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Effects of Supplemental LED Spectral Composition and Irrigation Electrical Conductivity on Vegetative Biomass, Fruit Yield and Quality, and Lighting Electrical Cost in Greenhouse Strawberry Production

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Abstract

Greenhouse strawberry production has rapidly increased around the world, since greenhouse production allows for protection from adverse weather events and optimized climate control. During the winter months, supplemental electric lighting is essential to maintain production. However, the use of supplemental lighting can account for up to 30% of operating expenses, impacting the profitability of production. In addition, strawberries are prized for their taste, so maintaining fruit quality during production is essential. This study examined the impact four different supplemental overhead LED spectral lighting treatments (red–blue (95% red, red-rich), pink, warm white, and white) and two different irrigation electrical conductivity (EC) levels (low = 2 mS cm^{−1} and high = 3 mS cm^{−1}) on morphology, physiology, fruit quality and electricity costs in two strawberry cultivars—cv. ‘Albion’ and cv. ‘Favori’—grown in rockwool during the 2023–2024 winter greenhouse season in Harrow, Ontario, Canada. The results showed that plants exposed to a broad spectrum generally had higher photosynthetic rates and vegetative biomass. However, a threshold was observed when the green light fraction was above 24% (i.e., plants grown under the white-light treatment), resulting in reductions in photosynthesis and vegetative biomass. Although differences in photosynthetic capacity and biomass were observed, there was no impact of the light spectrum or irrigation EC on yield in either cultivar. Compared to the red–blue spectrum, plants grown under pink and warm white were observed to have lower titratable acidity (TA) and higher ratios of total soluble solids (TSSs) relative to TA. Importantly, it was determined that due to the higher efficacy of the red–blue supplemental lighting fixtures, the red-rich spectrum resulted in the lowest estimated lighting electricity cost per kilogram under the tested conditions. This study suggests that the use of supplemental high-efficacy, narrow wavelength, red-rich supplemental lighting can maintain yield and improve economic feasibility for greenhouse-grown strawberries.

Academic Editors: Qingming Li and
Jie He

Received: 24 June 2026

Revised: 20 July 2026

Accepted: 28 July 2026

Published: 31 July 2026

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1. Introduction

Strawberry (*Fragaria x ananassa*) is a high-value horticultural crop that is widely consumed globally—prized for its taste and nutritional attributes. The cultivation of strawberry in controlled-environment agriculture (CEA) has rapidly increased in recent decades as

growers have tried to diversify their crop portfolios [1]. The adoption of greenhouse production practices has allowed for optimized environmental control throughout the year, facilitating year-round production in many cold locations [2]. One of the main determining factors for profitable year-round strawberry production is light, as it is a key driver of plant growth and development, influencing photosynthesis, morphology, secondary metabolite production, and, ultimately, yield. The shift to high-efficacy light-emitting diode (LED) technology during greenhouse production has enabled precise spectral control while reducing electrical costs [3–5]. This has offered growers new opportunities to tailor plant responses for improved performance [6].

Different wavelengths of light play distinct roles in the morphology and physiology of plants, which ultimately dictate yield and fruit-quality characteristics [6]. Red and blue light are both highly absorbed by plants and are highly energy-efficient [4,7]. Broader spectrums involving green, orange and far-red light can contribute to photomorphogenic responses that may be advantageous to overall plant growth [8]. In strawberry, previous studies have shown that the light quality/spectrum can effect nearly all aspects of growth, including vegetative growth, flower timing, yield, and fruit quality. Magar et al. [9] demonstrated that $80 \mu\text{mol m}^{-2} \text{s}^{-1}$ of supplemental blue light led to increased flower number compared to supplemental white or red light. Blue light has also been shown to increase the antioxidant, sugar content, aroma, and flavor profiles, although these effects seem to have interactions with genotype [10–12]. Meanwhile, supplemental red light has been shown to increase leaf development and overall plant biomass in everbearing strawberries [13]. However, the optimal supplemental spectral lighting composition that not only maximizes plant growth, yield, and fruit quality but also considers electrical costs remains unclear. In particular, it is important to analyze whether high-efficacy, red-rich, narrow-waveband lighting or a well-balanced, broad-spectrum lighting approach is optimal for production. This type of analysis is essential to promote economically sustainable greenhouse strawberry production year-round.

In addition to optimizing the light environment, the composition of the nutrient feed solution can play a critical role in strawberry production. The electrical conductivity (EC) of a feed solution can directly influence plant growth, vegetative vs. generative balance, and physiological processes related to yield and fruit quality. Some studies have demonstrated that optimized photosynthetic parameters are observed at EC levels of $2\text{--}4 \text{ mS cm}^{-1}$ [14]. However, some have indicated that lower EC levels of 1.3 mS cm^{-1} are optimal for improving fruit yield [15]. These contrasting findings highlight the complex relationship between nutrient management and plant growth patterns. Maintaining an appropriate EC level is essential to avoid nutrient imbalances and osmotic stress, which can negatively impact fruit yield and quality. Importantly, there is often a trade-off between vegetative and generative growth that can be impacted by nutrient regimes. Identifying this relationship is key to promoting sustainable long-term greenhouse strawberry production with high yield while also maintaining or improving sweetness and flavour.

Although both light spectrum and nutrient-solution EC can independently impact strawberry growth, their interactive effects remains poorly understood. Emerging research has shown that the light spectrum can impact nutrient uptake [16]. Understanding the interactive effects of these two important factors is key, since both energy inputs and nutrient management can directly impact the production efficiency and economic viability of greenhouse strawberries.

Therefore, this study evaluates how supplemental LED spectra and irrigation EC can influence vegetative growth, fruit yield, fruit quality, and lighting electricity costs during greenhouse strawberry production. The study used two cultivars (cv. ‘Albion’ and cv. ‘Favori’) in combination with four supplemental lighting spectra (red–blue, pink, warm

white, and white) and two irrigation EC levels (low = 2 mS cm⁻¹ and high = 3 mS cm⁻¹). By integrating the morphological, physiological, and yield parameters, this study aims to identify both lighting and fertigation strategies that can optimize fruit yield and quality while minimizing energy and resource inputs.

