Effect of solar irradiation, substrate type and environment on the growth and ornamental quality of *Euphorbia cotinifolia* plants

Efecto de la irradiación solar, tipo de sustrato y ambiente, sobre el crecimiento y calidad ornamental en plantas de *Euphorbia cotinifolia*

Efeito da irradiância solar, do tipo de substrato e do ambiente no crescimento e qualidade ornamental de plantas de *Euphorbia cotinifolia*

Jesús Mao Aguilar-Luna*
Liliana Hernández-Vargas[1]

Benemérita Universidad Autónoma de Puebla, Ingeniería Agroforestal. 73640. México.

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Abstract

Euphorbia cotinifolia L. is an ornamental plant of economic importance due to the red-purple color of its foliage. The objective of this research was to evaluate the effect of solar irradiation, substrate type and environment on the growth and ornamental quality of *E. cotinifolia* plants propagated from semi-woody cuttings. Two experiments were conducted from June 2022 to March 2023, in Tetela de Ocampo and Huitzilan de Serdan, Puebla, Mexico. Each experiment had 20 treatments. The experiments had a 2x5x2 factorial design; factor 1 was growth environments, its levels: temperate climate (STC), and subtropical (SHC). Factor 2 was solar irradiation, its levels: 80, 240, 347, 394, and 571 $\mu mol.m^{-2}.s^{-1}$. Factor 3 was the type of substrate, its levels: river sand with peat moss (AT), and forest soil with perlite (SP). At 243 days after rooting, the highest values were: 32.98 cm for terminal shoot growth, 4.80 $mm.day^{-1}$ in growth rate, 1.76 in robustness index, 1.32 in Dickson's index. The maximum anthocyanin concentration was 4.94 $mg.g^{-1}$ in red-purple leaves. The highest values and the red-purple color of the foliage (quality indicator) occurred when the plants were grown on AT substrate, at 571 $\mu mol.m^{-2}.s^{-1}$ in SHC climate. It is concluded that in tropical climate, plants develop with better quality; river sand with peat moss is recommended as substrate, and exposure to high light intensities.

*Corresponding author: mao.aguilar@correo.buap.mx

Resumen

Euphorbia cotinifolia L. es una planta ornamental de importancia económica por el color rojo-púrpura de su follaje. Se evaluó el efecto de la radiación solar, el tipo de sustrato y el ambiente, sobre el crecimiento y la calidad ornamental en plantas de *E. cotinifolia*, propagadas a partir de esquejes semileñosos. Dos experimentos se realizaron de junio 2022 a marzo de 2023, en Tetela de Ocampo y Huitzilan de Serdán, Puebla, México. Cada experimento tuvo 20 tratamientos. Los experimentos tuvieron un diseño factorial 2x5x2; el factor 1 fue ambientes de crecimiento, sus niveles: clima templado (STC) y subtropical (SHC). El factor 2 fue la irradiación solar, sus niveles: 80, 240, 347, 394, y 571 μmol.m^{-2}.s^{-1}. El factor 3 fue el tipo de sustrato, sus niveles: arena de río con turba (AT) y suelo forestal con perlita (SP). A los 243 días después del enraizamiento, los valores más altos fueron: 32,98 cm para el crecimiento del brote terminal, 4,80 mm.día^{-1} en tasa de crecimiento, 1,76 en índice de robustez, 1,32 en índice de Dickson. La concentración máxima de antocianinas fue de 4,94 mg.g^{-1} en hojas rojo-púrpura. Los valores más altos y el color rojo-púrpura del follaje (indicador de calidad), se presentaron cuando las plantas crecieron en sustrato AT, a 571 μmol.m^{-2}.s^{-1} en clima SHC. Se concluye que en clima subtropical, las plantas se desarrollan con mejor calidad; se recomienda como sustrato la arena de río con turba y su exposición a altas intensidades lumínicas.

Palabras clave: antocianinas, proporcionalidad biométrica, calidad de Dickson, índice de robustez, tasa de crecimiento.

