**RESEARCH**

# Physiological and biochemical responses of Chinese cabbage (*Brassica rapa* var. *chinensis*) to different light treatments

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## Abstract

**Background:** Artificial agriculture is promoted as an economically viable technology for developing plants under controlled conditions whereby light, water, and fertilizer intake are regulated in a controlled manner to produce maximum productivity with minimal resources. Artificial light has been used to produce high-quality vegetables because it can regulate plant growth and phytochemical production through light intensity, photoperiod, and spectrum modulation. This study aimed to compare the physiological and biochemical responses of Chinese cabbage (*Brassica rapa* var. *chinensis*) grown under artificial light with varying light intensities (75 and 150 μmol m$^{-2}$ s$^{-1}$), photoperiods (12:12 and 6:6:6:6 h), and wavelengths (blue, red, and magenta) to plants grown in a glasshouse under natural light. The novelty of this study lies in the manipulation of artificial LED lighting to achieve high-quality plant growth and phytochemical composition in *B. rapa* model vegetables for potential optimal productivity.

**Results:** The analysis revealed that *B. rapa* grown under artificial lights produced more consistent biomass yield and had a higher chlorophyll content than *B. rapa* grown under natural light (control). Plants grown under artificial lights have also been shown to produce biochemical compositions derived primarily from fatty acids, whereas plants grown under natural light have a biochemical composition derived primarily from alkanes. Twenty compounds were found to be statistically different between light treatments out of a total of 31 compounds detected, indicating that they were synthesized in response to specific light conditions. Exposure to the full artificial light spectrum (white) resulted in the absence of compounds such as dodecane and 2,6,10-trimethyltridecane, which were present in *B. rapa* grown in natural light, whereas exposure to the blue spectrum specifically induced the production of tetracosane. Eicosane, neophytadiene, L-(+)-ascorbic acid 2,6-dihexadecanoate, and (Z,Z,Z)-9,12,15-octadecatrienoic acid were all prevalent compounds produced in *B. rapa* regardless of light conditions, and their absence may thus affect plant development and survival.

**Conclusions:** The results show that cultivation under artificial light produced consistent biomass, high chlorophyll content, and phytochemical content comparable to natural light conditions (control). These findings shed light on how artificial light could improve the production efficiency and organoleptic qualities of Chinese cabbage.

**Keywords:** Biochemical composition, *Brassica rapa*, Gas chromatography–mass spectrometry (GC–MS), Light-emitting diode (LED), Light intensity, Photoperiod, Plant metabolites, Wavelength

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**Graphical Abstract**
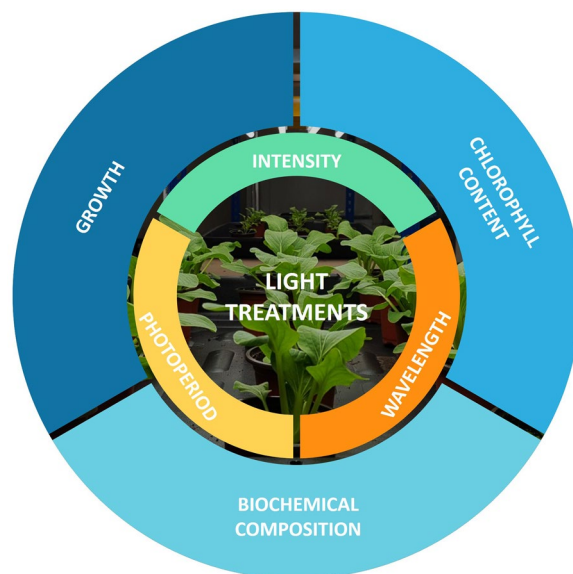


## Background

Light is a fundamental source of energy for plants to carry out photosynthesis. Light energy induces water splitting and reduces carbon dioxide into chemical energy needed for carbohydrate biosynthesis in photosynthetic organisms. Photosynthesis is regulated by the photoperiod, and the light qualities, i.e., wavelengths and intensities, all of which contributes to plant productivity [32, 58], biochemical composition [3], flowering time [22], and biomass yields [16]. Although natural light is preferred in most farming practices because it can result in substantial energy savings, the natural variation in light quantity is attributed to the flux in radiation and light intensity, reducing photosynthetic efficiency. Recently, urban agriculture has attempted to use artificial lighting to cultivate plants and accelerate carbon fixation via photosynthesis by altering the intensity, photoperiod, and spectrum, the three primary characteristics of light sources that have the most significant effect on plant growth and development [22, 48].

Light intensity has been demonstrated to regulate plant growth and metabolism by activating a suite of signal-transducing photoreceptors and driving photosynthetic carbon fixation, thereby influencing biomass production and the transition between growth-intensive and stress-resilient states [34, 72, 87]. Light intensity or total irradiance received by plants determines the rate of photosynthesis and is measured as quanta (mol $m^{-2}$ $s^{-1}$) or photosynthetic photon flux density (PPFD), which is the amount of photosynthetically active photons (400–700 nm) hitting a surface per unit area per unit time [51]. At low light intensities above the light compensation point, the photosynthetic rate increases proportionally to light intensity until reaching a maximum rate. However, when the intensity of the light increases further, chlorophyll can be damaged, resulting in a decrease in photosynthetic rate [84]. If $CO_2$ concentration and temperature are not the limiting factors, the light intensity can have a substantial influence on germination, seedling establishment, leaf proliferation and expansion, bud and flower initiation, and cell division [39, 85, 88].

Aside from light intensity, photoperiod has also been shown in studies to influence plant growth and regulate various developmental responses in plants, including systemic signaling and secondary metabolisms [1, 2, 30]. In conjunction with light intensity, photoperiod governs photosynthetic efficiency by providing a recurring cycle of varying ratios of uninterrupted light and dark periods to which a plant is exposed to throughout its life cycle, with substantial impacts on biomass accumulation and flower bud differentiation [57]. Day length is an exceptionally reliable seasonal variation for a plant since its continual shift throughout the year establishes the succession of seasons and how plants respond to fluctuating seasonal changes decide their living strategy and make critical developmental decisions [66]. This tactical decision is crucial for annual plants, needing to precisely plan for germination, development, reproduction, and

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senescence to complete a life cycle within 1 year, including synchronizing with pollinators, outwitting potential opponents, and modifying flowering time to avoid competition [20, 60]. However, although photoperiod modification is frequently used in protected cropping to induce or inhibit flowering, little to no attention has been devoted to photoperiod manipulation to maximize plant growth [1].

Another light property, the spectrum, has also been reported to influence plant development and metabolism and is thus associated with variability in plant growth and phytochemical accumulation [43]. Plants have evolved their distinct photoreceptor systems to mediate light responses from broad wavelengths, including red/far-red absorbing phytochromes, blue/UV-A absorbing cryptochromes and phototropins, and UV-B absorbing UVR8, with the majority of them containing more than one member encoded by a different gene but sharing a high degree of similarity within the same family [40, 49]. This has a significant impact on plant growth especially at several developmental stages, from seed germination to senescence, including the accumulation of essential phytochemicals such as anthocyanins, carotenoids, chlorophyll, phenolic compounds, and ascorbic acid. Thus, light-absorbing photoreceptor proteins and their signaling components are appealing targets for altering crop productivity and yield for future food production management [36]. The provision of optimal spectral quality for plant growth in artificial farming ensures that the plant reaches the maximum absorption of chlorophyll or photosynthetically active radiation (PAR) between 400 and 700 nm, for use in the photosynthesis process. Apart from white light, the most favorable spectrums for affecting plant growth and yield are blue (450–495 nm), red (650–700 nm), and a combination of blue and red, also known as magenta [62, 65].

The most convenient artificial light sources are light-emitting diodes (LEDs) that can provide precise spectrum with close illumination [34], stable spectrum distribution [91], and higher PAR efficiency [13] for beneficial agronomic planting. LEDs have been widely demonstrated to positively amplify crop production, trigger the synthesis of specialized metabolites, and enhance the post-harvest quality of fruits and vegetables to prevent food spoilage or rotting [26]. Gas chromatography–mass spectrometry (GC–MS) is a widely used tool for analyzing multivariate compounds in plants and agriculture chemicals, including pesticides and herbicides. It is usually used to identify non-polar or volatile compounds due to its high sensitivity and effectiveness in separating a complex of mixtures into its individual compounds [73]. Volatile compounds are essential for sessile plants to communicate with their environment beca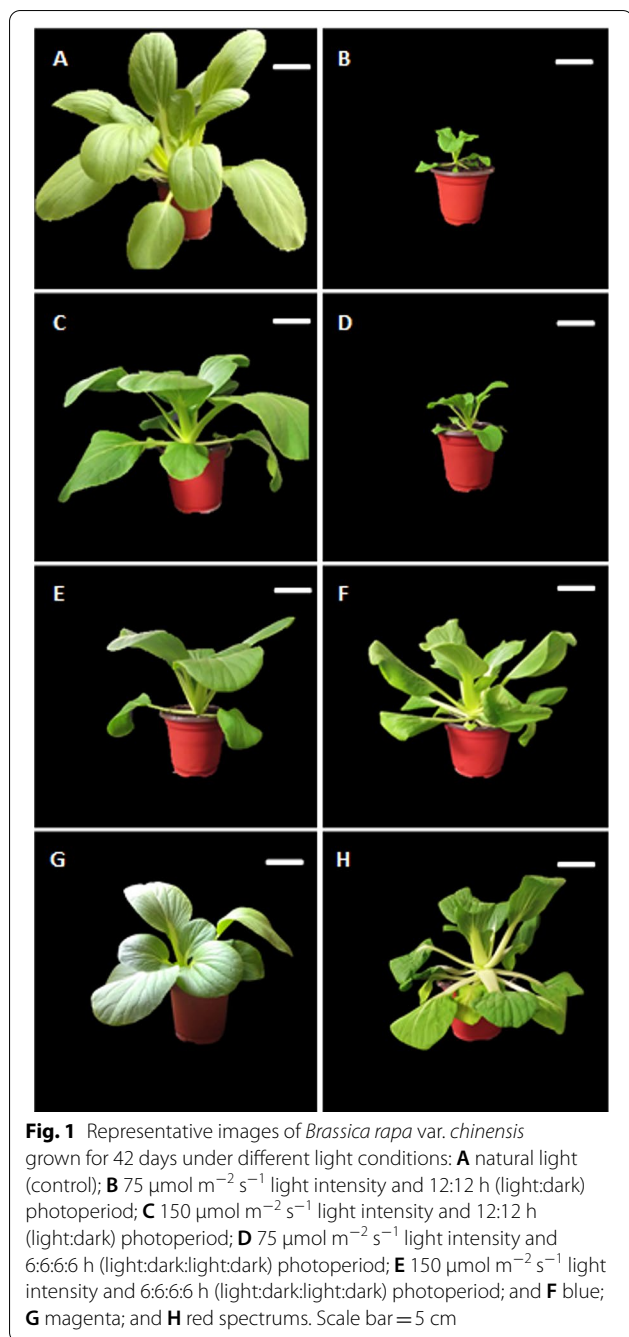use they act as natural defense against herbivores or pathogens [59], but they also provide flavor and aroma, which can affect the palatability of edible fruits and vegetables [8]. Plants in the genus *Brassica* produce various biochemical compounds such as alkanes, fatty acids, fatty alcohols, phenolics, and glucosinolates [41, 92]. These secondary metabolites have been linked to nutritional effects, pollinator attraction and defenses, and structural integrity in producing species [7, 45, 67].