2. Materials and Methods

2.1. Plant Material and Experimental Design

On 10 November 2023, strawberry (*Fragaria x ananassa*) cv. ‘Albion’ and cv. ‘Favori’ plug plants (135 cc) were planted in two greenhouses covered with diffusing glass with anti-reflection coating on both sides (70% haze/diffused light, Yuhua New Materials Co., Ltd. Jiaozuo, China) at the Harrow Research and Development Centre, Agriculture and Agri-Food Canada, Harrow, Ontario, Canada (42.03° N, 89.9° W). Each greenhouse had 76 m² of growing space and was divided into four quadrants using light abatement curtains (Obscura 9950 FR, Ludvig Svensson, Kinna, Sweden). The light abatement curtain blocks 99% of light transmission while allowing water vapour and air through. Strawberry plugs were planted directly into rockwool slabs (90 cm × 15 cm × 10 cm; Grodan® Prestige, Grodania A/S, Milton, ON, Canada) on hanging gutters at a plant density of 10 plants per linear meter. The daytime (2:00–18:00) temperature was 22 ± 2 °C, with a relative humidity between 65 and 75%. Nighttime temperature was 16 ± 2 °C, with a relative humidity between 65 and 75%. In addition, between 19:00 and 22:30, the temperature was further reduced to 12 ± 1 °C, with a relative humidity of 80–90%, following commercial standards. The greenhouses were enriched to a CO₂ level of 800 ppm during the day when not vented.

Four overhead supplemental light treatments were randomly applied to the 4 quadrants in each of the 2 greenhouses. The four treatments were as follows: red–blue (95.1% red, 4.4% blue, and 0.5% green—red-rich), pink, warm white, and white (Figure 1). Supplemental lighting was automatically turned off when the outside global solar radiation was above 300 W m⁻². The light abatement curtains that separated the lighting treatments were opened when lighting was off to minimize their influence on sunlight distribution within each greenhouse. Within each compartment, 4 horizontal airflow fans were also installed at the top of the greenhouses to mix air and minimize microclimate difference. Although all efforts were made to ensure the 4 quadrants had the same climatic conditions, some minor confounding effects related to microclimate might have been present due to the limited number of replications. Spectral composition was measured using a spectroradiometer (LI-820 spectrometer; LI-COR Biosciences, Lincoln, NE, USA); each spectrum can be found in Figure 1. The supplemental overhead lighting treatments were provided by VYPR-series light-emitting diodes (LED; Fluence by OSRAM, Austin, TX, USA). The photosynthetic photon flux density (PPFD) was 200 ± 4 µmol m⁻² s⁻¹ just above the crop canopy, as measured by a one-meter quantum light sensor (Li-COR 191R; Li-COR Biosciences, Lincoln, NE, USA). The supplemental daily light integral (DLI) was 11.52 mol m⁻² d⁻¹ for all treatments. The overall DLI exposed to the plants varied throughout the experiment and depended on the natural solar radiation. The light treatments began on 27 November 2023 and ran until the end of the experiment on 13 March 2024. All light treatments had a 16h photoperiod that ran from 2:00 to 18:00.

In addition to light treatments, plants were subjected to two different irrigation treatments that consisted of low (2 mS cm⁻¹) and high (3 mS cm⁻¹) electrical conductivity (EC). The fertigation formula was modified from that reported by Kroggel and Kubota [17]: N = 70 ppm, NH₄ = 7 ppm, P = 16 ppm, K = 120 ppm, Ca = 40 ppm, Mg = 12 ppm, Fe = 1 ppm, Mn = 0.55 ppm, Zn = 0.33 ppm, Bo = 0.5 ppm, and Mo = 0.05 ppm with a pH of 5.8. The fertigation solution was prepared using the Harrow Research and Development Centre fertigation machine (Harrow Research and Development Centre, Harrow,

ON, Canada), which allows for the mixing of individual nutrients to a desired solution composition. The low- and high-EC solutions had the same ratios of each nutrient, with the overall strength being modulated to reach the desired EC.

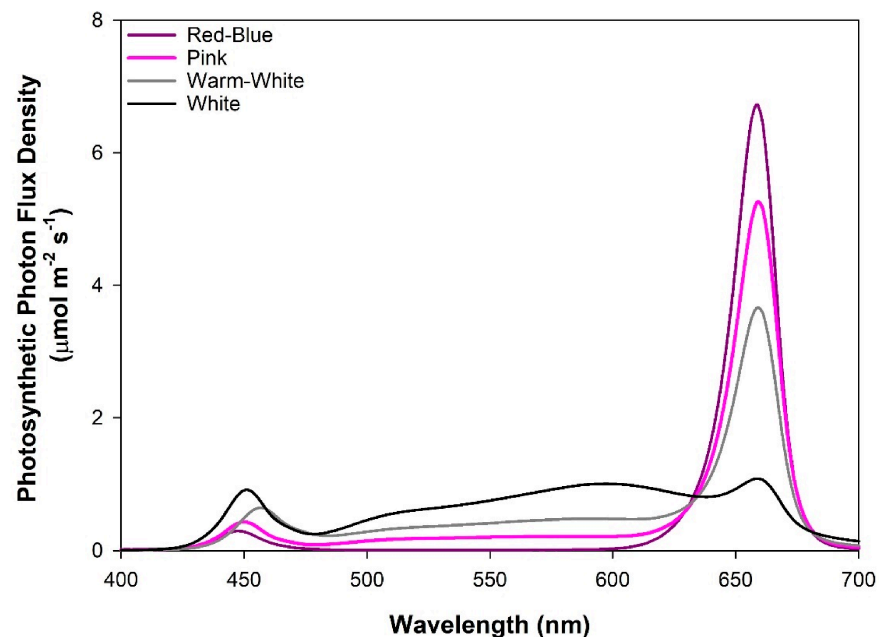


Figure 1. Light spectra of light treatments as determined at the top of the plant canopy using a LI-820 spectrometer (LI-COR Biosciences, Lincoln, NE, USA) during the night to remove any interference from natural solar radiation.

2.2. Morphological Measurements

On 11 March 2024, six randomly selected cv. ‘Albion’ plants were measured from each light and irrigation treatment and used to assess the morphological impact of both variables. The leaves were counted on each plant, removed, weighed, and passed through a LI-3100C (LI-COR Biosciences, Lincoln, NE, USA) to determine the total leaf area. The stems (i.e., all non-leaf aerial tissue) were also weighed. The leaves and stems of each plant were placed into separate paper bags and dried at 70 °C. After four days, the samples were removed from the oven and weighed to obtain their dry weights.

