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Comparative Evaluation of the Effectiveness of Sunlight and Artificial Grow Lights on the Growth and Biochemical Properties of Hydroponically Cultivated Leafy Vegetables

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Abstract

Enhancing the nutritional quality and growth rate of leafy vegetables through different light sources could advance the rapid growth of healthier crops under greenhouse conditions. This study investigated the effects of three light sources (natural sunlight, AiGrow™ LED light, and Philips™ LED light) on the growth and biochemical properties of hydroponically cultivated Oak Red and Lollo Bionda lettuce varieties. The plants were cultivated in a Nutrient Film Technique (NFT) hydroponic system under controlled greenhouse conditions and were grown for a period of four weeks before being harvested for extract preparation. Aqueous lettuce extracts were prepared and analyzed for total carbohydrate content (TCC) using the phenol-sulphuric acid method, total protein content (TPC) using the Lowry assay, total phenolic content (TPhC) using the Folin-Ciocalteu assay, and total flavonoid content (TFC) through the $AlCl_3$ spectrophotometric method. Antioxidant activity (AA) was assessed by the DPPH assay. Qualitative phytochemical tests identified the presence of polyphenols, terpenoids, saponins, and steroids across all samples. Results indicated that Oak Red lettuce grown under sunlight exhibited the highest levels of TCC (0.094 g/100 g), TPC (0.421 g/100 g), TPhC (0.228 mg GAE/g), and AA (69.18%), while Oak Red lettuce grown under AiGrow™ LED light had the highest TFC (0.721 mg QE/g). In terms of growth performance, AiGrow™ LED light was most effective for both lettuce varieties. Thus, according to the results obtained from this study, AiGrow™ LED light, which supported a maximum flavonoid content of 0.721 mg QE/g dried weight and comparable growth performance, can be recommended as a suitable alternative to sunlight for indoor hydroponic cultivation of Oak Red and Lollo Bionda lettuce.

Keywords: Hydroponic lettuce, Sunlight, Grow lights, Nutritional quality, Antioxidant activity

1. Introduction

Hydroponics is an innovative and efficient plant-growing technique that relies on a water-based nutrient solution providing an alternative to conventional agriculture.[1] This soilless method, which may or may not incorporate a substrate for mechanical support, has gained significant attention due to its ability to produce high yields in diverse crops, including herbs, ornamental plants, and a variety of vegetables such as tomatoes, lettuce, and cucumbers.[2]

Among the different hydroponic systems available, the Nutrient Film Technique (NFT) stands out as one of the most widely used due to its simplicity and effectiveness in fostering plant growth while conserving water. Other popular systems include deep-water culture, aeroponics, wick, and drip systems, each offering unique advantages depending on the crop and environmental conditions.[3]

Hydroponic systems are generally categorized into two groups: open and closed systems. In open systems, the nutrient solution is used once and then discarded, whereas closed systems recycle the nutrient solution, minimizing waste and enhancing sustainability.[4]

The NFT system, which was utilized in this research, falls under the closed system category. This technique involves suspending plants above a continuously flowing nutrient solution, ensuring that the plant roots are exposed to an aerated stream of water, which allows the roots to absorb moisture and oxygen efficiently (Figure 1).[5] The system's design ensures that the nutrient solution flows down the channels, aided by a gentle tilt, and is recirculated to the reservoir, promoting water conservation, and reducing the overall environmental impact of the system.[6]

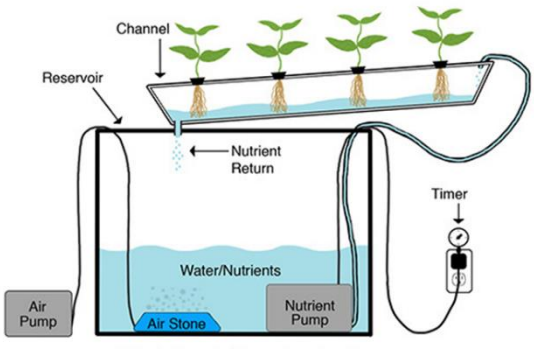

Figure 1. Nutrient film technique[7]

