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Decarboxylation of Cannabis Inflorescences Using Radio Frequency Heating Technology

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A B S T R A C T

This study investigates the decarboxylation of Cannabis sativa L. inflorescences (Blue Cheese variety) using radio frequency (RF) heating technology. The objective was to optimize the conversion of acidic cannabinoids (THCA, CBDA) into their neutral counterparts (THC, CBD). A factorial experiment in a completely randomized design (CRD) was conducted, examining two independent variables: voltage (180, 200, 220 V) and treatment time (1, 3, 5 min). The results demonstrated that both treatment time and voltage significantly influenced cannabinoid conversion, with a strong interaction effect between the two factors ($p < 0.05$). The highest THC yield was obtained at 200 V for 1- and 5-min treatments, while elevated voltage at 220 V did not further increase THC concentration and was associated with slight increases in CBN formation, suggesting partial degradation. Overall, RF heating provided rapid and efficient decarboxylation within minutes, outperforming conventional approaches that typically require prolonged heating. This study highlights the potential of RF heating as a scalable and energy-efficient technology for medicinal cannabis processing. By enabling precise control over energy input and treatment duration, RF heating can optimize cannabinoid activation while minimizing degradation, thus ensuring product quality and therapeutic efficacy.

Keywords: Cannabis, decarboxylation, radio frequency heating, cannabinoids, dielectric heating

1. Introduction

Cannabis (*Cannabis sativa* L.) is one of the oldest cultivated plants, traditionally used for medicinal, nutritional, and industrial purposes. Over recent decades, there has been growing scientific and commercial interest in cannabis due to its diverse array of bioactive compounds, particularly phytocannabinoids, terpenes, and flavonoids (Yang et al., 2020). Among these, cannabinoids are the most studied, with Δ^9-tetrahydrocannabinol (THC) and cannabidiol (CBD) being the principal molecules associated with psychoactive and therapeutic properties, respectively. However, in freshly harvested or dried cannabis inflorescences, these compounds predominantly exist in their acidic precursor forms: tetrahydrocannabinolic acid (THCA) and cannabidiolic acid (CBDA) (Jaidee et al., 2022). These acidic cannabinoids are pharmacologically inactive or only weakly active compared to their decarboxylated forms. Therefore, decarboxylation — the removal of a carboxyl group (-COOH) from THCA and CBDA — is an essential step to activate the therapeutic potential of cannabis-derived products (Moreno et al., 2020). The cannabis plant synthesizes cannabinoids via polyketide and terpenophenolic pathways, resulting in more than 120 structurally related compounds. In their natural state, cannabinoids accumulate as carboxylic acids, such as THCA, CBDA, and cannabigerolic acid (CBGA) (Jaidee et al., 2022; Moreno et al., 2020; Yang et al., 2020). Decarboxylation converts these molecules into their neutral analogues (THC, CBD, CBG) through heat or prolonged storage (Yang et al., 2020). For medicinal applications, this conversion is crucial, as THC is responsible for analgesic, antiemetic, and appetite-stimulating effects, while CBD provides anticonvulsant, anti-inflammatory, and anxiolytic properties (Jaidee et al., 2022).

If cannabis is consumed raw, such as in dietary supplements, the therapeutic benefits are limited because THCA and CBDA bind differently to cannabinoid receptors in the human endocannabinoid system (Yang et al., 2020). Thus, controlled decarboxylation is a prerequisite for producing standardized cannabis medicines, oils, and extracts. However, decarboxylation is not merely a linear reaction; it is influenced by temperature, duration, moisture content, and atmospheric conditions (Del Giudice & Di Stefano, 2023). Inadequate heating results in incomplete conversion, while excessive heating promotes degradation of THC into cannabinol (CBN), an oxidized derivative with sedative but less desirable pharmacological activity (Malabadi et al., 2024).

