Evaluation of Biochemical Composition in Field-Grown Tea (Cultiva: TRI 2043) Using Agrophotovoltaic-Driven LED Lighting

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Abstract. Agrophotovoltaic (APV) systems integrate agriculture and solar energy generation on the same land, offering sustainable solutions for food and energy production. In order to stay competitive in the global market for specialty teas, it is beneficial to enhance the biochemical composition of the Sri Lankan tea cultivars. This study examined the effects of wavelength provided by photovoltaic-powered LED light on yield and quality parameters of mature field-grown tea plants (cultivar TRI 2043), mainly focusing on pigment and polyphenol contents. An APV system-powered LED lights provided blue and red lights to tea plants. Sunlight served as the control. Yield, shoot density, and anthocyanin, polyphenol, and chlorophyll contents in tea shoots were measured. The light spectrum measurements showed that the control plants received natural light at 317-886 nm, while plants under APV systems received blue light at 420-460 nm, and red light at 600-700 nm. The anthocyanin was highest in the 1st and 2nd leaves, while polyphenol peaked in the bud and declined with leaf maturity. Chlorophyll content increased with leaf maturity. The anthocyanin content in the bud, 1st and 2nd leaves was significantly reduced ($p<0.05$) under blue light compared to the control, while red light showed no significant change. Blue light significantly increased ($p<0.05$) polyphenol, chlorophyll a, and total chlorophyll contents ($p<0.05$). Neither of the light treatments significantly affected ($p<0.05$) tea yield or shoot density. In conclusion, blue light can be effectively used to increase chlorophyll and polyphenol levels in tea leaves. The wavelength effects on anthocyanin content warrants further study.

Keywords: Tea (*Camelia sinensis* L. (O.) Kuntze), Agrophotovoltaic system, Tea quality.

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1 INTRODUCTION

As consumer preferences increasingly lean towards high-quality and specialty teas, there is a growing emphasis on enhancing their biochemical composition to enhance the nutritional value and emphasize unique beverage qualities. The quality of most specialty teas is intrinsically linked to the bioactive compounds that are present in these teas, including polyphenols (catechins), caffeine, amino acids such as theanine, various volatile secondary metabolites and pigment molecules. Amongst these, polyphenols hold particular significance, as tea is known to be one of the richest sources of flavonoids, which are responsible for its distinctive taste and colour, and the health benefits associated with its consumption [1]. In addition, anthocyanins, a type of flavonoid is significant in specialty teas such as purple tea due to their health-promoting properties and their contribution to the distinctive colour and taste of tea [2]. Similarly, chlorophyll is the most important pigment in green tea imparting its colour [3]. The accumulation of these quality and flavour-related compounds in tea leaves is directly influenced by environmental factors, including light, water availability, soil nutrients, and altitude [4].

Light regulates many plant physiological processes and biochemical pathways, including photosynthesis and the production of secondary metabolites. Different wavelengths of light influence distinct physiological processes; for instance, blue light enhances chlorophyll production and stomatal activity, while red light promotes photosynthesis and flowering. Ultraviolet (UV) light, on the other hand, stimulates the synthesis of protective pigments such as anthocyanins [5]. Light intensity is equally important, with optimal levels boosting photosynthesis and metabolite production, though excessive intensities can lead to photoinhibition.

In response to increasing land-use pressure and a growing demand for renewable energy, agro-photovoltaic (APV) systems have emerged as a promising solution. These systems combine agricultural production with photovoltaic (PV) energy generation on the same land, thereby optimizing land-use efficiency. In addition to energy production, PV panels offer the additional benefit of providing partial shading, which can mitigate heat stress and reduce water loss in crops [6]. However, a significant limitation of conventional APV systems is that these obstruct sunlight, impairing photosynthesis and the synthesis of quality-related metabolites in tea plants.

To overcome this challenge, advanced APV designs incorporate transparent PV modules or employing spatial arrangements that facilitate adequate sunlight penetration. A particularly innovative approach involves integrating light-emitting diode (LED) systems, powered by PV electricity generated, to supplement light beneath the panels. LEDs offer remarkable spectral flexibility and energy efficiency, allowing for precise tailoring of light delivery to specific wavelengths at optimal intensities. This targeted light manipulation can significantly enhance both plant growth and, crucially, the production of secondary metabolites such as anthocyanins [7].