The NFT system is particularly suitable for growing light-demanding plants like lettuce, spinach, and strawberries, which benefit from the consistent nutrient supply and efficient water usage that the system offers.[8]

For plants to grow and develop, they require energy, which they primarily obtain through photosynthesis. Light plays a crucial role in this process, as it stimulates the plant's growth and supports its physiological functions. Light quality: specifically, the spectrum of light, greatly influences plant growth, with blue light being particularly important for vegetative growth and red light for flowering and fruiting.[9] Natural sunlight provides an ideal balance of these light wavelengths, promoting healthy plant development. However, in controlled environments such as greenhouses or indoor farms, artificial lighting is often employed to supplement or replace natural light, enabling year-round cultivation of crops. The most commonly used artificial light sources in hydroponic farming include light-emitting diodes (LEDs) and fluorescent bulbs, both of which are energy-efficient and can be tailored to provide the specific light spectrum (400-700 nm) that plants require.[10]

Studies on the impact of light intensity on tomato plant growth have shown that increased light intensity can enhance plant density, leaf thickness, and stem strength. On the other hand, insufficient light can delay critical stages of growth, such as blooming and fruiting, which can reduce yield and overall plant health.[11]

Lettuce (*Lactuca sativa*) is a popular crop in hydroponic farming due to its relatively low resource requirements and fast growth rate. It is a rich source of essential nutrients, including vitamins A and K, and is widely cultivated in a range of varieties such as romaine, butterhead, and oak leaf.[14] For this study, two lettuce varieties: red oak and leaf green lettuce (Lollo Bionda), were selected due to their popularity in hydroponic systems and their distinctive characteristics. Red oak lettuce, with its burgundy-colored leaves and mild, nutty flavor, is known for its tender texture and resistance to bitterness (Figure 2).[15] Similarly, Lollo Bionda lettuce, also known for its delicate texture and mild taste, has become a staple in hydroponic farming due to its adaptability and high nutritional value (Figure 3).[16]

Figure 2. Oak red lettuce[12]

Figure 3. Leaf green lettuce[13]

Based on the literature review, this research focused on evaluating the effects of three different light sources: Philips™ light, AiGrow™ light, and natural sunlight on the growth, nutrient composition, antioxidant activity, and bioactive compounds of oak red and Lollo Bionda lettuce varieties. By investigating the effects of different lighting conditions on the overall health and productivity of lettuce in an NFT hydroponic system, this study aims to contribute valuable insights to optimize hydroponic practices and improve crop yield and quality.

2. Methodology

2.1 Sample Collection. The seeds of the two lettuce varieties (oak red, Lollo Bionda) were obtained from CodeGen International Sri Lanka (Figure 4).

Figure 4. (A) Oak red and (B) Lollo Bionda seeds

2.2 Seed germination of lettuce. The 28 mm soil pellets were soaked in water for 10 minutes. Seeds of oak red and Lollo Bionda were then placed in soil pellets and watered daily. The seeds were left to germinate for 3 weeks before they were transferred to the NFT system (Figure 5).

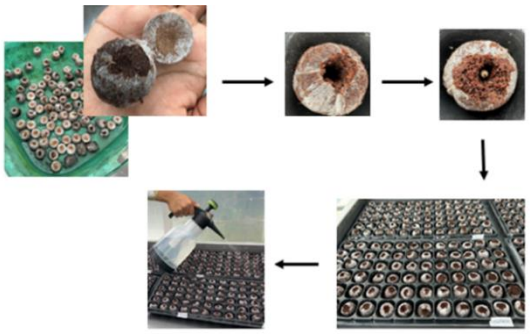

Figure 5. Steps of germination

2.3 Transferring seedlings to the NFT system and growth optimization. The pH and electrical conductivity (EC) values of the nutrient solution (fertilizer mixer) in the tank of the NFT system were balanced by adding AiGrow™ fertilizer A and B solutions at a ratio of 1:1 and KOH. Three levels of the NFT system were set up, each equipped with a different light source. Two levels of LED lighting were partially covered with a black net to avoid the effect of sunlight. The lettuce plants were then placed in the channels of the NFT system. The lettuce plants were allowed to grow for 4 weeks in the NFT system under three light sources (Figure 6).