Traditional decarboxylation methods rely on thermal conduction or convection, usually by heating cannabis in ovens, hot plates, or oil baths (Patra & Maiti, 2017). Typical conditions range between 100–145 °C for durations of 30–120 min. While effective, these methods often result in uneven heating, localized overheating, and degradation of cannabinoids and terpenes. Furthermore, long processing times consume significant energy and may reduce product quality due to volatilization of aromatic compounds (Patra & Maiti, 2017).

Radio frequency heating, also known as dielectric heating, is an emerging technology in the field of thermal processing (Gao et al., 2023). It utilizes electromagnetic waves in the range of 1–300 MHz to generate heat within a dielectric material. Unlike conventional heating, which relies on heat transfer

from the surface to the core, RF heating penetrates the material and induces molecular oscillations, producing volumetric heating (Dag et al., 2022). The mechanism of RF heating is based on the interaction between the oscillating electromagnetic field and dipolar molecules, such as water, within the material (Dujko et al., 2015). When exposed to the alternating electric field, these molecules attempt to align with the rapidly changing field, generating internal friction and heat (Sheppard et al., 2008). This process allows RF heating to deliver rapid, uniform energy distribution, reducing thermal gradients and processing times. RF heating has been widely studied in the food industry for pasteurization, drying, and disinfestation of grains, nuts, and fruits (Dag et al., 2022). It has also been applied in pharmaceutical processing for drying heat-sensitive products. Advantages of RF heating include deeper penetration compared to microwaves, adjustable electrode spacing to control energy intensity, and reduced processing times (Sheppard et al., 2008). These features make RF heating highly suitable for materials like cannabis inflorescences, which have heterogeneous structures and require uniform heating for consistent decarboxylation.

The application of RF heating to cannabis decarboxylation is a relatively unexplored area. However, its advantages align closely with the challenges faced in conventional decarboxylation. Cannabis inflorescences contain complex matrices of cannabinoids, terpenes, and lipophilic compounds, which require precise thermal control to preserve their integrity (Sommano et al., 2020). RF heating offers the possibility of rapid cannabinoid activation while minimizing degradation and volatilization of sensitive compounds (Grafström et al., 2019). In addition, RF systems can be designed with adjustable parameters such as electrode spacing, applied voltage, and treatment duration, allowing for precise control over the heating process. This flexibility enables optimization of decarboxylation conditions tailored to different cannabis cultivars, moisture contents, and processing scales. Importantly, RF heating is energy-efficient and scalable, making it attractive for industrial cannabis processing where consistency and throughput are critical.

Despite the promising potential of RF heating, few studies have systematically evaluated its application to cannabis decarboxylation. Most available research focuses on food preservation or pest control, with limited exploration of how RF parameters influence the conversion of cannabinoids. Key questions remain regarding the optimal combination of voltage and treatment duration to maximize THC yield, minimize CBN formation, and ensure reproducibility. This study addresses these gaps by applying a factorial Completely Randomized Design (CRD) to investigate the effects of voltage and time on the decarboxylation of Blue Cheese cannabis inflorescences using a prototype RF heating system. By systematically analyzing the main and interaction effects of these factors, the research aims to provide empirical data on the efficiency and reliability of RF heating for cannabis decarboxylation.

2. Materials and Methods

2.1. Plant material

The raw material used in this study consisted of cannabis (*C. sativa* L.) inflorescences of the Blue Cheese variety. Samples were harvested from Serm Ngam District, Lampang Province, Thailand, and stored under controlled conditions for 45 days post-harvest to stabilize moisture and cannabinoid profiles. The samples were visually inspected and stored in airtight containers to prevent external contamination and oxidation. Prior to RF treatment, samples were homogenized by gently breaking large clusters into smaller pieces (approximately 1–2 cm in length) to ensure uniform exposure.

2.2. Experimental design

The experiment followed a factorial completely randomized design (CRD), chosen for its efficiency in studying the combined effects of multiple independent variables. The two experimental factors were voltage (180 V, 200 V, and 220 V) and treatment duration (1, 3, and 5 min). This design produced nine treatment combinations, as presented in Table 1.

Table 1 – Factorial experimental design for the cannabis decarboxylation.