This emphasis on specialty teas is particularly relevant for products such as purple tea and green tea. Purple tea is derived from anthocyanin-rich cultivars and has gained considerable commercial importance in countries such as Kenya, China, and India. While Sri Lanka possesses cultivars with the potential for purple tea production,

increasing the anthocyanin content of these cultivars would be highly beneficial. Similarly, other specialty tea types could benefit from enhanced levels of other pigments such as chlorophyll (in green teas, Macha teas, etc.) and polyphenols. Modifying the light environment using APV-powered LED systems present a viable strategy to enhance the accumulation of polyphenols, anthocyanin and other bioactive compounds, thereby improving the overall quality of Sri Lankan tea cultivars.

Therefore, this study introduces a novel approach by integrating PV technology with LED lighting within APV systems. The objective of this study was to investigate the effect of different wavelengths of light (i.e. blue and red light) emitted by LED lights powered by photovoltaics on biochemical composition of tea shoots with 'three leaves and a bud', particularly on pigment content. The results can be used in enhancing tea quality, addressing the limitations of conventional APV systems and harnessing the benefits of tailored artificial lighting.

2 MATERIALS AND METHODS

2.1 Experimental site

The study was conducted from December 2024 to March 2025 at the 'Aroma Acres Study Fields', a research, teaching, and demonstration site located on the Meewathura farm, University of Peradeniya, Sri Lanka (7.25299 °N, 80.59576°E). The site is situated in the WM3 agro-ecological region, which belongs to the mid-country wet zone. The area experiences mean annual temperatures ranging from 18 °C to 32 °C, and an average annual rainfall of approximately 2500 mm.

2.2 Plant material and experimental design

Approximately 5 years old, field-grown tea plants (cultivar TRI 2043) were used, which were last pruned in 2024. The tea bushes were planted in two rows of a double hedgerow planting system [8], with seven uniform, healthy tea bushes as replicates per treatment in each plot. An APV system powered the lighting setup, with LED lights positioned 1.5 feet above the plant canopy. Three treatments were applied, including blue light (400–495 nm), red light (590–710 nm), and natural sunlight as the control treatment (Fig. 1A and B). The treatments were arranged as a randomized complete block design with two blocks. The treatments were randomized within the blocks (Fig. 1C).

The experiment was conducted over a 2-month period and blue and red light were supplied to plants using an APV System. The solar panels supplied power to the LED lights, and plants were illuminated for 12 h per day (6:00 a.m. – 6:00 p.m.). Blue shade netting (75% shade) was used to cover the sides of the plots to minimize light contamination from outside the plots. Standard agronomic practices, including fertilization and weeding, were uniformly applied across all treatments.

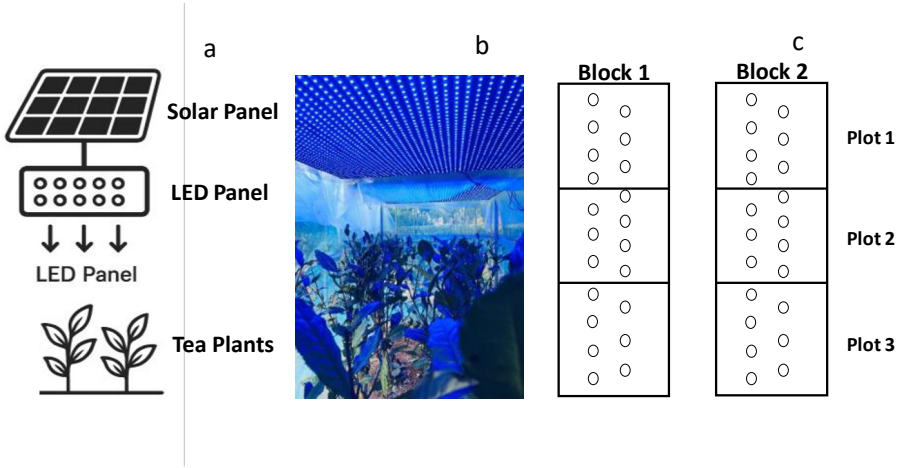

Fig. 1. The experimental setup: (a) A schematic diagram of the experimental setup, (b) photograph of the tea plants under blue light, and (c) experimental layout, where the plots were assigned to treatments (circles indicate tea plants).