In this study, we used GC–MS to analyze the biochemical compositions of hexane extracts of Chinese cabbage (*Brassica rapa* var. *chinensis*) synthesized in response to specific light intensity (75 and 150 µmol m$^{-2}$ s$^{-1}$) as well as specific photoperiods (12:12 h light:dark and 6:6:6:6 h light:dark:light:dark) and wavelength of lights (blue, red and magenta). As photoperiodism regulates flowering and other developmental transitions of plants by day/night length, we attempted to investigate whether a shorter (6:6) light:dark photoperiod, as opposed to the standard (12:12) light:dark photoperiod, can alter the circadian clocks of the plants and drive biological rhythms towards enhanced growth and metabolism rather than complex developmental programs, such as flower formation or senescence [29, 37, 66]. The magenta spectrum was tested as well because green plants under white light generally get their energy from the blue and red ends of the spectrum and absorb wavelengths other than green, and white light without green light would be magenta [55, 96]. The outcome of this analysis adds to our understanding of the effects of light regimes on the plant growth, chlorophyll content and accumulation of phytochemicals in *B. rapa* var. *chinensis* (hereafter referred to as *B. rapa*) and aids in the optimization and selection of environmental variables, such as light conditions that are likely to affect the yield and quality of the vegetables produced in controlled environments.

## Results
### Plant growth under the influence of light intensity, photoperiod, and wavelength

The present plant growth analysis under different light conditions revealed that artificial light produced a more consistent biomass yield than natural light (control groups). Plants grown in natural light produced biomass ranging from 21.6 to 70.2 g with an average mass of 39.9 ± 9.5 g (Fig. 1a), while plants grown under artificial light produced a lower but more consistent yield (Fig. 1b–e). According to our results, the mass distribution of *B. rapa* under 150 µmol m$^{-2}$ s$^{-1}$ light intensity ranged from 24.4 to 42.7 g (average 29.5 ± 5.3 g) for 12:12 h (light:dark) photoperiod, and from 10.5 to 23.7 g (average 15.9 ± 2.5 g) for 6:6:6:6 h (light:dark:light:dark) photoperiod. Plants grown under 75 µmol m$^{-2}$ s$^{-1}$ light intensity produced the lowest biomass yields,

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**Fig. 1** Representative images of *Brassica rapa* var. *chinensis* grown for 42 days under different light conditions: **A** natural light (control); **B** 75 µmol m$^{-2}$ s$^{-1}$ light intensity and 12:12 h (light:dark) photoperiod; **C** 150 µmol m$^{-2}$ s$^{-1}$ light intensity and 12:12 h (light:dark) photoperiod; **D** 75 µmol m$^{-2}$ s$^{-1}$ light intensity and 6:6:6:6 h (light:dark:light:dark) photoperiod; **E** 150 µmol m$^{-2}$ s$^{-1}$ light intensity and 6:6:6:6 h (light:dark:light:dark) photoperiod; and **F** blue; **G** magenta; and **H** red spectrums. Scale bar = 5 cm

ranging from 2.7 to 7.9 g (average 5.3 ± 1.0 g) for 12:12 h (light:dark) and 1.2 to 3.5 g (average 2.0 ± 0.5 g) for 6:6:6:6 h (light:dark:light:dark) photoperiods, respectively. Plants grown under a different spectrum (Fig. 1f–h) shows that the blue spectrum produced the highest biomass yields, ranging from 7.4 to 25.0 g (average 14.5 ± 3.6 g). The magenta spectrum, which produced biomass ranging from 6.0 to 22.0 g (average 12.7 ± 2.8 g), was followed by the red spectrum, which produced the

lowest biomass yield, ranging from 6.2 to 25.0 g (average 11.5 ± 4.1 g). ANOVA and Tukey HSD tests with $p < 0.05$ revealed a significant effect on the growth of *B. rapa* treated with different light intensities and photoperiods, but no significant difference in biomass yield between light spectrums (Fig. 2).

**Phenotypic variation of *B. rapa* induced by various light treatments**

Figure 3 depicts the phenotypic variation of *B. rapa* in response to different light treatments. Plants grown in natural light had more developed standing leaves but appeared pale green colorwise, whereas plants grown in artificial light (white) had well-developed standing leaves with a brighter greenish color. The spectrum study resulted in a different leaf shape and development in *B. rapa*, with more standing leaves produced by the blue and magenta spectrums than by the red spectrum, which produced sprawling leaves with many voids between the leaves. Regardless of leaf structure, plants grown under artificial lights appeared to have a more distinctive shade of green leaves than plants grown under natural light.

**Chlorophyll content in *B. rapa* leaves under various light treatments**

Table 1 presents the chlorophyll content of *B. rapa* under various lighting conditions. Compared to plants grown under artificial lights, *B. rapa* grown in natural light had the lowest chlorophyll content (11.34 ± 1.04 mg g$^{-1}$). The highest chlorophyll content was recorded in plants grown in the 12:12 h (light:dark) photoperiod, with 16.28 ± 0.73 mg g$^{-1}$ and 15.70 ± 0.88 mg g$^{-1}$ under 75 µmol m$^{-2}$ s$^{-1}$ and 150 µmol m$^{-2}$ s$^{-1}$, respectively. Plants grown in the 6:6:6:6 h (light:dark:light:dark) photoperiod had a lower chlorophyll content, with 14.75 ± 0.30 mg g$^{-1}$ and 15.02 ± 0.17 mg g$^{-1}$ under 75 µmol m$^{-2}$ s$^{-1}$ and 150 µmol m$^{-2}$ s$^{-1}$, respectively. In plants grown under different light spectrums, blue light had the highest chlorophyll content (13.26 ± 1.43 mg g$^{-1}$), followed by red light (12.79 ± 0.86 mg g$^{-1}$) and magenta light (11.08 ± 0.07 mg g$^{-1}$).