Resumo

A *Euphorbia cotinifolia* L. é uma planta ornamental de importância econômica devido à cor vermelho-púrpura de sua folhagem. Foi avaliado o efeito da radiação solar, do tipo de substrato e do ambiente no crescimento e qualidade ornamental de plantas de *E. cotinifolia*, propagadas a partir de estacas semi-lenhosas. Dois experimentos foram conduzidos de junho de 2022 a março de 2023, em Tetela de Ocampo e Huitzilan de Serdán, Puebla, México. Cada experimento tinha 20 tratamentos. Os experimentos tinham um projeto fatorial 2x5x2; o fator 1 era ambientes de crescimento, seus níveis: clima temperado (STC) e subtropical (SHC). O fator 2 foi a irradiância solar, seus níveis: 80, 240, 347, 394 e 571 μmol.m^{-2}.s^{-1}. O fator 3 foi o tipo de substrato, seus níveis: areia de rio com turfa (AT) e solo de floresta com perlita (SP). Aos 243 dias após o enraizamento, os valores mais altos foram: 32,98 cm para o crescimento do broto terminal, 4,80 mm.dia^{-1} na taxa de crescimento, 1,76 no índice de robustez, 1,32 no índice de Dickson. A concentração máxima de antocianina foi de 4,94 mg.g^{-1} nas folhas vermelho-púrpura. Os valores mais altos e a cor vermelho-púrpura da folhagem (indicador de qualidade) ocorreram quando as plantas foram cultivadas em substrato AT, a 571 μmol.m^{-2}.s^{-1} no clima SHC. Conclui-se que num clima subtropical, as plantas se desenvolvem com melhor qualidade; recomenda-se como substrato areia de rio com turfa e exposição a altas intensidades de luz.

Palavras-chave: antocianinas, proporcionalidade biométrica, qualidade de Dickson, índice de robustez, taxa de crescimento.

Introduction

The Caribbean Copper Plant (*Euphorbia cotinifolia* L.) is an ornamental shrub whose economic value depends on the dark red or purple color of its leaves. In Mexico, its demand as an ornamental plant increases in recent times, with prices that range from USD $4.44 to USD $59.18 depending on size. Its altitudinal distribution ranges from 200 to 2,600 m.a.s.l. (Charcape *et al*., 2015). It exists in warm and even cold places; it withstands lack of water and direct exposure to solar irradiation. It reaches a height of 3 to 4 m and a basal diameter of 35 cm. It has a highly branched crown and is a semi-deciduous perennial (de Oliveira & Sartori-Paoli, 2016).

The leaves are 2 to 6 cm long and 2 to 4 cm wide, opposite, alternate and ternate, ovate-rounded, with entire margins, truncate or emarginate apex. They exhibit a dark red or purple color, with petioles from 2 to 6 cm long that appear less reddish (El Mokni, 2023). Like all Euphorbiaceae, the presence of latex is evident from a very early age (de Oliveira and Sartori-Paoli, 2016; Jayalakshmi *et al*., 2021). Solar irradiation greatly influences the growth and development of *E. cotinifolia*. The intensity of solar irradiation directly affects stem elongation, leaf color and foliage retention. Low intensities of solar irradiation produce dull green leaves (Frajman & Geltman, 2021).

A quality plant has the capacity to adapt and develop under specific climatic and soil conditions (Villalón-Mendoza *et al*., 2016). According to Haase (2008), several indicators assess quality, such as robustness, which associates with vigor and success after transplanting. Dry biomass correlates with survival and reflects plant development in nursery. Basal diameter correlates with the weight of the aerial part and root system.

The robustness index measures plant resistance to wind desiccation, survival and potential growth in dry sites; its low values indicate plants of smaller size and larger stem diameter (Haase, 2008). The Dickson quality index evaluates morphological differences between plants and predicts their field behavior; higher index values indicate higher plant quality (Villalón-Mendoza *et al*., 2016). Additional quality indices for *E. cotinifolia* include anthocyanin production in leaves and red color intensity.

