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Evaluating the Stability of Cannabinoid Extracts Following Different Solvent Evaporation Conditions: A GC-MS/LC-MS Degradation Profiling Study

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Abstract

The stability of cannabinoid extracts during solvent evaporation is a critical factor influencing the quality, potency, and chemical fidelity of cannabis-derived products used in pharmaceutical, nutraceutical, and analytical applications. This study investigates how variations in evaporation temperature, pressure, and atmospheric conditions affect the degradation pathways of major cannabinoids, including THC, CBD, CBN, THCA, and CBDA. Using a controlled experimental design, extracts were subjected to atmospheric evaporation, vacuum-assisted evaporation, and nitrogen stream drying at temperatures ranging from 25°C to 60°C. Chemical changes were quantified through complementary GC–MS and LC–MS analyses, enabling detection of both volatile degradation markers and thermally sensitive intermediates. Results revealed that elevated temperatures significantly accelerated decarboxylation, oxidation, and isomerization processes, with 60°C producing the highest levels of degradation and impurity formation. Pressure and atmospheric composition further modulated degradation outcomes, with nitrogen-assisted evaporation providing superior preservation of cannabinoid integrity compared to atmospheric and vacuum conditions. GC–MS excelled in identifying volatile thermal degradation products, while LC–MS captured non-volatile acids and early-stage oxidative intermediates, underscoring the necessity of a multi-instrument analytical approach. Overall, the findings demonstrate that optimizing evaporation conditions particularly maintaining low temperatures and using oxygen-limited environments is essential for maximizing extract stability and ensuring accurate chemical profiling. This work provides a framework for refining industrial extraction protocols and highlights key considerations for maintaining cannabinoid integrity in high-value cannabis products.

Keywords: *Cannabinoid Stability, Solvent Evaporation Conditions, GC–MS Analysis, LC–MS Profiling, Degradation Study, Evaporation Condition.*

I. INTRODUCTION

➢ *Background to Cannabinoid Extraction and Stability*

Cannabinoids are a diverse class of bioactive compounds derived primarily from *Cannabis sativa L.*, with Δ9-tetrahydrocannabinol (THC), cannabidiol (CBD), and cannabinol (CBN) representing some of the most studied constituents due to their therapeutic relevance and chemical reactivity (Andre et al., 2024; Guerriero, G 2024). THC is the principal psychoactive compound and is known for its susceptibility to oxidative degradation, particularly its conversion to CBN under thermal or

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oxidative stress (Zhang, L et al., 2024; Idoko, I. P et al., 2024). CBD, a non-psychoactive cannabinoid with significant anti-inflammatory and anticonvulsant potential, is also chemically sensitive to heat, pH shifts, and light exposure, leading to isomerization or breakdown into secondary metabolites (Citti et al., 2018; Vandelli, M. A., & Cannazza, G. 2018). Meanwhile, CBN, often present in aged cannabis samples, serves as an indicator of oxidative degradation and has been adopted as a quality marker for extract stability (Pellegrini et al., 2021). The stability of cannabinoid extracts is critical for ensuring consistency, safety, and therapeutic efficacy across pharmaceutical, nutraceutical, and analytical applications. In pharmaceutical formulations, unstable extracts can alter potency, reduce therapeutic effects, and introduce unintended degradation products that may compromise safety profiles (Lucas et al., 2018). Nutraceutical products face similar challenges, as cannabinoid degradation can influence bioavailability and shelf life, particularly when exposed to variable storage or processing conditions (Hurgobin, B et al., 2024; Marks, M. D 2024; Calvi et al., 2018). From an analytical perspective, instability during sample preparation such as overheating during solvent evaporation can distort GC-MS or LC-MS quantification, leading to inaccurate profiling of cannabinoid content (Citti et al., 2024; Patel et al., 2022). Ensuring extract stability is therefore central to maintaining regulatory compliance, reproducibility of analytical results, and overall product quality (Zhang et al., 2021).

As research and industry applications of cannabis-derived products expand, understanding how extraction techniques and post-processing conditions affect cannabinoid integrity has become increasingly important. This forms the foundation for evaluating degradation pathways, optimizing solvent evaporation conditions, and developing standardized analytical workflows that preserve the chemical fidelity of cannabinoid extracts.

- *Problem Statement: Impact of Evaporation Conditions on Cannabinoid Integrity*

The post-extraction step of solvent removal is a critical determinant of cannabinoid integrity because it often exposes extracts to elevated temperatures, oxidative environments, and light, all of which can accelerate degradation reactions. Thermal stress during solvent evaporation, particularly at high temperatures, can lead to decarboxylation of acidic cannabinoids and subsequent formation of degradation products such as cannabinol (CBN) from Δ^9-tetrahydrocannabinol (THC), resulting in diminished potency and altered chemical profiles (García-Valverde et al., 2022; Lazarjani et al., 2021). Likewise, prolonged exposure to heat has been associated with increased degradation rates of cannabidiol (CBD) and other cannabinoids, highlighting kinetic effects that are dependent on both temperature and exposure time (García-Valverde et al., 2022; research on thermal kinetics illustrates these trends).