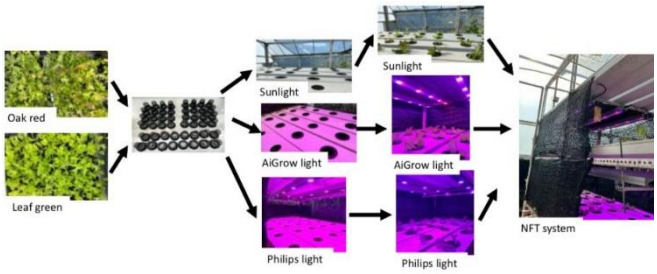

Figure 6. Transferring lettuce into the NFT system

2.4 Homogenization and Preparation of aqueous plant extracts. Once the lettuce plants were harvested after 4 weeks from the NFT system, the fresh weight of the lettuce was measured. They were then shredded and placed in the hot air oven for 48 hours at 40°C. Finally, they were crushed into a fine powder using a mortar and pestle and the dry weight was measured.

The dried lettuce powder samples were mixed with distilled water at a ratio of 1:20 in a beaker. Then the beakers were covered with an aluminium foil and placed in the hot air oven at 90°C for 15 minutes. The extracts were cooled to room temperature (RT) and filtered using Whatman No. 1 filter papers. Finally, the volumes of aqueous extracts were measured.

2.5 Total Carbohydrate Content (TCC) Analysis – Phenol Sulphuric Acid Method. For the preparation of the stock solution, 2.5 N HCl was prepared by mixing 5 ml of concentrated

HCl with 18.2 ml of distilled water. Then the measured 0.1 g of dextrose powder was mixed with 2.5 N HCl and boiled for 3 hours in a water bath. The solution was allowed to cool down at RT and neutralized with Na_2CO_3. Duplicates of a standard series were prepared by proportional dilution within the 50-250 µg/ml range (50, 100, 150, 200, 250 µg/ml) using dextrose. Then lettuce extracts were diluted 20 times and duplicates of each lettuce sample were prepared. 1 ml of 5% phenol was added to 1 ml of the standard series, blank (distilled water), and samples and they were incubated at RT for 10 minutes. After that 5 ml of 96% sulfuric acid was added to all the tubes and they were again incubated at RT for 20 minutes. Finally, the absorbance was measured at 490 nm using a UV-visible spectrophotometer.[17]

2.6 Total Protein Content (TPC) Analysis – Lowry Assay. Lowry A (2% Na_2CO_3 and 0.1 N NaOH), Lowry B (0.5% $CuSO_4$ and 1% sodium potassium tartrate), and Lowry C (Folin-ciocalteu reagent and distilled water in 1:1 ratio) solutions were prepared. A 1000 µg/ml stock solution of Bovine Serum Albumin (BSA) was prepared by dissolving 100 mg of BSA in 100 ml of distilled water. Then, duplicates of the BSA standard series were prepared using varying concentrations of 200, 400, 600, 800, and 1000 µg/ml. Extracts were diluted 20 times and duplicates of each sample were prepared. Then, the Lowry A and Lowry B mix was prepared at a 50:1 ratio. A volume of 5 ml from the mix was added to 1 ml of each standard series, blank (distilled water), and extract and they were incubated for 10 minutes at RT. A volume of 0.5 ml from Lowry C was then added to each tube and incubated for 30 minutes at RT. The absorbance was measured using a UV-visible spectrophotometer at 660 nm.[18]

2.7 Qualitative Analysis of Phytochemicals. The protocols used for qualitative phytochemical analyses are shown in Table 1.

