Horticulture, Environment, and Biotechnology (2026) 67:507–521
https://doi.org/10.1007/s13580-025-00794-9

RESEARCH REPORT

Enhanced biomass and essential oil yield in *Coriandrum sativum* L. through optimized additional night-time LED light spectra and dose

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Received: 28 September 2025 / Revised: 18 December 2025 / Accepted: 24 December 2025 / Published online: 16 January 2026
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Abstract

This study investigated the effects of supplemental light spectra and doses on essential oil yield, composition, and antimicrobial activity of *Coriandrum sativum* L. grown in Hanoi, Vietnam. Plants were cultivated for 9 weeks under varying light conditions: (i) different ratios of red and blue combined with ultraviolet A, green and/or far red, and (ii) lighting durations of 4, 6, or 8 h/night at photosynthetic photon flux density of approximately 120 µmol m^{-2} s^{-1}. Essential oils analysis identified four main constituents: linalool (21.06–44.13%), decanal (8.18–13.55%), (2*E*)-decenal (15.42–29.25%), and (2*E*)-dodecenal (3.32–8.72%). Supplemental lighting significantly affected plant biomass and oil yield ($p < 0.001$). The F2 treatment (75% red: 16.7% blue: 8.3% UV-A at 120 µmol·m^{-2}·s^{-1} in 6 h/night) produced the highest fresh biomass, dry biomass, essential oil, and linalool yields, increasing by factors of 1.88, 1.92, 2.69, and 4.84, respectively, compared with the control (solar light only). All oil samples inhibited growth of the seven tested microbial strains, though with varying effectiveness. Notably, treatment F4 showed the strongest activity against *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*. Overall, the results highlight the strong influence of spectral composition and light duration on biomass, oil yield, and antimicrobial activity of *C. sativum*, and demonstrate the potential of tailored LED lighting to enhance both productivity and quality in cultivation of *C. sativum*.

Keywords Cilantro · 2*E*-Decenal · Essential oil composition · Light spectra · Linalool · Supplemental night time irradiation

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1 Introduction

Coriandrum sativum L., belonging to Apiaceae family, is an aromatic annual herb used in culinary and medicinal practices (Moniruzzaman et al. 2014; Meena et al. 2014). Traditionally, it treats digestive, respiratory, and urinary disorders (Laribi et al. 2015). Cilantro (the aerial parts of *C. sativum*) is rich in bioactive compounds, including essential oil components like linalool and α, β-unsaturated aldehydes, which contribute to diverse pharmacological effects such as antimicrobial, antioxidant, neuroprotective, antidiabetic, and anti-inflammatory activities. *C. sativum* also functions as a functional food aiding heavy-metal detoxification and cardiovascular health (Mandal and Mandal 2015; Molina et al. 2020; Lin et al. 2022; Sahib et al. 2013; Mandal et al., 2015; Mahleyuddin et al. 2021). Cilantro extract was shown neuroprotective effects against toxins, neuroinflammation, and oxidative stress (Rodrigues et al. 2019; Cha et al. 2020); while coriander (the seed of *C. sativum*) extract reduced brain inflammation and aging markers in obese rats (Hardiany et al. 2024).

Beyond its medicinal value, *C. sativum* is used to prevent food spoilage and is gaining importance in pharmaceuticals, alternative medicine, and infection control (Bogavac et al. 2015, Denė et al., 2023). Its essential oil can be formulated into stable, biodegradable, and non-toxic nanoemulsions as natural preservatives (Cruz et al. 2024). The global *C. sativum* market, valued at USD 4.51 billion in 2024, is projected to reach USD 8.84 billion by 2030, driving efforts to enhance biomass, oil yield, and functional quality (Virtue Market Research 2025).

Light is a critical environmental factor for plant productivity, driving photosynthesis, secondary metabolite biosynthesis, and development (Dou et al. 2017). In essential oil-bearing plants, both light intensity and photoperiod strongly affect oil production. *Mentha piperita* L. (peppermint) requires a 15–16 h photoperiod to produce oil (Langston et al., 1954; Guenther 1961). *Anethum graveolens* L. (dill) oil content rises linearly with day length (Hälvä et al. 1992). In *Ocimum basilicum* L. (basil), six h d^{-1} of LED supplemental lighting at 100 µmol m^{-2} s^{-1} increased growth, biomass, and oil yield compared with under sunlight (Chu et al. 2022). Harakotr et al. (2019) reported that raising LED photosynthetic photon flux density (PPFD) significantly boosted growth and phytochemicals of some plant species, compared with the control.

Chlorophyll absorbs mainly red (R) and blue (B) light, making these wavelengths the most effective for photosynthesis (Lin et al. 2013). Consequently, R and B LEDs for indoor *C. sativum* cultivation has been extensively studied. Gao et al. (2022) tested different R: B ratios, and found that the 3R:1B treatment markedly enhanced growth, root and leaf weight, and total yield compared with monochromatic R or B. It also improved stomatal density, chlorophyll, photosynthesis, and reduced nitrate. Naznin et al. (2016) reported that highest biomass and antioxidants were obtained at R: B of 10:1 and 5:1, respectively. Goswami et al. (2024) demonstrated that biomass peaked under B light, but 50R:50B best enhanced photosynthesis, α-tocopherol, ascorbic acid, sugars, and volatiles.

Beyond R and B wavelengths, ultraviolet (UV)-A (365 nm), green (515–530 nm), and far-red (~730 nm) act as key signals shaping plant growth and development (Dou et al. 2017; Semenova et al. 2022; Park et al. 2025; Inthima et al. 2025). In *C. sativum*, adding UV-A light to a (20%R-80%W) spectrum during the last three days before harvest significantly increased shoot fresh weight, height and the number of leaves and branches (Somsong at al., 2024). While Fr added to an R-B-W spectrum (70:20:10) boosted height, biomass, internode length, and leaf area (Matysiak et al., 2021). Nguyen et al. (2020) showed that adding 6% Fr in an RB spectrum increased total phenolics and ascorbic acid. Lin et al. (2022) found balanced RGB at 150 µmol m^{-2} s^{-1} enhanced chlorophyll, carotenoids, and antioxidants, whereas higher B intensity (R: G:B = 1:1:4, 200 µmol m^{-2} s^{-1}) promoted flavonoids and antioxidant activity. McAusland et al. (2020) reported that complex RGB mixtures elevated aroma compounds, underscoring the role of spectral quality in *C. sativum* morphology and volatiles. Sotelo et al. (2025) indicated the highest shoot/root biomass, vitamin C, and phenolics under 53% R, 5% G, 13% B, and 29% Fr at 200 µmol m^{-2} s^{-1}, 16 h d^{-1}. Intermediate Fr lowered lutein and carotenoids, while higher G declined carotenoid, indicating this spectrum best supports biomass, nutrition, and energy efficiency in hydroponic *C. sativum*.

