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GROWTH AND ACCUMULATION OF PHENOLIC COMPOUNDS IN THYME (*Thymus vulgaris*) BASED ON THE BALANCE OF RED AND BLUE LED LIGHTS

Carlos de Jesús **Morales-Becerril**[1], María Teresa **Colinas-León**[1]*, Ramón Marcos **Soto-Hernández**[2], María Teresa **Martínez-Damián**[1], Guillermo **Mendoza-Castelán**[1]

[1]Universidad Autónoma Chapingo. Posgrado en Horticultura. Carretera Mexico-Texcoco km 38.5, Chapingo, Texcoco, State of Mexico, Mexico. C. P. 56227.
[2]Colegio de Posgraduados Campus Montecillo. Carretera Mexico-Texcoco km 36.5, Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.
* Author for correspondence: lozcol@gmail.com

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ABSTRACT

The new plant production methods that use artificial light to replace or complement sunlight have proven that changes in the wavelength of incidental light result in variations in growth, development and secondary metabolism of plants, depending on the genotype and other environmental conditions. However, these methods have been scarcely studied in medicinal and edible plants. The aim of this study was to determine the response of thyme plants (*Thymus vulgaris*) under different wavelengths. The plants were exposed to red light (660 nm), blue light (440 nm), white light and two proportions of red-blue for 16 hours a day at an intensity of 25 μmol m^{-2} s^{-1}. The treatments were isolated from sunlight and from each other. Red light was found to promote the formation of etiolated plants, with a low accumulation of chlorophyll, dry matter and phenolic compounds compared to the white light treatment. Blue light generated compact plants with a higher accumulation of chlorophyll and dry matter than red light, but similar to the white light treatment. In terms of phenolic compounds, accumulation was higher under the two latter treatments. The planting of thyme under a combination of blue-red light at a 3:1 ratio was found to result in a compact growth and to improve the accumulation of phenolic compounds.

Keywords: dry matter, secondary metabolism.

INTRODUCTION

In terms of plant food production, the past decades have been characterized by the search for methods that allow for the production of high amounts of high-quality, safe and environmentally friendly biomass in small spaces and with a high efficiency in the use of water, fertilizers and other inputs required for the production process. Vertical gardens, biofactories and the indoor plant production systems (IPPS) seem to be the production methods that best achieve these goals (Bures *et al*., 2018).

The lighting environment is one of the most carefully handled aspects of these production systems, since photosynthesis and photomorphogenesis depend mostly on the wavelength, intensity and duration of light exposure (Casierra-Posada and Peña-Olmos, 2015; Alrifai *et al*., 2019). LED lighting technology, due to its high electrical energy efficiency, low heat emission and high manipulation of the intensity and quality of the light emitted (Dutta-Gupta and Agarwal, 2017), has become the most widely used light source in these production systems, replacing or complementing sunlight (in some cases).

IPPSs are mainly used in the production of vegetables with a high economic value or of plants whose high market value is attributed to their useful phytochemical properties, such as medications or food. Reports show that the efficiency of an IPPS in in the production of biomass or secondary metabolites strongly depends on the genotype (Alrifai *et al*., 2019). In other words, the different species, and even different cultivars, respond in different ways when established in these systems, due to the effect of the quality of incidental light. This is a technical and scientific opportunity for research, which we decided to explore in this study.

Thyme (*Thymus vulgaris*), a species of the Lamiaceae family, is used in both cuisine and traditional medicine for its secondary metabolites (Hosseinzadeh *et al*., 2015). It is a highly branched plant, with a maximum height of 50 cm, rich in phenolic compounds, and its essential oil is mainly composed of the monoterpenes thymol and carvacrol, which give it its distinct aroma (Gimeno-Gasca, 2001).

