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The influence of light-emitting diodes and sulfur–silica on the growth, yield, and biochemical content in lettuce Influence of LEDs and sulfur–silica on lettuce

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ABSTRACT

Soilless cultivation with artificial lighting has the potential to augment vegetable crop production, particularly lettuce, but yields are lower compared to natural sunlight, especially in monochromatic light technologies. Research suggests that color blending with light-emitting diodes (LEDs) can enhance production, yet many overlook the importance of nutrient management. The use of sulfur–silica fertilizer, known for enhancing plant growth in low-light stress conditions, supports this assertion. The study employed a randomized complete block design with two factors, each repeated four times. The treatments included three LED light colors: white LED (L1), blue LED (L2), and red LED (L3). Two fertilizer treatments were applied: absence of sulfur–silica fertilizer (P1) and presence of sulfur–silica fertilizer (P2). The study finds that optimal growth of lettuce plants is achieved through the utilization of both red and white LED lights, with red LED yielding the highest fresh leaf weight. The red LED treatments outperform other LED colors in terms of protein, carbohydrate, and total energy production. Introducing sulfur–silica fertilizer can promote superior lettuce growth, albeit at the cost of reduced fresh leaf weight. The application of sulfur–silica fertilizer leads to decreased protein and carbohydrate levels but enhances the overall energy content of the lettuce.

1. INTRODUCTION

Lettuce (*Lactuca sativa* L.) is a nutrient-rich consumable plant with a high level of interest. This is because vegetable consumption in Indonesia stands at 97.3%, which is further driven by population growth [1]. Lettuce cultivation holds high economic value. The development of indoor lettuce cultivation presents a promising opportunity. This is associated with providing a solution to meet the increasing demand for food and nutrition in the face of extreme climate conditions and global warming, which lead to reduced crop production. Another issue arises in lettuce crops exposed to high levels of N, which is the accumulation of nitrate (NO_3^-) in leaves, stored in the vacuoles [2]. This has been associated with health issues in consumers [3].

Plants require light as an energy source for their growth and development. Inadequate light can disrupt physiological processes and photosynthesis [4]. Artificial lighting can be provided using light-emitting diodes (LEDs) to produce an electromagnetic spectrum that accelerates plant growth [5]. Supplemental LED lighting necessitates the provision of light characterized by specific quality and wavelength attributes. Plants exhibit optimal growth when exposed to light within the wavelength range of approximately 400–700 nm [6]. The red and blue LED lights as a substitute for sunlight support the photosynthesizing process in plants, ensuring the fulfillment of light requirements [7]. Plant growth remains suboptimal because of insufficient energy for photosynthesis despite LEDs not fully achieving effectiveness as a sunlight substitute.

Cultivating lettuce through soilless or indoor farming proves effective as it enables a controlled environment. The indoor farming concept facilitates easier regulation of environmental factors such as temperature and lighting, enabling optimal plant growth independent of external climate or land conditions [8]. Light is a crucial factor in plant cultivation and requires careful consideration when implementing indoor farming. Plants cultivated using the indoor farming concept do not receive sufficient light intensity, so light such as LEDs is needed

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as a substitute for sunlight. LEDs as a sunlight substitute are not fully effective, resulting in suboptimal plant growth attributed to insufficient energy for photosynthesis [9].

Prior investigations extensively delved into monochromatic light's impact on the growth and physiochemical conditions of leafy vegetables, such as lettuce, spinach, kale, and basil, at various light intensities [10,11]. Optimizing growth in soilless cultivation of lettuce using monochromatic artificial light technology tends to be focused on color-blending technology, achieved through adjusting the use of light waves at specific growth stages [12,13]. Artificial light at a wavelength of 437 nm, predominantly blue, can support chloroplast development, while light with a band at 678 nm, associated with red, plays a crucial role in promoting photosynthesis. The monochromatic yellow light has been reported to yield a negative response to lettuce growth due to its discrete nature and lack of red components [12]. The determinants of production in soilless plant cultivation are not solely determined by LED-emitted light but also involve nutrient management [14]. Sulfur and silica (Si), as essential nutrients, capable of stimulating plant growth under stressful conditions, can be considered for use in soilless lettuce cultivation using monochromatic light.

