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Climatic conditions on cannabidiol concentration in *Cannabis sativa* L. flowers

Condiciones climáticas sobre la concentración de cannabidiol en flores de *Cannabis sativa* L.

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ABSTRACT

Information on how climatic conditions affect cannabidiol (CBD) biosynthesis in *Cannabis sativa* is limited, restricting the development of the cannabis industry in Colombia. This study evaluated the CBD content in flowers cultivated in the Sierra Nevada de Santa Marta and compared the results with records from producers Colombian Caribbean under different temperature, relative humidity, and altitude conditions. Flowers from the Sierra Nevada de Santa Marta (1,800 m; 18–24 °C; 70–80% HR) were compared with records from Cannavida, Pharmacielo, and coastal producers (26–30 °C; 65–85% HR). Cannabinoids were quantified by HPLC-PDA and differences were evaluated using analysis of variance and Tukey's post hoc test. In the results, Flowers from the Sierra Nevada presented the lowest CBD concentration (1.25 ± 0.08% p/p), which was significantly lower than the values reported for Cannavida (2.0–4.0% p/p) and Pharmacielo (3.8% p/p). Higher temperatures and lower relative humidity in crops at sea level were associated with higher CBD concentrations, suggesting that heat and stress may promote cannabinoid accumulation. However, the observed variation may reflect differences in genotype and cultivation practices. These findings indicate that temperature, relative humidity, and altitude should be considered when selecting cultivation areas and designing management strategies. This study provides a basis for optimizing agronomic practices and breeding programs aimed at increasing CBD yield and the phytochemical quality of cannabis produced in Colombia.

Keywords: agronomic practices; cannabinoid profiling; environmental stress; genetic improvement; greenhouse cultivation; high-performance liquid chromatography

RESUMEN

La información sobre cómo las condiciones climáticas afectan la biosíntesis de cannabidiol (CBD) es limitada y restringe el desarrollo de la industria en Colombia. Este estudio evaluó el contenido de CBD en flores cultivadas en la Sierra Nevada de Santa Marta y comparó los resultados con registros de productores del Caribe colombiano bajo condiciones de temperatura, humedad relativa y altitud. Las flores de la Sierra Nevada de Santa Marta (1.800 m; 18–24 °C; 70–80% HR) se compararon con registros de Cannavida, Pharmacielo y productores costeros (26–30 °C; 65–85% HR). Los cannabinoides se cuantificaron mediante HPLC-PDA y las diferencias se evaluaron mediante análisis de varianza y la prueba *post hoc* de Tukey. En los resultados, las flores de la Sierra Nevada presentaron la menor concentración de CBD (1,25 ± 0,08% p/p), significativamente inferior a los valores de Cannavida (2,0–4,0% p/p) y Pharmacielo (3,8% p/p). Las temperaturas más altas y la menor humedad relativa en los cultivos a nivel del mar se asociaron con concentraciones elevadas de CBD, lo que sugiere que el estrés térmico e hídrico puede favorecer la acumulación de cannabinoides. Sin embargo, la variación observada puede reflejar diferencias en el genotipo y las prácticas de cultivo. Estos hallazgos indican que la temperatura, la humedad relativa y la altitud deben considerarse al seleccionar zonas de cultivo y diseñar estrategias de manejo. Este estudio proporciona una base para optimizar prácticas agronómicas y programas de mejoramiento orientados a incrementar el rendimiento de CBD y la calidad fitoquímica del cannabis producido en Colombia.

Palabras clave: cromatografía líquida de alta resolución; cultivo en invernadero; estrés ambiental; mejoramiento genético; perfil de cannabinoides; prácticas agronómicas

INTRODUCTION

Cannabis sativa L. is an annual dioecious plant native to central Asia, with a long history of use for its medicinal and psychoactive properties (Vozza Berardo et al., 2024 *et al*., 2023). Its taxonomy includes three main subspecies: *C. sativa*, *C. indica*, and *C. ruderalis*, each with distinctive morphological and chemical characteristics (Lapierre *et al*., 2023). The phytochemical composition of cannabis is complex, with more than 500 identified compounds, including cannabinoids, terpenoids, flavonoids, and other secondary metabolites (Lowe *et al*., 2021). Cannabinoids are primarily responsible for the plant's pharmacological effects, with tetrahydrocannabinol (THC) and cannabidiol (CBD) being the most studied.