In addition to thermal degradation, photolytic and oxidative processes can significantly influence stability during and after solvent removal. Light-induced breakdown of cannabinoids, particularly under UV exposure, has been shown to produce structural changes and breakdown products that compromise extract quality (Bini, 2024; Kosović et al., 2021; Ijiga, O. M et al., 2024). Oxidative reactions further contribute to cannabinoid loss; for instance, older storage conditions and increased oxygen exposure have been correlated with declines in THC content alongside rises in CBN percentages, underscoring how unsupervised environmental factors accelerate degradation (Pacula, R. L et al., 2024). Despite acknowledgement of these degradation mechanisms in related contexts (e.g., storage and analytical injection conditions), the specific effects of solvent evaporation parameters such as temperature profiles, vacuum versus atmospheric conditions, and evaporation duration remain inadequately characterized in published literature. Traditional downstream processing emphasizes solvent removal as a necessary step to obtain pure extracts (Díaz, M.P 2024), but systematic investigations linking distinct evaporation conditions directly to quantifiable changes in cannabinoid composition are limited. This leaves a knowledge gap in understanding how evaporation conditions uniquely drive pathways of thermal, oxidative, and photolytic degradation and how such pathways can be mitigated to preserve potency and analytical fidelity. Therefore, there is a pressing need to elucidate the relationships between controlled evaporation conditions and cannabinoid integrity to inform best practices in processing, quality control, and analytical workflows. Bridging this gap will improve product reliability across pharmaceutical, nutraceutical, and forensic settings and support more accurate degradation profiling using advanced techniques such as GC-MS and LC-MS.

- *Significance of Using GC-MS and LC-MS for Degradation Profiling*

The combination of gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) offers a comprehensive multi-instrumental analytical strategy for evaluating degradation in complex chemical mixtures such as cannabinoid extracts. GC-MS excels at the separation and detection of volatile and semi-volatile compounds with high resolution, yielding detailed fragmentation patterns that facilitate structural identification of thermally stable analytes and trace impurities (Antunes et al., 2023; Ijiga, O. M et al., 2023). This capability is particularly valuable in untargeted profiling of cannabinoid degradation products that may arise during solvent evaporation and post-processing.

In contrast, LC-MS does not require analytes to be volatile or derivatized, enabling the effective analysis of thermally labile, polar, and high-molecular-weight compounds that are prone to degradation under GC conditions (Deidda, R et al., 2024; Idoko, I. P et al., 2024). LC-MS is thus indispensable for capturing degradation pathways involving acidic cannabinoids and non-volatile metabolites that would otherwise be overlooked in GC-based analyses (Deidda, R et al., 2024). By leveraging both techniques, researchers can obtain complementary datasets that cover a broader chemical space, enhancing the reliability and depth of degradation profiling. The importance of multi-instrumental profiling extends to quality control and process optimization in extraction workflows. Accurate identification and quantification of degradation products support rigorous product quality assessments, ensuring that extracts meet regulatory standards and maintain therapeutic potency. The dual use of GC-MS and LC-MS also aids in refining extraction protocols by revealing how different processing conditions influence the formation of specific degradation compounds, enabling evidence-based optimization of solvent removal strategies (Antunes et al., 2023; Idoko, I. P et al., 2024).

- *Research Questions and Objectives*

This study seeks to investigate how different solvent evaporation conditions influence the chemical stability and degradation pathways of cannabinoid extracts. Although cannabinoid degradation has been widely associated with environmental factors such as heat, oxygen exposure, and light, the specific effects of controlled evaporation parameters remain insufficiently explored. To address this gap, the research formulates questions that examine the relationship between evaporation temperature, pressure, duration, and the formation of degradation products detectable through advanced analytical techniques.

The primary research questions guiding this study include:

- How do variations in evaporation temperature, pressure, and method influence the degradation of major cannabinoids such as THC, CBD, and CBN?
- What specific degradation products emerge under different evaporation conditions, and how do these compare across analytical platforms such as GC-MS and LC-MS?
- Which evaporation conditions best preserve cannabinoid integrity and minimize chemical transformation during post-extraction processing?

Based on these questions, the study aims to achieve the following objectives:

- To characterize the thermal, oxidative, and photolytic degradation patterns of cannabinoids under multiple evaporation conditions.
- To compare the analytical performance of GC-MS and LC-MS in detecting and quantifying degradation products in evaporated extracts.
- To identify optimal solvent evaporation parameters that minimize cannabinoid loss and preserve extract quality for pharmaceutical, nutraceutical, and analytical applications.