Mixed R, B, UV-A, G, and Fr lighting improves *C. sativum* growth, yield, essential oils, and antimicrobial activity in controlled environments, but field studies remain limited. Outdoor light is more variable in intensity and spectrum than indoor. Advances in LEDs make supplemental lighting a promising for enhancing outdoor *C. sativum* while saving energy by leveraging natural daylight. This study presents an approach for integrating supplementary multispectral night-time LED lighting into outdoor *C. sativum* cultivation, enabling efficient light utilization under realistic environmental conditions. Unlike previous research confined to indoor systems, this work simultaneously evaluated the effects of supplementary lighting on biomass, yield, chemical composition, and antibacterial activity of *C. sativum* essential oil within a single field experiment. Moreover, optimal light spectra and duration identified provides a practical lighting strategy to enhance both yield and quality in outdoor *C. sativum* production.

2 Materials and methods

2.1 Plant materials and lighting conditions

The experiment was conducted in an open field in Hanoi, Vietnam (N21°04′08″, E105°45′50″). Seeds of *Coriandrum sativum* L. were sown in October 2023 and transplanted in December 2023 at a spacing of 20 × 20 cm in an experimental area. This area was divided into five beds, each further subdivided into six plots (1 m² per plot). Each set of three plots represented three replicates of a lighting treatment, for a total of 10 treatments arranged in a completely randomized design. During the experiment, the ambient temperature ranged from 14 to 24 °C, and the relative humidity ranged from 75% to 85%, monitored using a TEROS 12 sensor (METER Group, USA). A supplemental lighting experiment was conducted over nine weeks, from 12 January to 9 March 2024. At the end of the cultivation period, the aerial parts (cilantro) of *C. sativum* (cultivar Baclieu-PD 414) were harvested for subsequent analysis and evaluation.

The average PPFD (400–700 nm) was 16.26 mol m^{-2} d^{-1}, with monthly averages of 17.34 in January, 15.00 in February, and 18.35 mol m^{-2} d^{-1} in March 2024, based on the DLI (daily light integral) database from SuntrackerTech (2024). Depending on the treatment, LED supplemental lighting was applied 2–4 h before sunrise (1:00–5:00 am) and after sunset (7:00–11:00 pm), aimed at extending the photoperiod for plants without overlapping natural sunlight. *C. sativum* was exposed to 4, 6, or 8 h of supplemental light daily to assess duration – lighting responses. LEDs were installed at a distance of 50 cm above the canopy to ensure uniform light distribution and spectral blending. A light uniformity index greater than 80% was verified before the experiment using a quantum sensor (LI-250 A Light Meter with LI-190SA Quantum Sensor, LI-COR Biosciences, USA). The downlight LED bulbs were suspended from ropes secured to poles at the ends of the beds. The poles enabled convenient adjustment of lamp height relative to the plant canopy using U-shaped locking pins. To prevent light spillover between adjacent cells, 35-cm-wide trenches were created between them. A control box regulated the light dose (illuminance and exposure duration), allowing both manual and automatic adjustment of lighting intensity and duration. To minimize shadows created by the LED frames and the lamps themselves, compact parabolic lampshades (base radius 18 cm, tilted height 10 cm) were used. An intensity of 120 µmol m^{-2} s^{-1} was delivered that is sufficient to support physiological responses without causing photodamage or heat stress to plant (Ptak et al. 2021). Three distinct spectral treatments designed by integrating R (660 nm) and B (440 nm) light with UV-A (365 nm), G (530 nm), or a combination of Fr (730 nm) and G (Table 1; Fig. 1) were measured by a USB2000+Fiber Optic Spectrometer. The techniques for planting, caring, fertilizing, and harvesting *C. sativum* plants were carried out according to the previous document (La et al. 2001).

2.2 Essential oil isolation

Each *C. sativum* sample consisting of 2.0–2.5 kg totally of aerial biomass (cilantro) was shredded and hydrodistilled for 3.5 h using a Clevenger type apparatus, repeated three times (Ministry of Health of Vietnam 2017). The essential oil was then separated and stored at −5 °C for further analysis.

2.3 Essential oil GC-MS and GC-FID analysis

Essential oils were analyzed using GC/MS-FID on an Agilent GC 7890 A system equipped with a Mass Selective Detector (Agilent 5975 C). Separation was achieved with an HP-5MS fused silica capillary column (60 m × 0.25 mm i.d., 0.25 µm film thickness). Helium served as the carrier gas at a flow rate of 1.0 mL/min. The injector temperature was set at 250 °C, with an injection volume of 1 µL and a split ratio of 1:100. The oven temperature program was: initial 60 °C, ramped to 240 °C at 4 °C/min. Detector temperatures were maintained at 270 °C. For MS analysis, conditions included an interface temperature of 270 °C, electron ionization (E.I.) mode with a detector voltage of 70 eV, a scan rate of 4.0 scan/s, and a mass range of 35–450 Da. FID analysis was performed under the same chromatographic conditions, with the FID detector maintained at 270 °C. Identification of essential oil constituents was based on comparison of their relative retention indices, determined by co-injection with a homologous series of *n*-alkanes (C5–C30), and by matching their mass spectral fragmentation patterns against MS libraries (NIST08, Wiley09, HPCH1607) (Adams 2017; Linstrom and Mallard 2021). Data were processed using MassFinder 4.0 (König et al. 2004). Relative concentrations of the identified components were calculated from FID peak areas without standardization.

2.4 Tested microbial strains

Antimicrobial activity of the oils was determined using 3 strains of Gram (+) bacteria (*Staphylococcus aureus* - ATCC 13709, *Bacillus subtilis* - ATCC 6633 and *Lactobacillus fermentum* - VTCC N4), 3 strains of Gram (–) bacteria (*Salmonella enterica* - VTCC, *Escherichia coli* - ATCC 25922 and *Pseudomonas aeruginosa* - ATCC 15442), 1 strain of yeast (*Candida albicans* - ATCC 10231). ATCC strains were sourced from the American Type Culture Collection, while VTCC strains were obtained from the Vietnam Type

Table 1 Supplemental light treatments in outdoor cultivation of *Coriandrum sativum*

Treatments	Spectral distribution					Light intensity (μmol·m⁻²·s⁻¹)	Duration (h d⁻¹)	Lighting time	Total daily supplemental light (mol·m− 2 ·d− 1)	Total daily light (mol·m− 2 ·d− 1)
	Red (%)	Blue (%)	UV-A (%)	Green (%)	Far red (%)					
F1	75	16.7	8.3	0	0	120 ± 10	4	3:00–5:00 am & 7:00–9:00 pm	1.728	17.99
F2	75	16.7	8.3	0	0	120 ± 10	6	2:00–5:00 am & 7:00–10:00 pm	2.592	18.85
F3	75	16.7	8.3	0	0	120 ± 10	8	1:00–5:00 am & 7:00–11:00 pm	3.456	19.72
F4	66.7	16.7	0	16.6	0	120 ± 10	4	3:00–5:00 am & 7:00–9:00 pm	1.728	17.99
F5	66.7	16.7	0	16.6	0	120 ± 10	6	2:00–5:00 am & 7:00–10:00 pm	2.592	18.85
F6	66.7	16.7	0	16.6	0	120 ± 10	8	1:00–5:00 am & 7:00–11:00 pm	3.456	19.72
F7	66.7	16.7	0	8.3	8.3	120 ± 10	4	3:00–5:00 am & 7:00–9:00 pm	1.728	17.99
F8	66.7	16.7	0	8.3	8.3	120 ± 10	6	2:00–5:00 am & 7:00–10:00 pm	2.592	18.85
F9	66.7	16.7	0	8.3	8.3	120 ± 10	8	1:00–5:00 am & 7:00–11:00 pm	3.456	19.72
F10	0	0	0	0	0	0		0		16.26