Environmental factors influence cannabinoid synthesis in *Cannabis sativa*. Climatic conditions, particularly temperature and altitude, can affect cannabinoid production (Payment & Cvetkovska, 2023). *Trancoso et al.* (2022) reported that plants grown at 28–30 °C tended to produce higher CBD concentrations in response to thermal stress, whereas Giupponi *et al*. (2020) found that altitude may influence cannabinoid concentrations through variations in UV radiation and atmospheric pressure. In addition to temperature and altitude, cultivation conditions such as plant nutrition, irrigation, lighting, and greenhouse environmental control can influence phytocannabinoid biosynthesis and accumulation in medicinal *Cannabis sativa* (Malík *et al.*, 2021).

THC is the primary psychoactive constituent, known for its euphoric, analgesic, and appetite-stimulating effects (Crane & Phan, 2021). On the other hand, CBD is a non-psychotropic cannabinoid with broad therapeutic potential, including anxiolytic, antipsychotic, anti-inflammatory, and neuroprotective properties (Peng *et al*., 2022). The ratio between THC and CBD varies significantly among different chemotypes or varieties of cannabis. Plants with a predominance of THC (>0.3%) and low CBD (<0.5%) are classified as Type I or psychoactive cannabis, whereas those with high CBD (>0.5%) and low THC (<0.3%) are classified as Type III or non-psychoactive hemp (Gilmore *et al*., 2023).

The growing global interest in the medical potential of cannabis has driven changes in policies and regulations in many countries. Uruguay, Canada, and several U.S. states have legalized both recreational and medicinal use, whereas other countries have approved medicinal use only (Boehnke *et al*., 2022).

In Colombia, Law 1787 of 2016 and Decree 613 of 2017 established the legal framework for safe and informed access to the medical and scientific use of cannabis and its derivatives (Congreso de Colombia, 2016; Presidencia de la República de Colombia, 2017). More recently, Resolution 227 of 2022 further regulated the licensing, quotas, and authorizations for the safe and informed use of cannabis and its derivatives in Colombia and established regulatory criteria related to THC content in cannabis derivatives (Ministerio de Justicia y del Derecho, Ministerio de Agricultura y Desarrollo Rural, & Ministerio de Salud y Protección Social, 2022).Despite the growing interest in medicinal cannabis in Colombia, a knowledge gap remains regarding how specific climatic conditions in different regions of the country affect CBD production. This information is crucial for optimizing cultivation and ensuring the quality and consistency of the final product. Furthermore, understanding these variations could enable Colombian producers to develop cultivation strategies adapted to each microclimate, potentially improving the yield and quality of medicinal cannabis produced in the country. Previous research in Colombia has documented regional variation in cannabinoid profiles, including CBD, THC, and CBN, among *Cannabis sativa* samples collected from the Llanos Orientales, Cauca,

Sierra Nevada de Santa Marta, and the Eje Cafetero (Florian *et al.*, 2009).

From an agronomic perspective, several studies have reported that *cannabis sativa* cultivated for medicinal purposes may exhibit improved cannabinoid profiles at intermediate altitudes. In general, elevations ranging from approximately 1,000 to 2,000 meters above sea level provide a favorable balance between solar radiation, temperature, and environmental stress. These conditions allow for adequate vegetative growth while simultaneously promoting increased production of cannabinoid-rich resin.

In humid tropical environments, however, these benefits require careful management of high humidity, pests and diseases, and post-harvest handling to produce high-quality CBD that meets regulatory and market standards (Punja *et al*., 2019).

This study is particularly relevant for Colombia, given its potential as a leading global producer of medicinal *cannabis sativa*. The country's diverse microclimates offer a unique opportunity to investigate how these variations affect product quality. The results of this study could provide valuable information to the emerging medicinal cannabis industry in Colombia, helping producers select optimal cultivation areas and adapt practices to local climatic conditions (Araméndiz-Tatis *et al.*, 2023).

The objective of this study was to compare the cannabidiol (CBD) content of *C. sativa* flowers cultivated in greenhouses in the Sierra Nevada de Santa Marta (Colombia) with data reported in the scientific literature and by companies such as Cannavida, Pharmacielo, and other local producers under different climatic conditions. The findings are expected to provide relevant information for optimizing medicinal *C. sativa* production, considering regional climatic variation.