E. cotinifolia produces anthocyanins in its leaves, which create its dark red or purple hue (Jayalakshmi *et al*., 2021). Intense solar irradiation stimulates anthocyanin production, potentially as a protective mechanism. Higher solar irradiation intensity results in increased anthocyanin production and darker red leaf coloration. The scientific literature on the use of solar irradiation as an agronomic and management factor for ornamental production in this species is limited. Under partial shade conditions, the foliage turns green, which reduces its ornamental value. Based on the above scenario, the goal of this research was to evaluate the effect of solar irradiation, substrate type and environment on the growth and ornamental quality of *E. cotinifolia* plants propagated from semi-woody cuttings.

Materials and methods

Experimental sites

The research was conducted from June 2022 to March 2023 (243 days), at two experimental sites (table 1).

Plant material

For each experiment, 150 semi-woody cuttings from healthy 12-year-old trees were used. The cuttings were 0.7 to 1.5 cm in diameter and 20 cm length. The apical end was cut at 45º above the bud and the basal end was cut horizontally below the bud. They were washed under running water and disinfected with N-(trichloromethylthio) cyclohex-4-ene-1,2-dicarboximide at a dose of 3 g in 1 L of water, immersed and left to dry in the shade for 12 h. To promote rooting of the cuttings, 0.3 % Indole-3-butyric acid was used.

Table 1. Experimental locations for growing *Euphorbia cotinifolia,* in Mexico, Years 2022 and 2023.

Site, State	N	W	ALT (m)	MAT (ºC)	MAP (mm)	Climate (Köppen)	Environment
Tetela de Ocampo, Puebla.	19°49’01”	97°47’36”	1764	13.9	971	Cwb	Sub-humid temperate climate (STC).
Huitzilan de Serdan, Puebla.	19°58’00”	97°41’00”	1230	24.7	1163.5	Cfa	Subtropical highland climate (SHC).

N: north latitude. W: west longitude. ALT: altitude. MAT: mean annual temperature. MAP: mean annual precipitation.

Substrates

Substrate 1 consisted of a mixture of river sand and peat moss (genus *Sphagnum*) (4:1, v:v). Substrate 2 consisted of a mixture of forest soil and perlite (3:1, v:v). For each experiment, 150 black nursery bags (15 x 20 cm) were filled, 75 with substrate one and 75 with substrate two. Throughout the experiment, the cuttings were kept at field capacity and watered every five days. The substrates were disinfected by autoclaving (All American 75x) at 121 ºC for 20 min.

Experimental phase

The cuttings were planted at a depth of 5 cm. The cuttings emitted callus and root primordium after two months, which were manifested with leaves and buds on the aerial system. Subsequently, the experimental phase began with the management of solar irradiation. Shade netting (Polisack) with different colors and shading percentages (90, 65, 50 and 30 %) and without cover was placed above the plants to filter the passage of solar irradiation, at a height of 60 cm above the ground.

The solar irradiance levels (80, 240, 347, 394 and 571 µmol.m^{-2}.s^{-1}, respectively) were obtained by previously averaging 200 data for each type of screen, randomly for one year, at different times of the day in full sun exposure. A light scout spectrometer (Quantum Light Meter), sn: 4957, mfg code: 1703, was used immediately below the shade net and above the plant. During the experiments, there were no pests, diseases, or weeds, and each plant received 10 g of 17-17-17 fertilizer every 40 days.

Treatments and experimental design

Each experiment consisted of 20 treatments. The experiments had a 2x5x2 factorial design; factor 1 was growth environments, its levels: STC and SHC. Factor 2 was solar irradiation, its levels: 80, 240, 347, 394, and 571 µmol.m^{-2}.s^{-1}. Factor 3 was the type of substrate, its levels: river sand with peat moss, and forest soil with perlite. The assignment of treatments to each experimental unit was in randomized blocks, with five replications.

Measurement of experimental variables

Terminal Shoot Elongation (TSE). It was the longitudinal measurement of the apical meristem, at the beginning and at the end of the experiment.

Growth Rate (GR). It was estimated with the equation of Hunt *et al*. (2002):

$$GR = \frac{\left[\frac{h2 - h1}{t2 - t1}\right]}{s}$$

Where: *h*2 = initial height of plant cutting. *h*1 = final plant height. *t*2 = end of the experiment. *t*1 = beginning of the experiment. *s* = bag area occupied by the plant.