2.3. Leaf Gas-Exchange Measurements

Leaf gas-exchange measurements were performed on cv. ‘Albion’ between 4 March 2024 and 7 March 2024. Representative leaves from each light and irrigation treatment were placed into a 2 cm² chamber of a Li-COR 6800 (LI-COR Biosciences, Lincoln, NE, USA) photosynthesis system with a fluorometer head attachment. The leaf temperature, relative humidity, and CO₂ concentration were set to 22 °C, 65%, and 800 ppm respectively. The leaf was exposed to 1500 μmol m⁻² s⁻¹ of light (90% red, 10% blue) until a steady-state photosynthetic rate was achieved. Once stable, leaf gas-exchange measurements were recorded. The light level was reduced in a step-wise fashion down to 0 μmol m⁻² s⁻¹. At each light level, the same protocol was repeated to obtain gas-exchange measurements after a 5–10 min stabilization period. The measurements were repeated four times for each light-irrigation combination.

The photosynthetic rates were plotted against PPFD and fitted to a regression line ($y = y_0 + a(1 - e^{(-b \cdot x)})$) using SigmaPlot 14.0 to determine the maximum photosynthetic rate. A linear regression line ($y = mx + b$) was used to calculate the quantum yield (QY)

and light compensation point (LCP) using the photosynthetic rates at the PPFD from 0 to 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

2.4. Yield

Harvest began on 8 January 2024 and occurred every other day until the end of the experiment on 13 March 2024. Fully ripe fruits (red with no white shoulders) were harvested from each treatment, counted, and immediately weighed.

2.5. Electricity Cost Associated with Supplemental Lighting

The electricity consumption for each lighting treatment was calculated using the following formula:

$$LEC = \frac{\sum_{t=0}^t \left(\frac{\left[\frac{PPFD}{FE} \right]}{1000} \right) * HOEP}{yield} \quad (1)$$

where t is the time period in hours throughout the production period; $PPFD$ is the light intensity for each lighting treatment ($\mu\text{mol m}^{-2} \text{s}^{-1}$); FE is the fixture efficacy ($\mu\text{mol J}^{-1}$) for each specific lighting fixture, as indicated by the manufacturer; $HOEP$ is the hourly electricity price obtained from the IESO [18] for the Ontario electricity grid (where the trial was performed). The on/off periods of the lights were accounted for using data from an ARGUS Titan (Argus Controls, Langley, British Columbia, Canada) climate control computer to account for sunny periods when the supplemental lighting would be off. The electricity cost per kg of production (LEC ; \$ CAD kg^{-1}) was then obtained for both cv. 'Albion' and cv. 'Favori' by dividing by the overall yield.

The economic analysis was limited to lighting electricity costs and does not include fixture cost, implications on heating, labour, nutrient inputs, and other greenhouse operating expenses.

2.6. Fruit Quality

The total soluble solid content (TSS(BRIX(°))) and titratable acidity (TA) were measured for each treatment on 13 March 2024. This is a recognized limitation of the study, and future experimentation should analyze fruit quality multiple times throughout production. During that harvest, fully ripe strawberries were pooled. Immediately after harvest, the calyx was removed, and the berries were juiced into a beaker using a garlic press. This was repeated several times to produce 6 mL per sample. The fruit juice was then placed on an Atago PR-101 α digital refractometer (Atago Co., Ltd., Tokyo, Japan) for TSS measurements. For TA, the procedure required 5 mL of fresh fruit juice. The fresh fruit juice was diluted to 50 mL using deionized water before the sample was put into a titrator (HI84532 titratable acidity mini titrator, Hanna Instruments, Ann Arbor, MI, USA). Titration was performed using Hanna's low-range titrant (0.1–2.0% citric acid detection range; H84532-50).

2.7. Statistical Analysis

All statistics were performed using SAS Studio 3.5. After a two-way analysis of variance (ANOVA), a multiple-means comparison between the different light and EC treatments was performed using Tukey's least significant difference with $p < 0.05$ indicating significant difference. A Pearson correlation analysis was also conducted using SAS Studio 3.5 for cv. 'Albion'.

3. Results

The light spectrum significantly influenced several vegetative growth parameters in cv. ‘Albion’ including leaf fresh weight ($p = 0.0194$), leaf dry weight ($p = 0.0346$), stem dry weight ($p = 0.0272$), and leaf area ($p = 0.0043$; Table 1). Overall, plants grown under the pink-light treatment exhibited the greatest vegetative growth, including leaf fresh and dry weights and leaf area. Plants under the warm-white treatment, particularly plants grown with high EC, also displayed high vegetative growth rates and had increased leaf numbers, leaf biomass, and leaf area compared to other treatments. Conversely, plants grown under the red–blue and white-light treatments were observed to be the smallest and had the least amount of vegetative growth (Table 1). The irrigation EC alone did not have a significant impact on vegetative growth, with the exception of specific leaf weight (SLW), as plants grown under high EC had higher SLW values, indicating slightly thicker leaves than those grown under low EC.

In both low- and high-EC irrigation treatments, plants grown under the pink and warm-white light treatments were observed to have the highest net carbon exchange rates (NCER; Figure 2A,B). While there was a slight decrease in the NCER of plants grown under the pink-light treatment with high-EC irrigation compared to low EC, generally speaking, there was no difference associated with irrigation EC treatments, indicating that light spectra had a larger impact on this parameter (Figure 2A,B; Table 2). With respect to quantum yield under lower light levels ($0\text{--}100\ \mu\text{mol m}^{-2}\text{ s}^{-1}$), there was no impact of light spectra or irrigation ECs (Table 2). Similarly, neither experimental factor had an impact on the light compensation point (LCP; Table 2).

As expected, the transpiration rate increased with increasing light intensity, with the increase being more rapid under lower light conditions ($0\text{--}100\ \mu\text{mol m}^{-2}\text{ s}^{-1}$) as stomata opened. In plants grown under low EC, the light spectrum had no impact on transpiration rates (Figure 2C). Under high EC, plants grown under the warm-white light spectrum tended to have the highest transpiration rate relative to other light spectra at each light level (Figure 2D).

Conversely, since water-use efficiency (WUE) is the ratio of NCER to transpiration, the WUE in plants grown with low EC was not impacted by the light spectrum and followed an asymptotic response similar to that of NCER (Figure 2E). For plants irrigated with high EC, since plants grown under the warm-white light spectrum had the highest transpiration level—greater than the NCER under the same light treatment—they tended to have the lowest WUE rates (Figure 2F).