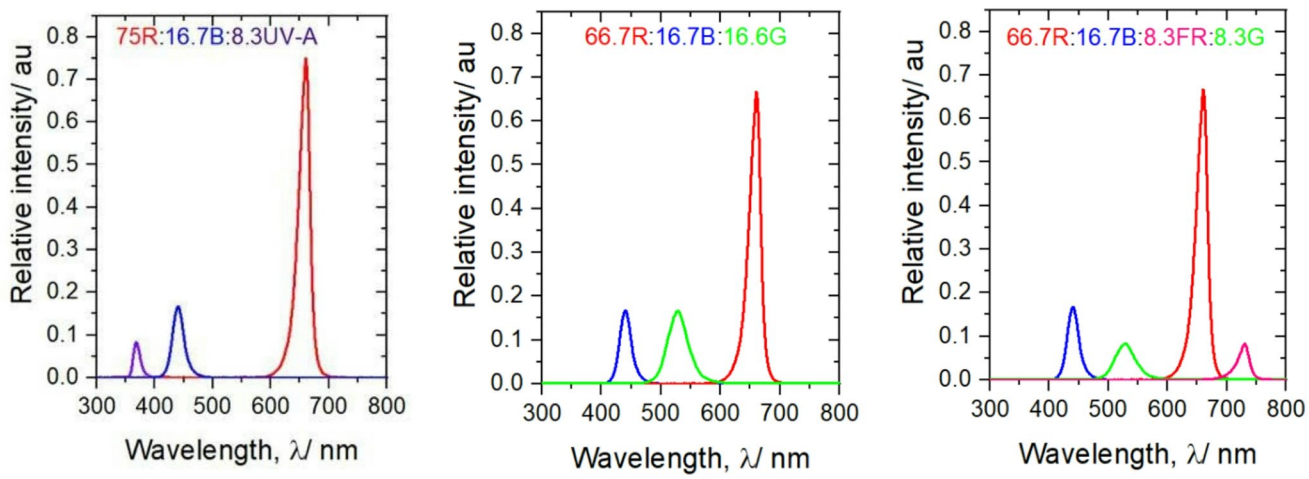


Fig. 1 The supplemental spectra with different proportions of radiation regions

Culture Collection, Institute of Microbiology and Biotechnology, Vietnam National University, Hanoi.

2.5 Screening of antimicrobial activity of essential oil

The minimum inhibitory concentration (MIC) and half-maximal inhibitory concentration (IC_{50}) of the essential oils were determined in triplicate using the broth microdilution method (Hadacek and Greger 2000; Cos et al. 2006). Stock solutions of the oils were prepared in dimethyl sulfoxide (DMSO) and serially diluted in sterile distilled water to obtain concentrations ranging from 16,000 to 15.625 µg mL^{-1} (a series of 11 concentrations diluted by a factor of 2). The dilutions were prepared in microtubes and transferred into 96-well microplates. Bacterial strains were cultured in double-strength Mueller–Hinton broth or double-strength tryptic soy broth, whereas fungal strains were grown in double-strength Sabouraud dextrose broth. Microbial suspensions were standardized to 5×10^5 CFU/mL for bacteria and 1×10^3 CFU/mL for fungi. Negative control contained only the culture medium without the serial dilutions of the essential oil and without microorganisms. While culture medium containing microorganisms without the serial dilutions of the essential oil served as positive control. Plates were incubated at 37 °C for 24 h, after which MIC values were recorded as the lowest concentration of the essential oil that completely inhibited microbial growth. IC_{50} values were calculated from the percentage of microbial growth inhibition, based on turbidity measurements obtained with an EPOCH2C spectrophotometer (BioTek Instruments, Winooski, VT, USA). Data were analyzed using Raw data software (Intercity Business Park Mechelen Noord, Mechelen, Belgium) according to the following equations:

$$\%\ \text{inhibition} = \frac{OD_{control(+)} - OD_{test\ agent}}{OD_{control(+)} - OD_{control(-)}} \times 100\% \quad (1)$$

$$IC_{50} = High_{Conc} - \frac{(High_{Inh\%} - 50\%)\,(High_{Conc} - Low_{Conc})}{(High_{Inh\%} - Low_{Inh\%})} \quad (2)$$

Where:

OD: Optical density; control (+): Cells in medium without antimicrobial agent; test agent: corresponds to a specific, known concentration of the antimicrobial agent; control (-): Culture medium without cells. $High_{Conc}/Low_{Conc}$: High and low concentrations of the test agent, respectively; $High_{Inh\%}/Low_{Inh\%}$: Percentage of microbial growth inhibition at high and low concentrations, respectively.

2.6 Statistical analysis

Data were analyzed using a single-factor completely randomized analysis of variance (ANOVA) to compare the effects of different lighting treatments. When significant differences were detected, mean values were separated using the least significant difference (LSD) test at $p \leq 0.05$, with analyses performed in IRRISTAT version 5.0 (International Rice Research Institute, Philippines). Pearson correlation analysis was performed using SPSS ver. 27.0.1 (IBM SPSS Statistics).

3 Results and discussion

3.1 Effect of supplemental light condition on biomass and essential oil yield of *Coriandrum sativum*

Overall, stem height, fresh biomass, and dry biomass were highest under the combined R: B:UV-A (75:16.7:8.3) spectra (see Table 2). This effect is likely due to the strong positive roles of high ratio R and of UV-A light in promoting growth, while the proportion of B light was kept constant across all nine supplemental lighting treatments. The best results were achieved in F2 (R: B:UV-A = 75:16.7:8.3; 120 µmol m^{-2} s^{-1}; 6 h/night), which produced mean values of 142.45 cm/plant for stem height, 214.53 g/plant for fresh weight, 41.83 tons/ha for fresh biomass, and 11.59 tons/ha for dry biomass. These values were significantly higher than those of other treatments ($\rho < 0.001$), representing 1.09-, 1.88-, 1.88-, and 1.92-fold increases, respectively, compared with the control.

The second-highest values were observed under the R: B:Fr: G spectra, likely reflecting the contribution of Fr light in stimulating plant growth. In contrast, treatments F4, F5, and F6 resulted in shorter stems (127.84–129.22 cm/plant) compared with the F10 control (130.46 cm/plant), suggesting that the higher proportion of G light in the R: B:G spectra suppressed stem elongation. Nevertheless, *C. sativum* grown under all nine supplemental lighting treatments produced significantly greater fresh and dry biomass (24.94–41.83 tons/ha and 6.48–11.59 tons/ha, respectively) than the F10 control grown under natural light alone (22.22 and 6.04 tons/ha; $\rho < 0.001$) (Table 2).