MATERIALS AND METHODS

The sampling procedure for flower sample analysis followed the standards established by the Colombian Agricultural Institute (ICA), and the same procedure was applied in this study to ensure comparability of results. This study was designed as an observational and comparative evaluation of cannabidiol (CBD) content in *C. sativa* samples cultivated under different climatic conditions in the Colombian Caribbean region.

Sampling

Samples were collected from greenhouse cultivations located in the Sierra Nevada de Santa Marta, Colombia (10°45'46.9" N, 73°52'38.8" W), at an altitude of 1,800 m above sea level. The geoclimatic conditions of the study site are characterized by an average annual temperature of 18-24 °C and an average relative humidity of 70-80%. Representative samples of dried cannabis flowers were collected from the company's greenhouse cultivations following standardized protocols (United Nations Office on Drugs and Crime [UNODC], 2022). Six 500 g samples of flowers were collected across the cultivated area, totaling 3 kg. The samples were labeled and stored in paper bags.

Sample preparation

Sample preparation followed AOAC Official Method 2018.10 (Mudge & Brown, 2020). The samples were homogenized by grinding to <1 mm, followed by sieving, and 200 mg subsamples were transferred into centrifuge tubes. Acetonitrile (40 mL) was added, and the mixture was sonicated for 30 min, centrifuged for 15 min

at 3,900 rpm, and filtered through a 0.2 µm membrane before analysis. Moisture content analysis of the various samples was conducted using the gravimetric method, a classical and widely adopted procedure for determining moisture percentage via weight differential. Initially, a representative cannabis flower sample, typically weighing between 5 and 10 g, was collected. The fresh sample was then accurately weighed using an analytical balance, and the mass was recorded as the 'initial weight' (W1). Subsequently, the sample was placed in a controlled-temperature drying oven, set between 60 °C and 105 °C, for a specified duration, which may range from several hours. This step is crucial for ensuring complete removal of moisture from the sample without inducing thermal degradation of its chemical constituents. Post-drying, the sample was removed from the oven and allowed to cool in a desiccator or a controlled-humidity environment to prevent moisture reabsorption. Once cooled, the dry sample was weighed, with this mass recorded as the 'final weight' (W2). Finally, moisture content (%) was calculated using the formula: Moisture Content (%) = [(W1 - W2) / W1] × 100, where W1 denotes the initial fresh sample mass and W2 the final dry sample mass. This method is straightforward and robust, yielding accurate and precise results when meticulously executed**.**

HPLC analysis

HPLC-PDA equipment equipped with a C18 column (150 × 2.1 mm, 1.8 µm) was used, with gradient elution using mobile phases of 20 mM ammonium bicarbonate (A) and acetonitrile (B), a flow rate of 0.4 mL/min, a three µL injection, and detection at 240 nm. Calibration standards for CBD and THC were prepared at five levels, ranging from 0.5 to 10 mg/L. Detection and quantification limits were established in accordance with official guidelines.

Statistical design and data analysis

A one-way analysis of variance (ANOVA) was conducted to compare the CBD content of samples from the Sierra Nevada de Santa Marta with reported data from other companies in the Caribbean region. Tukey's post hoc test was used to determine significant differences between specific groups. The significance level was set at $p < 0.05$. All statistical analyses were performed using R software version 4.1.0 (R Core Team, 2021).

RESULTS

Cannabinoid profile and chromatographic analysis

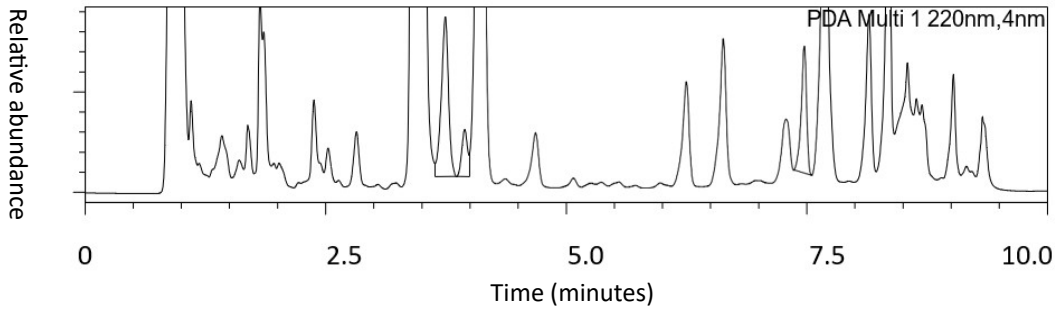
The cannabinoid profile of the analyzed *C. sativa* flowers is presented in Table 1. CBDA was the predominant cannabinoid, with a mean concentration of 13.45 ± 0.92% w/w, followed by CBD, with a concentration of 1.25 ± 0.08% w/w. The concentrations of Δ9-THC and THCA were 0.17 ± 0.02% and 0.47 ± 0.05% w/w, respectively. CBN, THCV, CBDV, and Δ8-THC were below the limit of quantification (<0.005%).