In the IPPSs, research has focused mainly on the use of blue light (420–480 nm), red lights (620–700 nm), combinations of these, and white light, with other wavelengths being used in a secondary manner (Landi *et al*., 2020). In lamiaceae, research focuses on species with culinary uses. In basil (*Ocimum* sp.), blue light, in comparison with red and white lights, promotes the formation of more compact plants (Matysiak and Kowalski, 2019). Likewise, the use of red light has been reported to help improve the antioxidative capacity of the extracts of this plant (Taulavuori *et al*., 2016). In Mexican mint (*Plectranthus amboinicus*), Noguchi and Amaki (2016) discovered that the wavelength of blue light (100 μmol m^{-2} s^{-1}) promotes apical dominance and the formation of compact plants, in comparison with treatments with the wavelengths of red and green lights, which promote less compact plants, and with greater lateral growth.

The use of low intensities of LED lights (< 50 μmol m^{-2} s^{-1}) is not common in IPPSs, although it is well-known that most plant photoreceptors respond to light intensities below 1 μmol m^{-2} s^{-1} (Paradiso and Proleitti, 2022). In this sense, thyme has been reported to resist low light conditions (Murillo-Amador *et al.* 2013; Tabbert *et al.* 2021), therefore investigating the responses of these plants to conditions of low light intensity is a great opportunity. This study applied LED light with wavelengths corresponding to the colors white, red, blue, red-blue 1:3 and red-blue 3:1 at 25 μmol m^{-2} s^{-1} on young thyme plants, with the main purpose of evaluating the effect on the growth and accumulation of phenolic compounds and flavonoids. The intention of

this is to contribute to the knowledge on the effect of applying different wavelengths at low intensities on this species in order to have a solid basis for its plantation in IPPS, as well as to contribute to the scientific knowledge in this area of plant physiology.

MATERIALS AND METHODS

The experiment was carried out between the months of April and June, 2021, in a greenhouse of the postgraduate department of horticulture at the Chapingo Autonomous University. Thyme seedlings were used, obtained from seeds (Vita®) which were germinated under greenhouse conditions, with a substrate composed of 70% peat and 30% perlite. During the first two weeks after germination, tap water was used to irrigate the plants. Fourteen days after germination, the plantlets were established in pots measuring 4 inches in diameter, with a substrate composed of 50% peat, 48% perlite and 2% vermicompost. Starting on that day and until the end of the experiment, 100mg L^{-1} of Multipurpose Ultrasol® fertilizer was applied once a week and irrigating with tap water every 2 days. Plants were kept under conditions of natural light for 28 days. On days 10 and 24, they sprouted to promote branching and the homogenization of the aerial section. They were then moved to conditions of entirely controlled light, where they remained for 35 days until the growth and secondary metabolism analyses.

As a light source for the colors blue and red and their combinations, RGB 5050 (Weluvfit®) LED strips were used, each with 30 modules per meter (5 m), mounted on wooden boards measuring 15x40 cm, and which help modify the light spectrum between 400 and 700 nm, adjusted to the requirements of each treatment (Table 1). As a source of white light, white 3528 (Tunix®) LED strips were used, each with 60 modules per meter. In both cases, the efficiency of the strips did not change in the duration of the experiment. The height of the boards was adjusted for the light to fall on the plants, at an intensity of 25 μmol m^{-2} s^{-1} between 14 and 21 cm (Table 1), using an Apogee® QMSW-SS radiometer. The photoperiod was 16 hours, starting at 6:00 h and ending at 22 h. The treatments were established in boxes 80x40x80 cm in length, width and height, respectively, with a white interior in order for the light to be

Table 1. Treatments used and height of the light plates in relation to the plants.

Treatment	Color	Height of light plate (cm)
1	White light	21¶
2	Red light(660 nm)†	12
3	Blue light (440 nm)	16
4	75% red light (660 nm) and 25% blue light (440 nm).	14
5	75% blue light (440 nm) and 25% red light (660 nm).	14

†Wavelength (nm) pointed out by the supplier. ¶Measured from the highest part of the plant.

reflected and distributed homogenously. Air circulation was provided by a 4-inch, 12 V fan placed on the rear side of the box, which was turned on for 10 min every hour between 6:00–11:00 and 18:00–22:00, and for 15 min between 12:00 and 17:00. Inside the boxes, the board with the LEDs for each treatment were placed on the top. The experimental unit consisted of one thyme plant. Five treatments were established with 10 repetitions each (Table 1). The experimental design was completely randomized. Inside each box, plants were rotated every day in order to reduce error due to the incidence of light on the repetitions in each treatment.