As mentioned above, R and B are particularly effective in promoting photosynthetic CO_2 assimilation (Lin et al. 2013). Interestingly, however, the lowest CO_2 assimilation in *C. sativum* occurred under monochromatic R, despite plants showing the strongest growth. Plant height, leaf area, fresh biomass, and dry biomass under R alone exceeded those under R: G:B, R:B, or B light (McAusland

Table 2 Biomass and essential oil yield of *Coriandrum sativum* cultivated under different light conditions

Treatment	Height of plant (cm/plant)	Fresh weight of plant (g/plant)	Water content (%)	Production of fresh biomass (ton/ha)*	Production of dry biomass (ton/ha)*	Essential oil content (% v/w, dry)	Production of essential oil (L/ha)*
F1	130.20 ± 0.88^{e}	184.64 ± 4.03^{c}	73.94 ± 0.23^{c}	36.01 ± 0.79^{c}	9.28 ± 0.08^{c}	0.361 ± 0.00^{g}	34.03 ± 0.67^{d}
F2	142.45 ± 0.53^{a}	214.53 ± 0.48^{a}	72.31 ± 0.29^{g}	41.83 ± 0.09^{a}	11.59 ± 0.03^{a}	0.496 ± 0.01^{a}	57.49 ± 0.03^{a}
F3	132.41 ± 0.80^{c}	192.76 ± 2.68^{b}	71.24 ± 0.18^{h}	37.59 ± 0.52^{b}	10.75 ± 0.15^{b}	0.385 ± 0.01^{d}	41.62 ± 0.55^{b}
F4	128.46 ± 0.80^{f}	155.56 ± 3.50^{e}	74.53 ± 0.25^{a}	30.33 ± 0.68^{e}	7.74 ± 0.17^{e}	0.402 ± 0.00^{b}	31.18 ± 0.71^{f}
F5	129.22 ± 0.09^{e}	135.31 ± 2.14^{g}	72.67 ± 0.30^{f}	26.38 ± 0.42^{g}	7.20 ± 0.11^{g}	0.492 ± 0.00^{a}	35.42 ± 0.59^{c}
F6	127.84 ± 0.49^{f}	129.22 ± 0.40^{h}	74.27 ± 0.13^{b}	25.20 ± 0.08^{h}	6.48 ± 0.02^{i}	0.365 ± 0.00^{g}	23.46 ± 0.19^{i}
F7	131.52 ± 1.33^{d}	127.92 ± 0.85^{i}	73.44 ± 0.08^{d}	24.94 ± 0.17^{h}	6.61 ± 0.04^{h}	0.380 ± 0.00^{e}	25.23 ± 0.30^{h}
F8	132.02 ± 0.11^{c}	162.80 ± 4.23^{d}	74.73 ± 0.13^{a}	32.41 ± 0.28^{d}	8.00 ± 0.21^{d}	0.396 ± 0.00^{c}	31.69 ± 0.74^{e}
F9	135.44^{b} ± 0.62	143.93 ± 0.52^{f}	73.41 ± 0.12^{d}	28.07 ± 0.10^{f}	7.47 ± 0.03^{f}	0.369 ± 0.00^{f}	27.66 ± 0.06^{g}
F10	130.46 ± 1.20^{d}	113.93 ± 0.47^{k}	72.75 ± 0.14^{e}	22.22 ± 0.09^{i}	6.04 ± 0.02^{k}	0.354 ± 0.00^{h}	21.34 ± 0.09^{k}
5% LSD	1.355	4.290	0.339	0.718	0.169	0.0045	0.833

Note: Mean values followed by the same letter within a column are not statistically different for 0.05 significant level ($n = 3$). Statistical analyses were performed using IRRISTAT ver. 5.0 (International Rice Research Institute, Laguna, Philippines) *Estimated values (cultivation distance of coriander: 20 × 20 cm, estimated number: 195,000 plants per ha)

et al. 2020). Other studies, however, found higher fresh and dry biomass under specific R: B ratios than under R alone (Naznin et al. 2016; Gao et al. 2022). Similarly, in *Solanum lycopersicum* L. (tomato) and in *Vaccinium* spp. (blueberry) seedlings, higher R in R–B light increased stem length and biomass (Nakonechnaya et al. 2022; Zhang et al. 2022). These effects align with the role of R in activating phytochromes, enhancing cell division, expansion, and hypocotyl elongation (Neff et al. 2000).

The positive effects of UV-A on cilantro plants observed in this study are similar to previous research results on other species. Supplemental UV-A enhanced shoot dry weight and leaf area in *Lactuca sativa* cv. 'Klee' (lettuce) (Chen et al. 2019), increased height in *Thymus daenensis* (denaian thyme) (Mumivand et al. 2021), significantly improved fresh leaf mass, dry mass/fresh mass ratio, and leaf area in *Ocimum basilicum* L. (basil) (Semenova et al. 2022). Adding UV-A to a B: G:R: Fr spectrum strongly promoted biomass and leaf area in *Brassica juncea* L. (red mustard) and *Ocimum basilicum* L. 'Gastronome' (basil) (Smirnov et al. 2023). These effects likely result from UV-A enhancing stomatal opening, photosynthesis, and carbon assimilation (Verdaguer et al. 2017).

Fr light also promoted *C. sativum* growth, although less strongly than UV-A. Somsong et al. (2024) reported that UV-A–treated plants showed greater height, more leaves and branches, and stronger root than those under Fr. Growth promotion by Fr was also noted in indoor cultivation with plant height and biomass increasing proportionally to the ratio of Fr incorporated in the spectral group (Akter et al. 2024). Hydroponic cultivation showed maximum biomass at R: Fr ~ 1.8 with low G light (Sotelo et al. 2025). In *Cucumis melo* L., 'Emerald' (melon) seedlings, height rose significantly with increasing Fr (Zhao et al. 2024). Although Fr lies outside PAR (400–700 nm) and is weakly photosynthetic alone (Zhen et al. 2021), combined with R it stimulates growth via the "Emerson effect," boosting photosynthesis and biomass (Li & Kubota, 2009; Lysenko et al. 2014). Fr supplemental to RGB or W LEDs (white light LEDs) significantly enhanced photomorphogenesis, increasing leaf expansion and shoot biomass up to 2.7-fold vs. control (Park et al. 2025). Another mechanism may be indirect stimulation of stomatal opening, increasing CO_2 uptake and carbon fixation (Demotes-Mainard et al. 2016).

The effect of G light on reducing the height growth of *C. sativum* in this study aligns with findings in basil and tomato (Chen et al. 2024). This inhibition may result from its deeper canopy penetration, allowing lower leaves to perceive photic signals and reducing shade avoidance, i.e., reducing stem elongation (Smith et al. 2017). Effects on biomass appear species-dependent: G light promoted fresh biomass in lettuce but decreased it in basil and tomato (Chen et al. 2024). Moderate increases in G enhanced melon biomass, whereas excessive G sharply reduced it (Zhao et al. 2024). Biomass gains in some species under G light may be attributed to the high utilization efficiency (Kim et al. 2004). Conversely, high G ratios can inhibit growth via spectral competition with R and B, weakening their dominant role in

photosynthesis and photomorphogenesis. In sensitive species, reduced R and B lower photosynthetic quantum efficiency (ΦPSII), ultimately limiting biomass accumulation (Smith et al. 2017).