Table 1. Qualitative phytochemical analyses test methods.[19]

Test	Methodology
Anthraquinones	2 ml of 10% ammonia solution was added and mixed with 0.5 ml of each extract.
Flavonoids	2 ml of 2% NaOH solution was added to 1 ml of each sample and 2 drops of diluted HCl was added.
Polyphenols	3 drops of diluted iodine solution were added to 1 ml of each sample.
Saponins	5 ml of distilled water was added to 1 ml of lettuce sample and vortexed for 10-15 minutes until froth was formed.
Steroids	0.5 ml of each sample was mixed with 0.5 ml of chloroform and 1 ml of concentrated H_2SO_4.
Tannins	2 ml of 5% $FeCl_3$ was added to 1 ml of each lettuce sample.
Terpenoids	2 ml of chloroform was added to each sample and 2 ml of concentrated H_2SO_4.

2.8 Total Phenolic Content (TPhC) Analysis – Folin-Ciocalteu Assay. A 1000 µg/ml gallic acid standard stock solution was made by mixing 1 mg of gallic acid powder with 10 ml of distilled water. Then a standard gallic acid series of different concentrations (20, 40, 60, 80, and 100 µg/ml) were prepared. 30 µl each of plant extract, blank (distilled water), standard solutions, 270 µl of distilled water, and 1.2 ml of 10% Folin-Ciocalteu reagent were mixed and placed in the dark for 5 minutes. Next, 1.5 ml of 7.5% Na_2CO_3 was added, and the mixture was incubated at RT for 90 minutes in the dark. Then using a UV-visible spectrophotometer, the absorbance was measured at 765 nm.[20]

2.9 Total Flavonoid Content (TFC) Analysis – $AlCl_3$ colorimetric method. A 100 µg/mL Quercetin stock solution was prepared by dissolving 1 mg of Quercetin powder in 10 mL of distilled water. Using this stock solution, duplicates of the Quercetin standard series were prepared at concentrations of 20, 40, 60, 80, and 100 µg/ml. 50 µl of each extract, blank (distilled water), standard solutions were transferred into separate test tubes. To each tube, 950 µl of distilled water was added to dilute the samples. Next, 0.2 ml of 10% $AlCl_3$ solution was added to each tube to initiate the reaction. After that, 0.2 ml of 1M potassium acetate solution was added to stabilize the complex formation. The reaction mixtures were incubated at room temperature (RT) for 30 minutes with intermittent shaking to ensure proper mixing and reaction completion. After incubation, the absorbance of each reaction mixture was measured at 415 nm using a UV-visible spectrophotometer.[21]

2.10 Antioxidant Activity (AA) Analysis – DPPH Radical Scavenging Assay. A DPPH stock solution was prepared by dissolving 40 mg of DPPH in 100 ml of methanol. The test tubes were filled with 25 µl of each leaf extract, 475 µl of distilled water, and 1 ml of DPPH working solutions. The reaction mixtures were incubated in the dark for 30 minutes. Then the absorbance was measured at 517 nm using a UV-visible spectrophotometer. The DPPH inhibition percentage was calculated using the following equation.[22]

$$Percentage\ inhibition\ of\ DPPH = \frac{Ac - As}{Ac} \times 100$$

(Ac – Absorbance of the control, As – Absorbance of the sample)

2.11 Statistical Analysis. All values are expressed as mean ± Standard Error. Microsoft Excel 2023 was used to calculate, the standard error of the mean value. IBM SPSS Statistics Version 29 was used to conduct the LSD test for multiple comparison analysis and One-Way ANOVA. A significant difference was defined as having a *p*-value less than 0.05.

3. Results

3.1 Harvested lettuce plants from the NFT system. The growth progression of the lettuce plants after 4 weeks that were harvested from the NFT system is shown in Table 2.

Table 2. Images of harvested lettuce plants after being kept in each condition for 4 weeks.

