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Optimizing lettuce (*Lactuca sativa* L.) growth and yield through enhanced light quality in vertical drip fertigation systems

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ABSTRACT

Optimizing light conditions has become crucial for enhancing crop yield, especially in controlled environments like vertical farming. Lettuce (*Lactuca sativa* L.), highly responsive to light variations, presents an ideal model for studying the influence of light quality on growth. Main objective was to evaluate the effects of light quality on the vegetative growth and yield of two lettuce varieties, 'Green Coral' and 'Red Coral,' in a home-based vertical drip fertigation system. Completely Randomized Design (CRD) was applied with five replicates and three treatments of T1: Control (no artificial light), T2: two horizontally arranged full spectrum LED light strips, and T3: three horizontally arranged full spectrum LED light strips. Number of leaves (NL), plant height (PH), and fresh weight (FW) were recorded across two growing seasons. Statistical analysis was conducted in one-way ANOVA and Tukey's test revealed that T2 significantly increased NL and PH in both varieties compared to T1 ($P<0.05$). The variety 'Green Coral' showed a significant increase in PH (6.7±0.72 cm) under T2. Wet weight was also significantly higher in T2 for both varieties, with 'Green Coral' yielding 6.2±0.54 g and 'Red Coral' 6.6±0.38 g. These results reported the positive impact of light quality on vegetative growth, suggesting the potential for improved yield in vertical farming.

Keyword: *Lactuca sativa,* light quality, vertical drip fertigation system

1. Introduction

The growing interest in controlled environment agriculture (CEA) production has been driven by challenges, such as climate change, land degradation, and population growth [1]. One promising approach within of CEA is vertical farming; it is the production of crops in vertically stacked layers under controlled environmental conditions [2]. The year-round production, less space requirement during production and possibly higher output with minimum resources could be conserved as the benefits of vertical systems. CEA relies on precise environmental control to optimize plant growth, and lighting plays a crucial role in this system. Among various lighting technologies, LEDs have revolutionized CEA due to their energy efficiency, long lifespan, and ability to deliver specific wavelengths of light for optimal plant development [3]. However, the successful implementation and adaptation of artificial growing systems largely depends on the precise regulation of environmental conditions. Among these factors, light is the most critical, as it plays a fundamental role in regulating the overall growth and development of plants [4]. Light plays an important role in different physiological processes which regulate plant morphogenesis, growth and development, biomass production and nutrients [5]. Under natural conditions, light is available across the full spectrum and influences plant physiology according to the time of day. In contrast, indoor farming relies on artificial light sources such as Light Emitting Diodes (LEDs) to deliver specific lighting profiles [6]. This allows for precise control over the spectral composition of light, including the ratios of red, blue, and far-red wavelengths, enabling the modulation of plant growth responses in a controlled environment [7]. Red light (approximately 660 nm) is known to promote stem elongation, flowering, and fruit production, while blue light (around 450 nm) influences chlorophyll synthesis, stomatal opening, and compact, healthy leaf development. Far-red light (approximately 730 nm), in interaction with red light, affects shade avoidance responses and flowering timing through phytochrome-mediated signaling. By adjusting the balance of these wavelengths, growers can optimize plant morphology, photosynthesis, and developmental timing to suit specific crop requirements [8].

Lactuca sativa L. is one of the most studied crops in vertical farming, as lettuce has a relatively short growing cycle, economic value, and is responsive to environmental factors such as light and nutrient availability [9]. Green Coral' Lettuce 'Lollo Bionda' (*Lactuca sativa var. crispa*) and 'Red Coral' Lettuce 'Lollo Rossa' (*Lactuca sativa var. crispa*) considered as commercial varieties of loose-leaf type. Usually, these leafy types contain more micronutrients than headed type lettuce varieties and the total production accounts for about 12t/ha at with around 20 plants/kg [10]. Due to different varieties of lettuce showing different morphological characteristics and growth response to environmental stimuli, it is an ideal species for exploring the effects of light quality on plant performance [11]. The fact that lettuce growth is highly sensitive to light spectra is evidenced by blue light promoting chlorophyll concentration in leaves and red-light stimulating stem elongation and leaf expansion [12]. It was recently reported that the combination of blue and red light synergistically increases overall plant growth and fresh weight in lettuce [13]. Despite the proven benefits of LED lighting in supporting lettuce growth, issues in optimal light intensity, quality, recent studies have confirmed that there is considerable ability to enhance leaf number, plant height, and biomass accumulation, via increasing the number of LED light strips or altering light spectra [14, 15]. Nevertheless, light intensity and spectral composition may have distinct effects on lettuce leaves, particularly among differently pigmented, structurally different, and photosynthetically efficient varieties [16].