**Plant metabolites in *B. rapa* under various light treatments**

The list of plant metabolites found in *B. rapa*, and their abundances under various light treatments, are shown in Tables 2 and 3, respectively. GC–MS analysis revealed a total of 31 compounds in hexane extracts of *B. rapa* leaves, including alkanes, alkenes, iodine-containing compounds, phenols, terpenes, fatty acids, fatty amides, fatty alcohols, vitamins, and sterols. Some compounds, such as eicosane, neophytadiene, L-(+)-ascorbic acid 2,6-dihexadecanoate,     (Z,Z,Z)-9,12,15-octadecatrienoic
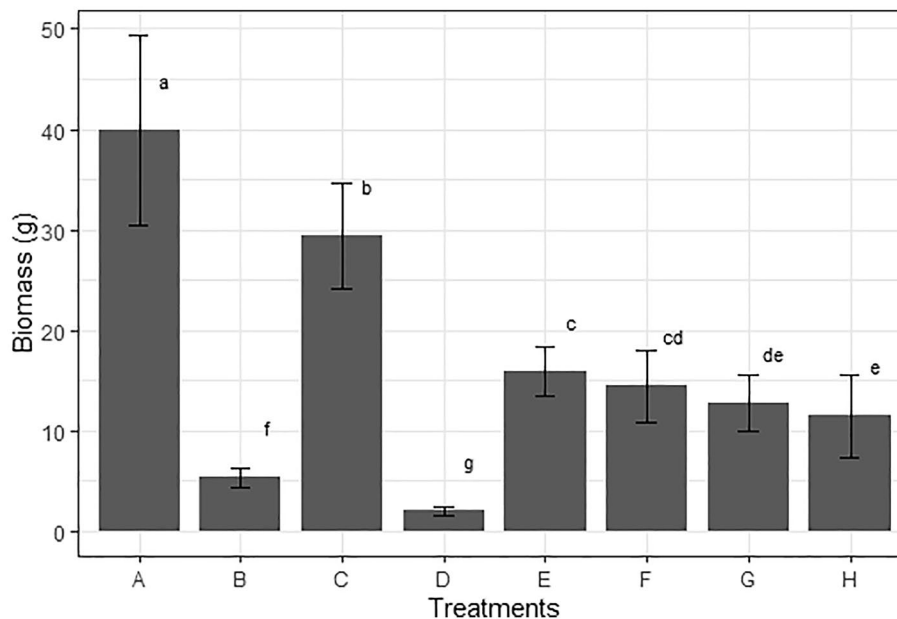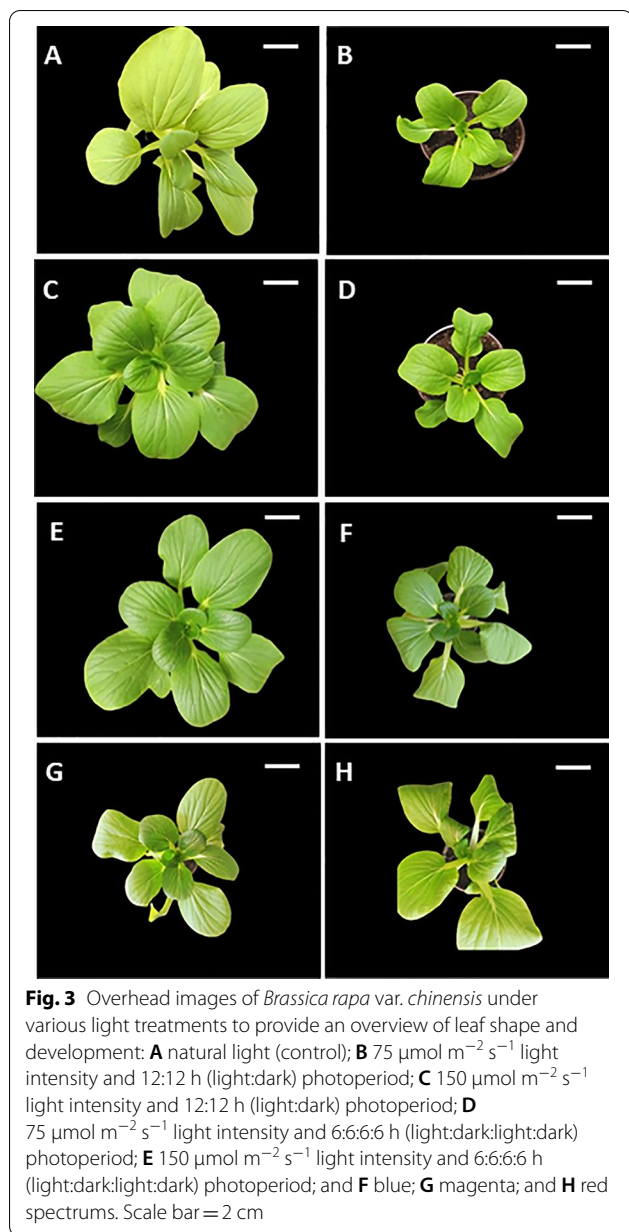
**Fig. 2** *Brassica rapa* var. *chinensis* biomass under different light treatments: **A** natural light (control); **B** 75 μmol m$^{-2}$ s$^{-1}$ light intensity and 12:12 h (light:dark) photoperiod; **C** 150 μmol m$^{-2}$ s$^{-1}$ light intensity and 12:12 h (light:dark) photoperiod; **D** 75 μmol m$^{-2}$ s$^{-1}$ light intensity and 6:6:6:6 h (light:dark:light:dark) photoperiod; **E** 150 μmol m$^{-2}$ s$^{-1}$ light intensity and 6:6:6:6 h (light:dark:light:dark) photoperiod; and **F** blue; **G** magenta; and **H** red spectrums. The error bars indicate the standard deviation. Different letters in lower case represent significant differences between treatments as determined by one-way ANOVA and the Tukey HSD post hoc test ($p < 0.05$)

acid, 1-heptacosanol, and vitamin E, were discovered to be present in all light treatments, while others, such as dodecane and 2,6,10-trimethyltridecane in natural light, and tetracosane in the blue spectrum, were discovered to be present only in specific treatments. Principal component analysis (PCA) used orthogonal transformation to explain the studied variables to examine the correlation between different light treatments. According to the results, plant metabolites differed depending on the light treatment, and PC1 and PC2 transformed data accounted for 45.9% of total data variability (Fig. 4). Based on the PCA score plot, each light treatment tended to cluster and separate from the other treatments. Despite artificial light treatments resulted in more closely related clusters/groups, *B. rapa* exposed to natural light formed a cluster distinct from the other treatments in the score plot. Figure 5 depicts a matrix of correlation values that provides detailed information about the relationships between metabolites under various light treatments. According to one-way ANOVA, 20 of the 31 compounds detected were significantly different ($p < 0.05$) under different light treatments (Fig. 6; Table 4).

## Discussion

Plants were grown in the same sized pot with the same growing media weight in both the plant growth room and the glasshouse. They were held at the same humidity, temperature, and $CO_2$ concentration in all treatments. The effect of light treatments on plant biomass differed significantly ($p < 0.05$) between plants grown in natural light (control) and plants grown in regulated illumination using artificial lights. Light intensity is one of the most significant factors driving photosynthesis for plant growth and secondary metabolite production [42]. Excessive light intensity reduces photosynthetic efficiency by damaging photosynthetic organelles [18], while low light intensity inhibits plant growth by interfering with gas exchange [94]. According to this study, plants grown in high light intensity had a higher growth rate or biomass than plants grown in low light (Fig. 1), and several other studies discovered similar results [50, 63, 95]. Specifically, the high light intensity of natural light causes a high rate of photosynthesis, resulting in growth of plants with higher biomass than plants grown under artificial lights. However, under a constant photoperiod (12:12 h

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**Fig. 3** Overhead images of *Brassica rapa* var. *chinensis* under various light treatments to provide an overview of leaf shape and development: **A** natural light (control); **B** 75 µmol m$^{-2}$ s$^{-1}$ light intensity and 12:12 h (light:dark) photoperiod; **C** 150 µmol m$^{-2}$ s$^{-1}$ light intensity and 12:12 h (light:dark) photoperiod; **D** 75 µmol m$^{-2}$ s$^{-1}$ light intensity and 6:6:6:6 h (light:dark:light:dark) photoperiod; **E** 150 µmol m$^{-2}$ s$^{-1}$ light intensity and 6:6:6:6 h (light:dark:light:dark) photoperiod; and **F** blue; **G** magenta; and **H** red spectrums. Scale bar = 2 cm

spectrum and consistent spectral distribution [34, 91]. Although natural light is widely used in agriculture, it has the drawback of being easily distracted by clouds, fog, or even the greenhouse cover. As a result, plant biomass production in natural light can be unpredictable. Despite having the largest leaves of any treatment, plants grown in natural light showed unequal leaf distribution, with certain leaves being larger on one side than the other, leading in an uneven crown appearance. This observation could be explained by the variable light intensity received by the *B. rapa* during the day in the glasshouse, as contrast to plants grown under constant artificial white light, which resulted in the leaves growing consistently across the crown. However, when the plants were exposed to light spectrums other than white light, their leaves grew irregularly and wrinkled, and appeared elongated specifically under the red spectrum.

Photoperiodism is another critical factor influencing plant physiology and growth, including the transition between vegetative and reproductive modes to develop lateral or flower buds [22, 34]. Plants adapt to the prevailing photoperiod by adjusting growth and flowering to energy availability, synchronizing by the circadian clock [15, 77]. Interactions between the circadian clock and photoperiod length during plant vegetative growth affect leaf number and size and their morphological and cellular properties, thereby influencing photosynthesis rate, starch metabolism, and vegetative phase change [6, 12, 83]. Plants grown in shorter light periods and lower light intensities were found to synthesize proportionally more starch during the day and degrade it more slowly at night [23, 24]. This study investigated *B. rapa* plants to the 6:6:6:6 h (light:dark:light:dark) photoperiod to examine if shortening both the light and dark periods could affect developmental phase changes, such as the transition from vegetative to floral growth, and redirect more energy toward accelerating plant growth and metabolism. However, our findings show that the 12:12 h (light:dark) photoperiod produced more biomass yield, implying that the shorter photoperiod (6:6:6:6 h light:dark:light:dark) was insufficient for the plants to perform optimal photosynthesis and other plant physiological functions. Furthermore, since *B. rapa* is a long-day plant [17], a photoperiod of 6:6:6:6 h (light:dark:light:dark) may not be sufficient to promote faster plant growth and development.

Chlorophyll is a green-colored compound contained in the chloroplast [56] that can act as an antioxidant [27] and is used to assess plant maturity, quality, and freshness [46, 81]. In addition, it is also the key factor for determining a plant's photosynthetic and growth capacity [44]. The primary chlorophyll, chlorophyll a, is a bluish-green pigment with the molecular formula C55H72N4O5Mg, whereas the accessory chlorophyll, chlorophyll b, is a

light:dark), a treatment of 150 µmol m$^{-2}$ s$^{-1}$ had higher biomass than a treatment of 75 µmol m$^{-2}$ s$^{-1}$, indicating that light intensity is one of the most critical limiting factors for plant photosynthesis, resulting in a significant difference in plant productivity in terms of biomass.