Robustness Index (RI). Also known as slenderness index; low values are associated with better plant quality, because it is more robust. It was determined with the equation:

$$RI = \frac{basal\ diameter\ (cm)}{(plant\ height\ (m)\ x\ \sqrt{basal\ diameter(cm)})}$$

Biometric Proportion Index (BPI). It is characterized by showing the development of the plant in the nursery. The following equation was used to obtain it:

$$BPI = \frac{dry\ biomass\ of\ aerial\ system(g)}{dry\ biomass\ of\ root\ system\ (g)}$$

Dickson Quality Index (DQI). Expresses the balance between robustness and vigor. The higher this index, the better the quality of the plant. The equation to determine it was:

$$DQI = \frac{total\ fresh\ weight\ of\ plant(g)}{\left(\frac{total\ height\ (cm)}{basal\ diameter\ (cm)}\right) + \left(\frac{fresh\ weight\ of\ aerial\ system\ (g)}{fresh\ weight\ of\ root\ system\ (g)}\right)}$$

Leaf color. For each treatment, 15 mid-section leaves were washed with distilled water to remove impurities. The leaves were dried at 40 ºC for 72 h in a drying oven (Riossa, Model H-41). The dried material was ground to a fine powder, of which 15 g were used. The sample was placed and compacted inside a circular white plastic container (4 cm diameter, 1 cm deep). Color measurement was performed on the compacted surface using a CR-400 colorimetry meter (Konica Minolta). Measurements included values of B (brightness), H angle (hue) and C index (color saturation). The measurement occurred under standard illumination conditions with adequate equipment calibration.

Total anthocyanins. An acidified methanol solution (80 %, v/v in distilled water with 1 %, v/v HCl) served as the extraction solvent due to its proven efficacy with anthocyanins. Each treatment utilized 2.5 g of dried leaf powder mixed with 50 mL of solution, a ratio that optimized extraction efficiency (González-Lázaro *et al*., 2024).

The extraction occurred through dynamic maceration at 150 rpm in three sequential stages: 2 h at room temperature, 10 h at 4 ºC in darkness, and 2 final hours at room temperature. This protocol maximized anthocyanin yield while minimized degradation; the low-temperature phase preserved anthocyanin stability (Enaru *et al*., 2021).

After each step, samples underwent centrifugation at 4000 rpm for 10 min at 4 ºC. Combined supernatants were filtered through a 0.45 µm nylon filter. Extraction yield evaluation occurred via spectrophotometric quantification using the differential pH method (Taghavi *et al*., 2022), with absorbance measured at 520 nm and 700 nm.

Statistical procedures

The data were subjected to analysis of variance, and when statistical differences between treatments were detected, Tukey’s mean comparison tests were performed ($P \leq 0.05$) with the statistical program Rstudio version 1.4.1717.

Results and discussion

Plant growth

The TSE showed statistical difference ($P \leq 0.05$) increased as solar irradiation increased, both in STC and SHC (figure 1A). The highest average value was 32.98 cm in plants grown on river sand with peat moss substrate, at 571 µmol.m^{-2}.s^{-1} in SHC. SHC had slightly higher TSE values, particularly at irradiation levels from 347 to 571 µmol.m^{-2}.s^{-1}. TSE was reduced by 32.68 % when plants were grown in STC at 80 µmol.m^{-2}.s^{-1}, regardless of the substrate used.

The GR showed statistical difference (P≤0.05) increased as solar irradiation increased, both in STC and SHC (figure 1B). The highest average value was 4.80 mm.day^{-1} in plants grown on a substrate based on river sand with peat moss, at 571 µmol.m^{-2}.s^{-1} in SHC. SHC had slightly higher GR values, particularly at irradiation levels from 394 to 571 µmol.m^{-2}.s^{-1}. The GR was reduced by 76.25 % when plants were grown in STC at 240 µmol.m^{-2}.s^{-1}, in forest soil with perlite substrate.