Table 1. *Cannabinoid profile of Cannabis sativa flowers determined by HPLC-PDA (n = 6)*

Cannabinoid	Mean ± SD (% w/w)
Δ8-Tetrahydrocannabinol (Δ8-THC)	< 0.005
Δ9-Tetrahydrocannabinol (Δ9-THC)	0.17 ± 0.02
Δ9-Tetrahydrocannabinolic acid (THCA)	0.47 ± 0.05
Cannabidiol (CBD)	1.25 ± 0.08
Cannabidiolic acid (CBDA)	13.45 ± 0.92
Cannabinol (CBN)	< 0.005
Cannabigerolic acid (CBGA)	0.17 ± 0.03
Tetrahydrocannabivarin (THCV)	< 0.005
Cannabigerol (CBG)	0.05 ± 0.01
Cannabichromene (CBC)	0.12 ± 0.02
Cannabidivarin (CBDV)	< 0.005

Note. Cannabinoid profile in Cannabis sativa flowers determined by HPLC (n=6). Data are expressed as mean ± standard deviation in % weight/weight on a dry basis. Values are expressed as mean ± standard deviation (% w/w, dry basis); values below 0.005% are reported as below the limit of quantification.

A representative HPLC-PDA chromatogram of the diluted flower extract is shown in Figure 1. Two main peaks were detected at retention times of 3.462 and 4.119 min and were assigned to CBDA and CBD, respectively.



Note. Peaks detected at 3.462 and 4.119 min were assigned to CBDA and CBD, respectively.

Figure 1. *Representative HPLC-PDA chromatogram of a diluted Cannabis sativa flower extract*

Moisture content

The moisture content of the six flower samples ranged from 12.38 to 12.72% w/w, with an overall mean of 12.57 ± 0.18% w/w (Table 2).

Table 2. *Moisture content in Cannabis sativa flower samples*

Sample	Moisture (% w/w)
S1	12.63
S2	12.45
S3	12.71
S4	12.55
S5	12.38
S6	12.72
Mean ± SD	**12.57 ± 0.18**

Comparison of CBD content among cultivation sites

Table 3 compares the climatic conditions and CBD concentrations reported for six medicinal cannabis production sites in the Colombian Caribbean. The Sierra Nevada de Santa Marta had the lowest mean CBD concentration (1.25 ± 0.08% w/w), whereas Pharmacielo had the highest (3.80 ± 0.30% w/w). Cannavida presented a mean CBD concentration of 3.00 ± 1.00% w/w.

Table 3. *Climatic conditions and CBD content reported for medicinal Cannabis sativa production sites in the Colombian Caribbean*

Company/Grower group	Altitude (m)	Temperature (°C), mean ± SD	Relative humidity (%), mean ± SD	CBD (% w/w), mean ± SD	Reference
Organization of Cannabis Growers—Sierra Nevada de Santa Marta	1,800	21 ± 3	75 ± 5	1.25 ± 0.08	This study
Small Producers—Barranquilla, Atlántico	0	28 ± 1	77.5 ± 2.5	2.40 ± 0.35	Araméndiz-Tatis *et al.*, 2023
Cannavida—La Guajira	0	29 ± 1	70 ± 5	3.00 ± 1.00	Observatorio de Conflictos Ambientales (2019)(OCA), n. d.

Exploratory statistical analysis of climatic variables

An exploratory multiple linear regression analysis was conducted to evaluate the relationship between CBD content and the climatic variables temperature and relative humidity. The fitted multiple linear regression model is expressed by Equation (1):

$$CBD = \beta 0 + \beta 1T + \beta 2RH$$

where *T* represents temperature, and *RH* represents relative humidity. The corresponding analysis of variance is presented in Table 4.