Despite producing significantly less biomass than plants grown in natural light, plants grown in artificial light demonstrated a smaller mass range, resulting in a more consistent biomass yield. This trend can be attributed to the more consistent growth of plants exposed to artificial light, such as LED, which is less affected by external light factors. LEDs are known for their precise

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**Table 1** Chlorophyll content of *Brassica rapa* var. *chinensis* leaves under varying light intensities, photoperiods, and light spectrums

| Light treatment | Chlorophyll a (µg/ml) | Chlorophyll b (µg/ml) | Total chlorophyll (µg/ml) | Chlorophyll content (mg/g) |
|---|---|---|---|---|
| Natural light | 17.17 ± 1.40[a,e] | 5.50 ± 0.69[a] | 22.68 ± 2.09[a] | 11.34 ± 1.04[a] |
| 75 µmol m$^{-2}$ s$^{-1}$, 12:12 | 23.72 ± 0.99[b] | 8.83 ± 0.53[b] | 32.55 ± 1.46[b] | 16.28 ± 0.73[b] |
| 150 µmol m$^{-2}$ s$^{-1}$, 12:12 | 23.09 ± 1.17[b,c] | 8.31 ± 0.59[b] | 31.40 ± 1.76[b] | 15.70 ± 0.88[b] |
| 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 | 22.10 ± 0.30[b,c,d] | 7.40 ± 0.31[b,c,d] | 29.60 ± 0.60[b,c] | 14.75 ± 0.30[b,c] |
| 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 | 22.52 ± 0.32[b,c,d] | 7.52 ± 0.09[b,c] | 30.04 ± 0.34[b,c] | 15.02 ± 0.17[b,c] |
| Blue | 20.15 ± 1.93[c,d,e] | 6.36 ± 0.93[a,c,d] | 26.51 ± 2.86[a,c] | 13.26 ± 1.43[a,c] |
| Magenta | 16.32 ± 0.09[a] | 5.97 ± 0.04[a,d] | 22.16 ± 0.14[a] | 11.08 ± 0.07[a] |
| Red | 19.86 ± 1.23[d,e] | 6.66 ± 0.49[a,c,d] | 25.58 ± 1.71[a,c] | 12.79 ± 0.86[a,c] |

Lowercase letters indicate significant differences between treatments ($p < 0.05$)

yellowish-green pigment with the molecular formula $C_{55}H_{70}N_4O_6Mg$. Table 1 shows that the chlorophyll content of *B. rapa* did not differ significantly between all artificial white light treatments, indicating that the combination of light intensity and photoperiod has the least influence on chlorophyll content, even if their fresh masses differed significantly. Plants grown under natural light, blue, magenta, and red spectrums, on the other hand, demonstrated no significant variations in chlorophyll content, indicating that the respective spectrums produced chlorophyll in a comparable quantity to naturally generated chlorophyll. In all treatments, chlorophyll a was approximately three times higher than chlorophyll b, which was within the typical chlorophyll a/b ratio in higher plants [56]. The higher abundance of chlorophyll a than chlorophyll b in plants may be due to the roles of chlorophyll a as a primary pigment in collecting light energy and emitting high electrons into photosystems I (P680) and II (P700) in photochemical reactions (photosynthesis), whereas chlorophyll b provides extra light energy to chlorophyll a by acting as a supporting photosynthetic pigment.

Plants grown under artificial light were distinctively bright green in color than plants grown under natural light (control) in the current study, except for those grown under the magenta spectrum. This might be due to the higher chlorophyll content, particular the 75 µmol m$^{-2}$ s$^{-1}$ under 12:12 h (ligh:dark) photoperiod, which resulted in the highest chlorophyll content among treatments. Low light intensity increases chlorophyll content and vice versa, which may be an adaptive behavior of the plants to capture as much light as possible by enhancing light harvesting complexes in the minimum amount of available light. Furthermore, because the light intensity was uniform in the controlled setting, the plants did not experience chlorophyll degradation, which can occur in natural light during fluctuations or excesses of light intensity. The pale green leaves of plants growing in natural light reflect their low chlorophyll content, which may be attributed to chlorophyll formation being inhibited by excessive light penetration [21]. The effect of photoperiod on chlorophyll content production revealed that a 12:12 h (light:dark) photoperiod produced more chlorophyll in *B. rapa* than a 6:6:6:6 h (light:dark:light:dark) photoperiod, which is consistent with a previous study that found shorter (6 h), longer (18 h), or continuous (24 h) light periods produced lower chlorophyll contents in leafy vegetables [2]. This study also showed that chlorophyll content was increased with extended photoperiod (12:12) under low (75 µmol m$^{-2}$ s$^{-1}$) light intensity or increased light intensity (150 µmol m$^{-2}$ s$^{-1}$) under shorter photoperiod (6:6:6:6 h light:dark:light:dark), indicating that photoperiod and light intensity are dependent factors in chlorophyll production. Plants grown in magenta light with low chlorophyll content yielded different results than those reported by Naznin et al. [53], who discovered that plants grown in a blue–red combination (magenta) produced higher chlorophyll content. This discrepancy may be due to a difference in the blue-to-red light ratio, affecting plant chlorophyll content.

Plant secondary metabolites, also known as phytochemicals, are by-products of healthy plants that do not contribute directly to plant growth and development. Its absence, unlike primary metabolites, has no immediate effect on death, but it does play a role in the long-term survival of organisms [31]. Secondary metabolites can be classified based on their vast diversity in structure, function, and biosynthesis. Most commonly found secondary metabolites are alkaloids, terpenoids, phenolic compounds, and nitrogen-containing compounds. Secondary metabolites also include both organic volatile and non-volatile compounds. However, only volatile organic compounds or non-polar compounds were examined in the present study, as these compounds are known to

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**Table 2** Compounds of *Brassica rapa* var. *chinensis* detected by GC–MS under various light treatments

| Name of compound | Retention time ($\pm$ 0.05 min)[a] | Molecular formula | Compound nature | Similarity index (SI) | CAS[b] | Present in respective treatment |
|---|---|---|---|---|---|---|
| Dodecane | 10.671 | $C_{12}H_{26}$ | Alkane | 92 | 13187-99-0 | Natural light |
| 2,6,10-Trimethyltridecane | 16.119 | $C_{16}H_{34}$ | Alkane | 92 | 3891-99-4 | Natural light |
| Hexadecane, 1-iodo | 16.232 | $C_{16}H_{33}I$ | Iodine-containing compounds | 93 | 544-77-4 | Natural light; blue; magenta; red |
| 2,4-Di-*tert*-butylphenol | 16.658 | $C_{14}H_{22}O$ | Phenol | 95 | 96-76-4 | All treatments except natural light |
| Nonadecane | 19.060 | $C_{19}H_{40}$ | Alkane | 93 | 629-92-5 | Natural light; magenta |
| Eicosane | 21.377 | $C_{20}H_{42}$ | Alkane | 92 | 112-95-8 | All treatments |
| Tetracosane | 22.379 | $C_{24}H_{50}$ | Alkane | 91 | 0-0-0 | Blue |
| Cyclononasiloxane, octadecamethyl- | 23.284 | $C_{18}H_{54}O_9Si_9$ | Alkane | 89 | 556-71-8 | 75 µmol m$^{-2}$ s$^{-1}$, 12:12; 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; magenta |
| Neophytadiene | 24.438 | $C_{20}H_{38}$ | Terpenes | 96 | 504-96-1 | All treatments |
| 3,7,11,15-Tetramethyl-2-hexadecene | 24.575 | $C_{20}H_{40}$ | Alkene | 93 | 2437-93-6 | All treatments except natural light |
| 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 24.964 | $C_{20}H_{40}O$ | Diterpene | 90 | 102608-53-7 | All treatments except red |
| Triacontane, 1-iodo | 26.018 | $C_{30}H_{61}$ | Iodine-containing compounds | 88 | 0-0-0 | Natural light; 150 µmol m$^{-2}$ s$^{-1}$, 12:12; 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; blue; magenta; red |
| Cyclodecasiloxane, eicosamethyl | 26.414 | $C_{20}H_{60}O_{10}Si_{10}$ | Alkane | 87 | 18772-36-6 | 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 |
| 7,10,13-Hexadecatrienoic acid (Z,Z,Z) | 26.490 | $C_{16}H_{26}O_2$ | Fatty acid | 91 | 7561-64-0 | Natural light; 75 µmol m$^{-2}$ s$^{-1}$, 12:12; 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 |
| L-(+)-Ascorbic acid 2,6-dihexadecanoate | 27.055 | $C_{38}H_{68}O_8$ | Vitamin | 88 | 28474-90-0 | All treatments |
| Phytol | 29.976 | $C_{20}H_{40}O$ | Diterpene | 96 | 150-86-7 | All treatments except blue |
| Hexacosane, 1-iodo | 30.223 | $C_{26}H_{53}I$ | Iodine-containing compounds | 90 | 0-0-0 | Natural light; 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; blue; magenta |
| 10 (E), 12(Z)-Conjugated linoleic acid | 30.375 | $C_{18}H_{32}O_2$ | Fatty acid | 91 | 2420-56-6 | 75 µmol m$^{-2}$ s$^{-1}$, 12:12; 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 |
| 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 30.520 | $C_{18}H_{30}O_2$ | Fatty acid | 95 | 463-40-1 | All treatments |
| Octadecanoic acid | 30.974 | $C_{18}H_{36}O_2$ | Fatty acid | 92 | 57-11-4 | 75 µmol m$^{-2}$ s$^{-1}$, 12:12; 150 µmol m$^{-2}$ s$^{-1}$, 12:12; 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 |
| 2-Methyltetracosane | 31.045 | $C_{25}H_{52}$ | Alkane | 80 | 1560-78-7 | All treatments except magenta |
| Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 37.079 | $C_{19}H_{38}O_4$ | Fatty acid ester compound | 87 | 23470-0-0 | All treatment except natural light |
| Gamma-Sitosterol | 37.160 | $C_{29}H_{50}O$ | Sterols | 69 | 83-47-6 | Natural light; 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 |
| 1-Linoleoyl glycerol @ 9,12-Octadecadienoic acid (Z,Z)- | 39.847 | $C_{18}H_{32}O_2$ | Fatty acid | 91 | 2277-28-3 | 75 µmol m$^{-2}$ s$^{-1}$, 12:12; 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 |
| 9,12,15-Octadecatrienoic acid, methyl ester | 39.959 | $C_{19}H_{32}O_2$ | Fatty acid ester compound | 87 | 301-0-8 | 75 µmol m$^{-2}$ s$^{-1}$, 12:12; 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6; blue |