The results obtained in this study demonstrate that the plant quality of *E. cotinifolia*, evaluated by morphophysiological indicators, is significantly influenced by solar irradiation and substrate type, with climate-dependent variations. TSE and GR showed a positive correlation with increasing solar irradiation in both STC and SHC, reaching maximum values of 32.98 cm and 4.80 mm.day^{-1}, respectively, at 571 µmol.m^{-2}.s^{-1} with river sand and peat moss substrate.

These findings agree with previous studies in ornamental species, where intense light promotes cell elongation and photoassimilate synthesis, enhancing primary growth (Paradiso & Proietti, 2022). However, the 32.68 % reduction in TSE and 76.25 % in GR suggest a critical photoenergetic limitation, like that observed in *Hibiscus rosa-sinensis* (L.) under moderate shading (Dos Santos *et al*., 2024).

Plant quality

The RI showed statistical difference (P≤0.05) decreased as solar irradiation increased, both in STC and SHC (figure 1C). The lowest average value was 1.76 in plants grown on river sand with peat moss substrate, at 571 µmol.m^{-2}.s^{-1} in SHC. Slightly lower RI values were observed in both environments, from 347 to 571 µmol.m^{-2}.s^{-1}; it is worth mentioning that low values of this index are desirable in plants. The RI increased by 70.91 % when plants were grown in SHC at 80 µmol.m^{-2}.s^{-1} in forest soil with perlite substrate.

Experiments showed that neither solar irradiation nor substrate type had a statistically significant effect (P≤0.05) on the BPI (figure 1D). Plants developed from cuttings maintained similar biometric proportions regardless of growth conditions. The DQI showed statistical difference (P≤0.05), increased as solar irradiation increased, both in STC and in SHC (figure 1E). The highest average value was 1.32 in plants grown on a substrate based on river sand with peat moss, at 571 µmol.m^{-2}.s^{-1} in SHC. In both environments, high DQI values were observed at radiation levels ranging from 347 to 571 µmol.m^{-2}.s^{-1}; higher values generally indicate better plant quality. DQI was reduced by 62.12 % when plants were grown in STC from 80 to 240 µmol.m^{-2}.s^{-1}, regardless of the substrate used.

RI decreased with higher irradiation levels (minimum value from 1.76 to 571 µmol.m^{-2}.s^{-1}), reflecting greater structural stability under high light conditions, contrary to the trend observed in heliophytes species such as *Bougainvillea glabra* (Choisy), where low irradiation induces thinner stems and less lignification (Asif *et al*., 2024). This divergence could be attributed to specific ecophysiological strategies of *E. cotinifolia*, which prioritizes the allocation of resources to leaf expansion over stem thickening at high irradiations.