Fruit yields of cv. ‘Abion’ were statistically similar among all light treatments with respect to fruit number, fruit weight, and average fruit weight across both EC levels (Figure 3A,C,E). While plants grown under pink, warm-white, and white light under high EC levels tended to have a higher fruit numbers per plant compared to their low-EC counterparts, there was no statistical significance (Figure 3A). Additionally, no significant difference in total fruit weight or average fruit weight was observed (Figure 3C,E). Similarly, cv. ‘Favori’ was observed to have no statistical differences in fruit number, fruit weight, or average fruit weight when compared across light treatments and EC levels (Figure 3B,D,F), although the fruit number and fresh weight tended to be lower under the warm-white light treatment (Figure 3B,C). Of note, cv. ‘Favori’ tended to produce more fruit per plant than cv. ‘Albion’ (Figure 3A,B), while cv. ‘Albion’ produced a slightly higher average fruit weights (Figure 3E,F). Fruit yield assessments were based on two independent replicates per treatment. While no statistical treatment effects were detected, the relatively low replication limits statistical power and may reduce the ability to detect subtle differences. Consequently, yield-related conclusions should be interpreted cautiously.

Table 1. Destructive measurement parameters (per plant) of cv. ‘Albion’ plants from 11 March 2024 grown under various lighting treatments and either low- or high-EC irrigation treatments. The average and standard error are representative of six randomly selected plants ($n = 6$). Within each parameter, different letter groups (A, B, C) indicate a statistical difference as determined by a two-way ANOVA using Tukey’s least significant difference, with $p < 0.05$ indicating significance. p -values of each factor and their interaction are shown at the bottom of the table.

Light Treatment	Irrigation Treatment	Leaf #	Leaf Fresh Weight (g)	Leaf Dry Weight (g)	SPAD	Stem Fresh Weight (g)	Stem Dry Weight (g)	Leaf Area (cm ²)	Specific Leaf Weight (cm ² g ^{−1})
Red–Blue	Low	21.0 ± 0.7 ^{BC}	33.7 ± 2.6 ^C	10.0 ± 0.7 ^B	43.4 ± 0.3 ^A	45.8 ± 5.9 ^{BC}	9.6 ± 1.3 ^{BC}	1033 ± 82 ^C	0.0097 ± 0.0002 ^{AB}
	High	19.6 ± 1.4 ^C	34.0 ± 2.7 ^C	11.0 ± 1.2 ^{AB}	43.5 ± 0.4 ^A	39.0 ± 3.1 ^C	8.7 ± 0.8 ^C	1060 ± 48 ^C	0.010 ± 0.0006 ^{AB}
Pink	Low	27.5 ± 2.9 ^A	47.9 ± 2.2 ^A	14.3 ± 0.8 ^A	41.8 ± 0.9 ^A	59.4 ± 3.5 ^A	13.0 ± 1.0 ^A	1435 ± 50 ^A	0.0099 ± 0.0004 ^{AB}
	High	21.5 ± 1.4 ^{BC}	37.7 ± 2.2 ^{BC}	12.2 ± 0.8 ^{AB}	43.8 ± 0.6 ^A	45.1 ± 2.4 ^{BC}	10.5 ± 0.7 ^{BC}	1139 ± 55 ^C	0.011 ± 0.0005 ^A
Warm White	Low	20.0 ± 1.4 ^{BC}	37.3 ± 3.2 ^{BC}	12.0 ± 1.3 ^{AB}	42.2 ± 1.1 ^A	43.5 ± 2.4 ^{BC}	10.0 ± 0.6 ^{BC}	1156 ± 65 ^{BC}	0.010 ± 0.0006 ^{AB}
	High	26.6 ± 0.7 ^A	44.4 ± 2.7 ^{AB}	14.2 ± 0.9 ^A	43.1 ± 0.7 ^A	52.1 ± 1.2 ^{AB}	12.1 ± 0.3 ^{AB}	1342 ± 59 ^{AB}	0.011 ± 0.0003 ^A
White	Low	19.8 ± 2.5 ^{BC}	35.6 ± 1.8 ^C	10.1 ± 0.5 ^B	41.4 ± 0.5 ^A	49.2 ± 1.8 ^B	9.6 ± 0.5 ^{BC}	1103 ± 44 ^C	0.0092 ± 0.0003 ^B
	High	24.7 ± 1.1 ^{AB}	36.6 ± 3.5 ^{BC}	12.1 ± 1.2 ^{AB}	41.8 ± 1.2 ^A	44.3 ± 2.9 ^{BC}	10.4 ± 0.8 ^{BC}	1110 ± 84 ^C	0.011 ± 0.0004 ^A
Light		0.1581	0.0194	0.0346	0.2012	0.0598	0.0272	0.0043	0.7900
Irrigation		0.4269	0.8314	0.2993	0.1749	0.0744	0.8183	0.6968	0.0231
Light*Irrigation		0.0042	0.0448	0.1793	0.7128	0.0118	0.0537	0.0120	0.5244