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**Table 2** (continued)

| Name of compound | Retention time ($\pm$ 0.05 min)[a] | Molecular formula | Compound nature | Similarity index (SI) | CAS[b] | Present in respective treatment |
|---|---|---|---|---|---|---|
| Methyl (Z)-5,11,14,17-eicosatetraenoate | 39.982 | $C_{21}H_{34}O_2$ | Fatty acid methyl ester | 77 | 59149-1-8 | 75 μmol m$^{-2}$ s$^{-1}$, 12:12; 150 μmol m$^{-2}$ s$^{-1}$, 12:12; 150 μmol m$^{-2}$ s$^{-1}$, 6:6:6:6; blue; magenta; red |
| Octadecanoic acid, 2,3-dihydroxypropyl | 40.338 | $C_{21}H_{42}O_4$ | Fatty acid | 90 | 123-94-4 | All treatments except natural light |
| 13-Docosenamide, (Z)- | 41.202 | $C_{22}H_{43}NO$ | Fatty amide | 91 | 112-84-5 | All treatments except red |
| Phenol,2,4-bis(1,1-dimethylethyl) phosphite | 42.776 | $C_{42}H_{63}O_3P$ | Phenol | 86 | 31570-4-4 | Natural light; magenta; red |
| 1-Heptacosanol | 43.267 | $C_{27}H_{56}O$ | Fatty alcohol | 95 | 2004-39-9 | All treatments |
| Vitamin E | 48.305 | $C_{29}H_{50}O_2$ | Vitamin | 95 | 59-2-9 | All treatments |

[a] Retention time based on RTX-5 capillary GC column with a dimension of 30 m $\times$ 0.25 mm $\times$ 0.25 μm

[b] CAS registry numbers follow Chemical Abstracts Service (CAS) Registry Database, American Chemical Society (ACS)

provide a variety of desirable quality attributes to vegetables and their products [14, 76]. The biochemical profiles of *B. rapa* were discovered to change when the light intensity and photoperiod were changed, potentially affecting the quality of vegetables grown in artificial farming. According to PCA analysis, artificial farming produced plants with more similar biochemical profiles compared to *B. rapa* grown under natural light, as shown in Fig. 3, with plants grown in natural light clustered apart from those grown in artificial lights. GC–MS analysis of *B. rapa* leaves detected common compounds in all light treatments, including phenolic compounds, fatty acids, fatty amides, terpenes, vitamins, alkanes, and sterols, all of which have been shown to significantly regulate plant growth and development, such as defenses against biotic and abiotic stresses [5, 10, 25, 33, 38, 74, 79, 80].

Several alkane compounds, such as dodecane and 2,6,10-trimethyltridecane, were discovered to be synthesized in response to specific light conditions and were only detected in *B. rapa* grown in natural light. As alkane biosynthesis is primarily associated with plant adaptation to environmental stress, such as uncontrolled water loss and damaging solar radiation, plants grown in natural light synthesize a diverse range of alkanes/alkenes to protect themselves from desiccation and other external stresses [64, 69, 90]. Although alkanes are more prevalent in *B. rapa* cultivated in natural light, compounds such as phenol, 2,4-bis(1,1-dimethylethyl)-, phosphite was found to be the most significantly abundant component ($p < 0.05$), accounting for 32.74% of all detected compounds in plants grown in natural light (Table 3). Several branches of the phenylpropanoid biosynthesis pathway produce phenolic compounds [19], which play an important role in stress resistance and plant development, particularly in the synthesis of lignin and pigments,

which provide structural stability and scaffolding support to plants [9]. The increased production of phenol, 2,4-bis(1,1-dimethylethyl)-, phosphite in *B. rapa* has now been connected to the high light intensity of natural illumination in the present study.

The detection of tetracosane, another alkane compound, in *B. rapa* grown under the blue spectrum may result from plant adaptation to the stresses induced by that spectrum, as the blue spectrum is reported to promote stomatal opening more effectively than other spectrums, resulting in more significant transpirational water loss [47, 70, 82]. In response, plants secrete alkanes as part of their surface waxes, functioning to protect the aerial epidermis from external stresses, thereby restraining the flow of water to the outside of the cell thus reducing the loss of water [11, 89, 90]. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester is a fatty acid compound found to be significantly higher in all artificial light treatments except the control plants, and it is thought to provide flavor and act as an antioxidant in the producing plants [78]. Plants produce reactive oxygen species (ROS) as a by-product of cellular metabolism or in response to environmental stress, such as high light intensity, which can damage iron–sulfur proteins, oxidize amino acid residues, generate more radicals, and damage DNA [68, 86]. As artificial lights did not cause extreme stress to *B. rapa*, as evidenced by the high chlorophyll content and light capturing capacity that did not exceed the amount required for photosynthesis. Thus, the increased production of hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester in plants grown under artificial light suggests its possible roles as an antioxidant to scavenge the ROS that may be produced as a cellular by-product in *B. rapa*. Besides, octadecanoic acid is synthesized explicitly in response to white artificial light at all

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**Table 3** The intensity of compounds detected in *Brassica rapa* var. *chinensis* under various light treatments

| Treatment | Detected compound | Intensity (%) |
|---|---|---|
| Natural light | 1. Dodecane | 1.36 |
| | 2. 2,6,10-Trimethyltridecane | 0.36 |
| | 3. Hexadecane, 1-iodo | 0.86 |
| | 4. Nonadecane | 0.13 |
| | 5. Eicosane | 13.5 |
| | 6. Neophytadiene | 2.47 |
| | 7. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 0.22 |
| | 8. Triacontane, 1-iodo | 1.25 |
| | 9. 7,10,13-Hexadecatrienoic acid (Z,Z,Z) | 0.26 |
| | 10. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 0.26 |
| | 11. Phytol | 4.68 |
| | 12. Hexacosane, 1-iodo | 2.34 |
| | 13. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 0.35 |
| | 14. 2-Methyltetracosane | 4.23 |
| | 15. Gamma-Sitosterol | 19.71 |
| | 16. 13-Docosenamide, (Z)- | 1.82 |
| | 17. Phenol,2,4-bis(1,1-dimethylethyl) phosphite | 32.74 |
| | 18. 1-Heptacosanol | 2.78 |
| | 19. Vitamin E | 10.68 |
| $75 \ \mu\text{mol m}^{-2} \text{ s}^{-1}$, 12:12 h (light:dark) | 1. 2,4-Di-*tert*-butylphenol | 1.65 |
| | 2. Eicosane | 1.05 |
| | 3. Cyclononasiloxane, octadecamethyl- | 0.84 |
| | 4. Neophytadiene | 4.9 |
| | 5. 3,7,11,15-Tetramethyl-2-hexadecen | 0.65 |
| | 6. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 1.67 |
| | 7. 7,10,13-Hexadecatrienoic acid (Z,Z,Z) | 0.51 |
| | 8. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 9.17 |
| | 9. Phytol | 1.38 |
| | 10. 10 (E), 12(Z)-Conjugated linoleic acid | 0.51 |
| | 11. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 4.79 |
| | 12. Octadecanoic acid | 2.09 |
| | 13. 2-Methyltetracosane | 1.08 |
| | 14. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 36.38 |
| | 15. 1-Linoleoyl glycerol @ 9,12-octadecadienoic acid (Z,Z)- | 0.71 |
| | 16. 9,12,15-Octadecatrienoic acid, methyl ester | 2.69 |
| | 17. Methyl (Z)-5,11,14,17-eicosatetraenoate | 3.05 |
| | 18. Octadecanoic acid, 2,3-dihydroxypropyl | 14.04 |
| | 19. 13-Docosenamide, (Z)- | 5.42 |
| | 20. 1-Heptacosanol | 4.82 |
| | 21. Vitamin E | 2.6 |