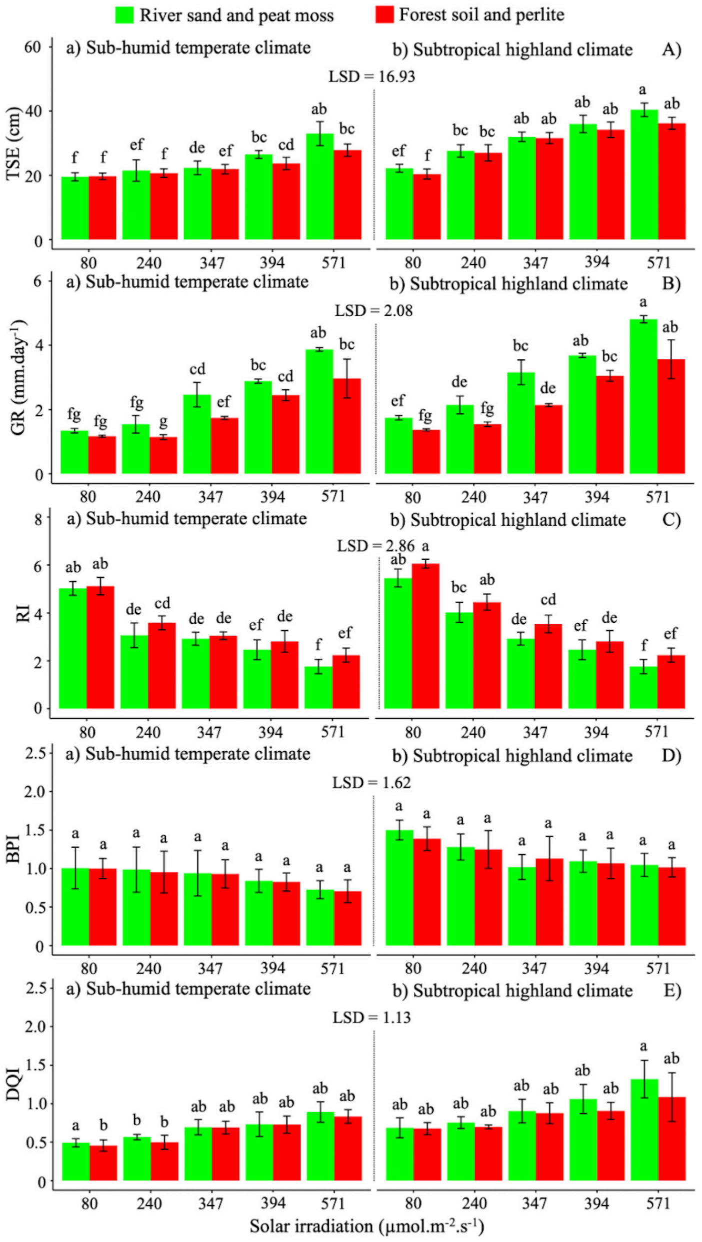

Figure 1. The development of *Euphorbia cotinifolia* is affected by the substrate and solar irradiation. A) Terminal Shoot Elongation (TSE), in B) Growth Rate (GR), in C) Robustness Index, in D) Biometric Proportion Index, in E) Dickson Quality Index. The vertical lines above the bars represent the standard error of the mean. LSD: Least Significant Difference. Different letters on the bars indicate significant differences between treatments according to Tukey's test (P≤0.05).

Remarkable results include the absence of a significant effect of the factors evaluated on BPI, indicating that *E. cotinifolia* maintains a constant ratio between aboveground and root biomass, regardless of the environment. This contrasts with studies done in *Ficus benjamina* (L.), where changes in light drastically altered this ratio (Hao *et al*., 2013), suggesting limited morphological plasticity in *E. cotinifolia*.

DQI increased with irradiation (maximum from 1.32 to 571 µmol.m^{-2}.s^{-1}); in that sense, Lin *et al*. (2019) confirmed that *Pentas lanceolata* (Forssk.) plant quality improved under optimal light conditions; supporting the use of DQI as an integral indicator of vigor. The 62.12 % reduction in STC with low irradiation highlights the vulnerability of this specie in suboptimal environments, like that reported in *Quercus rubra* (L.) (Desrosiers *et al*., 2024).

The differences between STC and SHC, with marginal advantages in SHC, could be related to greater thermal stability and rainfall, factors that would positively modulate photochemical efficiency (Pomar & Barceló, 2007; Lin *et al*., 2019). Furthermore, the superiority of the river sand with peat moss substrate suggests that drainage and aeration are critical for root development under high irradiation conditions, coinciding with observations in *Lantana camara* (L.) (Nascimento *et al*., 2020).

Leaf color

Leaf color parameters were statistically different ($P \leq 0.05$) based on environment, solar irradiation level and substrate type. Lower values of B indicated darker leaves, lower H values indicated more red-purple tones, and lower C values indicated more intense color (table 2). In the STC with river sand and peat moss, B, H and C parameters showed negative correlation with solar irradiation. B values decreased by 29.23 % from 80 to 571 $\mu mol.m^{-2}.s^{-1}$. H parameter showed the most dramatic response with a 66.76 % decrease. C parameter decreased by 25.77 %. With forest soil and perlite substrate, parameters also showed negative correlation, but their average values increased by 2.77, 2.20 and 3.99 % compared to river sand and peat moss.