When lettuce was cultivated under 100% blue light and a combination of 70% red + 30% blue LED lighting, the fresh mass per plant significantly exceeded that observed under other lighting regimes, including traditional greenhouse conditions. These LED treatments notably influenced the phytochemical profile and nutritional quality of the lettuce. Plants grown under the 70% red and 30% blue LED combination exhibited elevated levels of carotenoids and chlorophyll compared to greenhouse-grown counterparts [16]. Furthermore, lettuce exposed to 100% blue LED light demonstrated a 2.25-fold increase in vitamin C content. Enhanced photosynthetic activity and the highest quantum yield of Photosystem II (PSII) photochemistry were also observed under LED treatments. The improved accumulation of macro- and micronutrients in LED-grown lettuce is likely attributed to both the specific spectral properties of LED light and the reduced stress conditions within growth chambers relative to greenhouses [17].

In natural conditions, light is obtained in its complete spectrum and acts on field crops like rice according to the photoperiod, which changes throughout the seasons, affecting plant growth and development. [18, 19, 20]. Light conditions optimization in vertical farming is not only beneficial for plant growth, but also for energy efficiency and cost effectiveness [21]. Though energy efficient, the cost of LED lighting still constitutes a high operational cost for indoor farming systems. As such, the optimal number and type of LED light strips for maximizing vertical farm crop yield without going beyond the economic for required energy consumption are critical for vertical farm economic viability [22]. Previous studies have demonstrated the potential for two or more LED light strips to promote growth, but there remains a lack of clarity regarding whether additional light strips improve growth to diminishing returns [23]. Given this background, the primary objective of this study is to investigate the effects of light quality, specifically considering the number of LED light strips, on the vegetative growth of two distinct lettuce varieties.

2. Methods

2.1. Plant materials and the experimental procedure

The high-yielding two Lettuce varieties; 'Green Coral' Lettuce 'Lollo Bionda' (*Lactuca sativa var. crispa*) and 'Red Coral' Lettuce 'Lollo Rossa' (*Lactuca sativa var. crispa*) were used for the experiment. The experimental design followed a completely randomized design (CRD) with three treatments of T1: Control (no artificial light), T2: two horizontally arranged full spectrum LED light strips, and T3: three horizontally arranged full spectrum LED light strips. Each treatment was replicated five times. Seeds of two selected lettuce varieties were sown in sponge cubes, and seedlings were transplanted into the vertical drip fertigation hydroponic system 1.5 weeks after germination. The LED light strips were installed above the plants at 40cm height, and light treatments were applied continuously for 24 hours post-transplanting. The experiment was conducted in a home-based vertical hydroponic system located in Athurugiriya, Sri Lanka, from June to August 2024.

2.2. Crop management practices
There are various nutrition solutions on the market that comprise macro and micronutrients to help plants grow and develop. These solutions can be used during the vegetative and reproductive stages. Albert's nourishment is commonly utilized in greenhouse environments, soilless cultivation, and is readily available on the market. The Albert solution includes 10.6% N, 9.3% P, 16.3% K, 11% Ca, 2.25% Mg, 35 mg/kg B, 35 mg/kg Cu, 660 mg/kg Fe, 130 mg/kg Mn, 140 mg/kg Zn, and 20 mg/kg [24]. Albert's solution was utilized at a concentration of 3.8 g per liter. The site is positioned within the wet zone at an elevation of 30 meters above mean sea level, with an average annual temperature ranging between 27°C and 32°C.

2.3. Data collection
The average relative humidity recorded during the study was approximately 84%. Data on leaf number (LN) and plant height (PH) were collected weekly for four weeks after transplanting (WAT). Leaf counts included all newly emerged leaves, while plant height was measured from the base of the plant to the tip of the tallest leaf using a ruler. Fresh weight of the harvest (FW) measured 4 WAT.

2.4. Data analysis
Statistical analysis was performed using analysis of variance (ANOVA) to evaluate the effects of light treatments on leaf number plant height and Fresh weight. The statistical software Minitab 19 was used, and mean separation was conducted using Tukey's test at the significant level of $p \leq 0.05$.

