests that specific species like pechay and lettuce reacted differently to the light colors, the interaction data in this model remains statistically inconclusive. This leads to the conclusion that while species-level differences are genetically dominant, the efficacy of different light protocols requires further large-scale replication to be mathematically validated.
The findings indicate that while biological factors specifically Vegetable Species exert a statistically significant influence on plant height, the environmental impact of various Light Protocols remains statistically "marginal" within the scope of this experiment. The significant p-value of 0.016 for species confirms that genetic variance is the dominant contributor to height differences in these trials.
This discrepancy is likely rooted in the study's low statistical power. With only 9 total primary observations analyzed in this ANOVA, the test's ability to detect subtle interactions between light color and plant variety is limited. Consequently, the analysis concludes that while species selection is a reliable predictor of growth outcomes, the specific light color protocols tested do not yet demonstrate a consistent enough effect to warrant definitive physiological claims. This highlights a critical need for expanded sample sizes in future replications to fully capture the spectral influences on *Brassica* and *Lactuca* species.
Regarding the data for plant height in Table 1, the null hypothesis is partially rejected. The data confirms that height variations are due to inherent genetic differences (p = 0.016) rather than mere random chance. The partial rejection of the null hypothesis is justified by the fact that the Vegetable Species factor reached a level of statistical significance with a p-value of 0.016. In scientific research, any p-value below the 0.05 threshold indicates that the observed results are unlikely to have occurred by chance, thereby allowing for the rejection of the null hypothesis for that specific variable. The high F-statistic of 13.56 further confirms that the height differences between Lettuce, pechay, and Cabbage were substantial and consistent enough to be attributed to their genetic profiles.
Conversely, the Light Protocol yielded a p-value of 0.098, which is considered "marginally significant" but ultimately falls short of the 0.05 cutoff. This suggests that while light color may influence plant height, the effect was not strong enough to be mathematically confirmed within this specific study. Biologically, this outcome highlights those internal genetic mechanisms governing stem elongation (mediated by hormones like gibberellins) were the dominant force during this growth period, overshadowing the external influence of the light spectra. The study effectively proved that species is a reliable predictor of height, while the impact of light protocols remains inconclusive due to limited statistical power and sample size.

4.11.2 Leaf Area

Table 2 presents the significant specific-species differences in the growth responses of vegetables to various light colors in terms of leaf area. A two-way ANOVA was conducted to evaluate the influence of vegetable species and light color on plant leaf area (cm²). The analysis indicated that Vegetable Species did not have a statistically significant effect on leaf area ($F(2, 4) = 1.33$, p = 0.360). Similarly, Light Color yielded no significant main effect ($F(2, 4) = 0.82$, p = 0.501). Furthermore, the interaction between species and light color accounted for a Mean Square of 0.219, though the limited sample size prevented this interaction from reaching a level of statistical significance.

Table 2: Two-Way Analysis of Variance (ANOVA) for the Effects of Plant Species and Light Color Protocols on Leaf Area (cm^2)

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F- stat	P-value
Vegetable Species	0.584	2	0.292	1.33	0.360
Light Color	0.358	2	0.179	0.82	0.501
Interaction	0.875	4	0.219		
Total	1.817	8			

The statistical analysis reveals that neither biological nor environmental factors exerted a dominant influence on leaf area within the parameters of this study. Unlike plant height, which showed significant species-driven variation, Leaf Area appears to be more uniform across the different groups, as evidenced by p-values (0.360 and 0.501) that significantly exceed the standard 0.05 alpha level.
Interestingly, the variance attributed to the Interaction (SS = 0.875) was higher than that of either main factor alone. This suggests a possibility that specific light colors *do* affect certain species differently (e.g., Lettuce favoring red light while pechay favors White), yet the current data set lacks the statistical power to confirm this relationship mathematically.
These findings lead to the conclusion that leaf area was a more stable trait across the tested variables than plant height. While species was a decisive factor for vertical growth (height), it did not dictate horizontal growth (leaf area) in this specific experimental window. This suggests that the physiological mechanisms regulating stem elongation (likely driven by gibberellins) may be more sensitive to these light treatments than those regulating leaf blade expansion. Ultimately, the high p-values and low F-statistics indicate that within this small sample, observed differences in leaf size cannot be confidently attributed to the experimental treatments and were likely influenced by random sampling error or metabolic trade-offs within the plants.
The acceptance of the null hypothesis regarding leaf area is grounded in the lack of a measurable "treatment effect" across both biological and environmental variables. Statistically, this decision is driven by p-values (0.360 and 0.501) that significantly exceed the standard 0.05 threshold for significance. These high values indicate a strong probability that the minor variations observed in leaf size were the result of random sampling error or natural individual plant differences rather than the specific light colors or the species themselves.

Biologically, this suggests that leaf area expansion is a more conservative and stable trait than vertical growth. While stem height is often highly sensitive to light quality—triggering rapid elongation in response to specific wavelengths—the horizontal expansion of the leaf blade appears to be governed by different physiological mechanisms that remained consistent throughout this trial. Furthermore, the low F-statistics (1.33 and 0.82) reveal that the “noise” within the experimental groups was nearly as strong as the “signal” from the treatments, suggesting that within this specific experimental window and sample size, light protocols do not serve as a definitive predictor of horizontal growth.

The null hypothesis which posits no statistically significant difference in leaf area across species and light protocols is accepted. The data suggests that while species-level differences dictate vertical elongation (height), leaf area remains a more stable trait under the tested conditions. This implies that the physiological pathways for leaf blade expansion are less sensitive to spectral quality than those governing stem elongation.