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**Table 3** (continued)

| Treatment | Detected compound | Intensity (%) |
|---|---|---|
| 150 µmol m$^{-2}$ s$^{-1}$, 12:12 h (light:dark) | 1. 2,4-Di-*tert*-butylphenol | 2.16 |
| | 2. Eicosane | 3.44 |
| | 3. Neophytadiene | 3.75 |
| | 4. Triacontane, 1-iodo | 1.36 |
| | 5. 3,7,11,15-Tetramethyl-2-hexadecen-1-ol | 0.37 |
| | 6. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 1.05 |
| | 7. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 9.46 |
| | 8. Phytol | 1.2 |
| | 9. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 4.43 |
| | 10. Octadecanoic acid | 0.92 |
| | 11. 2-Methyltetracosane | 1.16 |
| | 12. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 47.04 |
| | 13. Methyl (Z)-5,11,14,17-eicosatetraenoate | 4.39 |
| | 14. Octadecanoic acid, 2,3-dihydroxypropyl | 8.19 |
| | 15. 13-Docosenamide, (Z)- | 2.43 |
| | 16. 1-Heptacosanol | 5.03 |
| | 17. Vitamin E | 3.64 |
| 75 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 h (light:dark:light:dark) | 1. 2,4-Di-*tert*-butylphenol | 1.53 |
| | 2. Eicosane | 1.43 |
| | 3. Cyclononasiloxane, octadecamethyl- | 2.31 |
| | 4. Neophytadiene | 7.49 |
| | 5. 3,7,11,15-Tetramethyl-2-hexadecene | 1.21 |
| | 6. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 2.4 |
| | 7. Triacontane, 1-iodo | 0.48 |
| | 8. Cyclodecasiloxane, eicosamethyl | 1.54 |
| | 9. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 8.04 |
| | 10. Phytol | 0.65 |
| | 11. Hexacosane, 1-iodo | 0.43 |
| | 12. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 3.62 |
| | 13. Octadecanoic acid | 1.81 |
| | 14. 2-Methyltetracosane | 0.54 |
| | 15. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 35.43 |
| | 16. 1-Linoleoyl glycerol @ 9,12-octadecadienoic acid (Z,Z)- | 0.71 |
| | 17. 9,12,15-Octadecatrienoic acid, methyl ester | 3.86 |
| | 18. Octadecanoic acid, 2,3-dihydroxypropyl | 15.59 |
| | 19. 13-Docosenamide, (Z)- | 5.57 |
| | 20. 1-Heptacosanol | 4.43 |
| | 21. Vitamin E | 0.94 |

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**Table 3** (continued)

| Treatment | Detected compound | Intensity (%) |
|---|---|---|
| 150 µmol m$^{-2}$ s$^{-1}$, 6:6:6:6 h (light:dark:light:dark) | 1. 2,4-Di-*tert*-butylphenol | 1.44 |
| | 2. Eicosane | 1.35 |
| | 3. Neophytadiene | 1.81 |
| | 4. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 0.5 |
| | 5. 7,10,13-Hexadecatrienoic acid (Z,Z,Z) | 0.29 |
| | 6. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 9.45 |
| | 7. Phytol | 0.6 |
| | 8. Hexacosane, 1-iodo | 0.32 |
| | 9. 10 (E), 12(Z)-Conjugated linoleic acid | 0.77 |
| | 10. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 26.24 |
| | 11. Octadecanoic acid | 2.35 |
| | 12. 2-Methyltetracosane | 0.53 |
| | 13. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 29.6 |
| | 14. Gamma-Sitosterol | 0.66 |
| | 15. 1-Linoleoyl glycerol @ 9,12-octadecadienoic acid (Z,Z)- | 1.11 |
| | 16. Methyl (Z)-5,11,14,17-eicosatetraenoate | 3.89 |
| | 17. Octadecanoic acid, 2,3-dihydroxypropyl | 12.34 |
| | 18. 13-Docosenamide, (Z)- | 1.3 |
| | 19. 1-Heptacosanol | 3.56 |
| | 20. Vitamin E | 1.87 |
| Blue | 1. Hexadecane, 1-iodo | 1.94 |
| | 2. 2,4-Di-*tert*-butylphenol | 1.51 |
| | 3. Eicosane | 2.13 |
| | 4. Tetracosane | 0.86 |
| | 5. Neophytadiene | 12.68 |
| | 6. 3,7,11,15-Tetramethyl-2-hexadecen | 1.15 |
| | 7. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 2.55 |
| | 8. Triacontane, 1-iodo | 1.57 |
| | 9. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 7.17 |
| | 10. Hexacosane, 1-iodo | 0.31 |
| | 11. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 7.48 |
| | 12. 2-Methyltetracosane | 0.9 |
| | 13. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 38.67 |
| | 14. 9,12,15-Octadecatrienoic acid, methyl ester | 0.35 |
| | 15. Methyl (Z)-5,11,14,17-eicosatetraenoate | 1.47 |
| | 16. Octadecanoic acid, 2,3-dihydroxypropyl | 10.38 |
| | 17. 13-Docosenamide, (Z)- | 1.04 |
| | 18. 1-Heptacosanol | 4.6 |
| | 19. Vitamin E | 3.26 |

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**Table 3** (continued)

| Treatment | Detected compound | Intensity (%) |
|---|---|---|
| Magenta | 1. Hexadecane, 1-iodo | 0.38 |
| | 2. 2,4-Di-*tert*-butylphenol | 1.18 |
| | 3. Nonadecane | 0.94 |
| | 4. Eicosane | 2.78 |
| | 5. Cyclononasiloxane, octadecamethyl- | 0.42 |
| | 6. Neophytadiene | 14.64 |
| | 7. 3,7,11,15-Tetramethyl-2-hexadecene | 3.25 |
| | 8. 2-Hexadecen-1-ol,3,7,11,15-tetramethyl | 1.33 |
| | 9. Triacontane, 1-iodo | 1.22 |
| | 10. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 6.49 |
| | 11. Phytol | 1.55 |
| | 12. Hexacosane, 1-iodo | 0.43 |
| | 13. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 7.17 |
| | 14. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 36.86 |
| | 15. Methyl (Z)-5,11,14,17-eicosatetraenoate | 1.97 |
| | 16. Octadecanoic acid, 2,3-dihydroxypropyl | 9.91 |
| | 17. 13-Docosenamide, (Z)- | 0.99 |
| | 18. Phenol,2,4-bis(1,1-dimethylethyl) phosphite | 2 |
| | 19. 1-Heptacosanol | 4.01 |
| | 20. Vitamin E | 2.48 |
| Red | 1. Hexadecane, 1-iodo | 1.08 |
| | 2. 2,4-Di-*tert*-butylphenol | 0.88 |
| | 3. Eicosane | 2.83 |
| | 4. Neophytadiene | 14.76 |
| | 5. 3,7,11,15-Tetramethyl-2-hexadecene | 2.31 |
| | 6. Triacontane, 1-iodo | 1.23 |
| | 7. L-(+)-Ascorbic acid 2,6-dihexadecanoate | 6.25 |
| | 8. Phytol | 2.11 |
| | 9. 9,12,15-Octadecatrienoic acid, (Z,Z,Z)- | 5.53 |
| | 10. 2-Methyltetracosane | 0.95 |
| | 11. Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester | 36.61 |
| | 12. Methyl (Z)-5,11,14,17-eicosatetraenoate | 1.73 |
| | 13. Octadecanoic acid, 2,3-dihydroxypropyl | 15.65 |
| | 14. Phenol,2,4-bis(1,1-dimethylethyl) phosphite | 1.41 |
| | 15. 1-Heptacosanol | 5.69 |
| | 16. Vitamin E | 0.97 |

light intensities of 75 μmol m$^{-2}$ s$^{-1}$ and 150 μmol m$^{-2}$ s$^{-1}$ and photoperiods of 12:12 h (light:dark) and 6:6:6:6 h (light:dark:light:dark), but the mechanisms by which this fatty acid is synthesized in response to specific light conditions remain to be elucidated.