3. Results and Discussion

3.1. Effect of light quality on vegetative growth responses

Number of leaves: The effect of light quality on the vegetative growth of lettuce varieties 'Green Coral' and 'Red Coral' was evaluated through three different treatments, focusing on the number of leaves as a key growth parameter. In the 'Green Coral' variety (Locarno RZ), preliminary observations during the first week after transplantation showed consistent leaf numbers across all treatments. T1, T2, and T3 each produce between 2.2±0.44 and 2.4±0.54 leaves per plant (P = 0.783), suggesting that light quality exerted negligible effect during the initial growth phase. By the second week, a slight increase in LN was noted across all treatments, although the differences were statistically insignificant (P>0.05). By the third week, treatment effects became more significant (P<0.05). The T2, with two LED strips, produced significantly higher LN (4.8±0.44) compared to the control (3.8±0.47), T3, with three LED strips, produced 4.4±0.54 of LN, which significantly differs from T1 or T2. In the fourth week, the NL continued to increase across all treatments, with significant differences detected (P<0.05) (Table 1).

Table 1. The effect of light quality on the number of leaves of lettuce varieties 'Green Coral' and 'Red Coral' at 4 WAT

Treatment	Number of leaves of lettuce							
	'Green coral' variety (Locarno RZ)				'Red coral' (Concorde RZ)			
	1st WAT	2nd WAT	3rd WAT	4th WAT	1st WAT	2nd WAT	3rd WAT	4th WAT
T1	2.2±0.44^{a}	3.4±0.54^{a}	3.8±0.47^{b}	4.6±0.54^{b}	2.0±0.47^{a}	2.6±0.56^{a}	4.2±0.83^{b}	5.0±0.70^{ab}
T2	2.4±0.54^{a}	3.8±0.44^{a}	4.8±0.44^{a}	5.4±0.54^{a}	2.4±0.27^{a}	3.6±0.08^{a}	5.6±0.54^{a}	6.0±1.00^{a}
T3	2.4±0.54^{a}	3.8±0.44^{a}	4.4±0.54^{ab}	4.8±0.83^{ab}	2.4±0.39^{a}	3.2±0.40^{a}	4.8±0.44^{ab}	4.4±0.54^{b}
P value	0.783	0.351	0.021	0.022	0.29	0.089	0.014	0.021

For the 'Red Coral' variety (Concorde RZ), similar results were observed, though the effects of light treatments were more significant at earlier stages. In the first week after transplanting, no significant differences were detected among treatments (P = 0.29), with all treatments producing approximately two leaves per plant. By the second week, plants grown under T2 had an increase in LN (3.6±0.08) compared to T1 (2.6±0.56), although the difference was not statistically significant (P = 0.089). By the third week, T2 markedly surpassed both T1 and T3, yielding 5.6±0.54 leaves, in contrast to 4.2±0.83 and 4.8±0.44 leaves in T1 and T3, respectively. In the fourth week, plants in T2 exhibited higher LN (6.0±1.00) whereas T1 produced 5.0±0.70 leaves and T3 yielded 4.4±0.54 leaves, respectively.

The results indicate that light quality, specifically the use of two LED strips (T2), positively influences the vegetative growth of both lettuce varieties during critical growth phases, particularly in weeks two and three after transplanting. In contrast, the control treatment (T1) and the use of three LED strips (T3) did not consistently enhance leaf development to the same extent. This outcome suggests that an optimal number of light sources, rather than an increased number, may be more effective in promoting growth. Previous studies have shown similar effects of light quality on lettuce growth, where balanced LED light quality enhances photosynthetic efficiency, promoting leaf expansion and biomass accumulation [25] Moreover, varying the intensity and spectral composition of LED lights can trigger different physiological responses, such as altering chlorophyll concentration and influencing the hormonal regulation of growth [26]. It is probable that the increased leaf number in T2 results from a more favorable light intensity and spectral composition, stimulating photosynthesis without imposing light stress, which may have occurred in T3.

These findings align with current research on the use of artificial lighting in controlled environments that optimal LED lighting significantly improved the yield and quality of leafy vegetables, particularly lettuce, under vertical hydroponic farming systems. Thus, LED light supplementation, as reported in this study, can be a practical tool for enhancing the growth of lettuce varieties in controlled environments.

3.2. Interaction between light quality and variety on leaf development

The interaction between light quality and variety in plant growth is crucial in optimizing management practices, particularly in controlled environments like greenhouses or growth chambers. In the current study, the interaction effect between light quality, specifically the use of LED light strips, and variety on the NL was investigated after four weeks of transplanting.