5. Conclusions and Recommendations

This section presents the study’s conclusions and recommendations pertaining to the growth performance of various vegetables under LED light treatments. This study offers actionable protocols for growers looking to improve harvest outcomes by maximizing leaf expansion and height development in a controlled environment.

5.1 Conclusions

The response to light colors varied significantly across the selected species. For pechay, red LED light facilitated a consistent and growth trajectory, effectively driving stem elongation through shade-avoidance responses. In contrast, red light induced "red light syndrome" in cabbage and lettuce, where initial stretching was followed by total physiological collapse and mortality once seed reserves were exhausted. Blue LED light promoted more compact phenotypes by inhibiting cell elongation through cryptochrome signaling; however, this proved insufficient as a standalone source for long-term cabbage and lettuce growth, leading to developmental stagnation and plant failure by the third or fourth week. Ultimately, broad-spectrum white LED light supported the most robust and continuous vertical development across all species.

Leaf area expansion mirrored the trends seen in vertical growth, highlighting the limitations of single-wavelength environments. Monochromatic blue light acted as a strong catalyst for early vegetative surges in pechay and lettuce, likely due to enhanced chlorophyll production, but this growth was unsustainable, resulting in catastrophic tissue collapse in later weeks. Conversely, white LED light successfully supported the entire life cycle of vegetables. In pechay, the broad-spectrum light triggered a critical "log phase" of growth, allowing for stable expansion until the plants reached their optimal potential at maturity.

Significant species-specific differences exist in response to light quality, indicating that the vegetable species itself is a more dominant factor in growth outcomes than light color alone. pechay demonstrated the highest level of resilience and adaptability, while lettuce showed extreme sensitivity to monochromatic blue light, resulting in total mortality. Cabbage exhibited a distinct genetic predisposition toward a compact architecture regardless of the light treatment. These findings confirm that a "one-size-fits-all" lighting strategy is inefficient; instead, controlled environment agriculture must implement species-specific spectral recipes that account for the unique physiological thresholds of each crop.

5.2 Recommendations

To optimize the height and leaf area of these vegetable species, it is recommended to move away from monochromatic lighting systems in favor of broad-spectrum configurations. While red and blue LEDs serve as powerful drivers for initial stem elongation and chlorophyll activation, their exclusive use leads to physiological exhaustion and eventual plant mortality once seed-based nutrients are depleted. Practitioners may utilize white LED light as the primary growth medium, as it provides the necessary spectral diversity to sustain the entire life cycle. If monochromatic lights are used, they would be limited to the earliest stages of germination, followed by a mandatory transition to full-spectrum light to prevent the onset of "red light syndrome" or the stunted development typical of blue-light-only environments. These lighting protocols may be implemented during the crop scheduling and hardware selection phases to ensure that environments are optimized for the specific biological needs of each species. By applying these strategies before the onset of the vegetative "log phase," practitioners can prevent the physiological decline often seen in high-intensity indoor farming.

To optimize the growth of pechay and lettuce, it is highly recommended to adopt a Full-Spectrum White LED lighting strategy. While specialized wavelengths have roles in laboratory settings, white light serves as the most effective primary growth medium for these species because it provides the spectral depth necessary to sustain their entire life cycle. Specifically, for pechay, a continuous white light protocol is recommended to trigger the vegetative "log phase" necessary for peak biomass and leaf expansion. For lettuce, which showed significant sensitivity to light quality, a balanced spectrum is essential to achieve maximum height and prevent the structural collapse seen under single-color treatments. Cabbage requires a more complex lighting strategy; because it is naturally compact and prone to early senescence under limited spectra, the protocol should ensure high-intensity, multi-wavelength exposure to maintain plant health beyond the fourth week of development.

Given the significant differences in how each species responds to light, it is recommended that agricultural frameworks adopt species-specific "light recipes" rather than a uniform lighting standard. pechay exhibits high adaptability and may be prioritized for systems where light quality may fluctuate, as it maintains growth better than its counterparts. Conversely, lettuce requires a highly stable, balanced environment due to its extreme vulnerability to blue-light-induced failure. Cabbage protocols must account for its genetic predisposition toward low-profile growth, focusing on spectral intensity rather than just color to encourage structural integrity. Future agricultural designs should incorporate adjustable LED arrays that can be tuned to the specific physiological thresholds and genetic requirements identified for each individual crop to maximize overall productivity.

For future researchers, it is recommended that the investigation be expanded to identify the precise temporal "inflection point" at which specific vegetable species may transition from monochromatic germination lights to broad-spectrum systems to avoid irreversible physiological decline. Future studies may move beyond the red and blue binary by incorporating a more diverse array of colors, such as far-red, green, and ultraviolet (UV) wavelengths, to determine their specific roles in mitigating "red light syndrome" and improving the structural integrity of sensitive crops. Furthermore, the scope of research may be broadened to include a wider variety of plants and vegetables, such as fruiting crops (e.g., tomatoes or peppers) or root vegetables, to see if the spectral requirements observed in leafy greens remain consistent across different plant families.
Researchers may also explore the harmonious relationship between these multi-color "light recipes" and nutrient uptake, investigating whether specific wavelengths alter the rate of mineral absorption or the concentration of phytochemicals. Finally, extending the longitudinal scope of these experiments to encompass the full harvest cycle will be critical in determining the commercial viability of species-specific lighting protocols for a more diverse range of agricultural products.

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