	Oak Red	Lollo Bionda
Sunlight		
AiGrow™ Light		
Philips™ Light		

3.2 Morphological parameters of the lettuce

3.2.1 Average Plant Height

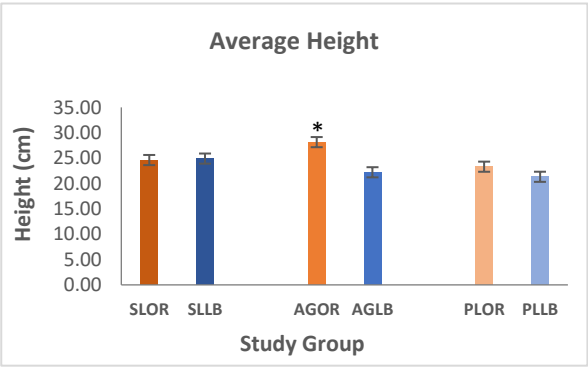

Figure 7. Average height of the harvested lettuce plants. (* represents $p<0.05$ compared to the SLOR group, SL = Sunlight, AG =

AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

The average height of the AGOR group was significantly higher compared to the SLOR group. PLOR displayed the lowest average height among the oak red plants (Figure 7).

The highest average height in Lollo Bionda was reported in SLLB and the lowest was reported in PLLB (Figure 7). However, there were no significant differences between the groups.

3.2.2 Average Leaf Number

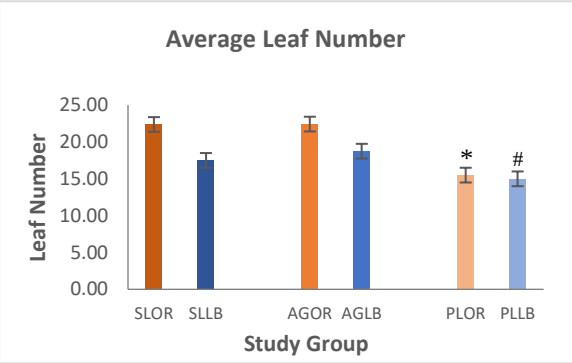

Figure 8. Average leaf number of the harvested lettuce plants. (* represents $p<0.05$ compared to the SLOR group and # represents $p<0.05$ compared to the SLLB group, SL = Sunlight, AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

The average leaf number of the SLOR and AGOR groups was comparably similar. PLOR displayed the lowest average leaf number, which was significantly low compared to the SLOR group (Figure 8).

The highest average leaf number in Lollo Bionda was reported in AGLB and the lowest was reported in PLLB which was significantly low compared to the SLLB group (Figure 8).

3.3 Total Carbohydrate Content (TCC) Analysis

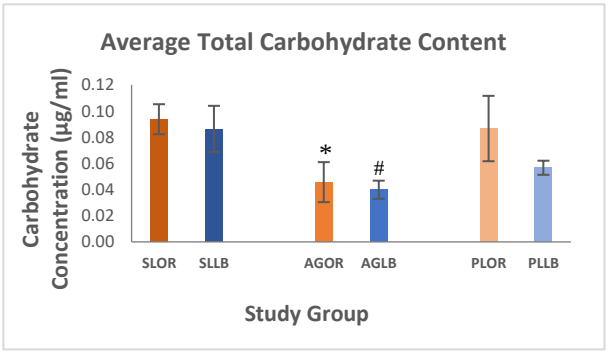

Figure 9. Average TCC analysis of the harvested lettuce plants. (* represents $p<0.05$ compared to the SLOR group, and # represents $p<0.05$ compared to the SLLB group, SL = Sunlight, AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

SLOR group displayed the highest average TCC in oak red and the AGOR displayed the lowest average TCC in oak red (Figure 9).

The highest average TCC in Lollo Bionda was reported in SLLB and the lowest was reported in AGLB (Figure 9).