The light spectrum was measured using a spectroradiometer (SpectraPen mini, Czech Republic), 3 times per day, 9.00 am,12.00 pm, and 3.00 pm on bright sunny days.

2.3 Biochemical measurements

Anthocyanin Content.

Total anthocyanin content was measured weekly from harvested flushes (three leaves and bud). Samples were extracted using ethanol: distilled water: HCl solution (70:30:1, v/v/v), centrifuged twice at 4430 rpm for 10 min at 4 °C, and diluted 40 times before absorbance measurement at 530 nm using a UV-visible spectrophotometer. Anthocyanin concentration (mg/100 g fresh weight) was calculated using cyanidin-3-glucoside as the standard (MW = 449.2 g mol^{-1}, ε = 26,900 $L \cdot mol^{-1} \cdot cm^{-1}$) following the method of [9].

$$\text{Total anthocyanin content (mg cyanidin} - 3 - \text{glucoside equivalent per 100 g FW)} = \frac{A \times MW \times DF \times 10^3}{\varepsilon \times 1}$$

where,
A = Absorbance (Abs) at 530 nm
MW (molecular weight) = 449.2 g/mol for cyanidin-3-glucoside (cyd-3-glu)
DF = dilution factor (40)
1 = cuvette path length in cm
Ɛ = 26900 molar extinction coefficients, in L x mol^{-1} x cm^{-1}, for cyd-3-glu
10^3 = factor for conversion from g to mg

Polyphenol Content.
Leaf polyphenols were quantified weekly using the Folin–Ciocalteu method. Methanolic extracts (80%) were reacted with 0.25 N Folin–Ciocalteu reagent and 1 N sodium carbonate. Absorbance was measured at 725 nm. Gallic acid was used to construct a standard calibration curve, and results were expressed as gallic acid equivalents (GAE, mg g^{-1}) as described by [10].

Chlorophyll Content.
Chlorophyll a, b, and total chlorophyll were extracted from leaf tissue using 80% acetone and quantified by measuring absorbance at 645 nm and 663 nm. Concentrations were calculated using the equations proposed by [11].

- Chlorophyll a (mg g^{-1}) = $[12.7 \times A_{663} – 2.69 \times A_{645} \times V / (1000 \times W)$
- Chlorophyll b (mg g^{-1}) = $[22.9 \times A_{645} – 4.68 \times A_{663}] \times V / (1000 \times W)$
- Total chlorophyll (mg g^{-1}) = $[20.2 \times A_{645} + 8.02 \times A_{663}] \times V / (1000 \times W)$

where V is the extract volume and W is the sample fresh weight.

Yield and Shoot Density.
Fresh flush yield was recorded weekly by weighing harvested shoots. Shoot density was measured using a 0.04 m² quadrant placed randomly within each treatment plot. Three replicates were assessed per treatment.

2.4 Statistical analysis

All parametric data were analyzed using one-way analysis of variance (ANOVA). Significant differences between treatments and control were determined using Duncan's multiple range test at a 95% confidence level ($p < 0.05$). Statistical analyses were performed using SAS software [SAS Institute Inc., USA].

3 RESULTS AND DISCUSSION

3.1 Light Spectrum

Light spectrum measurements showed that control plants under open conditions received light in wavelengths between 317-886 nm (Figure 2a). The APV systems provided blue and red light at peaks of 420-460 nm and 600-700 nm, respectively (Figure 2b and c, respectively).