In the SHC with river sand and peat moss, leaves exhibited better red-purple color accentuation. B values decreased by 41.77 %, H values decreased by 63.05 %, and C decreased by 25.33 %. With forest soil and perlite, parameters also showed negative correlation with average values that increased by 1.03, 10.38 and 0.44 %. To produce ornamental plants, color is an important characteristic. The color spectrum is limited by the genetics of the species itself, as is the case with *Euphorbia pulcherrima* (Willd. ex Klotzsch) (Lozoya-Gloria *et al*., 2023). *E. cotinifolia* changes its leaf color tones according to the environment where it grows, and the intensity of solar irradiation perceived.

Temperature affects pigment accumulation, offering lighter shades at high temperatures and darker shades at low temperatures (Noda, 2018). The reddish or purple coloration is determined by anthocyanins, pigments common in plants growing under conditions of light stress, such as direct exposure to the sun. The pigments are generated by their own electronic structure, which interacts with sunlight to alter the wavelengths that are then reflected by the plant tissue. Colors result from a combination of residual wavelengths and the perceived color depends on each observer (Zhao & Tao, 2015).

In *Euphorbia hirta* (L.) leaves exposed to more sunlight develop a higher concentration of anthocyanins, which gives them a more reddish hue compared to leaves growing in shade, which tend to be greener (Gupta & Gupta, 2019); this situation was like the present study. The final color is determined by several factors that contribute to the intensity and spectrum (Rosati & Simoneau, 2006). If the cell pH is acidic the orange and red pigments are more stable; if slightly acidic to neutral the pigments are purple and violet; if alkaline the pigments are blue (Zhao & Tao, 2015). The substrate also influences leaf color; a higher phosphorus content in forest soil intensifies the reddish or purple tones, as opposed to sandy soils (Zhao & Tao, 2015; Lozoya-Gloria *et al*., 2023).

Table 2. Color attributes in leaves (dehydrated and ground) of *Euphorbia cotinifolia*, as a function of solar irradiation and substrate type.

SUB-HUMID TEMPERATE CLIMATE

	River sand and peat moss			**Forest soil and perlite**		
Solar irradiation ($\mu mol.m^{-2}.s^{-1}$)	**B (%)**	**H (ºh)**	**C**	**B (%)**	**H (ºh)**	**C**
80	50.53 c	90.32 e	50.43 d	50.67 b	90.55 e	53.11 c
240	43.18 b	73.87 d	44.08 cd	46.78 b	76.32 d	44.99 bc
347	39.09 c	56.55 c	41.23 bc	39.11 b	57.81 c	41.44 bc
394	38.11 b	50.36 b	40.54 b	39.99 a	51.13 b	43.67 b
571	35.76 a	30.02 a	37.43 a	36.00 a	32.12 a	39.41 a
Mean	41.33	60.22	42.74	42.51	61.58	44.52
CV (%)	6.99	4.51	6.12	6.74	6.58	7.48
LSD	3.97	3.90	3.42	4.03	5.31	4.79

SUBTROPICAL HIGHLAND CLIMATE

	River sand and peat moss			**Forest soil and perlite**		
Solar irradiation ($\mu mol.m^{-2}.s^{-1}$)	**B (%)**	**H (ºh)**	**C**	**B (%)**	**H (ºh)**	**C**
80	44.33 b	54.43 d	47.99 c	46.87 b	55.82 d	48.00 d
240	30.04 b	40.40 c	42.31 c	30.41 b	40.45 c	44.55 cd
347	27.92 b	37.87 bc	39.17 bc	28.66 b	39.54 b	41.32 bc
394	27.58 b	34.06 b	38.50 b	27.87 b	34.11 b	38.58 ab
571	25.81 a	20.11 a	35.83 a	26.08 a	22.44 a	35.99 a
Mean	31.13	37.37	40.76	31.97	38.47	41.68
CV (%)	6.80	7.67	7.53	8.59	9.05	6.78
LSD	5.07	4.03	3.95	5.99	4.83	3.60

B: brightness, H: hue, C: color saturation. CV: coefficient of variation. LSD: minimum significant difference. Means with the same letter in a column are not significantly different according to Tukey´s test ($P \leq 0.05$).

Anthocyanins in leaves

E. cotinifolia plants in SHC accumulated 5.72 % more anthocyanins in their leaves than those in STC. Plants grown in river sand and peat moss accumulated 3.12 % more anthocyanins than those in forest soil and perlite. At 571 µmol.m^{-2}.s^{-1}, plants accumulated 7.76 times more anthocyanins than at 80 µmol.m^{-2}.s^{-1} (figure 2).