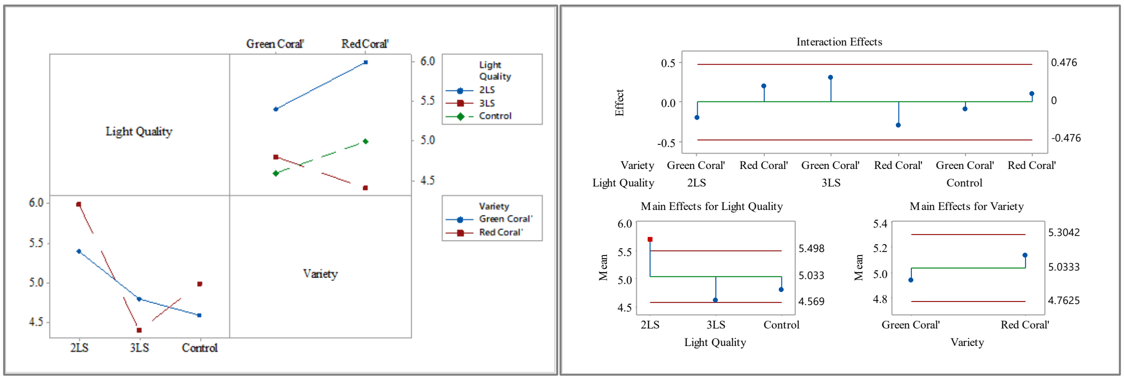

Figure 1. Effect of main effect (a) and interaction between light quality and variety (b) on the number of leaves
Note: 2LS- (T2), 3LS- (T3)

Figure 1a shows the main effects of light quality (2 LED strips, 3 LED strips, and control) and lettuce variety ('Green Coral' and 'Red Coral') on leaf development. The two experimental light configurations T2 and T3 evaluated in this study elicited statistically significant morphological responses in foliar development (P<0.05). The average of the NL under T2 is 5.498, which is above the decision line, suggesting that T2 significantly increases the NL. The mean NL under T3 (4.866) and the control treatment (5.033) are below the decision limit, indicating that they do not significantly influence the LN compared to the overall mean. Thus, T2 appears to be the most effective light treatment for promoting leaf growth. The variety 'Red Coral' had a slightly higher mean NL (5.3042) compared to 'Green Coral' (5.0333). Both means fall within the decision limits, indicating no significant difference in NL between the two varieties at the α=0.05 significance level. The analysis reveals that while light quality significantly affects NL, particularly with 2 horizontal LED light strips showing a positive impact, there is no significant difference between the two lettuce varieties or their interactions with light treatments. This suggests that 'Green Coral' and 'Red Coral' respond similarly to light quality, and the optimal growth response is achieved under the 2 LED light strip treatment.

The points fall within the decision limits, indicating that no significant interaction effects are present between the light quality and variety factors at the α=0.05 level. (Figure 2b). The effect of light quality on LN is consistent across both lettuce varieties, without significant changes when combining the effect of light treatments with different varieties. This supports findings by [27], who reported that the use of specific LED light spectra can significantly increase leaf area and biomass in lettuce. Interestingly, the addition of a third LED strip reduced leaf production, suggesting a possible negative effect of light oversaturation, consistent with research by [27] who found that excessive light intensity can inhibit photosynthesis by causing photoinhibition or stress in plants. However, the lack of significant interaction between light quality and variety implies that both varieties respond similarly to light treatments, though 'Green Coral' seemed to benefit more from the optimal (2 LED strips) light environment. This suggests that while light quality is a key driver of leaf production, the genetic potential of plant varieties might set a ceiling for improvement [28].

Plant height: The effect of light quality on the plant height of lettuce varieties 'Green Coral' and 'Red Coral' was evaluated through three different treatments. In the 'Green Coral' variety (Locarno RZ), in the first week, significant differences in PH were observed among treatments (P<0.05). T2 led to the highest PH (3.4±0.53 cm), which was significantly greater than T3 (2.2±0.56 cm). T1 did not significantly differ from either T2 or T3. The results indicate that in the initial week after transplantation, plants subjected to T2 showed more growth, whereas those under T3 exhibited slower development.