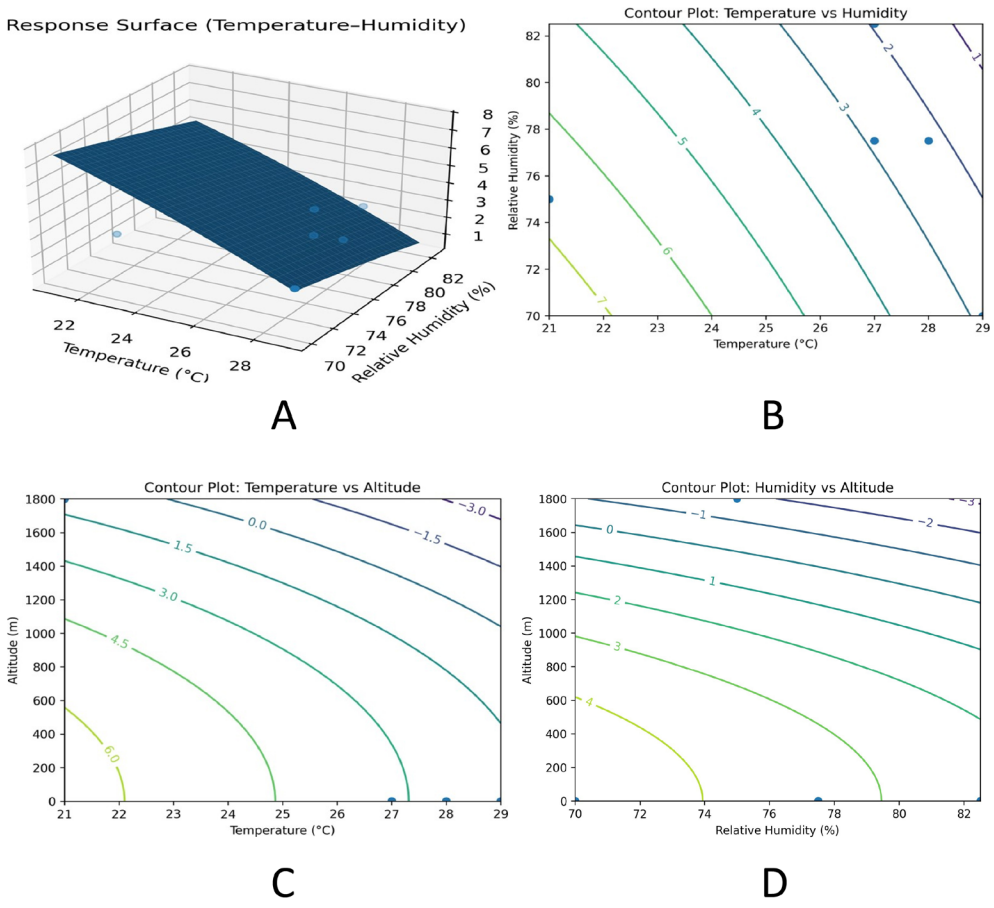
Table 4. *Analysis of variance for the exploratory multiple linear regression model relating CBD content to temperature and relative humidity*

Source	SS	df	MS	F	*p*-value
Temperature	1.723	1	1.723	2.730	0.197
Relative humidity	0.059	1	0.059	0.090	0.779
Residual	1.895	3	0.632	—	—
Total	3.677	5	—	—	—

Temperature accounted for the largest proportion of the variation explained by the model; however, its effect was not statistically significant ($p = 0.197$). Relative humidity contributed less to the explained variation and was also not statistically significant (p =

0.779). Therefore, the statistical results do not provide sufficient evidence to establish significant individual effects of temperature or relative humidity on CBD content under the evaluated conditions.

Figure 2 presents the exploratory graphical relationships between predicted CBD content and the climatic variables included in the comparative dataset. The three-dimensional response surface and the corresponding temperature–relative humidity contour plot showed a gradual variation in predicted CBD content across the evaluated ranges. Additional contour plots were used to visualize the pairwise relationships between temperature and altitude and between relative humidity and altitude.