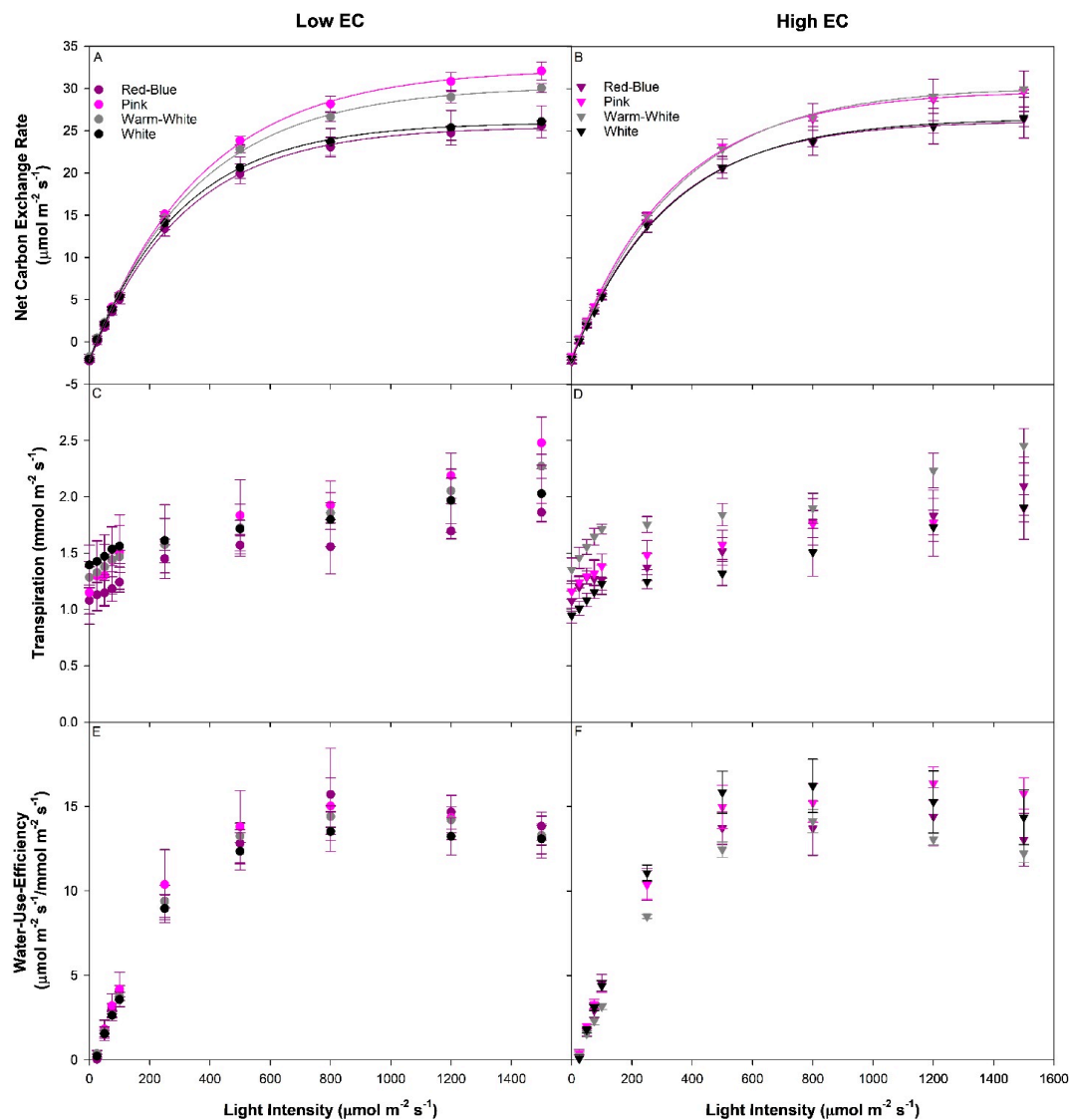


Figure 2. Leaf light response curves (A,B), transpiration vs. light intensity (C,D), and water-use-efficiency (WUE; (E,F)) of cv. ‘Albion’ plants grown under various light treatments and irrigated with low EC (A,C,E) or high EC (B,D,F) as determined using a Li-COR 6800 with a red/blue (90/10) light attachment (LI-COR Biosciences, Lincoln, NE, USA). Data points and error bars represent the average and standard error ($n = 4$) of four randomly selected leaves from each treatment combination. Regression lines in panels A and B were fit to $y = y_0 + a(1 - e^{(-b \cdot x)})$.

The lighting spectrum influenced electricity consumption throughout the experiment, with the red–blue (red-rich) treatment exhibiting the lowest electricity usage (94.33 kW m^{-2}), while the white-light treatment had the highest usage (125.77 kW m^{-2} ; Table 3). These differences were primarily associated with reductions in light-fixture efficacy as spectral output broadened from narrowband red–blue (95.1% red) to full-spectrum white lighting.

The electricity cost for cv. ‘Albion’ ranged from $\$1.85 \text{ kg}^{-1}$ to $\$3.40 \text{ kg}^{-1}$, with the lowest cost observed under the red–blue (red-rich) light treatment with high EC (Table 3). A similar overall trend was observed in cv. ‘Favori’, where red–blue light generally resulted in the lowest electricity cost per kilogram of fruit produced. Relative to the red–blue treatment within the same irrigation EC treatment, electricity cost associated with broad-spectrum treatments increased by up to 73.5% in cv. ‘Albion’ and 58.6% in cv. ‘Favori’. The lower yield at low irrigation EC under red–blue light (Figure 3D) led to a higher lighting electricity

cost per kg of fruit produced and might have resulted in the relatively smaller percentage difference with pink and warm-white light treatments at low irrigation EC (Table 3).

Overall, regardless of cultivar and irrigation EC treatment, the red–blue (red-rich) light treatment generally resulted in the lowest lighting electricity cost. These results indicate that the use of a more energy-efficient lighting spectrum can substantially reduce the electricity cost related to lighting while maintaining comparable yield under equivalent light intensities.

Table 2. Summary of physiological parameters of cv. ‘Albion’ as determined with a Li-COR 6800 with a red/blue (90/10) light source. Measurements were taken at a CO₂ concentration of 800 ppm, temperature of 22 °C, and relative humidity of 65%. The maximum photosynthetic rates (Pn_{max}) were calculated according to $y = y_0 + a(1 - e^{(-b \cdot x)})$, while quantum yields and light compensation points (CP) were calculated using $y = mx + b$, with measurements from 0 to 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Values represent the mean $\pm$ the standard error of the mean with $n = 4$. Different letter groups represent statistical difference within each parameter as determined by a two-way ANOVA using Tukey’s least significant difference, with $p < 0.05$ indicating a significant difference. p -values of each factor and their interaction are shown at the bottom of the table.

Light Treatment	Irrigation Treatment	Pn _{max} ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Quantum Yield ($\mu\text{mol}_{\text{CO}_2} \text{m}^{-2} \text{s}^{-1} / \mu\text{mol}_{\text{photon}} \text{m}^{-2} \text{s}^{-1}$)	Light Compensation Point ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
Red–Blue	Low	27.60 $\pm$ 0.81 ^D	0.073 $\pm$ 0.004 ^A	28.0 $\pm$ 2.7 ^A
	High	28.15 $\pm$ 0.73 ^{CD}	0.076 $\pm$ 0.002 ^A	25.4 $\pm$ 2.8 ^A
Pink	Low	34.33 $\pm$ 1.15 ^A	0.077 $\pm$ 0.003 ^A	23.7 $\pm$ 1.5 ^A
	High	31.39 $\pm$ 0.27 ^{ABC}	0.076 $\pm$ 0.002 ^A	18.8 $\pm$ 1.4 ^A
Warm White	Low	32.03 $\pm$ 0.71 ^{ABC}	0.072 $\pm$ 0.002 ^A	20.6 $\pm$ 2.6 ^A
	High	32.33 $\pm$ 2.31 ^{AB}	0.073 $\pm$ 0.001 ^A	22.9 $\pm$ 4.1 ^A
White	Low	27.99 $\pm$ 1.91 ^{CD}	0.074 $\pm$ 0.002 ^A	26.7 $\pm$ 2.3 ^A
	High	28.47 $\pm$ 1.89 ^{BCD}	0.072 $\pm$ 0.002 ^A	24.7 $\pm$ 2.6 ^A
Light		0.0017	0.3841	0.1705
Irrigation		0.6870	0.7784	0.5912
Light*Irrigation		0.5431	0.6307	0.5126

Table 3. Analysis of electricity usage related to lighting, average lighting electricity cost per kilogram, and the average percentage increase or decrease compared to the red–blue treatment under the same irrigation EC treatment for both cv. ‘Albion’ and cv. ‘Favori’. The hourly cost of electricity was obtained from the IESO [18]. No statistical difference was determined between the lighting and irrigation treatments with respect to lighting electricity costs within either cultivar as determined by a two-way ANOVA using Tukey’s least significant difference, with $p < 0.05$ as the level of significance.