By the second week, T2 still maintained the highest PH (4.2±0.53 cm), although the differences between treatments were not statistically significant (P>0.05). T1 (3.9±0.32 cm) and T3 (3.4±0.59 cm) produced slightly lower heights compared to T2. This indicates that although the trend of increased PH in T2 continues, the differences between treatments have not become clearly defined by the second week. In the third week, plants under T2 continued to exhibit a higher PH (5.2±0.41 cm); but no significant differences were observed between treatments (P>0.05). Significant differences reappeared in the fourth week (P=0.006). T2 produced the tallest plants (6.7±0.72 cm), significantly exceeding T1 (4.5±0.30 cm) and T3 (5.7±1.26 cm).

Table 2. The effect of light quality on the vegetative growth – plant height of lettuce varieties "Green Coral" and "Red Coral" at 4 WAT

Treatment	Plant Height (cm)							
	'Green coral' variety (Locarno RZ)				'Red Coral' variety (Concorde RZ			
	1st WAT	2nd WAT	3rd WAT	4th WAT	1st WAT	2nd WAT	3rd WAT	4th WAT
T1	2.6±0.27^ab	3.9±0.32^a	4.3±0.37^a	4.5±0.30^b	2.6±0.54^ab	3.6±0.54^b	2.9±0.46^b	3.2±0.70^b
T2	3.4±0.53^a	4.2±0.53^a	5.2±0.41^a	6.7±0.72^a	3.0±0.00^a	4.4±0.54^a	4.8±0.47^a	6.7±0.72^a
T3	2.2±0.56^b	3.4±0.59^a	4.3±1.06^a	5.7±1.26^ab	2.2±0.44^b	4.0±0.00^ab	4.7±0.59^a	5.4±1.05^a
P value	0.007	0.097	0.084	0.006	0.029	0.047	0.000	0.000

For the 'Red Coral' variety (Concorde RZ), in the first week, significant differences in PH were observed between treatments (P<0.05). Similar to the 'Green Coral' variety, T2 produced the tallest plants (3.0±0.00 cm), while T3 had the shortest (2.2±0.44 cm). These results indicate that, even during the early stages of growth, T2 induces better growth for the 'Red Coral' variety as compared to the other treatments. In the second week, significant differences were also found between treatments (P<0.05). T2 again produced the highest PH (4.4±0.54 cm), followed by T3 (4.0±0.00 cm), and T1 yielded the shortest plants (3.6±0.54 cm). The statistical significance of these results suggests that T2 consistently induce better growth compared to T1. In the third week, the differences between treatments became even more significant (P < 0.001). T2 led to significantly greater PH (4.8±0.47 cm) compared to T1 (2.9±0.46 cm). T3 (4.7±0.59 cm) produced nearly the same height as T2, and both were significantly taller than T1. This indicates that T2 and T3 effectively enhance the growth of the 'Red Coral' variety, however, T1 regularly exhibits suboptimal efficacy relative to the other two treatments. By the fourth week, the differences in PH became highly significant (P<0.001). T2 once again produced the tallest plants (6.7±0.72 cm) with compare to T1 (3.2±0.70 cm). T3 also produced taller plants (5.4±1.05 cm) than T1, though it was significantly shorter than T2. These results suggest that T2 is the most effective treatment for the 'Red Coral' variety, with consistent and significant improvement in PH observed throughout the growth period. The results indicate that light quality, specifically the use of two LED strips (T2), positively influences the vegetative growth of both lettuce varieties during critical growth phases, particularly in weeks two and three after transplanting.

These results are in line with previous studies that suggest increasing light intensity can promote photosynthetic efficiency, leading to enhanced plant growth [29]. Blue light has been shown to inhibit stem elongation in lettuce through its impact on photomorphogenic responses. Specifically, blue LED light exposure inhibits stem or leaf elongation in lettuce[30]. In contrast, the control treatment (T1) and the use of three LED strips (T3) did not consistently enhance leaf development to the same extent. This suggests that beyond a certain threshold, additional light does not necessarily enhance growth further, which could be due to light saturation where the plant's photosynthetic process is operating at maximum efficiency [31].

3.3. Interaction between light quality and variety on the plant height

Different varieties may respond uniquely to varying light intensities, affecting overall plant growth parameters and yield. Growers can enhance productivity by identifying the optimal combination of light quality and variety. The PH at harvestable age was mainly affected by light quality (Figure 3a). There was no significant interaction effect between light quality and variety on PH (Figure 3b). Figure 2 (a) illustrates that both Green Coral and Red Coral varieties exhibit a reduction in plant height when the number of light strips is incresed. Under the T2, both varieties reported significantly greater PH than the control group (P<0.05).