Experiments	Incubation time (min)	Voltage (V)
1	1	180
2	1	200
3	1	220
4	3	180
5	3	200
6	3	220
7	5	180
8	5	200
9	5	220

For each experiment, approximately 5 g of homogenized cannabis inflorescences were placed in a non-conductive glass container (borosilicate) positioned at the geometric center of the electrode gap. The electrode spacing was fixed at 15 cm for all treatments to ensure comparability. Once positioned, the desired voltage setting was applied, and the RF heating process was initiated for the designated duration (1, 3, or 5 min). At the end of each treatment, samples were immediately cooled to room temperature using forced air to stop further thermal reactions. Each treatment combination was performed in triplicate. The design allowed for evaluation of both main effects and interaction effects of voltage and time on cannabinoid profiles.

2.3. Cannabinoid extraction and analysis

Chemical analysis of cannabinoids was conducted using high-performance liquid chromatography (HPLC). Approximately 200 mg of treated cannabis sample was finely ground using a ceramic mortar and pestle. The powder was transferred into a 15 mL centrifuge tube and extracted with 10 mL of methanol (HPLC grade, Labscan, Thailand). Samples were vortexed for 2 min and sonicated for 15 min at 25 °C. After extraction, the tubes were centrifuged at 4000 rpm for 10 min, and the supernatant was filtered through a 0.22 µm PTFE membrane filter before injection into the HPLC system. (Hirunyasiri et al., 2024).

The HPLC system was equipped with a quaternary pump, autosampler, column oven, and photodiode array detector. A C18 reversed-phase column (250 × 4.6 mm, 5 µm particle size) was used as the stationary phase. The mobile phase consisted of acetonitrile and water (75:25, v/v) with 0.1% formic acid, delivered at a flow rate of 1.0 mL/min. The column temperature was maintained at 30 °C, and detection was performed at 220 nm. Injection volume was 20 µL (Hirunyasiri et al., 2024). Standard calibration curves for THCA, THC, CBDA, CBD, and CBN were prepared using certified reference materials (Sigma-Aldrich, USA). Calibration curves were linear in the range of 0.5–100 µg/mL with correlation coefficients (R^2) greater than 0.998. Limits of detection (LOD) and quantification (LOQ) were determined as 0.05 µg/mL and 0.2 µg/mL, respectively.

2.4. Data collection and statistical analysis

THC and CBN concentrations were expressed as mean ± standard deviation of three replicates. Data were subjected to Analysis of Variance (ANOVA) using SPSS software (version 29.0, IBM, USA). The model included main effects of voltage and time, as well as their interaction. When significant effects were detected, mean comparisons were performed using Duncan test at a significance level of $p < 0.05$.

3. Results

3.1. Interaction effects

The factorial experiment revealed significant effects of both treatment time and voltage on THC and CBN concentration in cannabis inflorescences. Mean values are summarized in Table 2.

Table 2 - Effect of treatment time and voltage of radio frequency on THC and CBN concentration.

Incubation time (min)	Voltages (Volts)	THC (mg/g)	CBN (mg/g)
1	180	11.59 ± 1.82^{d}	0.117 ± 0.016^{c}
	200	18.86 ± 2.71^{bc}	0.157 ± 0.014^{ab}
	220	13.03 ± 0.33^{cd}	0.120 ± 0.007^{bc}
3	180	15.49 ± 2.37^{a}	0.145 ± 0.021^{a}
	200	14.53 ± 1.74^{cd}	0.128 ± 0.012^{bc}
	220	14.50 ± 1.28^{ab}	0.126 ± 0.014^{a}
5	180	13.68 ± 2.16^{cd}	0.123 ± 0.016^{bc}
	200	18.14 ± 0.44^{cd}	0.153 ± 0.003^{bc}
	220	17.77 ± 0.41^{ab}	0.154 ± 0.002^{a}

Different superscript letters within the same column indicate significant differences among treatments at $p < 0.05$.