Note. (a) Three-dimensional response surface as a function of temperature and relative humidity; (b) contour plot of temperature and relative humidity; (c) contour plot of temperature and altitude; and (d) contour plot of relative humidity and altitude. The points represent the cultivation sites included in the comparative dataset.

Figure 2. *Exploratory graphical relationships between climatic variables and predicted CBD content*

The graphical projections showed gradients in predicted CBD content across the evaluated temperature, relative humidity, and altitude ranges. Nevertheless, these graphical patterns should be interpreted cautiously because the statistical model included only temperature and relative humidity, whereas altitude was incorporated exclusively in the complementary pairwise visualizations. Furthermore, the limited number of observations ($n = 6$) restricts the statistical power and predictive capacity of the analysis. Consequently, the results should be considered exploratory associations rather than evidence of significant or causal climatic effects on CBD accumulation.

DISCUSSION

Cannabinoid profile and chromatographic behavior

The chromatographic profile of the representative diluted flower extract was predominantly composed of cannabidiol-type compounds. The two principal peaks detected at retention times of 3.462 and 4.119 min were assigned to cannabidiolic acid (CBDA) and cannabidiol (CBD), respectively. Their clear chromatographic separation indicates that the HPLC-PDA conditions provided adequate resolution for distinguishing the acidic and neutral forms of cannabidiol.

In the representative chromatogram, CBDA was the predominant compound, with a concentration of 11.75531%, whereas CBD was detected at 1.09580%. The analytical report estimated a total CBD content of 11.41% (114.05 mg/g, dry basis), reflecting the combined contribution of CBD and its acidic precursor. This profile is consistent with plant material in which cannabinoids remain predominantly in their native acidic form. In fresh or non-decarboxylated cannabis tissues, CBDA is the principal biosynthetic precursor of CBD and is progressively converted into the neutral cannabinoid through heating, aging, or processing.

The mean cannabinoid profile obtained from the six analyzed samples confirmed this behavior. CBD was detected at 1.25 ± 0.08% w/w, whereas CBDA reached 13.45 ± 0.92% w/w. In contrast, Δ9-THC and THCA were present at substantially lower concentrations of 0.17 ± 0.02% and 0.47 ± 0.05% w/w, respectively. Other cannabinoids, including CBN, THCV, CBDV, and Δ8-THC, remained below the limit of quantification (<0.005% w/w). Although THC-related peaks were not detectable in the representative chromatographic run, the analysis of the complete sample set revealed low but quantifiable mean concentrations of Δ9-THC and THCA.

The predominance of CBD over Δ9-THC, with a CBD:THC ratio of 7.35, is consistent with a non-psychoactive or Type III chemotype according to the classification described by Gilmore *et al.* (2023). The high CBDA concentration is also relevant from a therapeutic perspective because this cannabinoid has been associated with anti-inflammatory and anticonvulsant properties (Antezana *et al.*, 2025). Therefore, evaluating CBD alone may underestimate the overall abundance of cannabidiol-type compounds and the potential medicinal value of the analyzed flowers.

The low concentrations of Δ9-THC and THCA suggest a reduced likelihood of psychoactive effects. The Δ9-THC content was also below the 1% threshold established by Colombian regulations for non-psychoactive cannabis. Minor cannabinoids such as CBG and CBC, although present at comparatively low concentrations, may contribute to the overall biological response through synergistic interactions commonly described as the entourage effect (Hayduk *et al.*, 2024). Nevertheless, the magnitude and clinical relevance of these interactions require further experimental validation.

The use of validated and robust chromatographic methods is essential for obtaining reliable and comparable cannabinoid measurements across laboratories (Giese *et al.*, 2015; Ayala *et al.*, 2024). Recent studies have also demonstrated the applicability of validated HPLC and GC methods for the quantitative determination of cannabinoids and terpenes in cannabis extracts (Lazarjani *et al.*, 2024). In this study, sample preparation and chromatographic analysis were conducted according to AOAC Official Method 2018.10, supporting the analytical traceability of the reported cannabinoid profile. However, differences between the concentrations observed in the representative chromatogram and the mean values reported for the six samples should be interpreted as sample-to-sample variability rather than analytical inconsistency.

Moisture content and post-harvest quality

The mean moisture content of the analyzed flowers was 12.57 ± 0.18% w/w, with individual values ranging from 12.38 to 12.72% w/w. This relatively narrow interval indicates consistent drying conditions among the six samples. Moisture contents within approximately 10–15% are generally considered suitable for maintaining flower stability while limiting excessive drying and reducing the risk of microbial deterioration or accelerated cannabinoid degradation (Lumu *et al*., 2024).