Thirty-five days after the treatments began, plant heights and the number of branches (tertiary, quaternary and subsequent) were recorded. The relative chlorophyll index was calculated using a SPAD unit meter by KONICA MINOLTA®, model SPAD-502Plus; each measurement -one repetition- came from the average of 10 random takes across the length and width of the plant. The fresh and dry weights of the aerial section and of 30 specific leaves were recorded using a METTLER® model AJ150L analytic scale; for drying, a Márquez® stove was used, at 60 °C until constant weight. Given the difficulty of separating all the leaves of the plant, as well as their tiny size and the speed at which they dehydrate, a sample of 30 leaves was taken from the low part of the branches formed during the light treatments and it was measured using a LI-COR®, model LI-3100 foliar area integrator. The specific weight of the leaves was calculated by dividing the dry weight of the leaf by the foliar area.

For the extraction of phenolic compounds, 2 g of fresh and ground plant material was used per repetition. It was then placed into test tubes and 10 ml of 80% methanol was added. The tubes were covered and taken to a bath with ultrasound in a cycle, 10 min on, 5 min off and another 10 min on. Finally, the plant material was separated from the extract by centrifuging at 1000 g for 5 min. To quantify the total phenolic compounds (T.P.C.) from the supernatant, a 20 µL aliquot was taken, which was incubated with 480 µL of water, 25 µL of a Folin-Ciocalteau reagent solution 1:1 and 975 µL of a 2.5% sodium carbonate solution for an hour at room temperature. The absorbance of the colored product was measured at 740 nm in a spectrophotometer against a white containing no gallic acid nor extract. The concentration value the T.P.C. was calculated from a standard gallic acid curve (1–20 mg L^{-1}, coefficient of correlation $R^2 = 0.9905$).

To quantify total flavonoids (T.F.), a 20 µL aliquot was taken from the extract used in the quantification of T.P.C. and incubated for 40 min at room temperature with 980 µL of methanol at 80 %, 2000 µL of potassium acetate 1 M and 2000 µL of 10% aluminum chloride. Absorbance was measured at 415 nm with a spectrophotometer against a white without any quercetin nor extracts of the sample. The value of the concentration of the T.F. was calculated from a standard quercetin curve (1.25–10 mg L^{-1}, coefficient of correlation $R^2 = 0.96$).

An analysis of variance (ANOVA) was performed by each of the variables considered, with a significance level of 0.05; in case it resulted significant, Tukey's multiple means comparison test ($p \leq 0.05$) was carried out. To compare the different treatments against the white light treatment, Dunnett's test ($p \leq 0.05$) was carried out. The SAS statistical program, version 9.0, was used.

RESULTS AND DISCUSSION

The chances promoted by the treatments were statistically significant ($p \leq 0.05$) for height, number of branches, and the compacting of thyme plants. Height recorded the highest values in treatment four with significant differences with all the other treatments (Table 2). This treatment also generated the greatest fresh weight, but without statistical differences for this variable, with treatments one and five. These results can be explained considering that the growth and development of a plant is influenced, among many other factors, by the growth and development of phytochromes (stimulated by red, distant red and blue lights) and of cryptochromes (stimulated by blue and green lights) and the balance between them (Stutte, 2009; Casal, 2013).

Table 2. Average values for the variables of height, number of branches, compacting, fresh weight and dry weight of thyme plants (*Thymus vulgaris*), treated with different colored lights for 35 days (n = 7).