Light Treatment	Irrigation Treatment	Electricity Usage (kW m ⁻²)	Lighting Electricity Cost (\$ CAD kg ⁻¹)	Change Compared to Red–Blue (%)
cv. ‘Albion’				
Red–Blue	Low	94.33	1.96	N/A
	High		1.85	N/A
Pink	Low	106.12	2.30	17.3%
	High		2.13	15.1%
Warm White	Low	113.20	2.44	24.5%
	High		2.41	30.3%
White	Low	125.77	3.40	73.5%
	High		2.33	25.9%

Table 3. Cont.

Light Treatment	Irrigation Treatment	Electricity Usage (kW m ^{−2})	Lighting Electricity Cost (\$ CAD kg ^{−1})	Change Compared to Red–Blue (%)
cv. ‘Favori’				
Red–Blue	Low	94.33	1.94	N/A
	High		1.52	N/A
Pink	Low	106.12	1.86	−4.1%
	High		2.08	36.8%
Warm White	Low	113.20	2.52	29.9%
	High		2.41	58.6%
White	Low	125.77	1.95	0.5%
	High		2.33	53.3%

While total soluble solids (TSS) values ranged from 9.2 to 10.8, there was no significant difference between light treatments or EC levels (Table 4). The light spectrum did significantly impact titratable acidity (TA), with fruits under the red–blue and white-light treatments having the highest levels and those under the pink and warm-white treatments having the lowest levels (Table 4). Consequentially, TSS:TA ratios were the lowest in fruit from the red–blue and white treatments and the highest under pink and warm-white light treatments. Irrigation ECs did not significantly affect TSS, TA, or the TSS:TA ratio, and there was no interactive effect between light treatment and irrigation EC.

Pearson correlation analysis conducted on cv. ‘Albion’ using treatment means reveals that the maximum photosynthetic rate strongly correlated with vegetative biomass parameters of leaf area ($r = 0.89, p = 0.003$), leaf dry weight ($r = 0.88, p = 0.004$), and stem dry weight ($r = 0.83, p = 0.009$) (Table 5). This indicates that an increasing photosynthetic capacity promoted vegetative growth. However, Pn_{max} and vegetative biomass parameters did not significantly correlate with generative traits (fruit number, total fruit weight, or average fruit weight). This observation supports the notion that enhanced photosynthetic capacity and biomass accumulation did not translate into greater yield in this study. Additionally, TA negatively correlated with Pn_{max} and vegetative biomass parameters, while TSS:TA was positively correlated. Overall, enhanced photosynthetic capacity did lead to larger plants but did not increase yield in cv. ‘Albion’.

Table 4. Fruit quality analysis (total soluble solids (° Brix) and titratable acidity (TA)) of cv. ‘Albion’ fruit harvested on 13 March 2024 and grown under various light treatments and either low- or high-EC irrigation treatments. The averages and standard errors are representative of six fruit-juice samples ($n = 6$). Within each parameter, different letter groups (A, B, C) indicate a statistical difference as determined by a two-way ANOVA using Tukey’s least significant difference, with $p < 0.05$ indicating a significant difference. p -values of each factor and their interaction are shown at the bottom of the table.

Light Treatment	Irrigation Treatment	TSS (° Brix)	TA (g 100 mL ^{−1})	TSS:TA
Red–Blue	Low	9.3 ± 0.2 ^A	0.91 ± 0.03 ^A	10.2 ± 0.4 ^C
	High	9.9 ± 0.6 ^A	0.84 ± 0.06 ^{AB}	11.5 ± 0.6 ^C
Pink	Low	9.8 ± 0.6 ^A	0.58 ± 0.01 ^C	17.0 ± 1.1 ^A
	High	9.3 ± 0.6 ^A	0.69 ± 0.03 ^{BC}	14.4 ± 1.2 ^{ABC}
Warm White	Low	9.9 ± 0.4 ^A	0.68 ± 0.08 ^{BC}	15.3 ± 1.5 ^{AB}
	High	10.8 ± 0.3 ^A	0.66 ± 0.04 ^{BC}	16.9 ± 1.4 ^A
White	Low	9.2 ± 0.3 ^A	0.81 ± 0.07 ^{AB}	11.6 ± 1.0 ^C
	High	9.2 ± 0.2 ^A	0.76 ± 0.06 ^{ABC}	12.7 ± 1.1 ^{BC}

Table 4. Cont.

Light Treatment	Irrigation Treatment	TSS (° Brix)	TA (g 100 mL ⁻¹)	TSS:TA
Light		0.0886	0.0066	0.0007
Irrigation		0.4168	0.8311	0.7506
Light*Irrigation		0.4914	0.5890	0.4014