Si is classified as a beneficial or useful element for plant growth [15,16]. The positive effects of silica on crops encompass increased yield, enhanced resistance to pests and diseases (biotic factors), and alleviation of metal toxicity, salt stress, and drought stress (abiotic factors) [17]. Silica is recognized as an essential nutrient for plant growth. The application of silica serves as a nutrient and stimulates plant stress responses in challenging conditions [18]. Silica is a versatile micronutrient that provides advantages under stressed conditions. Silica fertilizer application has an impact on the height, fresh weight, dry weight, and leaf count of pak choi plants, even when they are subjected to heavy metal stress [19]. Plants subjected to stress respond to silica by reinforcing cell walls to maintain growth stability [20]. Silica within plant tissues can enhance plant photosynthesis activity [21].

The cultivation of lettuce using LED lights and the application of sulfur–silica fertilizer to enhance production have not been widely explored. The provision of silica is expected to help address the issue of insufficient lighting in indoor farming. This research aims to examine the influence of LED light colors and the addition of silica fertilizer using a wick hydroponic system to increase lettuce production in indoor cultivation.

2. MATERIALS AND METHODS

2.1. Time, Place, and Materials

The study was conducted from September to December 2022 in the Plant Ecophysiology Laboratory, Faculty of Agriculture, University of Jember. The materials used in this research included Batavia Anizel lettuce variety, sulfur–silica fertilizer, blue, white, and red LED lights, AB mix nutrient solution, rockwool, Lux meter (Kyoritsu 5202 Digital Light Meter Lux Meter), TDS meter (Total Dissolved Solids-Hanna-instrument-HI98192), and pH meter.

The nutrient solution was created by blending solutions A and B with the aid of AB mix fertilizers. The concentration of the AB mix nutrient solution ranged from 500 to 600 ppm for the first 12 days after transplanting (DAT). The nutrient concentration was increased to 800–1000 ppm until the 20th DAT. The concentration was further increased to 1200–1400 ppm until the time of harvest after reaching the 20th DAT. The concentrations of sulfur and silica fertilizer used were 150 ppm and 650 ppm, respectively.

2.2. Experimental Design

The research utilized a randomized complete block design (RCBD) with two factors, each repeated four times. The treatments included three LED light colors: white LED (L1), blue LED (L2), and red LED (L3). The LED light intensities used in this study are presented in Table 1.

Subsequently, there were two fertilizer treatments: without sulfur–silica fertilizer (P1) and with sulfur–silica fertilizer (P2). The silica–sulfur fertilizer employed is soluble plant fertilizer, a form of nanomaterial fertilizer created by the Korean company Kosifarm Co. The observed variables encompassed plant height, root length, root weight, leaf count, leaf area, fresh shoot weight, chlorophyll content (SPAD), approximate (ash content, total fat content, water content, total energy, carbohydrates, and protein content), as well as sulfur–silica content.

2.3. Measurement of Physicochemical Content and Data Analysis

The water content was determined using the oven-drying method, comparing the initial and final weights (constant weight of the sample after drying). Ash content was assessed using a muffle furnace. Fat content was determined using the Soxhlet method. The protein content in the leaf sample was analyzed following the Kjeldahl method [22]. Carbohydrate content was determined through differentiation, which involves calculating the carbohydrate content of each leaf sample using the formula: 100% – (% water + % ash + % protein + % fat).

The determination of sulfur content in plant tissues was carried out using the spectrophotometry method. Meanwhile, the determination of silica content was conducted using the gravimetric test method. Data analysis for this research involved analysis of variance and Duncan's post hoc test ($p < 0.05$).

3. RESULTS AND DISCUSSION

The analysis of variance results suggest that there is no significant interaction effect between LED light colors and sulfur–silica fertilizer on all observed variables [Table 2]. Individually, LED light colors exhibit a significant influence on plant height, leaf count, leaf area, root length, and fresh shoot weight. The application of sulfur–silica fertilizer significantly affects the fresh shoot weight and plant height variables. Proximate tests and sulfur–silica content in plants were not subjected to analysis of variance in this study; therefore, the data are presented descriptively.