The water contents in cilantro ranged from 71.24 to 74.73%. Treatments F1, F2, and F3 with R: B:UV-A (75:16.7:8.3) had the lowest values, indicating greater dry matter accumulation. Higher water content under F4-F9 may result from G light. Ma et al. (2022) reported that replacing R and B with G enhanced net photosynthesis but reduced stomatal conductance and transpiration, improving intrinsic water use efficiency. This reduced water loss and improved water use efficiency likely explain the greater water accumulation in plant tissues. Essential oil concentration was highest under R: B:G (66.7:16.7:16.6). Among individual treatments, similar to the height and biomass values, F2 produced the highest value (0.496%), while the others (0.361–0.492%) were all significantly higher than the control F10 (0.354%).

Essential oil yield is a critical parameter in evaluating cultivation efficiency of essential oil-bearing plants. Under R: B:UV-A (75:16.7:8.3) lighting, cilantro produced higher oil yields than the other spectral groups. Consistent with biomass and oil concentration, the highest oil yield was in F2 (57.49 L/ha), significantly higher ($p<0.01$) than the other eight treatments (23.46–41.62 L/ha) and 2.69 times greater than the control (21.34 L/ha).

The essential oil concentrations obtained fall within reported ranges, though values vary with cultivar origin, weather conditions, and geographical location (Al-Khayri et al. 2023; Svetlana 2025); growth stage (Ramezani et al. 2009); fertilizer dosage (Hadi et al. 2022); and plant parts (Bhuiyan et al. 2009). To our best knowledge, no previous studies have examined lighting effects on essential oil concentration of outdoor-grown *C. sativum*.

Regarding the effects of spectral quality, all evaluated indicators of growth and essential oil accumulation in *C. sativum* reached their highest values under the UV-A spectrum treatments with a high R ratio (F1–F3). The spectrum group containing Fr & G (F7–F9) ranked second in growth parameters, including plant height, fresh and dry biomass. In contrast, the spectrum group containing G (F4–F6) produced the second-highest essential oil content and yield. With respect to photoperiod, most evaluated indicators achieved their highest values under 6 h/night of supplementary lighting. Exceptions were observed in the Fr & G spectrum group (plant height peaked under 8 h/night), and in the G spectrum group (biomass reached its maximum under 4 h/night).

3.2 Effect of supplemental light conditions on essential oil composition of *Coriandrum sativum*

The essential oil extracted from cilantro under supplemental lighting contained 28–38 compounds, representing 94.37–98.18% of total composition (see Table 3). Oxygenated monoterpenes (25.29–49.4%) and oxygenated hydrocarbons (37.52–67.07%) dominated. Four main constituents were linalool (21.06–44.13%), decanal (8.18–13.55%), (2*E*)-decenal (15.42–29.25%), and (2*E*)-dodecenal (3.32–8.72%). Linalool concentrations in all nine supplemental lighting treatments exceeded the control ($p<0.01$), with the maximum (44.13%) in F6 (R: B:G = 66.7:16.7:16.6; 120 μmol m^{-2} s^{-1}; 8 h/night). In the R: B:UV-A and R: B:G: Fr groups, F2 (37.84%), and F8 (43.95%) yielded the highest value, demonstrating the optimal effect of 6 h/night supplemental lighting. In general, *C. sativum* grown under supplemental UV-A illumination exhibited lower linalool concentration than those grown under the other spectrum groups. Other three major compounds peaked in different treatments: decanal (F3), (2*E*)-decenal (F10), and (2*E*)-dodecenal (F1). Unlike linalool, (2*E*)-decenal was significantly lower in all treatments versus control ($p<0.01$), while decanal and (2*E*)-dodecenal showed no consistent pattern (Table 3).

Linalool, an acyclic monoterpene with a sweet, floral, citrus-like odor and 7.4 ppb detection threshold (McAusland et al. 2020), is abundant in aromatic plants and widely used in perfumes, lotions, soaps, shampoos, detergents and cleaning agents. Its enantiomers exhibit anti-inflammatory (Peana et al. 2002), antioxidant (Liu et al. 2012), anti-cancer (Elbe et al. 2022), neuroprotective (Sabogal-Guáqueta et al. 2019), and antidepressant activity (dos Santos et al. 2022). Incorporated into collagen matrices, linalool accelerated wound healing with reduced inflammation and scar formation in mouse skin tissue, in vivo (Lyu et al. 2017). Its concentration varies across *C. sativum* cultivars (Svetlana 2025). In this study, cilantro linalool yields under supplemental multispectral light reached 9.14–21.75 L/ha, significantly higher ($p<0.01$) than the control (4.49 L/ha). Yields of linalool and other major compounds, except decanal, peaked in F2, with linalool 4.84-fold higher than control (Fig. 2).

The essential oil from the leaves of a commercial *C. sativum* sample in the United States (Potter, 1996) contained two major compounds also identified in the present study: (2*E*)-decenal (12.1%) and (2*E*)-dodecenal (15.6%). Likewise, oil from Kenyan *C. sativum* leaves (Matasyoh et al. 2009) shared three major compounds, excluding linalool: decanal (14.3%), (2*E*)-decenal (15.9%), and (2*E*)-dodecenal (6.2%). Whereas, commercial Slovakian oils contained linalool (66.07%), camphor (8.34%), geranyl acetate (6.91%), and cymene (6.35%) (Kacániová et al., 2020).

Table 3 Composition of essential oils of *Coriandrum sativum* cultivated under different light conditions