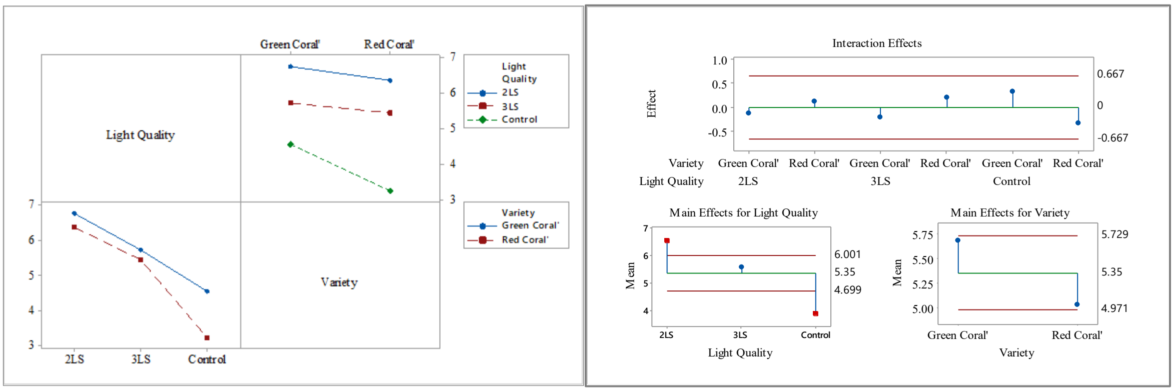

Figure 2. Effect of main effect (a) and interaction between light quality and variety (b) on plant height
Note: * 2LS- (T2), 3LS- (T3)

'Green Coral' reported greater growth in terms of plant height under the T2 condition than 'Red Coral' across all light treatments. These results align with recent research suggesting that moderate increases in light intensity, particularly through specific light spectra like those provided by LED strips, enhance plant growth and biomass accumulation [32, 33].

The highest values for PH were observed under the 2 light strips, which corresponds to findings that balanced light intensity promotes optimal photosynthetic efficiency [34]. Optimal light conditions are essential for enhancing photosynthesis and growth in both 'Green Coral' and 'Red Coral' lettuce. A balanced red and blue light spectrum with proper light–dark cycles promotes healthy vegetative growth, while red varieties may benefit from slightly higher light exposure due to their pigment needs [35].

The T3, while initially seeming to promote growth, shows a decline in PH for both varieties when compared to the T2. This decline suggests that, after a certain threshold, increasing light intensity may not yield proportionate benefits, possibly due to light saturation where the plants photosynthetic capacity has reached its peak. Overexposure to intense light can also lead to photoinhibition, where photosynthetic efficiency decreases [36]. This suggests that 'Green Coral' is more responsive to enhanced light conditions than Red Coral, possibly due to genetic differences in light-use efficiency [37]. The differential response between the two varieties may be attributed to variation in chlorophyll content or differences in their ability to use specific wavelengths of light for photosynthesis [38]. Red Coral has reported lower mean PH indicating that it is less responsive to the provided light quality treatments, possibly due to a lower photosynthetic capacity or adaptation to different environmental conditions.

The control group, which likely represents natural or low-light conditions, consistently shows the lowest plant height values for both varieties. This emphasizes the role of artificial light in promoting growth in controlled environments. Research by supports these findings, showing that low-light environments significantly reduce growth rates in lettuce due to insufficient photosynthetic activity [39]. These results indicate that light quality had a significant effect on enhancing plant growth, which is in agreement with previous studies on the positive effects of supplemental LED lighting in controlled environments [40]. The T2 condition, representing a moderate light intensity, optimizes photosynthetic efficiency and results in better growth. In contrast, the control condition, with minimal or no artificial light, yields the lowest plant height, likely due to limited photosynthetic activity [41].

The Figure 2b suggests minimal interaction between the two factors light quality and variety, as the lines remain relatively parallel across all light treatments. This lack of significant interaction indicates that both ‘Green Coral’ and ‘Red Coral’ respond similarly to changes in light quality, albeit with ‘Green Coral’ maintaining a consistently higher plant height. Although Green Coral outperforms ‘Red Coral’ in terms of plant height, the relative influence of light quality on both varieties is comparable. These results align with findings from [42] which reported that while light quality strongly affects plant growth, variety-specific interactions with light are often less pronounced in lettuce. Furthermore, the minimal interaction suggests that future studies may focus on optimizing light treatments for different lettuce varieties independently, as the effect of light quality on plant growth is likely to remain consistent across varieties.