The treatment with red LED lights (L3) resulted in the tallest lettuce plants, reaching a significant height of 19.39 cm, differing significantly

Table 1: Light and intensities used in the study (lux).

Red	Blue	White
1334	698	1780
1356	562	1938
1320	586	1820
	Mean	
1336.67	615.33	1846

Table 2: The summary of the analysis of variance results for all observed variables.

Variable	F-value		
	LED Color (L)	Sulfur–Silica Fertilizer (P)	L × P
Plant height	20.23**	4.99*	1.71ns
Root length	4.69*	0.19ns	2.39ns
Root weight	2.46ns	0.47ns	1.52ns
Leaf count	33.13**	0.04ns	1.18ns
Leaf area	18.11**	0.25ns	0.36ns
Shoot weight	4.15*	10.49**	0.22ns
Chlorophyll content	1.21ns	0.43ns	0.32ns

Notes: *p < 0.05, **p < 00.1, ns, not significant (p > 0.05)

Table 3: The influence of LED lights on plant height, leaf count, and leaf area of lettuce.

LED Color	Plant Height (cm)	Leaf Count	Leaf Area (cm2)
White	18.5 ± 0.35b	15.88 ± 1.25a	69.93 ± 9.72b
Blue	17.5 ± 0.9c	12.38 ± 0.52b	65.97 ± 12.5b
Red	19.39 ± 0.79a	12.38 ± 1.3b	101.56 ± 14.01a

Notes: The data are presented as mean ± standard deviation. Numbers followed by different letters indicate significant differences based on the Duncan's test at a 5% level of significance·

from other LED light treatments [Table 3]. Red LED lights exhibited a dominant effect on plant growth, proving that red light is optimal for plant photosynthesis [23]. The exclusive provision of red light can lead to unbalanced growth, resulting in taller but thinner plants with thinner leaves. Red light promotes plant height through auxin activation. The white LED lights produced the highest number of leaves, with 15.88 leaves, significantly differing from other LED light treatments [24]. The variation in light intensity attributed to the plants contributes to this difference, with low-light intensity restricting vegetative growth [25]. Red and blue LED lights have lower intensity compared to white light treatments [26].

The use of red LED lights resulted in the largest leaf area, measuring 101.56 cm², differing significantly from other light colors [Table 3]. This stems from the fact that red LED lights are more supportive of plant growth compared to other light colors. Red LED lights have a better wavelength for inducing better leaf growth in plants compared to blue LED lights [26]. The white LED lights (L1) produced the highest root weight compared to other LED light treatments, amounting to 15 g [Table 4]. Under white light, optimal conditions for indoor cultivation of lettuce plants can be provided. The white LED lights produced the longest root length, measuring 15.48 cm, differing significantly from other LED light treatments. White light is typically used as a control because its color closely resembles sunlight, and there's a possibility that this similarity could influence the root length results [27].

The red LED light treatment resulted in the highest shoot fresh weight, measuring 94.58 g, differing significantly from the other LED light treatments. The superior photosynthetic support provided by the red color, compared to other colors, can be attributed to this [28]. Red light has the highest electrical efficiency value, making it optimal for photosynthesis. The suitability of red light's wavelength for the photosynthesis process promotes plant production. The significant

Table 4: The influence of LED lights on lettuce shoot weight, root length, and root weight.

LED Color	Shoot Weight (g)	Root Length (cm)	Root Weight (g)
White	73.75 ± 12.75b	15.48 ± 2.56a	15.00 ± 2.67a
Blue	72.50 ± 8.02b	11.85 ± 2.08b	11.88 ± 2.59a
Red	82.50 ± 7.56a	14.51 ± 2.66a	14.38 ± 3.20a

Notes: The data are presented as mean ± standard deviation. Numbers followed by different letters indicate significant differences based on the Duncan's test at a 5% level of significance.

effect of red LED light on enhancing light morphogenesis results from its strong absorption by photosynthetic pigments [29].