3.4 Total Protein Content (TPC) Analysis

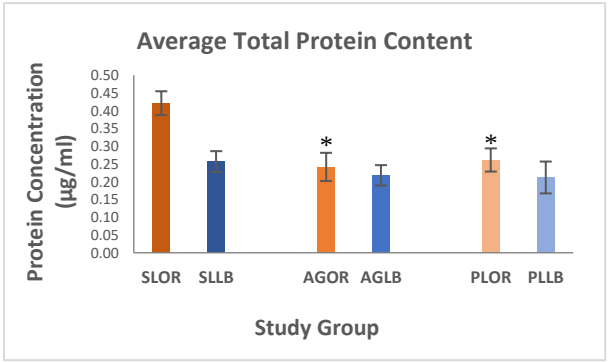

Figure 10. Average TPC Analysis of the harvested lettuce plants. (* represents $p<0.05$ compared to the SLOR group, SL = Sunlight,

AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

The average TPC of the SLOR group was significantly higher compared to the AGOR and PLOR groups. AGOR displayed the lowest average TPC in oak red (Figure 10).

The highest average TPC in Lollo Bionda was reported in SLLB and there were no significant differences between the groups (Figure 10).

3.5 Qualitative Analysis of Phytochemicals

Table 3. Results of Phytochemical Analysis (√-Present; x-Absent)

Phytochemical	PLOR	PLLB	AGOR	AGLB	SLOR	SLLB
Saponins	√	√	√	√	√	√
Polyphenols	√	√	√	√	√	√
Tannins	x	x	x	x	x	x
Terpenoids	√	√	√	√	√	√
Anthraquinones	x	x	x	x	x	x
Steroids	√	√	√	√	√	√

(SL = Sunlight, AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

Results showed that Polyphenols, Terpenoids, Saponins, and Steroids were present in all the lettuce samples (Table 3). However, Tannins and Anthraquinones were absent in all groups.

3.6 Total Phenolic Content (TPhC) Analysis

The average TPhC of the SLOR group was significantly higher compared to the AGOR group which displayed the lowest average TPhC in oak red (Figure 11).

TPhC in Lollo Bionda was significantly high in SLLB compared to the other two groups. The lowest TPhC was reported in AGLB (Figure 11).

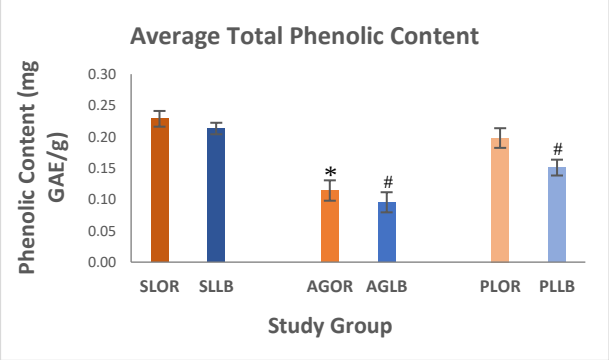

Figure 11. Average TPhC Analysis of the harvested lettuce plants. (* represents $p<0.05$ compared to the SLOR group, and # represents $p<0.05$ compared to the SLLB group, SL = Sunlight, AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

3.7 Total Flavonoid Content (TFC) Analysis

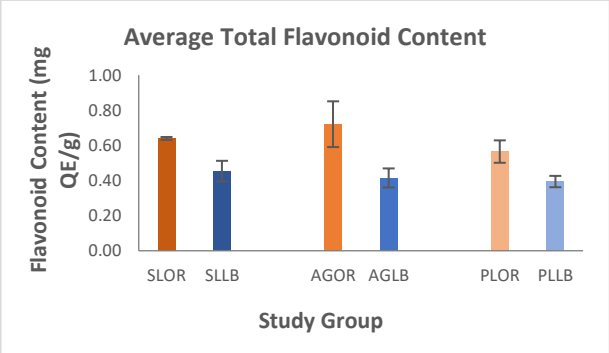

Figure 12. Average Total Flavonoids Content Analysis of the harvested lettuce plants. (SL = Sunlight, AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

The average TFC of the AGOR group was higher compared to the SLOR and PLOR groups. PLOR displayed the lowest average TFC in oak red (Figure 12). However, there were no significant differences between the groups.