Treatment	Height (cm)	Number of branches	Compacting (g m^{-2})	Fresh weight (g)	Dry weight (g)
1	19.10 b[†]	31.50 b	1.90 a	3.57 ab	0.36 a
2	19.47 b	32.75 ab	1.10 b	2.57 b	0.21 c
3	16.40 b	36.50 ab	1.67 a	2.55 b	0.27 bc
4	28.02 a	43.25 a	0.94 b	4.35 a	0.25 bc
5	18.97 b	36.00 ab	1.69 a	3.20 ab	0.32 ab
DMSH[¶]	7.17	11.43	0.25	1.19	0.073
C.V.[§]	16.1	14.54	7.81	16.84	11.73

[†]Measurements with the same letters in each column are not different (Tukey, $p \leq 0.05$). [¶]HLSD: honest least significant difference; C.V.[§]: coefficient of variation.

White light promotes a similar balance to sunlight, whereas monochromatic treatments with red or blue light induce a clear imbalance, which leads to a reduction in growth (Landi *et al*., 2020). In the case of red-blue combinations, the proportion determines a greater or reduced growth (Hernández *et al*., 2016). The results show that, in thyme, a greater proportion of red light promotes an increase in growth; in addition, they partially coincide with those reported for tomato plants, where a reduction in the red-blue proportion reduces growth, with its peak in the treatment with red light (Hernández *et al*., 2016).

The dry weight was greater in treatments one and five, and lower in the remaining treatments. A greater accumulation of dry weight in polychromatic treatments and under a high ratio of red-blue light has also been observed in *Mentha longifolia* (Sabzalian *et al*., 2014), *Oncidium* 'Gower Ramsey' (Chung *et al*., 2010) and cucumber

(Cucumis sativus L*)* (Miao *et al*., 2016). This effect has been related to the photosynthetic process, since it has been proven that white light itself and blue light (compared to red light) promote a higher proportion of a/b chlorophyll a/b (Hamdani *et al*., 2019), the adequate functioning of stomata (Lanoue *et al*., 2018), an adequate distribution of chloroplasts (Su *et al*., 2014), a greater abundance of the enzyme Rubisco (Landi *et al*., 2020) and a high rate of net assimilation (Lanoue *et al*., 2018).

Compacting is the relation between dry weight and height. It represents a quality parameter in plants that, after being harvested, are dehydrated for their conservation and later use, as in the case of thyme. The results show that, although there were differences between treatments, only white light maintained a maximum value, despite not being statistically different to T3 and T5 (Table 2).

Another parameter with a desirable increase in thyme is branching. Our results show significant differences ($p \leq 0.05$) between the treatment with white light (T1) and the R-B 3:1 (T4) (Table 3), the latter displaying the highest mean. Greater branching is related to a greater sprouting of auxiliary buds, promoted by a change in the balance of auxins and cytokinins, which tends towards the latter (Casal, 2013). This tendency in T4 may two explanations: 1) the greater height of plants under this treatment reduces the concentration of auxins (basipetal movement from the apex) in the lowest buds of the branches, while the concentrations of cytokinins (acropetal movement from the root) is not altered (given that the buds are very close to the roots), which promotes their sprouting; and 2) the hormonal imbalance is an effect of the quality of the incidental light. The precedents on the effect of the quality of light on the hormonal balance that promotes the sprouting of buds are very scarce.

The effect of the quality of incidental light on thyme plant leaves resulted in statistically significant lights for all the variables evaluated ($p \leq 0.05$) (Table 4). The highest value

Table 3. Comparison of the averages of the response variables in thyme plants (*Thymus vulgaris*) treated with different colored lights in regard to white light, taken 35 days after the beginning of treatments (n = 7).

Variable	White	T2	T3	T4	T5
Height (cm)	19.1	=†	=	31.83 %	=
Number of branches	31.5	=	=	27.16 %	=
Compacting (g m^{-1})	1.90	-42.10 %	=	-50.52 %	=
Fresh wieght (g)	1.57	=	=	=	=
Dry weight (g)	0.36	-41.66 %	-25 %	-30.55 %	=
Leaf area(cm^2)	7.42	=	=	=	=
Estimated chlorophyll (SPAD)	34.55	=	=	=	=
Specific leaf weight (mg cm^{-2})	2.72	-25.73 %	=	=	-13.02 %

†The symbol "=" indicates that there are no significant differences (Dunnett, $p \leq 0.05$) between treatments for the indicated variable. Percentages indicate the magnitude of positive or negative variation in regard to the treatment with white light.