Several studies have found that stimulating with a specific wavelength of light promotes the biosynthesis of secondary compounds such as anthocyanins, carotenoids, and flavonols in leafy greens and seedlings [13, 71, 75]. As LEDs can emit over specific spectral areas and control
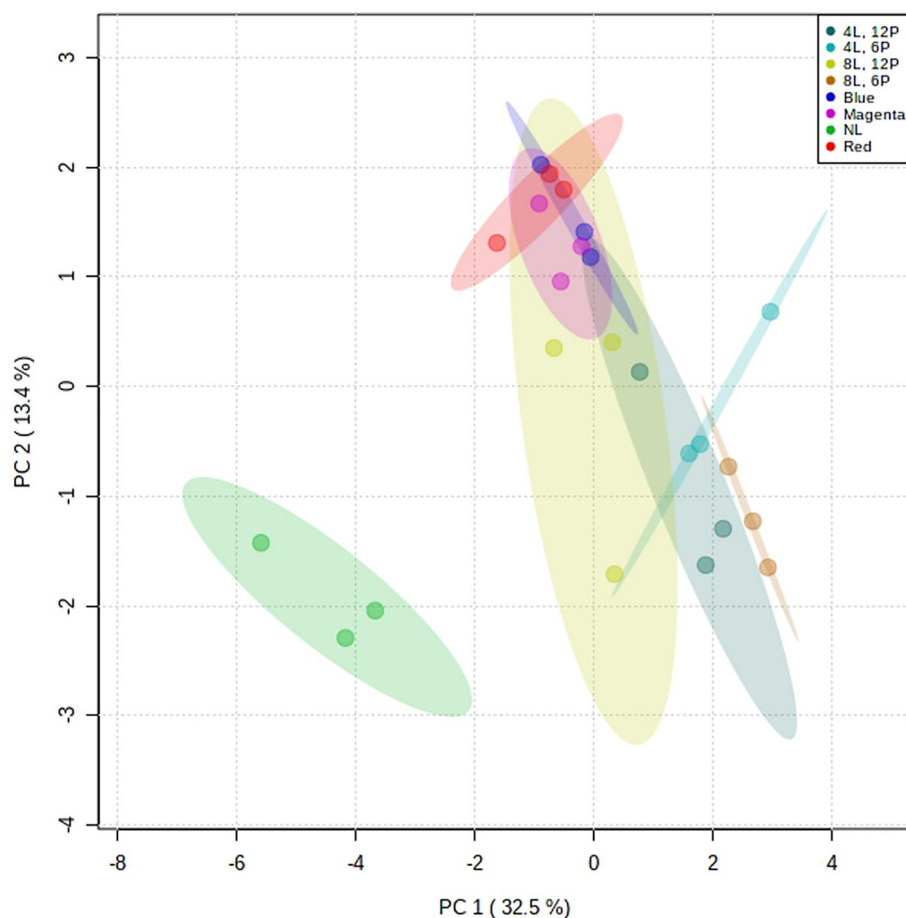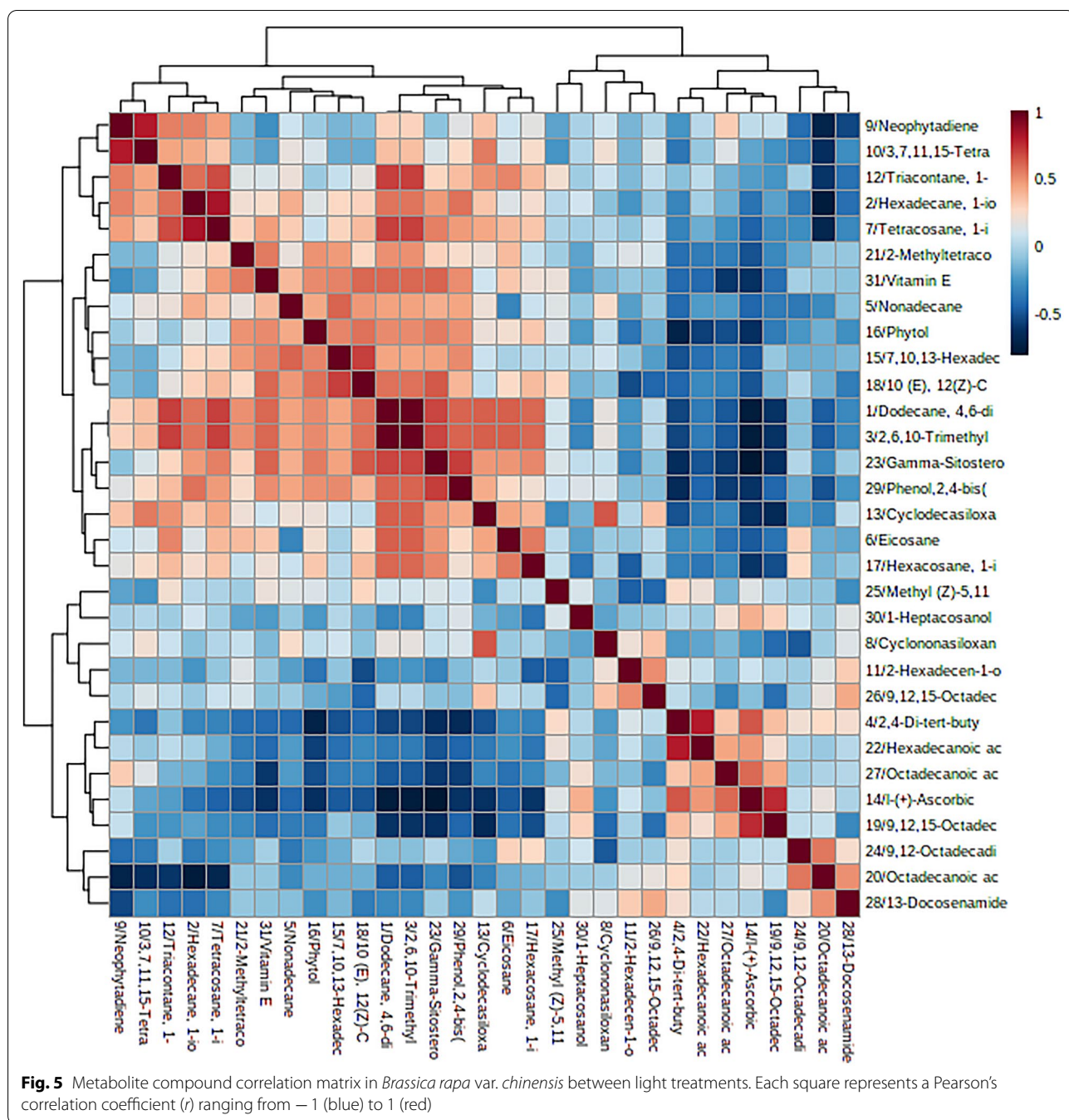
**Fig. 4** Principal component analysis (PCA) two-dimensional score plot for identifying relationships between different light treatments on *Brassica rapa* var. *chinensis*. Colored ellipses (size determined by a 0.95-probability level) show the observations grouped by treatment. The legend indicating various light treatments is as follows: 4L, 12P (75 µmol $m^{-2}$ $s^{-1}$ light intensity and 12:12 h light:dark photoperiod); 4L, 6P (75 µmol $m^{-2}$ $s^{-1}$ light intensity and 6:6:6:6 h light:dark:light:dark photoperiod); 8L, 12P (150 µmol $m^{-2}$ $s^{-1}$ light intensity and 12:12 h light:dark photoperiod); 8L, 6P (150 µmol $m^{-2}$ $s^{-1}$ light intensity and 6:6:6:6 h light:dark:light:dark photoperiod); Blue (blue spectrum); Magenta (magenta spectrum); NL (natural light); and Red (red spectrum)

the amount of photosynthetically active and photomorphogenic radiation required for plant growth and development, matching LED wavelengths to photoreceptors in plants can allow for developmental changes including secondary metabolism to achieve optimal output [28]. On the other hand, plants can regulate their metabolism appropriately in response to changes in solar radiation and adapt to different light conditions without jeopardizing essential metabolites for growth and development, which may affect plant quality [57, 93, 95]. Eicosane, neophytadiene, L-(+)-ascorbic acid 2,6-dihexadecanoate, and (Z,Z,Z)-9,12,15-octadecatrienoic acid are common compounds synthesized in *B. rapa* under all light conditions, and their absence may directly or indirectly impair average growth and survival in the environment.

In the metabolite correlation analysis (Fig. 5), phenol, 2,4-bis(1,1-dimethylethyl)-, phosphite, which expressed as the highest compound in plants under natural light, showed a positive correlation with gamma-sitosterol ($r = 0.7192$), 2,6,10-trimethyltridecane ($r = 0.6224$) and dodecane, 4,6-dimethyl ($r = 0.6224$), but a negative correlation with 2,4-di-*tert*-butylphenol ($r = -0.6458$) and L-(+)-ascorbic acid 2,6-dihexadecanoate ($r = -0.605$). Meanwhile, hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester, which appeared to be the most abundant compound under artificial light, was found to be negatively correlated with many other compounds, implying that its production may have suppressed the production of those compounds under various artificial light treatments. Nonetheless,

**Fig. 5** Metabolite compound correlation matrix in *Brassica rapa* var. *chinensis* between light treatments. Each square represents a Pearson's correlation coefficient (*r*) ranging from − 1 (blue) to 1 (red)

the production of hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl) ethyl ester correlated positively with 2,4-di-*tert*-butylphenol ($r=0.8119$), ʟ-(+)-ascorbic acid 2,6-dihexadecanoate ($r=0.4934$), and octadecanoic acid, 2,3-dihydroxypropyl ($r=0.558$). Overall, 20 of the 31 compounds detected differed significantly when subjected to a different treatment (Table 4), indicating that their presence was greatly influenced by the light treatments, affecting plant growth and development.

## Conclusions

The rising global population growth is a key driver for an increase in demand of beneficial plant for consumption or medicinal purposes. This has shifted the need for a more controlled growing systems such as greenhouses and vertical farming that use artificial lighting to replace and/or mimic outdoor conditions. The current comparative study was carried out to determine the optimal conditions for producing *B. rapa* under
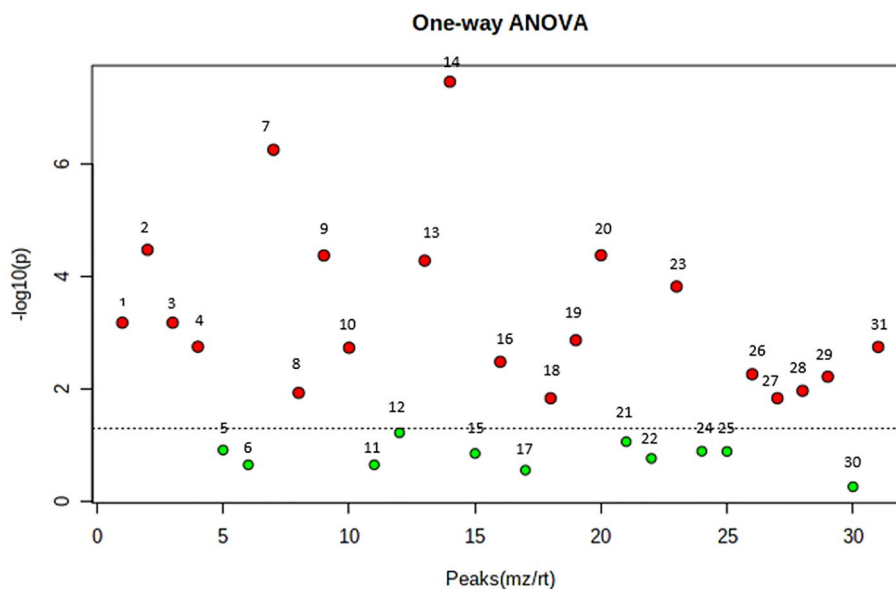
**Fig. 6** Significantly different metabolite compounds in *Brassica rapa* var. *chinensis* in response to various light treatments as determined by one-way ANOVA and the Tukey HSD post hoc test ($p < 0.05$). Numbers according to the compound codes in Table 4

artificial LED lighting. The findings indicate that artificial light resulted in a more consistent, albeit lower, biomass than plants grown under natural light (control). Besides, apart from the magenta spectrum, artificial lighting produced plants with higher chlorophyll content and thus a greener/fresher appearance, which may have an impact on the organoleptic properties of the produce. GC–MS analysis of *B. rapa* leaf extracts also revealed the presence of phytocompounds synthesized in response to specific light conditions, indicating that manipulating light intensity, photoperiod, and spectrum can result in a different physiological and biochemical output of *B. rapa*.