The highest average TFC in Lollo Bionda was reported in SLLB and the lowest was reported in PLLB (Figure 12).

3.8 Antioxidant Activity (AA) Analysis – DPPH Radical Scavenging Assay

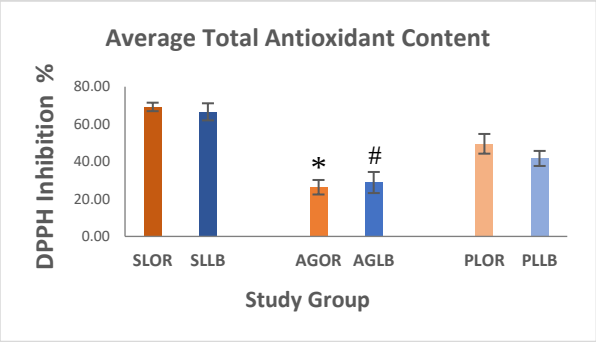

Figure 13. Average Antioxidant Content Analysis of the harvested lettuce plants. (* represents $p<0.05$ compared to the SLOR group, and # represents $p<0.05$ compared to the SLLB group, SL = Sunlight, AG = AiGrow™ Light, PL = Philips™ Light, OR = Oak Red, LB = Lollo Bionda).

The average AA of the SLOR group was significantly higher compared to the AGOR group which displayed the lowest average AA in oak red (Figure 13).

The highest average AA in Lollo Bionda was reported in SLLB and the lowest was reported in AGLB (Figure 13) which was significantly lower compared to the SLLB group.

4. Discussion

This study evaluated the effects of three distinct light sources (sunlight, AiGrow™ light, and Philips™ light) on the growth, biochemical composition, and antioxidant capacity of hydroponically grown Oak Red and Lollo Bionda lettuce using a Nutrient Film Technique (NFT) system. The primary objective was to identify the light conditions that optimize growth and nutritional benefits for these lettuce varieties, contributing to advancements in indoor agriculture.

The germination phase used soil pellets as a medium to provide consistent nutrient delivery and physical support, ensuring uniform seedling development and minimizing variability. These conditions were essential to establish healthy seedlings for hydroponic growth. The pH and EC of the nutrient solution were carefully balanced in the NFT system to optimize nutrient uptake and minimize plant stress, critical factors for achieving reliable growth outcomes. The experimental setup was designed to create distinct light environments while minimizing light interference between treatments, ensuring valid comparisons of the effects of each light source on plant performance.

Growth assessments revealed that sunlight favored the growth height of Lollo Bionda lettuce, while AiGrow™ light was the most effective for Oak Red. When considering the leaf count, both lettuce types performed best under AiGrow™ light. These findings suggest that while natural light supports some growth aspects, artificial light can be optimized to promote other growth parameters, making AiGrow™ light an ideal substitute under controlled indoor conditions, such as a temperature range of 28–30°C, relative humidity of 55–65%, and a photoperiod of 16 hours of light and 8 hours of darkness. As indoor farming expands, understanding the specific needs of each plant variety in response to artificial light becomes crucial.

Upon harvesting, the fresh weight of each plant was recorded, and leaves were processed for biochemical analyses. The study evaluated carbohydrate, protein, phenolic, flavonoid, and antioxidant content, using aqueous extracts from dried lettuce samples. In line with existing literature, lettuce exhibits minimal carbohydrate levels, a trait favorable for low-carbohydrate diets.[27] Carbohydrate content was assessed using the Phenol-Sulfuric Acid method, which utilizes sulfuric acid to dehydrate polysaccharides, forming detectable compounds when reacted with phenol.[28] The sunlight-exposed Oak Red group (SLOR) showed the highest carbohydrate levels at 0.094 g/100 g dried weight, surpassing other groups. Previous studies indicate that wavelengths within the red (620–750 nm) and blue (450–495 nm) spectrum promote carbohydrate accumulation in plants.[29] Given that sunlight provides a full spectrum (400–700 nm), these

results align with previous findings, reaffirming the role of sunlight in carbohydrate synthesis.