Compounds (%)[a]	RI[b]	F1[c]	F2[c]	F3[c]	F4[c]	F5[c]	F6[c]	F7[c]	F8[c]	F9[c]	F10[c]
n-Nonane	898	0.98	0.68	0.99	0.71	0.59	1.56	0.54	0.89	0.64	0.47
α-Pinene	938	1.83	1.37	1.42	1.62	2.26	3.56	1.18	2.70	1.34	0.96
Camphene	955	0.22	0.13	0.19	0.15	0.18	0.42	0.14	0.20	Tr	Tr
β-Pinene	983	0.14	0.13	0.12	0.13	0.17	0.28	Tr	0.21	Tr	0.11
Myrcene	991	0.21	0.15	Tr	0.16	0.20	0.42	0.15	0.28	Tr	Tr
n-Decane	999	0.15	Tr	0.17	0.11	Tr	0.21	Tr	0.16	Tr	Tr
n-Octanal	1002	0.49	0.44	0.35	0.44	0.57	0.65	0.49	0.58	0.45	0.58
p-Cymene	1028	0.88	0.55	1.01	0.81	1.09	1.68	0.98	1.26	0.99	1.07
Limonene	1033	0.48	0.29	0.39	0.36	0.38	0.87	0.36	0.50	0.32	0.16
γ-Terpinene	1062	1.92	1.30	0.75	1.02	1.23	2.15	0.66	2.07	0.96	0.21
n-Octanol	1068	0.18	0.17	Tr	0.13	0.17	0.20	0.11	0.17	Tr	0.11
trans-Linalool oxide (furanoid)	1076	Tr	Tr	0.26	0.20	0.24	0.28	0.39	0.21	0.28	0.99
2-Nonanone	1091	Tr	Tr	Tr	0.15	Tr	0.16	Tr	Tr	Tr	Tr
cis-Linalool oxide (furanoid)	1092	Tr	Tr	0.28	0.30	0.35	0.23	0.20	0.22	0.30	1.16
Fenchone	1093	Tr	Tr	Tr	Tr	Tr	0.23	0.20	0.21	Tr	Tr
Linalool	1102	33.54	37.84	32.53	32.21	38.45	44.13	37.83	43.95	33.05	21.06
Nonanal	1105	0.24	0.16	0.43	0.26	0.26	0.27	0.28	0.27	0.28	0.48
Camphor	1155	1.47	1.31	2.01	1.26	1.25	1.92	1.98	1.44	0.93	0.54
n-Nonanal	1171	Tr	Tr	0.17	Tr	Tr	Tr	Tr	Tr	Tr	Tr
cis-Linalool oxide (pyranoid)	1174	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	0.25
Borneol (=*endo*-Borneol)	1175	0.2	0.13	Tr	Tr	Tr	Tr	Tr	Tr	0.21	Tr
trans-Linalool oxide (pyranoid)	1178	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	0.28
Santalone	1185	Tr	Tr	Tr	Tr	Tr	0.11	Tr	0.13	Tr	Tr
Terpinen-4-ol	1185	0.11	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
α-Terpineol	1197	0.28	Tr	0.22	0.59	0.68	0.57	0.26	0.59	0.18	Tr
(4*E*)-Decenal	1198	0.28	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Methyl chavicol (=Estragole)	1203	Tr	Tr	Tr	Tr	Tr	Tr	0.20	Tr	Tr	Tr
Decanal	1207	10.53	9.09	13.55	11.41	8.18	8.55	9.67	10.44	12.13	13.06
Citronellol	1228	0.14	0.18	0.13	0.12	Tr	0.12	Tr	0.12	Tr	Tr
Geraniol	1255	1.36	1.36	Tr	1.27	1.25	1.14	1.53	1.32	1.11	0.60
Linalyl acetate (=Linalool acetate)	1257	Tr	Tr	1.38	Tr	Tr	Tr	Tr	Tr	Tr	Tr
(2*E*)-Decenal	1265	18.91	19.36	16.60	17.90	20.98	15.42	16.67	17.51	19.87	29.25
(2*E*)-Decen-1-ol	1269	2.35	3.55	2.32	3.14	2.58	1.85	2.38	1.34	1.46	2.20
n-Decanol	1271	1.78	2.04	2.82	2.43	1.45	1.53	1.76	1.21	1.61	1.86
Geranial	1274	Tr	0.18	0.17	Tr	Tr	Tr	Tr	Tr	Tr	Tr
(2*E*,4*Z*)-Decadienal	1296	0.14	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Undecanal	1308	0.55	0.55	0.95	0.71	0.48	0.43	0.61	0.51	0.66	0.88
Decanoic acid	1361	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	0.26
(2*E*)-Undecenal	1366	1.95	2.16	2.46	2.23	2.01	1.18	2.03	1.61	2.50	3.08
(2*E*)-Undecen-1-ol	1370	0.19	0.28	0.28	0.39	0.27	0.15	0.23	Tr	0.14	0.22
Undecanol	1372	Tr	0.14	0.15	0.13	Tr	Tr	Tr	Tr	Tr	Tr
Geranyl acetate	1383	0.78	0.53	Tr	0.64	0.62	0.78	0.62	0.55	0.58	0.66
Linalyl isobutanoate	1385	Tr	Tr	0.65	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Dodecanal	1410	1.36	1.03	1.28	1.30	1.06	0.73	1.21	0.77	1.27	1.37
(2*E*)-Dodecenal	1470	8.72	7.58	8.44	8.16	5.89	3.32	7.76	4.61	8.14	8.11
(2*E*)-Dodecen-1-ol	1471	0.87	1.04	Tr	1.27	0.91	0.61	0.19	Tr	0.47	0.47
n-Tridecanal	1512	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	0.11
(2*E*)-Tridecenal	1572	0.2	0.25	0.27	0.26	0.23	0.15	0.52	0.13	0.25	0.35
Tetradecanal	1614	0.42	0.33	0.43	0.45	0.47	0.29	0.50	0.25	0.47	0.51
(2*E*)-Tetradecenal	1675	3.12	2.94	3.95	3.92	3.28	2.03	4.02	1.76	3.78	4.17
(2*E*)-Pentadecenal	1778	0.11	Tr	0.17	0.17	0.14	Tr	0.26	Tr	Tr	Tr
(2*E*)-Hexadecenal	1881	0.11	Tr	0.16	0.13	Tr	Tr	0.16	Tr	Tr	Tr
Phytol	2116	0.15	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Total		**97.34**	**97.24**	**97.45**	**96.64**	**97.87**	**98.18**	**96.07**	**98.17**	**94.37**	**95.59**
Monoterpene hydrocarbon		4.8	3.37	2.87	3.44	4.42	7.7	2.49	5.96	2.62	1.44

Table 3 (continued)

Compounds (%)[a]	RI[b]	F1[c]	F2[c]	F3[c]	F4[c]	F5[c]	F6[c]	F7[c]	F8[c]	F9[c]	F10[c]
Oxygenated monoterpenoids		37.88	41.53	37.63	36.59	42.84	49.4	43.01	48.61	36.64	25.54
Hydrocarbons		1.13	0.68	1.16	0.82	0.59	1.77	0.54	1.05	0.64	0.47
Oxygenate hydrocarbons		52.5	51.11	54.78	54.98	48.93	37.52	48.85	41.16	53.48	67.07
Benzenoids		0.88	0.55	1.01	0.81	1.09	1.68	1.18	1.26	0.99	1.07
Oxygenated diterpenoids		0.15	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Others		Tr	Tr	Tr	Tr	Tr	0.11	Tr	0.13	Tr	Tr
Number of compounds quantified		38	32	35	37	32	36	34	33	28	32

Note: [a]Order of compounds eluted on the HP-5MS column; [b]RI: retention index of compounds on the HP-5MS column; [c]Standard deviation were insignificant and excluded from the Table to avoid congestion ($n=3$); Tr: Trace (concentration < 0.1%)