The chlorophyll content (SPAD value) in lettuce plants reached the highest at 23.45 units under red LED lights (L3), with no significant difference observed compared to other LED light colors [Figure 1]. High light intensity in excessive conditions causes a decrease in plant chlorophyll, while insufficient light intensity can impede chlorophyll formation, resulting in reduced chlorophyll content [30].

The application of sulfur–silica fertilizer (P2) resulted in the tallest lettuce plants, measuring 18.73 cm, and significantly differed from the treatment without sulfur–silica fertilizer [Figure 2]. The growth enhancement is likely a result of the synergistic interaction between sulfur (S) and nitrogen (N) elements during the protein assimilation process in plants [31]. Silica (Si) also plays a crucial role, influencing the uptake of N, P, and K elements in lettuce plants [32]. In nutrient-deficient conditions, Si facilitates the uptake of NPK elements through complex physiological processes. These processes include upregulation of N-supply genes, conjugation with phosphorus to reduce the availability of toxic substances, and regulation of stelar K+ outward rectifier channel expression. Ultimately, this helps maintain xylem hydraulic conductance under water-deficit conditions [33].

Negative interactions between Si and NPK nutrient uptake have been observed under certain circumstances. Si can enhance nitrogen uptake under normal conditions, it might not effectively remobilize nitrogen to the leaves, indicating lower efficiency in nitrogen utilization [33]. Si-presence tends to reduce NPK content in lettuce leaves and roots in normal conditions, particularly as lettuce is an intermediate Si accumulator [34,35]. The presence of Si can enhance the growth of lettuce through the nitrogen dilution effect [34]. Linear application of

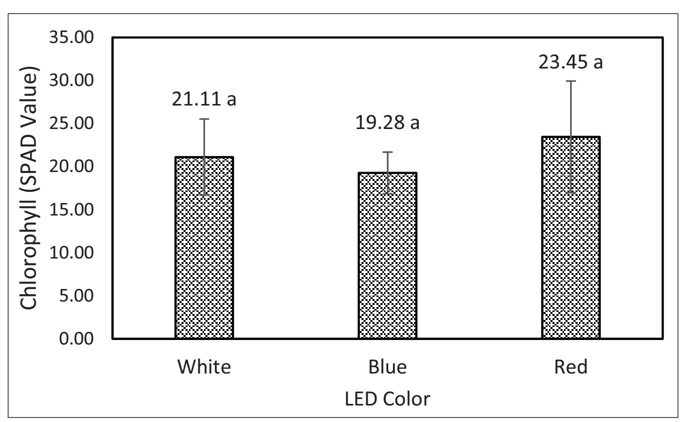

Figure 1: The influence of LED light colors on lettuce plant chlorophyll content (SPAD value). Notes: Different letters following the numbers indicate significant differences based on the Duncan's test at a 5% level of significance.

Si (up to 84 mg L^{-1}) increased the fresh weight of lettuce [36]. A dose of 0.4 mM Si enables a greater shoot fresh mass of lettuce [37]. This is reinforced by research showing a significant difference in the height of lettuce plants with Si fertilizer compared to Si-absence (control).

The treatment with sulfur–silica (P2) resulted in the highest number of lettuce leaves yielding 13.58 leaves [Figure 2]. The presence of sulfur in plants has been identified to influence plant responses to nitrogen (N) element application [38]. Insufficient sulfur (S) conditions in plants may disrupt the uptake of N elements, consequently affecting plant growth, as both S and N are essential nutrients crucial for protein synthesis [39].

The incorporation of silica–sulfur (Si-S) in plants has been observed to stimulate the production of antioxidant compounds, mitigating oxidative damage and enhancing plant tolerance to stress [40-42]. Si availability has been linked to an increased rate of photosynthesis, serving as a mitigation strategy against drought stress and mineral toxicity, while S enhances the biosynthesis of growth-related hormones. The application of S-Si also indirectly contributes to achieving improved harvest quality. High rate of nitrogen and sufficient phosphorus fertilization can influence the yield and postharvest quality of lettuce [43]. Si application (4 mL L^{-1}) can reduce lettuce mass loss within the range of 2.57% to 4.17% [44].