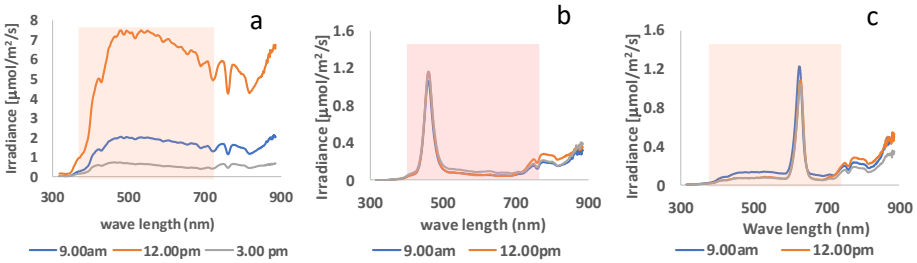

Fig. 2. a. Light spectrum in the control plants, b. under blue light, and c. under red light.

3.2 Anthocyanin Content

Anthocyanin contents of the different leaves of the shoots are presented in Table 1. Significant differences ($P<0.05$) in anthocyanin contents were observed in the bud/ leaves with different maturities (within each column) of shoots as well as amongst the different light treatments (within each row). In cultivar TRI 2043, the highest content of anthocyanin was observed in the 1st and 2nd leaves of the shoot under all lighting conditions. The bud contained the lowest anthocyanin content, followed by the 3rd leaf.

Table 1. Anthocyanin content of different leaves of the shoot under different lighting conditions.

	Anthocyanin Content (mg per 100 g Fresh weight)		
	Blue light	**Red light**	**Control**
Bud	$15.28\pm14.68^{c, B}$	$54.74\pm33.54^{a, A}$	$48.11\pm26.52^{c, AB}$
1st leaf	$38.68\pm14.87^{b, B}$	$104.19\pm34.91^{a, A}$	$78.69\pm26.73^{b, A}$
2nd leaf	$58.27\pm9.32^{a, B}$	$108.54\pm13.53^{a, A}$	$103.84\pm22.00^{a, A}$
3rd leaf	$48.31\pm13.94^{ab, A}$	$64.65\pm31.23^{a, A}$	$57.42\pm13.35^{bc, A}$

Note: Values represent mean ± standard deviation (n = 7). The superscript simple letters with each value indicate Duncan grouping of values within a column (under each light treatment). The superscript capital letters indicate Duncan grouping of values within a row (under each growth stage in the leaves of the shoot). The same letters indicate no significant differences and different letters indicate significant differences at $p<0.05$.

The present study revealed that leaf anthocyanin content was lowest in the bud, with higher concentrations observed in the first and second leaves compared to the third leaf. Specifically, blue light treatment significantly decreased anthocyanin content in the bud, first, and second leaves ($p<0.05$), although no significant difference was found in the third leaf compared to the control. In contrast, the increase in anthocyanin levels in all leaf growth stages (bud, first, second, and third) under red light was not statistically significant.

Blue light plays a crucial role in various aspects of plant development, including chloroplast development, stomatal opening, and photomorphogenesis, influencing seedling growth, stem elongation, leaf expansion, and leaf morphology [12]. While high-energy blue photons are efficiently absorbed by chlorophyll a and b, enhancing

photosynthetic activity, their energy efficiency for photosynthesis is slightly lower than red light due to heat dissipation during photochemical reactions [13]. In contrast, red light is highly efficient for photosynthesis, aligning with chlorophyll's absorption peaks and inducing both photosystem I and II activities. It also promotes carbohydrate accumulation and biomass production in plants. The higher quantum yield of red light, compared to blue light makes, it a key component in artificial lighting systems designed for plant growth [14]. Nevertheless, natural sunlight offers a comprehensive and balanced spectrum across the photosynthetically active radiation (PAR) range, ensuring optimal energy distribution for photosynthesis through the activation of accessory pigments, such as carotenoids, which effectively capture wavelengths less absorbed by chlorophyll [13].

Anthocyanin biosynthesis is primarily under genetic control is also significantly modulated by external environmental factors, particularly light quality. Despite its importance in regulating stomatal activity and promoting vegetative development, blue light may redirect metabolic energy towards primary physiological processes at the expense of secondary metabolite synthesis, especially in younger tissues. This metabolic shift likely explains the reduced anthocyanin content observed in buds and the first two leaves under blue light. Research studies reported that blue light can downregulate key photoreceptors (e.g., CRY1/2, PHOT1/2) and transcription factors (e.g., MYBs, bHLHs) crucial for anthocyanin biosynthesis [7; 15], which aligns with the findings of the present study.