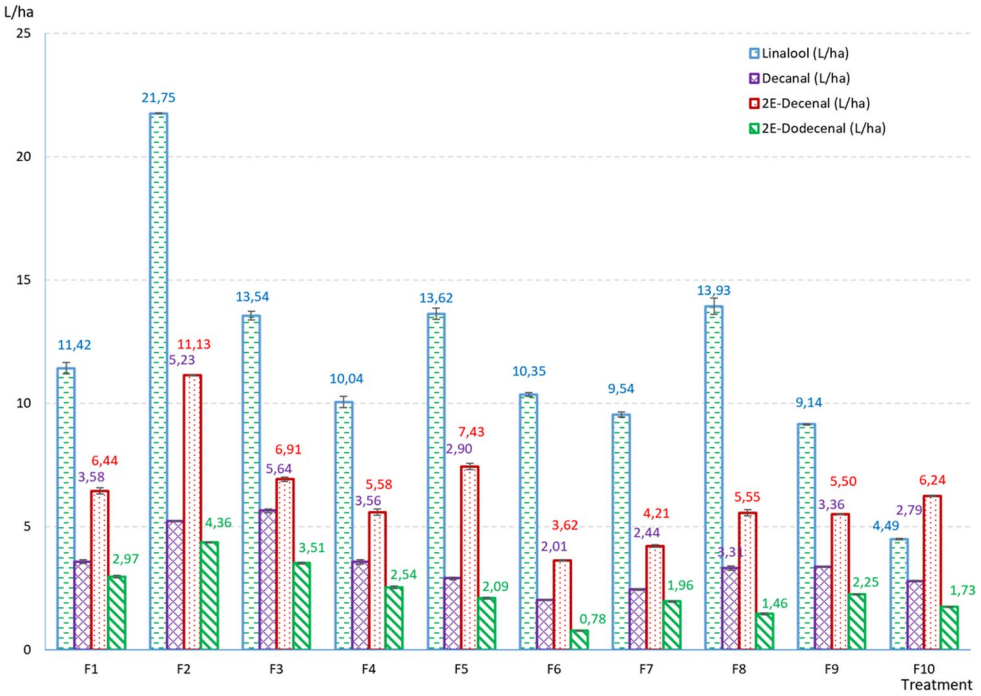


Fig. 2 The yields of four essential oil main constituents of *Coriandrum sativum* cultivated under different light conditions ($n=3$)

These findings confirm that chemical profiles of *C. sativum* oil vary with geography, season, and variety. Linalool content is highly variable among populations of aromatic plants worldwide, growth stages, and plant parts (Orav et al. 2011; Mandal and Mandal 2015). Some cilantro oils lack linalool entirely (Satyal and Setzer 2020). In hydroponically grown *C. sativum* under multispectral light, decanal and (2*E*)-decenal were the predominant components, whereas linalool and (2*E*)-dodecenal were absent from the leaf oil. Light quality was reported to influence decanal concentration when the R and B ratios were varied (Lin et al. 2022).

3.3 Effect of supplemental light conditions on antimicrobial activity of *Coriandrum sativum* essential oil

The antibacterial activity of cilantro essential oil was evaluated against seven strains of microorganisms: three Gram-positive bacteria (*Staphylococcus aureus*, *Bacillus subtilis*, *Lactobacillus fermentum*), three Gram-negative bacteria (*Salmonella enterica*, *Escherichia coli*, *Pseudomonas aeruginosa*) and one yeast strain (*Candida albicans*). Regarding the results in the Table 4, treatment F4 showed the strongest effect, with IC_{50} values ranging from 15.6 ± 2.35 to 6222 ± 568 µg mL^{-1} (highest inhibition against *S. aureus*, *E. coli*, and *C. albicans* strains), and MIC values from 62.5 to 8000 µg mL^{-1} (ranked first in inhibition against *S. aureus*, *L. fermentum*, *E. coli*, and *P. aeruginosa*). Treatment F3 also showed relatively strong activity, with IC_{50} values of 19.5 ± 2.89–3111 ± 273 µg mL^{-1} (highest inhibition against *B. subtilis*) and the MIC values of 62.5–4000 µg mL^{-1} (highest inhibition against *B. subtilis*, *S. enterica*, and *C. albicans* strains). Treatment F5 was most effect against *P. aeruginosa* (IC_{50} = 30.1 ± 2.97 µg mL^{-1}), while F10 showed the strongest inhibition against *L. fermentum* and *S. enterica* (IC_{50} = 1500 ± 125 and 1968 ± 178 µg mL^{-1}, respectively). This likely due to its high content of (2*E*)-decenal, a compound with reported antibacterial activity against *S. aureus*,

Table 4 Antimicrobial activity of essential oils of *Coriandrum sativum* cultivated under different light conditions in comparison with their oil main constituents

Treatments	Values (μg mL^{-1})	The concentration of essential oil inhibiting the tested microorganisms (%)						
		Gram (+) bacteria			Gram (–) bacteria			Yeast
		Staphylococcus aureus	*Bacillus subtilis*	*Lactobacillus fermentum*	*Salmonella enterica*	*Escherichia coli*	*Pseudomonas aeruginosa*	*Candida albicans*
F1	IC_{50}	1854 ± 109	1852 ± 157	2476 ± 199	3333 ± 236	2074 ± 187	46.7 ± 3.69	73.7 ± 5.68
	MIC	4000	4000	4000	8000	8000	250	250
F2	IC_{50}	469 ± 57	1412 ± 134	4667 ± 399	3080 ± 206	3167 ± 258	145 ± 15.7	2093 ± 19.1
	MIC	2000	2000	8000	4000	8000	250	4000
F3	IC_{50}	99.4 ± 8.46	19.5 ± 2.89	3297 ± 310	3111 ± 273	231 ± 18.74	40.3 ± 3.47	37.1 ± 2.98
	MIC	250	62.5	8000	4000	1000	250	62.5
F4	IC_{50}	15.6 ± 2.35	123 ± 10.29	2384 ± 188	6222 ± 568	39.1 ± 4.34	38.5 ± 3.98	26.7 ± 3.06
	MIC	62.5	250	4000	8000	62.5	250	250
F5	IC_{50}	50.2 ± 4.76	20.9 ± 3.09	6222 ± 672	6025 ± 547	378 ± 38.0	30.1 ± 2.97	53.9 ± 4.78
	MIC	250	62.5	8000	8000	1000	250	250
F6	IC_{50}	246 ± 19.2	95.6 ± 10.46	2632 ± 213	5962 ± 459	263 ± 19.7	199 ± 18.9	43.7 ± 5.41
	MIC	1000	250	4000	8000	1000	1000	250
F7	IC_{50}	1520 ± 124	445 ± 36.8	2740 ± 197	6095 ± 587	286 ± 25.6	177 ± 14.8	169 ± 15.9
	MIC	2000	1000	4000	8000	2000	500	500
F8	IC_{50}	460 ± 40.9	466 ± 42.1	2699 ± 201	4040 ± 479	519 ± 54.9	195 ± 20.1	218 ± 24.0
	MIC	4000	2000	4000	8000	1000	500	500
F9	IC_{50}	1862	1538 ± 137	1632 ± 125	3000 ± 198	2710 ± 258	597 ± 60.7	932 ± 105
	MIC	4000	2000	4000	4000	4000	1000	2000
F10	IC_{50}	1857 ± 168	469 ± 50.7	1500 ± 125	1968 ± 178	2718 ± 277	176. ± 16.7	169 ± 190
	MIC	4000	1000	4000	4000	4000	1000	1000
Linalool	MIC	6.66[(1)]; 2500[(2)]; 200[(3)]; 1024[(4)]; 1250[(6)]; 31,250[(7)]; 5000[(8)]; 18.8[(9)]	1250[(6)]	385,625[(10)] (inhibited growth of 0.5% bacteria)	1950[(7)] (subsp. *enterica* serovar Choleraesuis)	6.66[(1)]; 2500–5000[(2)]; 200[(3)]; 630[(6)]; 1950[(7)]; 2500[(8)]; 9.4[(9)]	> 13.3[(1)]; 1024[(4)]; 431[(5)]; 630–1250[(6)]; 2500[(8)]	0.2[(1)]
Decanal	MIC	100[(3)]; 62.5–125[(11)]; ≤ 500[(12)]	≤ 500[(12)]	-	-	100[(3)]; ≤ 500[(12)]	≤ 500[(12)]	≤ 500[(12)]
(2*E*)-Decenal	MIC	250[(13)]	-	-	-	500[(13)]	-	-
(2*E*)-Dodecenal	MIC	4[(14)]; 105[(15)]	4[(14)]	-	-	> 1000[(14)]	> 1000[(14)]	-