At 200 V, the highest THC content was observed, reaching 18.86 ± 2.71 mg/g after 1 min and 18.14 ± 0.44 mg/g after 5 min. These results indicate that moderate voltage combined with either short or extended exposure optimizes decarboxylation efficiency. In contrast, at 180 V, THC concentrations were consistently lower, ranging between 11.59 ± 1.82 mg/g (1 min) and 15.49 ± 2.37 mg/g (3 min), suggesting incomplete conversion under low energy input. Interestingly, at 220 V, THC levels plateaued between 13.03 ± 0.33 mg/g and 17.77 ± 0.41 mg/g, indicating that excessive voltage did not improve yield and may have initiated degradation pathways.

CBN, a degradation product of THC, showed modest but significant increases with longer treatment times and higher voltages. Concentrations ranged from 0.117 ± 0.016 mg/g at 180 V/1 min to 0.154 ± 0.002 mg/g at 220 V/5 min. This pattern reflects the dual role of RF heating while promoting decarboxylation, excessive exposure may accelerate THC oxidation into CBN.

ANOVA results confirmed significant effects of both treatment time ($p = 0.046$) and voltage ($p = 0.001$) on THC concentration, with a strong interaction effect ($p = 0.003$), as showed in Table 3. For CBN, voltage was significant ($p = 0.032$), while treatment time alone was not ($p = 0.131$). The strong interaction effect highlights the importance of optimizing both parameters simultaneously rather than independently.

Table 3 - ANOVA results on the effect of treatment time and voltage of radio frequency on THC and CBN concentration.

Compounds	Source	Sum of Squares	df	Mean Square	F	Sig.
THC	Corrected Model	149.105a	8	18.638	6.421	.001
	Intercept	6310.336	1	6310.336	2174.129	.000
	Time * Voltage	69.221	4	17.305	5.962	.003
	Time	21.356	2	10.678	3.679	.046
	Voltage	58.528	2	29.264	10.082	.001
	Error	52.244	18	2.902		
	Total	6511.686	27			
	Corrected Total	201.350	26			
CBN	Corrected Model	.006a	8	.001	4.390	.004
	Intercept	.499	1	.499	2842.239	.000
	Time * Voltage	.004	4	.001	5.550	.004
	Time	.001	2	.000	2.285	.131
	Voltage	.001	2	.001	4.176	.032
	Error	.003	18	.000		
	Total	.509	27			
	Corrected Total	.009	26			

3.2. Main effects

The main effects of time and voltage on the decarboxylation of cannabinoids under RF heating are presented in Table 4.

Table 4 - Main effects of time and voltage on THC and CBN content during decarboxylation by RF heating.

Factor	Investigate value	THC (mg/g)	CBN (mg/g)
Time	1	14.49±3.71^{b}	0.131±0.022^{a}
	3	14.84±1.68^{b}	0.133±0.017^{a}
	5	16.53±2.42a	0.144±0.017^{a}
Voltage	180	13.58±2.50^{b}	0.128±0.020^{b}
	200	17.18±2.59^{a}	0.146±0.017^{a}
	220	15.10±2.21^{b}	0.134±0.018^{ab}

Different superscript letters within the same column indicate significant differences among treatments at $p < 0.05$.

Effect of Time

Variation in heating duration significantly influenced the decarboxylation efficiency of cannabinoids. THC levels increased progressively with time, from 14.49 ± 3.71 mg/g at 1 min to 16.53 ± 2.42 mg/g at 5 min. Statistical analysis revealed that 5 min of RF heating produced significantly higher THC

concentrations ($p < 0.05$) compared to 1 and 3 min, which were not significantly different from each other. This result suggests that extending heating time enhanced the conversion of acidic precursors (THCA) into neutral THC, reflecting more complete decarboxylation (Tran et al., 2024).

For CBN, no significant differences were observed among the time intervals, with values ranging between 0.131 ± 0.022 mg/g and 0.144 ± 0.017 mg/g. The consistency across time indicates that under the tested conditions, prolonged heating up to 5 min did not markedly increase oxidative degradation of THC to CBN. This demonstrates that RF heating within this timeframe promotes effective decarboxylation without excessive degradation.