Red light, in contrast, exhibited a more complex influence. Some studies show that red light inhibits anthocyanin production in certain crops such as grape [16]. However, this response could be a species- or tissue-specific response. Red light is known to activate phytochromes and downstream signaling components, such as HY5 and the MYB–bHLH–WD40 complex, which collectively promote anthocyanin-related gene expression. Moreover, red light may stimulate ABA-related pathways that support both anthocyanin synthesis and its subsequent vacuolar transport, compensating for potential reductions in pigment levels [17]. These mechanisms likely explain the stable anthocyanin concentrations observed under red LED treatment in this study.

Anthocyanins are known to play a photoprotective role in young, growing leaves by mitigation against photodamage allowing leaves to grow and develop normally [18], and also an adaptive strategy to reduce insect herbivory [19]. In tea, the anthocyanins are useful as it imparts health benefits and in production of special teas such as purple and pink teas which have high commercial values. Red light is known to stimulate anthocyanin biosynthesis in many crops including leaves of *Aglaonema commutatum* [20], and American cranberry [21]. In the present study, varying red light intensities were not tested. The study was conducted only for a period of 2 months. Therefore, it may be interesting to test increased red light intensity for a longer period of time in developing the anthocyanin levels in tea shoots.

3.3 Total polyphenol content.

As shown in Table 2, the highest total polyphenol content was present in the bud, with concentrations progressively decreasing as the leaf matured. This study also found that

blue light treatment significantly increased polyphenol content particularly in the bud and second leaf ($p<0.05$) compared to the control, while no significant difference was observed in the first and third leaves. Conversely, red light treatment did not significantly alter the total polyphenol content in any of the tested leaves (bud, first, second, or third leaf) compared to the control ($p<0.05$).

Table 2. The total polyphenol content of different leaves under different lighting conditions.

	Total Polyphenol Content (mg g^{-1} fresh weight)		
	Blue light	**Red light**	**Control**
Bud	$1.1\pm0.44^{a, A}$	$0.34\pm0.03^{a, B}$	$0.41\pm0.05^{a, B}$
1st leaf	$0.27\pm0.11^{b, A}$	$0.34\pm0.11^{a, A}$	$0.22\pm0.08^{b, A}$
2nd leaf	$0.43\pm0.07^{b, A}$	$0.22\pm0.06^{a, B}$	$0.27\pm0.07^{b, AB}$
3rd leaf	$0.21\pm0.09^{b, A}$	$0.26\pm0.04^{a, A}$	$0.14\pm0.11^{b, A}$

Note: Values represent mean ± standard deviation (n = 7). The superscript simple letters with each value indicate Duncan grouping of values within a column (under each light treatment). The superscript capital letters indicate Duncan grouping of values within a row (under each growth stage in the leaves of the shoot). The same letters indicate no significant differences and different letters indicate significant differences at $p<0.05$.

Tea leaves are a rich source of health-promoting secondary metabolites, including flavonoids, caffeine, theanine, and volatile compounds. Light plays a crucial role in regulating the biosynthesis of these metabolites, and various studies have utilized shading techniques to manipulate light intensity and, consequently, modify tea quality [22]. Previous research indicates that blue light, particularly at 470 nm, can enhance the production of volatile compounds and activate their associated genes [23; 12]. Furthermore, short-term exposure to high-intensity blue light during the night has been shown to upregulate key transcription factors (e.g. MYBs, CRY2/3, SPAs, HY5), leading to increased anthocyanin and catechin content [24].