The application of sulfur–silica fertilizer (P2) resulted in the largest lettuce leaf area, measuring 80.47 cm². Silica (Si) decreases the levels of aluminum (Al) and iron (Fe) in plants under adequate conditions, also enhancing the availability of phosphorus (P) for plant uptake through phosphorus conjugation [45]. Available P, in turn, promotes plant growth, including increased leaf area, because it enhances photosynthetic activity and cell expansion [43]. Sulfur (S) leads to a larger leaf area when its requirements are met [46]. Applying Si to the foliage can enhance plant photosynthesis, influencing leaf area [47]. The N/S ratio in plants is also influenced by the availability of sulfur, which can affect plant photosynthesis rates with positive impacts on yield.

The treatment with sulfur–silica fertilizer (P2) produced the highest chlorophyll content (SPAD value), measuring 22 units [Figure 2]. This condition describes how plants can efficiently utilize available light. Efficient light utilization, coupled with a sufficient supply of soluble silicon for plants, can regulate CO_2 metabolism efficiently [48]. In this study, Si under adequate condition was able to provide higher chlorophyll values per leaf tissue area.

The treatment with sulfur–silica fertilizer (P2) resulted in the longest root length, measuring 14.17 cm [Figure 3]. Si levels positively correlate with P availability in plants, which can benefit root development [45]. The treatment with the absence of sulfur–silica fertilizer produced the lowest root weight, at 13.73 g, but it did not significantly differ from the sulfur–silica treatment. Phosphorus is absorbed by plants in the form of inorganic phosphate ions (HPO_4^{2-} or $H_2PO_4^{-}$) through the roots, playing a crucial role in various physiological processes within the plant (Zenda et al., 2021) [49]. Phosphorus also facilitates early shoot growth, accelerates ground cover for erosion protection, improves the quality of fruit, vegetable, and grain crops, and is essential for seed formation.

Adequate Si levels in plants increased P accumulation, leading to elevated dry matter and plant photosynthesis rates, thereby enhancing root uptake [50]. Silica (Si) has been documented to enhance the uptake of phosphorus by forming conjugates with it, thereby reducing the availability of toxic substances and minimizing the toxicity of minerals [33]. Sulfur (S) contributes to the biosynthesis of growth-related hormones [49]. In lettuce plants, sulfur is integral to the formation of cysteine and methionine, two essential amino acids required for the biosynthesis of hormones [41,51]. Sulfur, involved in the biosynthesis of growth-related hormones such as auxins, cytokinins, and gibberellins, plays pivotal roles in regulating cell division, cell elongation, and cell differentiation.

The treatment in the presence of sulfur–silica fertilizer (P2) resulted in the highest shoot fresh weight, measuring 81.25 g [Figure 3]. This is likely due to the influence of sulfur availability on plant growth. Adequate sulfur (S) for plants can increase protein content in plant tissues, contributing to enhanced plant growth [50]. Adequate Si levels can increase the fresh weight of tomato plants [52]. Si attributed to the increased water uptake in plant cells, which is essential for photosynthesis and the distribution of photosynthates throughout the

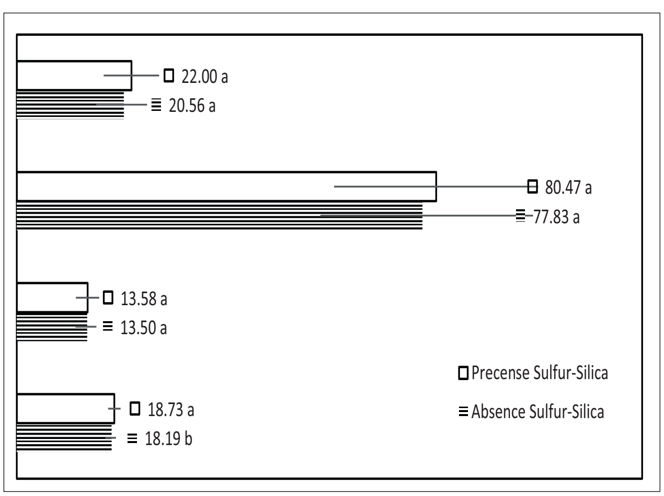

Figure 2: The influence of silica fertilizer on lettuce plant height, leaf count, leaf area, and chlorophyll content (SPAD value). Notes: Different letters following the numbers indicate significant differences based on the Duncan's test at a 5% level of significance.