3.4. Influence of light quality on fresh weight of ‘Green Coral’ and ‘Red Coral’ lettuce varieties

The FW of the tested two varieties was affected by the tested two different light treatments. The FW of the ‘Green coral’ variety was higher significantly after extra LED light strips were established. Green Coral lettuce would be more likely to use supplemental LED lighting compared to 'Red Coral'. Compared with red-blue or red-blue-green LED treatment, 'Green Coral' was subjected to higher fresh weight increase and phytochemical content, indicating more efficient photosynthesis and greater light use. 'Red Coral' reacted in a medium way, possibly due to part of its energy being spent on pigment production rather than biomass [43].

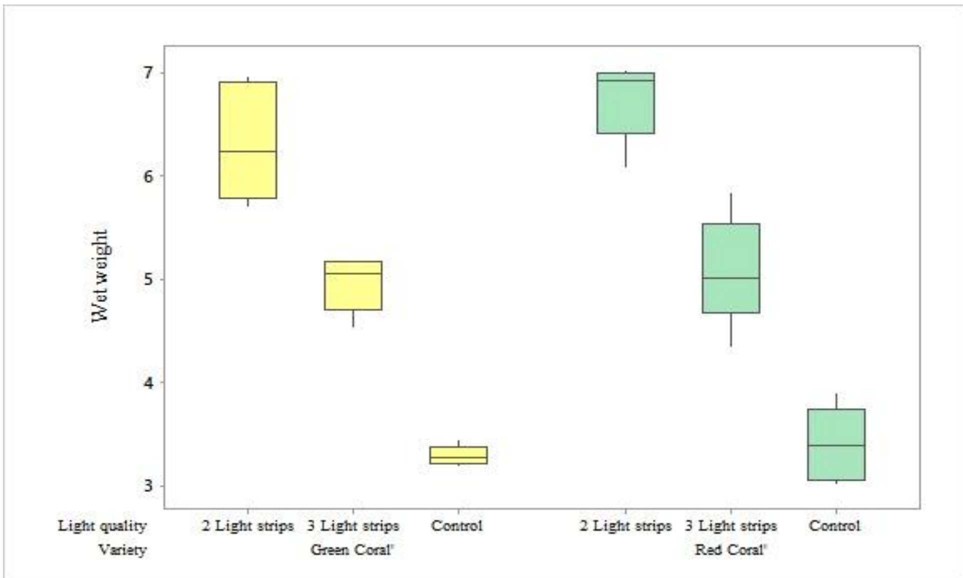

Figure 3. Effect of light quality and variety on the fresh weight of selected two varieties
Note: 2 light strips- (T2), 3 Light strips - (T3)

The Control (T1) had the lowest fresh weight (3.2±0.11 grams). Installing two horizontal LED (T2) led to a significant increase in FW (6.2±0.54 g), suggesting enhanced growth $P<0.05$. Using three horizontal LED (T3) yielded a FW of 4.9±0.25 g, lower than T2 but significantly higher than the control. The drop from T2 to T3 indicates that while increased light may initially promote growth, there is an optimal level, and more light might stop the growth.

The fresh weight of the ‘Red coral’ variety showed an identical pattern. The FW of the control treatment was 3.4±0.30 g. The FW had increased to 6.6±0.38 g with T2. This significant plant growth further reports the advantages of increased exposure to light. Similar to ‘Green coral’, the FW experienced a modest decrease at an average of 5.0±0.5 g when T3 was utilized. This suggests that like ‘Green coral’ variety, there may be a threshold beyond which more light is neither necessary nor beneficial for growth. According to the data, adding more LED lighting considerably increases the fresh weight of lettuce; the best treatment seems to be two LED light strips. Although increased light appears advantageous for both red and green coral varieties, two strips are optimal, as additional light has minimal effect on development. Enhanced LED lighting favors lettuce growth and wet weight up to an optimum level, beyond which additional light has little effect. This supports the hypothesis that two LED light strips are best for both 'Green Coral' and 'Red Coral' cultivars without energy wastage [44].

3.5. Analysis of interaction effect of fresh weight as affected by light quality and variety effect

The two lettuce varieties, 'Green Coral' and 'Red Coral,' exhibited distinct growth responses to light treatments, indicating that genetic differences influence their fresh weight under varying light conditions.