Protein levels were assessed using the Lowry assay method, which relies on the formation of monovalent copper ions that react with the Folin reagent to produce a blue complex, indicating protein presence.[30] The sunlight-exposed Oak Red group (SLOR) showed the highest protein levels, with a mean value of 0.421 g/100 g dried weight. Higher protein concentrations are linked to light sources with significant blue light ratios (450–495 nm), which boost soluble protein levels.[29] Sunlight encompasses this range, supporting our findings that natural light fosters protein synthesis effectively.

Qualitative phytochemical analyses revealed the presence of polyphenols, terpenoids, saponins, and steroids across all groups, while tannins and anthraquinones were absent. According to a previously conducted study, the phytochemical analysis of Red Leaf lettuce (RL) and Green Leaf lettuce (GL) revealed the presence of phenols, alkaloids, saponins, flavonoids, tannins, and terpenoids. The study further highlighted that RL contained higher amounts of phenols, alkaloids, and saponins compared to GL, while both varieties exhibited similar levels of flavonoids, tannins, and terpenoids.[31] These findings align with the qualitative phytochemical analyses in this study, emphasizing the variations in phytochemical composition across lettuce varieties. Phytochemicals play diverse roles in plants, including defense against environmental stressors, protection against pests and pathogens, regulation of growth and development, and adaptation to abiotic stress conditions such as drought and UV radiation.[32]

Polyphenols, in particular, play a crucial role in plant resilience and physiological functions, deriving from phenylpropanoid and pentose phosphate pathways.[33] The phenolic content, determined using the Folin-Ciocalteu method, was also highest in the SLOR group, with a mean value of 0.228 mg GAE/g dried weight. According to previous studies, the broad spectrum of sunlight (400–700 nm) facilitates phenolic synthesis, aligning with existing studies on the role of red and blue light in phenolic accumulation.[34]

In evaluating flavonoids, a secondary metabolite critical to plant color, aroma, and stress defense,[35] $AlCl_3$ colorimetric method was used, which binds to hydroxyl groups on flavonoids to form stable complexes detectable at specific wavelengths.[36] The highest flavonoid concentration was observed in the AiGrow™ light-exposed Oak Red group (AGOR), with a mean value of 0.721 mg QE/g dried weight. Interestingly, these results diverged from previous findings where blue LED light (450–495 nm) maximized flavonoid content.[37] This could be due to the unique spectral composition of the AiGrow™ light, which emphasizes UV-A wavelengths (315–400 nm).

To assess antioxidant activity, the DPPH radical scavenging assay was employed, measuring the ability of lettuce to neutralize free radicals.[38] Antioxidants donate electrons or hydrogen atoms to stabilize free radicals, reducing potential cellular damage.[39] The SLOR group demonstrated the highest antioxidant capacity with a 69.18% inhibition. This finding is consistent with a previous study showing that full-spectrum sunlight maximizes antioxidant activity in green leafy vegetables by activating compounds responsive to UV and visible light.[32]

5. Conclusion

This study demonstrates that sunlight is the most effective light source for maximizing growth, biochemical content, and antioxidant potential in hydroponically grown Oak Red and Lollo Bionda lettuce using an NFT system. AiGrow™ light served as a viable alternative, supporting substantial growth and bioactive compound synthesis, though slightly less effective than sunlight in promoting bioactive compounds. In contrast, Philips™ light, with its limited spectrum, was the least effective across all parameters, underscoring the critical role of spectrum and intensity in optimizing plant health. While this study provides valuable insights, it was limited by the controlled

experimental setup, which may not fully reflect real-world farming conditions. Additionally, the study only explored two lettuce varieties and a limited range of artificial light sources. Future research could explore the integration of multiple light sources, varying light intensities, and other crop species to further optimize hydroponic farming systems. These findings pave the way for advancements in light-source optimization and system design, ultimately contributing to improved crop outcomes and nutritional quality in hydroponic agriculture.

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