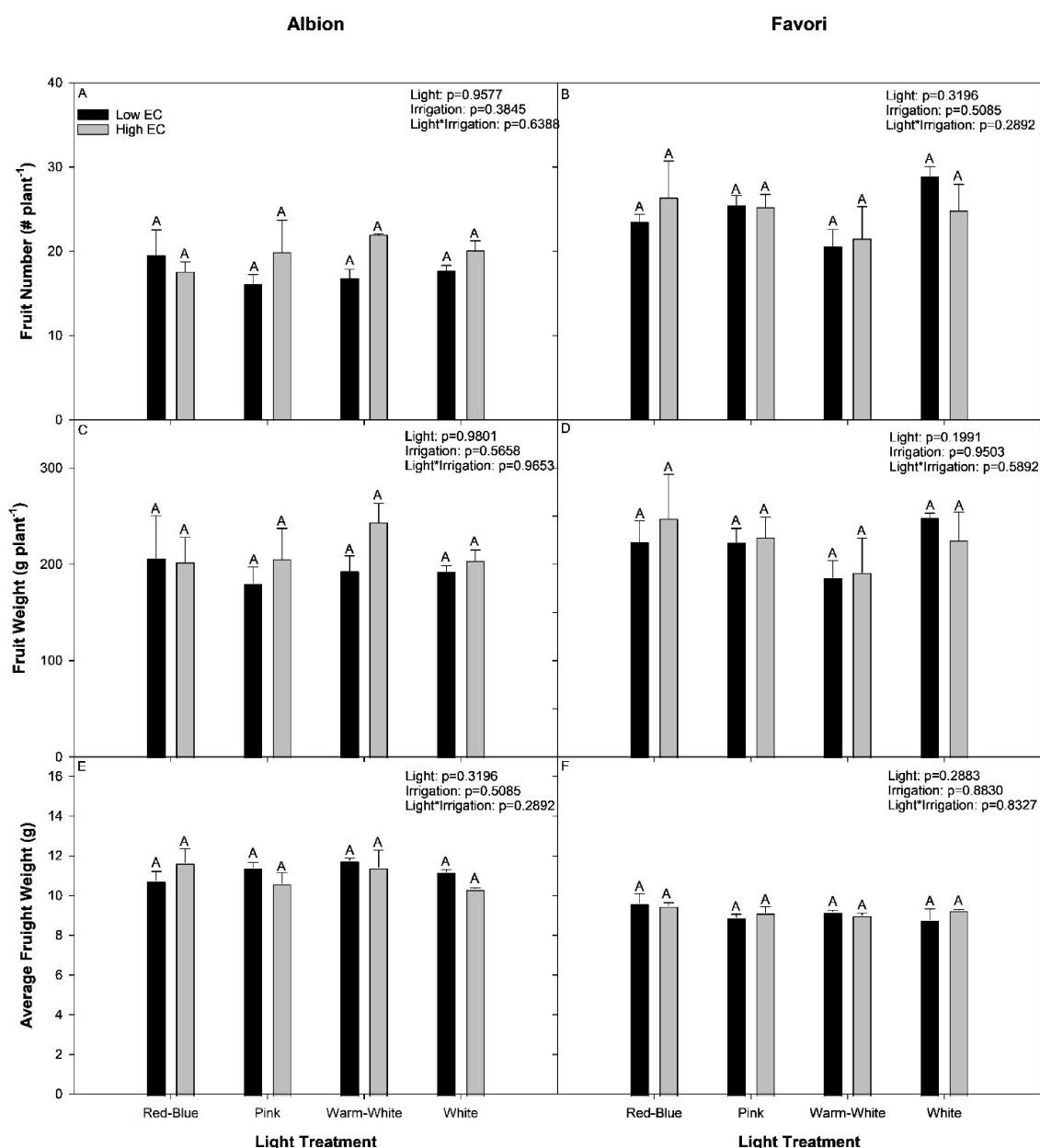


Figure 3. Total yield parameters from strawberry (cv. 'Albion' (panels (A,C,E)) and cv. 'Favori' (panels (B,D,F))) grown under different supplemental light treatments and either low (black bars) or high (grey bars) irrigation EC treatments. Harvest began on 8 January 2024 and ended on 13 March 2024. Panels (A,B) represent the total fruit number per plant, panels (C,D) represent the total fruit weight per plant, and panels (E,F) represent the average fruit weight. The bars and standard error bars represent the average and standard errors of the mean for two independent replicates ($n = 2$). Within each panel, different letter groups indicate a statistical difference as determined by a two-way ANOVA using Tukey's least significant difference, with $p < 0.05$ indicating significance. p -values of each factor and their interaction are shown in the top-right corner of each panel.

Table 5. Pearson correlation heatmap of physiological, vegetative growth, yield, and fruit quality variables across the eight light x EC irrigation treatment combinations for cv. ‘Albion’. Positive correlations are shown in green, while negative correlations are shown in red, with colour intensity indicating the strength of the correlation coefficient (r).

	Pn _{max}	Leaf Area	Leaf Dry Weight	Stem Dry Weight	Fruit Number	Fruit Weight	Average Fruit Weight	TSS	TA	TSS:TA
Pn _{max}	1.00	0.89	0.88	0.84	−0.17	−0.03	0.36	0.54	−0.95	0.96
Leaf Area	0.89	1.00	0.92	0.95	−0.08	0.06	0.31	0.59	−0.88	0.90
Leaf Dry Weight	0.88	0.92	1.00	0.90	0.13	0.24	0.19	0.65	−0.90	0.94
Stem Dry Weight	0.84	0.95	0.90	1.00	0.08	0.11	0.03	0.44	−0.84	0.85
Fruit Number	−0.17	−0.08	0.13	0.08	1.00	0.89	−0.53	0.22	0.13	−0.01
Fruit Weight	−0.03	0.06	0.24	0.11	0.89	1.00	−0.09	0.60	0.05	0.15
Average Fruit Weight	0.36	0.31	0.19	0.03	−0.53	−0.09	1.00	0.64	−0.26	0.34
TSS	0.54	0.59	0.65	0.44	0.22	0.60	0.64	1.00	−0.45	0.64
TA	−0.95	−0.88	−0.90	−0.84	0.13	0.05	−0.26	−0.45	1.00	−0.97
TSS:TA	0.96	0.90	0.94	0.85	−0.01	0.15	0.34	0.64	−0.97	1.00

4. Discussion

4.1. Impact of the Light Spectrum on the Morphology and Physiology of cv. 'Albion'

The light spectrum a plant is grown under can exert strong control over its physiological properties, resulting in morphological changes. Here, we observed that cv. 'Albion' plants grown under the red–blue and white-light treatments had the lowest photosynthetic rates (Figure 2A,B; Table 2), which corresponded to the lowest vegetative biomass and leaf area (Table 1). Conversely, plants grown under light spectra that contained some green light (pink and warm white) had the highest photosynthetic and biomass parameters, but too much green light, such as in the white-light treatment, reduced these parameters. It is worth noting that morphological and physiological measurements were only conducted on cv. 'Albion'. While similar trends were visually observed in the morphology of cv. 'Favori', the results from cv. 'Albion' should not be extrapolated to cv. 'Favori'. The addition of green light has been shown to increase plant growth rates [19,20]. In tomatoes, adding green light to a supplemental light spectrum has been shown to increase not only biomass but also fruit production [8]. Similarly, the introduction of green light to a red–blue spectrum in a sole-source lighting setting was observed to increase biomass gain in lettuce [21].