Young tissues are metabolically more active and exhibit higher expression of genes involved in secondary metabolite biosynthesis. Blue light, known to activate transcription factors such as HY5 and MYBs, likely enhanced flavonoid and polyphenol biosynthesis pathways more efficiently in these younger tissues. In contrast, older, third leaves may have already passed their peak metabolic activity, thus showing no significant changes in response to blue light [24]. In plants, polyphenols act as protectants against abiotic stresses such as drought, salinity, extreme temperatures, high light intensities and UV radiation as well as biotic stressors such as diseases and insects [25; 26]. These are strong antioxidants, characterized by interaction with reactive oxygen species, which manifests itself not only in plants but also in the human body, once they enter body through food [26]. Therefore, the deliberations of the study will be valuable in enhancing the biological activity of tea, which is a rich source of polyphenols.

3.4 Chlorophyll content.

As presented in Table 3, chlorophyll a, chlorophyll b, and total chlorophyll contents consistently showed the lowest levels in the buds, gradually increasing with leaf

maturity, regardless of the light treatment. The present study also revealed that none of the treatments showed a significant difference between them ($p<0.05$) or compared to the control across the different leaf maturities. Regarding total chlorophyll content, blue light led to a significant increase ($p<0.05$) compared to the control, but only in the bud. Neither blue nor red light treatments caused a significant difference in total chlorophyll content in the first, second, or third leaves compared to the control.

Table 3. Chlorophyll a, b, and total chlorophyll contents (mg g^{-1} fresh weight) of different leaves of the shoot under different lighting conditions.

		Blue light	Red light	Control
Chlorophyll a	Bud	$0.41\pm0.13^{a, A}$	$0.23\pm0.01^{a, B}$	$0.23\pm0.03^{a, B}$
	1st leaf	$0.65\pm0.08^{a, A}$	$0.61\pm0.05^{b, A}$	$0.55\pm0.04^{b, A}$
	2nd leaf	$0.85\pm0.58^{b, A}$	$0.86\pm0.15^{bc, A}$	$0.89\pm0.06^{c, A}$
	3rd leaf	$1.03\pm0.25^{b, A}$	$1.21\pm0.07^{c, A}$	$0.95\pm0.11^{c, A}$
Chlorophyll b	Bud	$0.06\pm0.03^{a, A}$	$0.07\pm0.05^{a, A}$	$0.07\pm0.01^{a, A}$
	1st leaf	$0.19\pm0.04^{a, B}$	$0.26\pm0.03^{b, A}$	$0.21\pm0.02^{b, AB}$
	2nd leaf	$0.33\pm0.01^{b, A}$	$0.46\pm0.17^{c, A}$	$0.36\pm0.06^{c, A}$
	3rd leaf	$0.38\pm0.07^{b, A}$	$0.45\pm0.17^{c, A}$	$0.30\pm0.07^{c, A}$
Total Chlorophyll	Bud	$0.55\pm0.12^{a, A}$	$0.33\pm0.03^{a, A}$	$0.34\pm0.04^{a, A}$
	1st leaf	$0.76\pm0.13^{ab, A}$	$0.90\pm0.06^{b, A}$	$0.80\pm0.04^{b, A}$
	2nd leaf	$1.37\pm0.34^{c, A}$	$1.51\pm0.24^{c, A}$	$1.37\pm0.20^{c, A}$
	3rd leaf	$1.31\pm0.19^{bc, A}$	$1.76\pm0.17^{c, A}$	$1.35\pm0.28^{c, A}$
Chlorophyll a/b ratio	Bud	5.39 ± 0.89	2.22 ± 0.18	3.04 ± 0.76
	1st leaf	4.19 ± 1.58	2.36 ± 0.1	2.40 ± 0.49
	2nd leaf	2.20 ± 0.63	2.05 ± 0.79	2.66 ± 0.38
	3rd leaf	2.86 ± 1.1	2.33 ± 0.2	3.37 ± 1.1

Note: Values represent mean ± standard deviation (n = 7). For each parameter, the superscript simple letters with each value indicate Duncan grouping of values within a column (under each light treatment). The superscript capital letters indicate Duncan grouping of values within a row (under each growth stage in the leaves of the shoot) for each parameter. The same letters indicate no significant differences and different letters indicate significant differences at $p<0.05$.