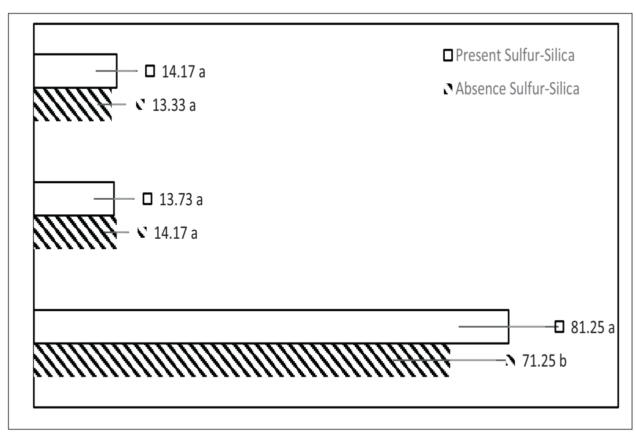

Figure 3: The influence of sulfur–silica fertilizer on lettuce plant root length, shoot weight, and root weight. Note: Different letters following the numbers indicate significant differences based on the Duncan's test at a 5% level of significance.

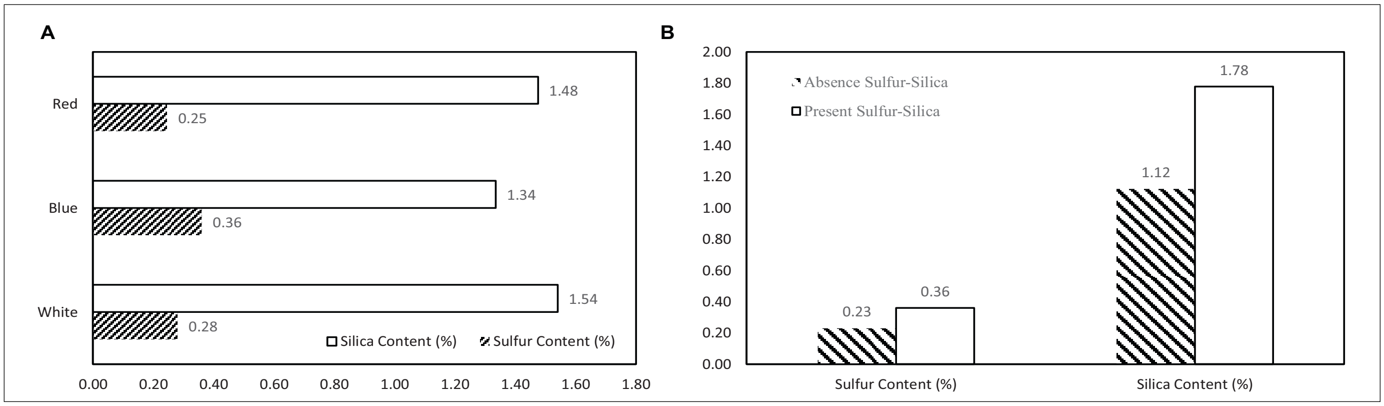

Figure 4: The influence of **(A)** LED light color and **(B)** sulfur–silica fertilizer on the sulfur and silica content in lettuce plants.

Table 5: The influence of LED light color and sulfur–silica fertilizer on the proximate analysis results of lettuce plants.

Treatment	Ash Content (%)	Total Fat (%)	Carbohydrate (%)	Protein (%)	Water Content (%)	Total Energy (kcal 100 g^{-1})
LED color						
White	0.84	0.37	2.46	1.55	94.79	19.84
Blue	0.88	0.52	2.68	1.36	94.57	20.91
Red	0.96	0.42	2.70	1.73	94.56	21.60
Sulfur–silica fertilizer						
Absence	0.88	0.45	2.62	1.63	94.66	20.63
Presence	0.91	0.42	2.60	1.46	94.61	20.93

plant. The fresh weight of plants is highly influenced by their water content.