Like lettuce, strawberry is a small canopy crop that does not have the same issues related to light penetration as vining greenhouse crops such as tomatoes. In fact, a strawberry canopy is closer in light environment to a single leaf than a vertical vining-crop canopy. Therefore, it is more appropriate to look at the impact of green light in this way. Although red and blue light are more readily absorbed by leaf chlorophyll [7,22], green light is able to penetrate deeper within a leaf [23–25]. While increased green light penetration through the canopy has been shown to not be the case in large vertical vining-crop [26], this higher rate of penetration within a single leaf can lead to increased photosynthetic rates. In fact, the removal of green lighting from a white-light spectrum was observed to reduce real-time photosynthesis and photosynthetic capacity in lettuce [27]. Therefore, we suggest that the addition of green light to a supplemental light spectrum can increase photosynthetic capacity and biomass. However, it is important to note that there seems to be an upper limit as to the percentage of green light that is beneficial [28]. The percentage of green light was approximately 0.5%, 12%, 24%, and 43% for the red–blue, pink, warm-white, and white-light treatments, respectively. Within the tested commercial spectra, the warm-white treatment (24% green) was associated with greater photosynthetic capacity and biomass than the white-light treatment (43% green). However, the experiment was not designed to independently isolate the green-light percentage from the other wavelengths. Since the percentage of green light is associated with the broadness of a spectrum, utilizing a broad spectrum that does not positively impact plant attributes or yield and has a lower efficacy may be detrimental to overall profitability.

4.2. Impact of Spectral Composition and EC on Fruit Yield and Quality

Fruit yield was similar among all light compositions and irrigation EC treatments. This result aligns well with previous work that showed that, under uniform PPFD, strawberry yield remained similar under different spectral compositions [29]. Although, there were differences in the photosynthetic rate and biomass production, no impact on yield was observed. This suggests that the increases in carbon fixation and photo-assimilate production were partitioned to vegetative biomass as opposed to fruits [30]. Future research should look at the ability to drive photo-assimilate partitioning to the fruit to take advantage of high carbon fixation rates under certain light spectra.

The sustained yield under the low-EC treatment suggests that this level of fertigation is sufficient for strawberry production. This result corroborates a previous study that suggested a reduced nitrogen rate can improve flower and fruit development in strawberries

under sole-source lighting [31]. Our results suggest that a reduced fertigation regime can maintain yield and reduce the fertilizer requirement and may provide opportunities to reduce fertilizer inputs and associated production costs. Future research related to EC levels should focus on levels lower than 2 mS cm^{-1} to find the lower limit acceptable to maintain yield and further reduce this input cost for growers.

Surprisingly, the EC levels did not affect TSS or titratable acidity. In an Australian field trial, lowering the EC from 3 mS cm^{-1} to 2 mS cm^{-1} was observed to improve berry sweetness, a trait often associated with TSS levels [32]. In contrast, for strawberry plants grown in a growth chamber, an EC level of 3.0 mS cm^{-1} increased TSS, vitamin C, and antioxidant levels compared to those grown at 1.5 mS cm^{-1} [33]. Key differences between the aforementioned studies and ours could explain the discrepancies between the results—namely, the growing environment (field [32], growth chamber [33], or greenhouse (ours)) and cultivars. This suggests that the EC requirements of strawberry plants, including growth media and genotypes, may be dependent on the growing environment.

Titratable acidity (TA) and the ratio of TSS:TA have been associated with the sweetness and bitterness flavour profiles of strawberries. Here, we observed that broad-spectrum lighting generally reduced the titratable acidity compared to the red–blue light treatment and, conversely, increased the TSS:TA ratio. The conclusion that narrow-spectrum supplemental lighting can increase TA and reduce TSS:TA is also supported by research in tomatoes [34] and strawberries [11]. This finding suggests that utilizing a more narrow-wavelength supplemental lighting strategy can alter acidity-related quality traits commonly associated with flavour perception [35].

4.3. Red-Rich, Narrow-Wavelength Supplemental Lighting Can Reduce Lighting-Associated Costs While Maintaining Yield

During winter production, the introduction of electrical lighting is a large operating expense for growers and can represent up to 30% of operating costs [36–39]. Therefore, identifying technologies or strategies to reduce lighting-associated costs is an important factor for improving the economic sustainability of strawberry production. Within the parameters tested in this study (i.e., fixture type, electricity prices in the region, production system and local climate), the red-rich red–blue lighting maintained statistically similar yield while reducing the estimated lighting electricity costs relative to broader-spectrum fixtures. When normalized for irrigation ECs, our study showed that utilizing high-efficacy, red-rich, narrow-wavelength supplemental lighting can significantly reduce lighting electricity costs without compromising yield. Since the underlying differences in fixture efficacy are 33.3% between red–blue (red-rich) and white treatments, the differences in electricity cost per Kg of strawberry (73.5% in “Albion” and 58.6% in “Favori”) are likely associated with both the yield difference and photon efficacy of different light treatments. Therefore, high-efficacy, red-rich, narrow-wavelength supplemental LED lighting fixtures can reduce lighting-associated electricity use and costs, two barriers to profitable, year-round greenhouse strawberry production [40]. Although the current cost of white LED chips is lower than that of red or blue LED chips because of massive white LED chip production and economies of scale (for general lighting), the cost difference is expected to diminish as more red-rich or red–blue LED growing light is adopted in CEA.

5. Conclusions

The presented study demonstrates that supplemental LED light compositions can influence vegetative growth, fruit quality, and lighting electricity costs in greenhouse strawberry production. The economics of the study are limited in scope to lighting electricity costs and do not take into account other production costs (i.e., fixture costs, labour, nutrients,

heating, etc.). Fruit yield remained statistically similar across all lighting and irrigation EC treatments in both cv. ‘Albion’ and cv. ‘Favori’. Under the tested winter greenhouse conditions, red-rich red–blue fixtures (95.1% red, 4.4% blue and 0.5% green light) provided the lowest estimated lighting electricity cost per kilogram of fruit because of their higher fixture efficacy while maintaining yield comparable to that of broader-spectrum fixtures. In contrast, spectra containing moderate amounts of green light promoted greater vegetative biomass and photosynthetic capacity in cv. Albion. These findings suggest that narrow wavelength light is sufficient to drive yield while also having a cost saving benefit due to the intrinsically higher fixture efficacy.

Author Contributions: J.L.: Conceptualization, data curation, formal analysis, investigation, methodology, writing—original draft, and writing—review and editing. S.S.L.: Data curation, investigation, writing—review and editing. C.L.: Data curation and investigation. X.H.: Conceptualization, funding acquisition, investigation, project administration, supervision, writing—original draft, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare that financial support was received for this work and/or publication. The study was funded by a grant from Agriculture and Agri-Food Canada to X.H. for project J-003433.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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