Table 4. Comparison of the leaf variables of fresh weight, dry weight, SPAD, leaf area and specific weight in response to the treatments with light on thyme plants (Thymus vulgaris) taken 35 days after the experiment began (n = 7).

Treatment	Fresh leaf weight (mg)	Dry leaf weight (mg)	Estimated chlorophyll (SPAD)	Leaf area (cm^2)	Specific weight ($mg\ cm^{-2}$)
1	215.02 a[†]	20.20 a	34.55 ab	7.42 ab	2.72 ab
2	160.57 e	16.27 d	33.20 b	8.09 a	2.02 c
3	204.55 b	19.47 b	37.52 a	6.70 b	2.91 a
4	187.40 c	18.72 c	33.95 ab	6.54 b	2.87 a
5	167.07 d	16.05 d	37.25 ab	6.76 b	2.37 bc
DMSH[¶]	5.29	0.55	4.16	1.03	0.40
C.V.[§]	1.29	1.40	5.40	6.66	7.09

[†]Means followed by the same letter in each column are not different (Tukey, $p \leq 0.05$). [¶]HLSD: honest least significant difference; [§]C.V.: coefficient of variation.

for fresh weight was obtained in T1 and the lowest, in T2. In the case of dry weight, the highest value was observed in T1 and the lowest, in T2 and T5 (Table 4). A reduction in these variables due to red light was observed in chili pepper plants *(Capsicum annuum* L.*) by* Gangadhar *et al.,* (2012), who argued that the highest dry weight observed in the polychromatic treatments (red-blue, white) against the monochromatic ones was due to the fact that blue and red lights together, in the polychromatic treatments, increase the efficiency of the photosynthetic process, given that it is these precise wavelengths that absorb chlorophyll. However, the results from this study do not coincide with those observed in other Lamiaceae such as wild mint (*Mentha arvensis* L.) (Nishioka *et al.,* 2008) and perilla (*Perilla frutescens* L. Btitt) (Nishimura *et al.,* 2009), in which red light increased the fresh and dry weights of leaves.

The highest foliar area was obtained in the treatment with red light (T2), without any differences with white light (T1), while the remaining treatments displayed a significantly lower foliar area ($p \leq 0.05$) (Table 4). In perilla (Nishimura *et al*., 2009) and wild mint (Nishioka *et al*., 2008), an increase had already been reported in the foliar area under red light, in comparison with other light colors. Several studies have attributed foliar expansion promoted by red light to the influence the latter has on the calcium and potassium canals in the epidermal cells, which allow for a flow of ions which, via an osmotic process, promotes growth (Volkenburgh, 1999).

The specific weight of leaves has been used as an estimator of photosynthesis, of the interception and absorption of light, as well as an indicator of the accumulation of carbohydrates in these organs (González-Pérez *et al*., 2018). In this study, T2 and T5 has a lower specific leaf weight (Table 4), in comparison with the other treatments. In the case of T2, the foliar area and dry weight are greater, whereas the content of chlorophyll is equal to T5, which led to the reduction of the specific weight of leaves related to a higher foliar expansion without an increase in photosynthesis.

The treatments applied generated changes in total phenols (Figure 1). The blue light (T3) and the combinations blue-red (T4 and T5) generated a higher concentration of phenols than in T1 and T2. For the flavonoids, the highest concentrations were recorded in T1 and T5 (Figure 1). In contrast to white light, the treatments with blue lights and R-B 25:75 were observed to increase the concentration of phenolic compounds (Table 4). In the case of the flavonoids, the red light reduced its concentration in regard to white light, whereas the blue light increased it (Table 5).