Note: [1]Pattnaik et al. 1997; [2]Reichling et al. 2006; [3]Liu et al. 2012; [4]Silve et al., 2015; [5]Liu et al. 2020; [6]Varia et al. 2020; [7]Silva et al. 2021; [8]Öztürk et al. 2023; [9]Krapež et al. 2024; [10]Di Matteo et al. 2024; [11]Mahboubi and Feizabadi 2009; [12]Carev et al. 2023; [13]Bisignano et al. 2001; [14]Daniel-Jambun et al. 2017; [15]Ortiz-Ruíz et al. 2024

E. coli (Bisignano et al. 2001), and antifungal activity against some strains (Bojke et al. 2020). However, no clear correlation was observed between the supplemental light treatments and antimicrobial activity of the oils (Table 4).

The antimicrobial activity of cilantro essential oil may result from the synergistic effect of linalool, (2*E*)-decenal, and other constituents. In this study, several samples showed stronger inhibition against certain microbial strains than previously reported. Talebi et al. (2024) found that only undiluted coriander seed oils (100%) inhibited *P. aeruginosa*, *E. coli*, and *S. aureus*, despite containing 63.17–74.15% linalool. Similarly, Sourmaghi et al. (2015) reported fruit oil rich in linalool (66.3%) and γ-terpinene (5.3%) inhibited *S. aureus* (MIC 3125 μg mL^{-1}) and *E. coli* (MIC 781 μg mL^{-1}), stronger than the control here, but weaker against *P. aeruginosa* (MIC 6250 μg mL^{-1}). Commercial oils with 72.4–73.5% linalool inhibited *C. albicans* (MIC 750–1250 μg mL^{-1}), comparable to the control in the present study (Powers et al. 2018; Orchard et al. 2019). By contrast, Kenyan leaf oil lacking linalool showed much weaker

Table 5 Correlation coefficients between main constituent concentrations of *Coriandrum sativum* essential oil and their antimicrobial activity

Main constituents	*Staphylococcus aureus*	*Bacillus subtilis*	*Lactobacillus fermentum*	*Salmonella enterica*	*Escherichia coli*	*Pseudomonas aeruginosa*	*Candida albicans*
Linalool (%)	-0.258	-0.052	0.178	0.475*	-0.259	-0.087	-0.001
Decanal (%)	0.222	0.006	-0.282	-0.521*	0.025	0.137	-0.123
(2*E*)-Decenal (%)	0.362	0.072	-0.073	-0.417	0.320	0.194	0.138
(2*E*)-Dodecenal (%)	0.204	0.305	-0.035	-0.390	0.367	-0.161	0.167

Note: *Correlation is significant at the 0.05 level (2-tailed). Pearson correlation analysis was performed using SPSS ver. 27.0.1 (IBM SPSS Statistics)

inhibition against *S. aureus* (MIC 108 mg mL^{-1}), *E. coli* (MIC 163 mg mL^{-1}), and none against *P. aeruginosa* (Matasyoh et al. 2009). Several studies confirmed the antimicrobial role of linalool: Guo et al. (2021b) showed that linalool disrupted cell structure and caused cytoplasmic leakage in *Shewanella putrefaciens*, while Shen et al. (2022) reported that linalool fumigation inhibited *Botrytis cinerea* (gray mold) on postharvest tomatoes. Linalool was also reported to reduce membrane potential, disrupt the cell membrane, and promote the release of nucleic acids, ultimately leading to *P. aeruginosa* cell death (Liu et al. 2020). In addition, it induces depolarization of the cytoplasmic membrane and leakage of intracellular nucleic acids, thereby compromising the structural integrity of *P. fluorescens* cells (Guo et al. 2021a). Previous studies exhibited the antibacterial activity of linalool, decanal, (2*E*)-decenal, and (2*E*)-dodecenal, showing variable MIC values (Table 4).

Overall, supplemental multispectral LED illumination at night altered the cilantro oil antimicrobial activity, enhancing effects against five (except *L. fermentum* and *S. enterica*) of seven tested microorganisms depending on the supplemental lighting conditions. A correlation analysis has been conducted between the relative abundances of the main compounds (linalool, decanal, (2*E*)-decenal, and (2*E*)-dodecenal) and the antimicrobial activity (IC_{50} and MIC values against the seven tested microorganism strains). The Pearson correlation coefficients are presented in Table 5, showing significant correlations ($p<0.05$) between the concentrations of linalool and decanal and their antimicrobial activity against *S. enterica*. The remaining compounds showed weak or inconsistent correlations with antimicrobial activity against the tested strains.

4 Conclusions

Nighttime supplemental multispectral LED lighting enhanced *C. sativum* growth, biomass, and essential oil yield. The R: B:UV-A (75:16.7:8.3) showed the strongest effect, followed by R: B:Fr: G (66.7:16.7:8.3:8.3), demonstrating positive roles of UV-A and Fr spectra alongside R light, with B constant. The F2 treatment (R: B:UV-A = 75: 16.7: 8.3, 120 µmol m^{-2} s^{-1}, 6 h/night) most effectively promoted growth and oil accumulation compared with the control F10 (natural sunlight only). Supplemental lighting increased linalool but reduced (2*E*)-decenal, with nine treatments producing higher levels of the four main oil constituents. Oils from all ten treatments inhibited all seven tested microbial strains, with stronger effect against *S. aureus*, *B. subtilis*, *E. coli*, *P. aeruginosa*, and *C. albicans*, but not *L. fermentum* and *S. enterica*. Future work should clarify links between multispectral LED light and cilantro oil antimicrobial properties.

Acknowledgements The authors thank Phan Quyen for technical support.

Author contributions Thi Nghiem Vu: Funding acquisition, conceptualization, methodology, carried out the experiment, writing original draft preparation; writing review and editing. Ha Thi Thu Chu: Conceptualization, methodology, carried out the experiment, formal analysis, writing original draft preparation; writing review and editing; Thuy Thi Thu Dinh: Formal analysis, writing review and editing. Tran Quoc Tien: Writing review and editing. Phat Tien Do: Writing review and editing. Khanh Quoc Tran: Supervision, writing review and editing. William N. Setzer: Supervision, writing review and editing. All the authors have read and agreed to the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. This research was funded by Institute of Materials Science (Grant number CSCL04.01/23–24).

Data availability All of the data supporting the findings of this study are included in this article.

Declarations

Ethical approval Not applicable.

Consent for publication All authors agreed to publish the article.

Conflict of interest The authors declare that they have no conflicts of interest.

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