The observed moisture level therefore suggests adequate post-harvest drying and storage practices. Nevertheless, moisture content alone does not fully describe product stability. Storage temperature, oxygen exposure, light, packaging conditions, and storage duration can also influence the conversion and degradation of cannabinoids. Longitudinal studies would be required to determine whether the cannabinoid profile remains stable throughout storage and processing.

Climatic conditions and CBD variation among cultivation sites

The comparison with other medicinal cannabis producers in the Colombian Caribbean showed marked differences in CBD concentration among cultivation sites. The Sierra Nevada de Santa Marta samples exhibited the lowest mean CBD content, at 1.25 ± 0.08% w/w, whereas Pharmacielo reported the highest mean value, at 3.80 ± 0.30% w/w. Cannavida reported CBD concentrations between 2.0 and 4.0%, corresponding to a mean of approximately 3.00 ± 1.00% w/w. Producers located in Turbaco, Barranquilla, and other areas of Magdalena presented intermediate CBD concentrations of approximately 2.10–2.40% w/w.

Cannavida operates in La Guajira under sea-level conditions characterized by relatively high temperatures of approximately 28–30 °C and lower relative humidity of approximately 65–75%. These conditions may favor cannabinoid accumulation by imposing thermal and hydric stress on the plants. Previous studies have reported that elevated temperature and other abiotic stressors can modify cannabinoid biosynthesis and secondary-metabolite accumulation in *C. sativa* (Trancoso *et al.*, 2022; Giupponi *et al.*, 2020). High temperatures and reduced relative humidity may act as environmental stressors that stimulate the production of defensive secondary metabolites, including cannabinoids (Toth *et al.*, 2020).

In contrast, the Sierra Nevada de Santa Marta cultivation site is located at 1,800 m a.s.l. and is characterized by lower temperatures of 18–24 °C and relative humidity of 70–80%. Under these milder thermal conditions, the plants may experience lower thermal stress, which could contribute to the lower CBD concentrations observed. However, this interpretation remains provisional because altitude simultaneously modifies temperature, solar radiation, ultraviolet exposure, atmospheric pressure, and daily temperature variation. Consequently, the effect attributed to altitude cannot be separated from the effects of these covarying environmental conditions using the present dataset.

The intermediate CBD values reported for producers in Turbaco, Barranquilla, and Magdalena are compatible with the possibility that moderate climatic conditions produce intermediate cannabinoid profiles. Nevertheless, the comparison does not establish a direct dose–response relationship between climate and CBD concentration because the evaluated producers also differed in genotype, agronomic practices, nutrient management, harvest time, greenhouse design, and post-harvest treatment.

Pharmacielo represents an important exception to a strictly climatic interpretation. Despite operating under climatic conditions similar to those of other producers in Magdalena, it reported the highest mean CBD concentration. Greater environmental

control in high-technology greenhouses may contribute to this result by enabling more precise regulation of temperature, humidity, irrigation, radiation, and crop nutrition (Martínez Rivera *et al.*, 2019). Plant genetics and cultivation practices may also strongly influence cannabinoid biosynthesis and could explain why producers exposed to similar regional climates exhibited different CBD concentrations (Milay *et al.*, 2020).

The observed pattern is broadly consistent with the findings of Trancoso *et al.* (2022), who reported that plants cultivated at temperatures of approximately 28–30 °C tended to produce higher CBD concentrations in response to thermal stress. However, the present comparison should not be interpreted as demonstrating that elevated temperature necessarily increases CBD content. The cultivation sites were not evaluated under a controlled experimental design, and the climatic variables were not manipulated independently.

Statistical interpretation of climatic variables

The exploratory regression and ANOVA results indicated that temperature accounted for a larger proportion of the modeled variation in CBD concentration than relative humidity. However, neither temperature (p = 0.197) nor relative humidity (p = 0.779) showed a statistically significant individual effect. Therefore, the graphical trends observed in the response surface and contour plots should be interpreted as exploratory associations rather than evidence of causal climatic effects.