Effect of Voltage

Applied voltage was another critical factor affecting cannabinoid content. At 200 V, the highest THC yield (17.18 ± 2.59 mg/g) was obtained, which was significantly greater ($p < 0.05$) than that observed at 180 V (13.58 ± 2.50 mg/g) and 220 V (15.10 ± 2.21 mg/g). These findings highlight that moderate voltage settings optimize RF heating by providing sufficient energy to accelerate decarboxylation while minimizing thermal degradation.

For CBN, voltage also exerted a notable influence. CBN levels increased from 0.128 ± 0.020 mg/g at 180 V to 0.146 ± 0.017 mg/g at 200 V, while a moderate level (0.134 ± 0.018 mg/g) was observed at 220 V. Statistical comparison indicated that 200 V resulted in significantly higher CBN formation compared to 180 V, whereas 220 V did not differ significantly from either group. This suggests that while increased voltage promotes more complete decarboxylation, it may also initiate partial degradation pathways at higher intensities.

The results demonstrate that time primarily influences the completeness of decarboxylation, as reflected by increasing THC concentration, while voltage modulates both decarboxylation and degradation, with 200 V providing the most favorable balance between THC production and limited CBN formation. These findings underline the importance of carefully optimizing RF heating parameters to maximize cannabinoid yield and stability in the decarboxylation process.

4. Discussion

The results clearly demonstrated that RF heating effectively induces decarboxylation of THCA into THC. The elevated THC yields at 200 V confirm that intermediate voltage provides sufficient energy to trigger the decarboxylation reaction while avoiding excessive degradation (Jaidee et al., 2022). This aligns with previous findings that decarboxylation is sensitive to both temperature and duration (Del Giudice & Di Stefano, 2023), where under-treatment yields incomplete conversion and over-treatment promotes oxidation (Malabadi et al., 2024).

Treatment time played a key role in determining cannabinoid outcomes. A 1-min exposure at 200 V already produced high THC levels, indicating that RF heating enables rapid volumetric energy transfer (Vashisth et al., 2021). Extending treatment to 5 min further sustained high THC levels but also slightly increased CBN concentrations, suggesting that prolonged exposure begins to promote secondary degradation (Grafström et al., 2019). This is consistent with conventional heating studies, where extended heating beyond the optimal point reduces cannabinoid quality.

Voltage directly affects the strength of the electromagnetic field and, consequently, the heating rate. At low voltage (180 V), incomplete decarboxylation was evident, as THC concentrations remained relatively low across all times. Conversely, at 220 V, while initial THC formation was substantial, the efficiency plateaued, and CBN increased, implying that the high energy intensity may cause localized overheating and accelerate oxidative degradation (Sheppard et al., 2008). This highlights the need to carefully balance voltage settings to optimize energy transfer without compromising product quality.

The performance of RF heating can be attributed to its unique mechanism (Gao et al., 2023). The oscillating electric field interacts with polar molecules, primarily water, within cannabis tissues, generating internal friction and rapid heat distribution (Sheppard et al., 2008). This accelerates decarboxylation uniformly across the inflorescence, unlike surface heating methods. However, excessive voltage likely produces micro-hotspots that catalyze THC oxidation into CBN (Khalifa, 2022), as reflected in the higher CBN values at 220 V. Moisture content may also play a role, as dielectric heating efficiency is directly linked to water content, which could influence cannabinoid transformation pathways (Guo et al., 2010).

5. Conclusion

This study demonstrated that RF heating is an efficient and controllable method for the decarboxylation of *C.sativa* L. inflorescences. By applying different voltages and treatment durations in a factorial design, we established that both parameters significantly influenced the conversion of THCA to THC and the formation of CBN. The optimal conditions were identified as 200 V for 1–5 min, which yielded the highest THC concentrations with minimal degradation. In contrast, lower voltages resulted in incomplete decarboxylation, while higher voltages promoted partial oxidative conversion to CBN. Future work should expand to other cultivars, investigate terpene preservation, and evaluate large-scale industrial applications to fully establish the commercial feasibility of this technology.

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