The results of proximate testing revealed that the red LED light treatment led to higher protein and carbohydrate content compared to other LED treatments [Table 5]. In contrast, the blue LED light treatment exhibited the highest total fat content. The red LED light demonstrated superior lettuce growth. Red LED light positively influences lettuce development toward enhanced growth, while blue LED light induces the most significant impact on secondary metabolism [53]. The specific components of total fat, such as fatty acids, have been widely documented to influence seedling development, particularly in lettuce plants. Changes in fatty acid composition do not exhibit a dominant effect on growth after leaf emergence [54,55].

The treatment with sulfur–silica fertilizer resulted in a higher total energy content in lettuce compared to the control (absence of sulfur–silica). This is attributed to the sufficient availability of sulfur (S), which meets the nutritional needs of the plant for metabolism. Sulfur has an essential role in enhancing protein synthesis in plants compared to the plant's ability to absorb nitrogen [56]. Excessive sulfur fertilization can result in the accumulation of nutrients in plants. This condition can cause plant toxicity and, consequently, affect plant protein production. The type of fertilizer supporting the formation of compounds in plants can influence the nutrient content in plants [57].

The proximate analysis results showed that the highest ash content was found in the red LED light treatment and sulfur–silica fertilizer treatment. Ash content is associated with the physical quality of leafy vegetables obtained after harvest. Spraying lettuce with sulfur–silica fertilizer during cultivation significantly increases the possibility of deposits, which contribute to a higher ash content in the vegetables. The proximate analysis results revealed that the water content of lettuce ranged from 94% in each treatment, whether it was the LED light treatment or the application of sulfur–silica fertilizer. This aligns with the water content of lettuce obtained in another research, which was also around 95.27% [58]. This indicates that the lettuce grown in this study meets the quality standards for marketability.

Inadequate moisture levels in lettuce leaves can lead to wilting and diminished crispness, thereby compromising the overall lettuce quality [59,60]. Conversely, elevated water content increases susceptibility to microbial growth and spoilage. The optimal storage temperature for lettuce falls within the range of 0°C to 5°C [61]. Maintaining a relative humidity of 98%–100% is crucial to prevent leaf desiccation and the associated loss of mass and quality [62].

The white LED light treatment resulted in the highest sulfur content, measuring 1.54%. The blue LED light treatment produced the highest sulfur content in lettuce, at 0.36% [Figure 4A]. In the context of this study, a statistical or theoretical determination of how light intensity and wavelength affect sulfur–silica absorption in lettuce plants cannot be made. The sulfur–silica fertilizer has the potential to elevate the endogenous sulfur–silica content in plants [Figure 4B]. Sulfur in plants generally has the potential to induce plant resilience to abiotic stress [63]. In other research, silica content can regulate low-light stress and enhance the photosynthesis rate in plants [64,65].

4. CONCLUSION

The red LED light treatment yielded the highest fresh shoot weight (82.50 g). On the contrary, the white LED treatment produced the best root length (15.48 cm) and root weight (15.00 g), although not significantly different from the red LED, which exhibited root length and root weight of 14.51 cm and 14.38 g, respectively. Moreover, the red LED light treatment resulted in the highest protein (1.73%), carbohydrate (2.70%), and total energy (21.60 kcal 100 g^{-1}) content compared to other LED light colors. The application of sulfur–silica fertilizer led to the most robust lettuce plant growth, albeit with the lowest fresh shoot weight of 81.25 g. The addition of sulfur–silica fertilizer resulted in diminished protein (1.46%) and carbohydrate (2.60%) content but the highest total energy content (20.93 kcal 100 g^{-1}). In this study, the variation in LED light color may not clearly indicate its relationship with sulfur–silica content in lettuce plants. However, the addition of sulfur–silica fertilizer demonstrated the potential to increase the endogenous sulfur and silica content in the plants.

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6. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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8. CONFLICT OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

9. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

10. DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to privacy and ethical considerations, some data may be restricted. Additional details regarding data access and any relevant conditions can be provided upon inquiry.

11. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

12. PUBLISHER'S NOTE

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