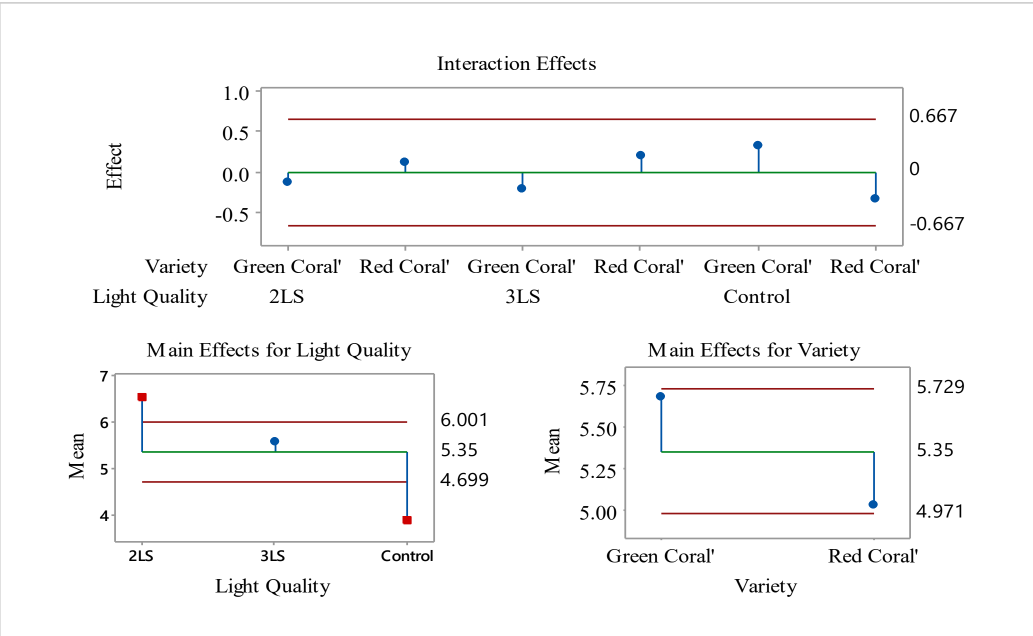

Figure 4. Effect of the main effect (a) and interaction between light quality and variety (b) on fresh weight accumulation at 4 WAT

According to Figure 4 the response to light quality differs between 'Green Coral' and 'Red Coral.' Specifically, 'Green Coral' shows a relatively consistent effect across the different light quality treatments, while 'Red Coral' reports a more significant fluctuation, particularly under the control treatment, where its effect drops below zero. This variation suggests that 'Red Coral' is more sensitive to changes in light quality, exhibiting a greater decline in FW under control condition with compared to 'Green Coral.' These trends highlight the importance of considering both variety and light quality simultaneously when optimizing growing conditions for maximum biomass production. There is no significant interaction between light quality and variety on FW of the selected two varieties. According to Figure 4, light quality plays a crucial role in promoting plant biomass, with the T2 being the most effective for both varieties.

The control treatment, lacking artificial light, consistently results in the lowest FW. While the Red Coral variety performs slightly better than Green Coral across all treatments, both varieties respond positively to additional light. The interaction between light quality and variety was not significant ($P>0.05$). However, the diminishing returns observed under the T3 suggest that there is an optimal threshold of light exposure, beyond which further increases do not benefit plant growth. This finding is in line with a recent study on the optimal balance of light intensity in horticulture [45] which emphasizes that both light quantity and quality must be carefully managed to maximize yield without causing stress to the plants.

4. Conclusion

The data indicated that the application of two horizontal LED light strips resulted in statistically significant improvements in leaf development, plant height, and biomass accumulation compared to the control and three horizontal LED light configurations for two selected lettuce varieties in the vertical drip fertigation system ($p < 0.05$). There is no significant interaction effect between light quality and variety on vegetative responses and yield. However, both factors individually influenced growth parameters, with consistent trends observed across treatments. This suggests that optimizing light quality can still improve key vegetative traits such as number of leaves, plant height, and fresh weight in lettuce, regardless of variety. These findings highlight the importance of spectral composition and intensity in enhancing plant growth inside controlled environment agriculture systems, especially in vertical drip fertigation systems. The findings provide practical understandings for researchers and commercial growers aiming to improve yield and quality indicators. By employing specifically designed lighting regulations, stakeholders might potentially attain more resource-efficient and economically sustainable lettuce production.

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