## Methods
### Plant materials and growth conditions
*Brassica rapa* seeds were obtained from the Green World Genetics (GWG) Sdn. Bhd. (Malaysia). The seeds were sown at a depth of one inch in reusable plastic flowerpots ($9 \times 6 \times 8$ cm), and each pot contained approximately 100 g of peat moss as the growing medium. Between three to five seeds per pot were sown initially, thinning around 1 week after the emergence of shoots, leaving one plant per pot. Twenty pots were used for each treatment to study the effects of light intensities (75 and 150 μmol m$^{-2}$ s$^{-1}$) and photoperiods (12:12 h light:dark and 6:6:6:6 h light:dark:light:dark) of white light (400 to 700 nm) on plant growth, chlorophyll content, and biochemical profile, and the treatments were carried out in triplicates in a plant growth room. To study the effects

of light spectrums, different sets of plants were initially grown for 4 weeks under white light at 150 μmol m$^{-2}$ s$^{-1}$ and 12:12 h (light:dark), before being exposed to different spectrums, namely blue (450–495 nm), red (650–700 nm), and magenta (a blue–red combination), at 75 μmol m$^{-2}$ s$^{-1}$ and 12:12 h (light:dark), for the final 2 weeks. The light spectral experiment was also carried out in triplicate, and the plants were recorded for their fresh weight, chlorophyll content, and biochemical profile. The plant growth room was maintained at a constant temperature of $23 \pm 2$ °C. Control groups were cultivated in a climate-controlled greenhouse maintained under natural daylight with a temperature of $23 \pm 2$ °C and relative humidity of $59 \pm 1\%$. All plants were irrigated with MS [52] solution twice a week. Light intensity was measured with the MQ-303 Apogee Quantum Flux Meter, and the wavelength was confirmed with the LI-180 LI-COR spectrometer. The photoperiod was controlled using the Eurosafe Timer Controller. Environmental factors such as carbon dioxide concentration, temperature, and humidity were set equal in both the glasshouse and growth room using HT-2000 Digital $CO_2$ meter (Sabah, Malaysia).

### Biomass measurement and post-harvest storage
When the plants reached harvest age after 42 days (6 weeks) of cultivation, they were harvested by cutting off the bottom of the stalk. Yellowing, decaying, and bruised leaves were discarded. The weighing was carried out for individual plants before the plants were frozen at $-80$ °C for biochemical analysis. The mean of

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**Table 4** List of significant and non-significant metabolite compounds produced by *Brassica rapa* var. *chinensis* in response to various light treatments

| Compound code | Name of compound |
|---|---|
| 1 | Dodecane, 4,6-dimethyl* |
| 2 | Hexadecane, 1-iodo* |
| 3 | 2,6,10-Trimethyltridecane* |
| 4 | 2,4-Di-*tert*-butylphenol* |
| 5 | Nonadecane** |
| 6 | Eicosane** |
| 7 | Tetracosane, 1-iodo* |
| 8 | Cyclononasiloxane, octadecamethyl-* |
| 9 | Neophytadiene* |
| 10 | 3,7,11,15-Tetramethyl-2-hexadecen-1-ol* |
| 11 | 2-Hexadecen-1-ol,3,7,11,15-tetramethyl** |
| 12 | Triacontane, 1-iodo-** |
| 13 | Cyclodecasiloxane, eicosamethyl-* |
| 14 | L-(+)-Ascorbic acid 2,6-dihexadecanoate* |
| 15 | 7,10,13-Hexadecatrienoic acid (Z,Z,Z)** |
| 16 | Phytol* |
| 17 | Hexacosane, 1-iodo-** |
| 18 | 10 (E), 12(Z)-Conjugated linoleic acid* |
| 19 | 9,12,15-Octadecatrienoic acid, (Z,Z,Z)-* |
| 20 | Octadecanoic acid* |
| 21 | 2-Methyltetracosane** |
| 22 | Hexadecanoic acid, 2-hydroxy-1-(hydroxy)** |
| 23 | Gamma-Sitosterol* |
| 24 | 9,12-Octadecadienoic acid (Z,Z)-** |
| 25 | Methyl (Z)-5,11,14,17-eicosatetraenoate** |
| 26 | 9,12,15-Octadecatrienoic acid, methyl ester* |
| 27 | Octadecanoic acid, 2,3-dihydroxypropyl* |
| 28 | 13-Docosenamide, (Z)-* |
| 29 | Phenol,2,4-bis(1,1-dimethylethyl) phosphite* |
| 30 | 1-Heptacosanol** |
| 31 | Vitamin E* |

* Significant ($p < 0.05$)

** Non-significant ($p > 0.05$)

plant biomass was used to calculate the total biological yield for each treatment. The samples were then freeze-dried to retain most phytochemical compositions before being blended and sieved into a powder of approximately 0.5 mm in size. All samples were stored at −20 °C before analysis.

### Preparation of plant extracts
Approximately 20 mg of leaf powder was extracted in 1 ml of hexane and sonicated at 50–60 Hz for 30 min at 30 °C. Then, the solution was placed in a thermomixer (Eppendorf Thermomixer) for 2 h at 30 °C with 800 rpm. The hexane extracts were then centrifuged (Eppendorf MiniSpin Mini Centrifuge) at 8000 rpm for 10 min. Supernatants were collected and transferred into a new microcentrifuge tube. It was then concentrated and dried using a speed vacuum concentrator (Eppendorf Concentrator Plus, Germany) for 1 h at 30 °C. The extracts were re-dissolved in hexane (Merck, HPLC Grade) with the desired concentration of 5 mg/ml before injecting 1 μl into GC–MS (Shimadzu GCMS-QP2020 NX, Japan) for analysis (modified from Sharma et al. [67]).

### Gas chromatography–mass spectrometry analysis
The single quadrupole GCMS-QP2020 NX (Shimadzu, Japan) GC–MS equipped with RTX-5 capillary GC column with a dimension of 30 m × 0.25 mm × 0.25 μm was used to identify the volatile compounds in *B. rapa* extracts. Helium was used as a carrier gas with a pressure of 75 kPa. The ion source temperature was set at 250 °C, and the interface temperature was 280 °C. The mass spectrometer detector was in full scan mode, and the scan range was set at *m/z* 35–550. Mass spectra were taken at 70 eV. The initial temperature was set at 80 °C for 1 min, and finally increased to 280 °C with 5 °C/min and held for 10 min (modified from Sharma et al. [67]). The data were assessed by total ion count (TIC) for the recognition and quantification of compounds. The mass spectrum of each identified compound was then compared with the published spectra in the NIST17 Library (Version 2.3; [54]).

### Determination of chlorophyll content
Chlorophyll a and b were extracted by placing 0.05 g of leaf powder in 25 ml of 80% acetone. Samples were sonicated for 30 min at 30 °C for a frequency of 50–60 Hz. Samples were then filtered with Whatman No. 2 filter paper, and the chlorophyll contents were measured at an absorbance value of 645 and 663 nm using a UV–VIS Spectrophotometer (Genesys, USA). Total chlorophyll contents were obtained by the sum of chlorophyll a and chlorophyll b content according to the modified method from Kasim and Kasim [35] and Arnon [4] with the calculations as below:

Chlorophyll a $(\mu g/ml) = 12.7\,(A663) - 2.69\,(A645),$

Chlorophyll b $(\mu g/ml) = 22.9\,(A645) - 4.68\,(A663),$

Total chlorophyll $(\mu g/ml) = 20.2\,(A645) + 8.02\,(A663).$

### Data analysis
The data were statistically analyzed ($p < 0.05$) using one-way ANOVA and Tukey HSD post hoc tests

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implemented in R statistical software version 3.3.0 [61]. All experiments were done in triplicate, and the results were presented as mean ± standard deviation (SD). Principal component analysis (PCA) was performed using MetaboAnalyst 5.0 statistical software on the abundance of the volatile compounds detected in *B. rapa* extracts to determine the significant variables that explain the relationships between different light treatments. Pearson correlation analysis was performed to understand the correlation between the identified metabolites, and the correlation values were presented in a correlation matrix.

### Abbreviations
GC–MS: Gas chromatography–mass spectrometry; LED: Light-emitting diode; PAR: Photosynthetically active radiation; PCA: Principal component analysis; PPFD: Photosynthetic photon flux density; ROS: Reactive oxygen species; TIC: Total ion count.

### Authors' contributions
WTLY and KFR conceived this research and designed experiments; NSS, WTLY and KFR participated in the design and interpretation of the data; NSS, BEC and KAK performed experiments and analysis; WTLY, KAK and KFR supervised the project; NSS and WTLY wrote the first draft of the manuscript and all authors participated in the revisions of it. All authors read and approved the final manuscript.

### Availability of data and materials
All data generated or analyzed during this study are included in this published article.

## Declarations

### Ethics approval and consent to participate
Not applicable.

### Consent for publication
Not applicable.

### Competing interests
The authors declare that they have no competing interests.

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