The graphical projections suggested that CBD content varied across the evaluated ranges of temperature, relative humidity, and altitude. In the observed dataset, warmer sea-level sites generally presented higher CBD concentrations, whereas the high-altitude Sierra Nevada site showed the lowest value. Nevertheless, the limited number of observations ($n = 6$) substantially restricts the statistical power, robustness, and predictive capacity of the model. In addition, altitude was included only in complementary graphical comparisons and was not incorporated into the reported regression equation. Its apparent relationship with CBD must therefore be interpreted cautiously.

The available data do not permit the independent contributions of temperature, humidity, altitude, genotype, cultivation technology, and management practices to be quantified. The comparatively high CBD concentration reported for Pharmacielo despite climatic similarity with other Magdalena producers further demonstrates that environmental variables alone cannot explain the observed variation. These findings support a multifactorial interpretation in which climate interacts with genetics, greenhouse technology, crop management, and post-harvest conditions.

Limitations and implications

The principal limitation of this study is the small number of samples and cultivation sites. The six samples analyzed from the Sierra Nevada may not fully represent the intraspecific, spatial, seasonal, and genetic variability of medicinal *C. sativa*. Furthermore, the comparative values from other producers were obtained from scientific literature and technical reports rather than from samples analyzed simultaneously under an identical experimental protocol. Differences in analytical methods, cultivars, harvesting stages, drying conditions, and reporting criteria may therefore contribute to the observed variation.

Only flowers were analyzed in the present study. Other plant tissues, including leaves and roots, may contain distinct profiles of cannabinoids and other secondary metabolites (Jin *et al.*, 2020). Future investigations should include larger and seasonally replicated sampling campaigns, standardized analytical procedures, genotype identification, and controlled measurements of greenhouse temperature, relative humidity, radiation,

irrigation, and nutrient availability. Studies examining cannabinoid stability during storage and processing, as well as bioavailability and pharmacokinetics, would also strengthen the assessment of medicinal quality.

Despite these limitations, the results provide an initial comparison of cannabinoid profiles under contrasting cultivation conditions in the Colombian Caribbean. The observed differences indicate that site selection and environmental management should be considered together with genetics and cultivation technology when designing strategies to optimize CBD production. A controlled, multiseason experimental design will be necessary to determine whether the apparent associations with temperature, humidity, and altitude persist after the effects of genotype and management practices are separated.

CONCLUSIONS

The presented data suggest that climatic conditions, particularly temperature and relative humidity, may play an important role in the CBD content of *C. sativa* flowers cultivated by different producers in the Colombian Caribbean region. High temperatures and low relative humidity favor the accumulation of CBD, whereas lower temperatures and higher relative humidity could be associated with lower levels of this cannabinoid. The statistical analysis revealed significant differences in CBD content among medicinal cannabis companies in the Colombian Caribbean region. These differences could be influenced, at least in part, by climatic conditions, including temperature and relative humidity. It is recommended to conduct longitudinal studies with larger sample sizes to confirm and expand these findings. Future research should also consider other cannabinoids and bioactive compounds. This translation maintains the key points of the original text, emphasizing the need for more comprehensive studies and a broader scope in future research on cannabis compounds. From a scientific perspective, this study contributes new empirical evidence on the relationship between climatic factors and cannabinoid production under tropical cultivation conditions. These results provide a valuable basis for optimizing cultivation site selection, greenhouse management strategies, and genetic improvement programs aimed at enhancing CBD yield and ensuring the phytochemical quality of medicinal cannabis produced in Colombia.

ETHICAL CONSIDERATIONS

Although this study does not involve human or animal subjects, ethical guidelines for plant research were followed. The corresponding permission was obtained from the organization of cannabis growers for sample collection, and all local and national regulations related to the cultivation and handling of Cannabis sativa for medicinal use were respected.

AUTHOR CONTRIBUTIONS

Conceptualization, F.J.C.-C.; Methodology, J.O.-A. and J.D.S.-C.; Software, J.D.S.-C.; Validation, J.O.-A.; Formal Analysis, J.O.-A.; Investigation, J.D.S.-C.; Resources, F.J.C.-C.; Data Curation, J.O.-A.; Writing—Original Draft Preparation, J.D.S.-C.; Writing—Review & Editing, J.D.S.-C.; Visualization, J.D.S.-C.; Supervision, J.O.-A.; Project Administration, F.J.C.-C.; Funding Acquisition, F.J.C.-C. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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