Blue light, with its higher energy content, is known to activate specific photoreceptors, particularly cryptochromes. This activation subsequently triggers signaling pathways that upregulate chlorophyll biosynthesis. Increased activity of key enzymes within the tetrapyrrole biosynthetic pathway, such as glutamyl-tRNA reductase, 5-aminolevulinic acid dehydratase, and protochlorophyllide oxidoreductase, are known to be regulated by blue light-mediated signaling, increasing chlorophyll accumulation under blue light [27].

In contrast, red light is primarily absorbed by phytochromes, which are crucial for photomorphogenesis but seem less directly involved in modulating chlorophyll biosynthesis in tea plants [27]. Studies such as [28], suggest that red light's effect on chlorophyll composition is more pronounced when combined with blue light. Blue light significantly enhances chloroplast development, leading to increased chloroplast density

and thicker leaf tissues, which directly improves chlorophyll content. In the absence of blue light, chlorophyll content tends to be lower, as red light alone does not optimize chloroplast development as effectively. Therefore, while red light contributes to photosynthesis, its impact on chlorophyll composition is significantly enhanced when paired with blue light, which better regulates the photosynthetic apparatus and overall leaf growth [7].

Exposure to blue light significantly enhances the synthesis of chlorophyll pigments, notably chlorophyll a [29]. This is attributed to the stimulation of chloroplast development and increased stomatal conductance under blue wavelengths, collectively optimizing the plant's photosynthetic capacity. However, these findings do not align with the observations in the current study, warranting further investigation. As the present study was conducted only for a short period, it may be recommended to continue the study for a longer period with higher light intensities.

3.5 Yield and shoot density.

In the present study, none of the treatments significantly ($p<0.05$) affected yield and shoot density compared to the control during the study period (Fig. 3a and 3b).

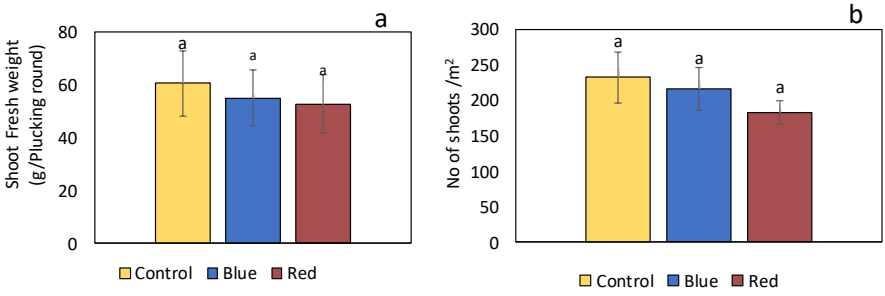

Fig. 3. (a) Tea yield (shoot Fresh weight per Plucking round) and (b) shoot density under different lighting conditions. Error bars are SE of means, and the same letters denote no significant differences between treatments ($P<0.05$)

Blue and red light play complementary roles in regulating shoot development and overall plant morphology. While red light promotes stem elongation, its sole application can lead to excessive vertical growth and abnormal structures such as elongated shoots and curled leaves, as observed in several crops, including potato and lettuce [Ju et al., 2024]. In contrast, blue light acts as a growth modulator by suppressing stem elongation and promoting proper shoot and leaf development. Even low intensities of blue light are sufficient to correct morphological abnormalities induced by red light. When combined, red and blue light exert a synergistic effect, supporting both elongation and structural integrity, leading to balanced and healthy plant growth. The effectiveness of this combination is, however, dependent on the species and developmental stage [7]. Although the current study was limited to a three-month observation period, the results suggest promising short-term effects of APV-driven LED lighting on tea yield and quality. If these effects persist or improve over multiple harvest cycles, it could potentially lead

to sustained improvements in biochemical composition and overall productivity. However, long-term studies are needed to confirm the stability of these responses across different seasons and growth stages.

4 CONCLUSION

This study demonstrated that blue light, delivered by PV-powered LEDs, significantly reduced anthocyanin content while concurrently enhancing chlorophyll and total polyphenol contents. In contrast, red light did not significantly alter anthocyanin, polyphenol, or chlorophyll contents compared to the control. Notably, neither light treatment significantly improved yield or shoot density. It is therefore recommended that treatments be continued for a longer duration with increased light intensities to assess their long-term effects.

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