In the SHC, substrate differences were less pronounced at different irradiation levels. In both substrates and environments, anthocyanin concentration increased in relation to solar irradiation, which indicated that irradiation was a key factor in anthocyanin production. At 80 µmol.m^{-2}.s^{-1}, anthocyanin production was low (0.42 mg.g^{-1}) in predominantly green leaves with slight red mottling. At 571 µmol.m^{-2}.s^{-1}, production reached 4.94 mg.g^{-1} in purple-red leaves.

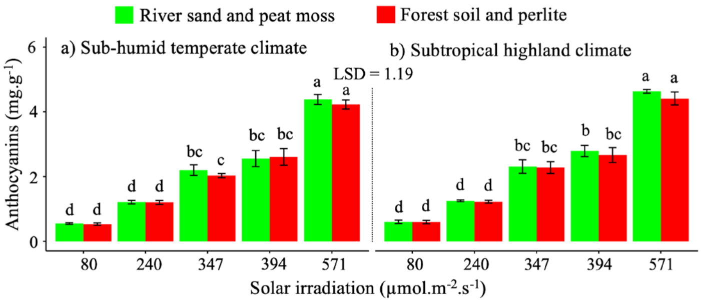

Figure 2. Concentration of total anthocyanins in leaves of *Euphorbia cotinifolia* is influenced by substrate type and solar irradiation, in two environments. The vertical lines above the bars represent the standard error of the mean. LSD: Least Significant Difference. Different letters on the bars indicate significant differences between treatments according to Tukey's test ($P \leq 0.05$).

At higher intensities of solar irradiation, there is a gradual accumulation of anthocyanins and a decrease in chlorophyll production (Pomar & Barceló, 2007). This may be due to an increased production of photosynthates, since more sugar molecules are attached to the anthocyanin, which affects its color and stability (Lozoya-Gloria *et al.*, 2023). It is also a protection mechanism against ultraviolet radiation, excess light and defense against pathogens (Noda, 2018). The anthocyanins protect chloroplasts from photoinhibition (Pomar & Barceló, 2007).

The range of red-purple colors present in *E. cotinifolia* leaves is determined by anthocyanins. Of these, cyanidin-3-O-glucoside and peonidin-3-O-glucoside are responsible for this coloration. These flavonoids are common in plants with red to purple hues; it is the most common group of pigments in flowers and the most studied (Chandler & Brugliera, 2011). The intensity and quality of these flavonoids are influenced by light and water; they belong to the phenylpropanoid class and control chromaticity through their synthesis and glycosylation in the cytosol, which is subsequently transported to the vacuoles (Rosati & Simoneau, 2006; Noda, 2018).

It is likely that solar irradiation and the type of substrate favor the presence of other anthocyanins such as pelargonidin (with orange to red colors) and delphinidin (with purple and blue colors) (Rosati & Simoneau, 2006; Zhao & Tao, 2015). Or even a mixture with other flavonoids such as flavones and flavonols, creating combinations that provide greater color variation (Rosati & Simoneau, 2006; Noda, 2018). The implications of the research suggest the need to further investigate anthocyanin biosynthesis to understand the molecular mechanisms controlling pigmentation. The accentuation of the red-purple color in leaves of *E. cotinifolia*, grown in subtropical highland climate, at high intensities of solar irradiation and river sand with peat moss as substrate, can reduce the costs of production of quality plants and extract useful pigments for the pharmaceutical industry.

Conclusions

The plant quality of *Euphorbia cotinifolia* is higher when they develop in a subtropical highland climate, at 571 µmol.m^{-2}.s^{-1} of solar irradiation (30 % shading mesh) and river sand with peat is used as substrate. They show a red-purple color in their foliage, due to the high concentration of anthocyanins (4.94 mg.g^{-1}). At 243 days after rooting, plants grew 4.80 mm.day^{-1} and elongated 32.98 cm; their robustness index was 1.76 and Dickson's 1.32.

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