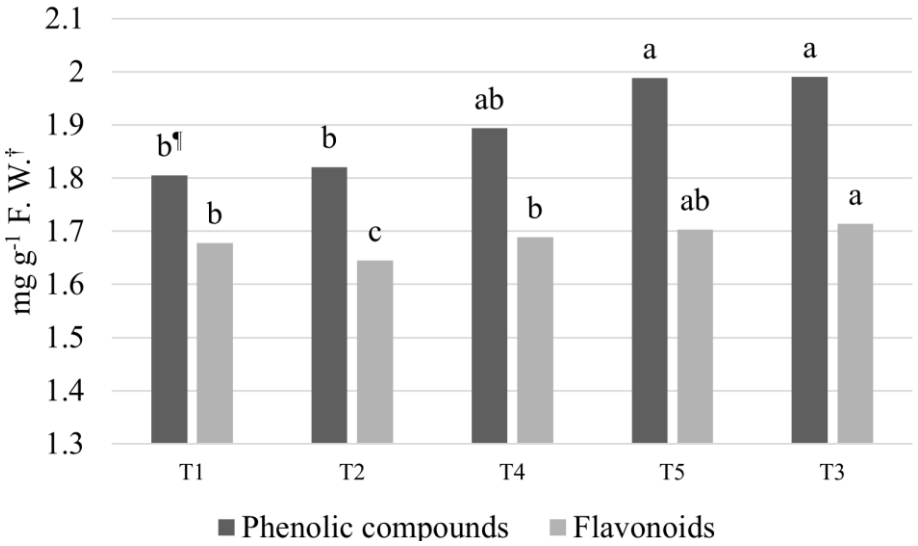

Figure 1. Effect of incidental light on the content of phenolic compound in thyme. †P. F.: dry weight. ¶Columns of the same variable with the same letter are not statistically different (Tukey, $p \leq 0.05$).

Table 5. Contrast of different light colors regarding white light on the concentration of total phenols and flavonoids in thyme plants (*Thymus vulgaris*) after 35 days of treatment.

Variable	T1	T2	T3	T4	T5
[Phenolic compounds] (mg g^{-1} P. F.†)	1.80	=¶	+10.26 %	=	+10.15 %
[Flavonoids] (mg g^{-1} P. F.)	1.67	-1.96 %	+2.12 %	=	=

†Fresh weight. ¶The symbol "=" indicates that there are no statistical differences (Dunnett, $p \leq 0.05$) between white light (T1) and the additional treatments for the variable indicated. Percentages indicate the magnitude of the positive or negative variation regarding the treatment with white light.

The biosynthetic pathways of the phenolic compounds are easily altered by the light conditions in which plants are found (Alrifai *et al*., 2019; Landi *et al*., 2020). Many reports coincide in that the blue light increases the biosynthesis and concentration of phenolic compounds, whereas red light produces the opposite effect in crops such as lettuce (*Lactuca sativa*) (Johkan *et al*., 2010), strawberry (*Fragaria vesca*) (Choi *et al*., 2015) and basil (*Ocimum basilicum*) (Taulavuori *et al*., 2016).

The role of blue light in the biosynthetic pathway of phenolic compounds is related to key enzymes in this pathway, such as PAL (phenylalanine ammonia-lyase), the activity of which increases under different artificial light qualities (Kim *et al*., 2015). Likewise, there have reports of an increase in the expression of the genes that codify the enzymes C_4H (cinnamic 4-hidroxylase), CHI (chalcone isomerase), FLSII (flavonol synthase II), ANS (anthocyanidin synthase) (Thwe *et al*., 2014), F3´H (flavonoid 3´ hydroxylase) and FLS (flavonol synthase), under blue light in contrast with white and red light (Kim *et al*., 2015), which participate in different biosynthesis pathways of phenolic compounds.

Regarding flavonoids, there have also been reports of a similar behavior to that of phenolic compounds in general, in the sense that blue light increases its synthesis (Taulavuori *et al*., 2016). Liu *et al*. (2018) found that the increase in the synthesis of flavonoids under blue and green light (in comparison to white and red light) is correlated to a greater expression of the genes that codify enzymes PAL, 4CL and CHS. These enzymes participate in the synthesis pathway of this group of polyphenols, which may support the explanation of the behavior described.

CONCLUSIONS

Treating thyme plants with a 75% blue – 25% red light combination produces plants with an adequate growth, since it favors the compacting accumulation of dry matter and a higher concentration of phenolic compounds.

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