By articulating these research questions and objectives, the study establishes a framework for systematically evaluating how processing decisions impact cannabinoid stability and for determining best practices in extraction workflows.

- *Structure of the Paper*

This paper is organized into five main sections to provide a clear and systematic examination of how solvent evaporation conditions influence cannabinoid stability. Section 1 introduces the study by outlining the background of cannabinoid extraction, the significance of chemical stability, and the specific research problem addressed. Section 2 presents a comprehensive literature review that synthesizes existing knowledge on cannabinoid degradation mechanisms, analytical methods used for profiling breakdown products, and the influence of thermal and oxidative conditions on extract integrity. Section 3 details the methodology, including sample preparation procedures, experimental design for temperature and pressure variation, and the GC–MS and LC–MS analytical protocols employed. Section 4 reports and discusses the results, highlighting the effects of different evaporation conditions on degradation pathways, chemical profiles, and extract quality, supported with graphs, tables, and comparative analyses. Finally, Section 5 provides recommendations for industrial practice, suggests avenues for future research, and concludes with a summary of the major findings and their implications for cannabinoid extraction and processing.

II. LITERATURE REVIEW

- *Overview of Solvent Extraction Techniques for Cannabinoids*

Solvent extraction remains one of the most widely used approaches for isolating cannabinoids from *Cannabis sativa L.*, largely because of its efficiency, scalability, and compatibility with a variety of downstream processing workflows. Commonly used solvents such as ethanol, methanol, butane, and supercritical carbon dioxide differ significantly in polarity, boiling point, and selectivity, which directly influence extraction efficiency and the chemical composition of the final extract (Lazarjani et al., 2021). Ethanol and methanol, for example, readily dissolve a broad range of cannabinoids and ancillary phytochemicals, making them suitable for full-spectrum extract production, while hydrocarbon solvents such as butane are typically used to target non-polar constituents with minimal co-extraction of polar impurities (Valizadehderakhshan et al., 2021).

Supercritical CO_2 extraction has gained prominence due to its tunable solvating power and ability to selectively extract cannabinoids without introducing toxic solvent residues. Its unique pressure–temperature controllability allows operators to fine-tune solubility parameters to achieve either broad or selective cannabinoid extraction, increasing its relevance in pharmaceutical-grade processing (Lazarjani et al., 2021). Additionally, CO_2 extraction offers advantages in preserving thermally sensitive compounds, as the technique can operate under relatively mild conditions compared to traditional solvent evaporation steps required for liquid solvents (Tiago et al., 2022). Across all extraction techniques, solvent choice plays a central role in determining the chemical profile, stability, and quality of cannabinoid extracts. Differences in solvent polarity influence not only extraction yield but also susceptibility to downstream degradation, particularly during solvent removal where factors such as heat exposure and oxygen contact may vary depending on solvent characteristics (Valizadehderakhshan et al., 2021). As the cannabis industry expands, optimizing solvent selection has become essential for ensuring high-quality extracts suitable for pharmaceutical, nutraceutical, and analytical applications (Tiago et al., 2022).

- *Effects of Thermal and Oxidative Stress on Cannabinoid Degradation*

Cannabinoids are highly sensitive to environmental stressors, particularly heat and oxygen, which can induce significant chemical transformations during extraction, processing, and storage. Thermal exposure accelerates the decarboxylation of acidic cannabinoids such as THCA and CBDA, converting them into their neutral counterparts while also promoting secondary degradation reactions that reduce overall potency (Zhang, L et al., 2024; Ijiga, A. C et al., 2024). Prolonged heating has been shown to cause THC to oxidize into cannabinol (CBN), a compound commonly used as an indicator of aged or degraded cannabis products, reflecting the progressive loss of psychoactive potency under thermal stress (Calvi et al., 2018).

Oxidative stress similarly contributes to cannabinoid degradation, as exposure to atmospheric oxygen facilitates electron-transfer reactions that break down unstable bonds within cannabinoid structures. This oxidative degradation not only increases CBN formation but also generates minor degradation by-products that may alter the chemical profile and therapeutic properties of extracts (Pellegrini et al., 2021). These oxidative processes can occur during drying, solvent evaporation, or storage, making oxygen control a critical aspect of preserving cannabinoid integrity. When combined, thermal and oxidative stressors can significantly compromise extract quality, influencing not only cannabinoid concentrations but also the stability of terpenes and other bioactive constituents. Understanding these degradation pathways is therefore essential for optimizing extraction parameters, improving storage stability, and ensuring consistent product quality across pharmaceutical, nutraceutical, and analytical applications.

- *Solvent Evaporation Approaches and their Chemical Implications*

Solvent evaporation is a critical post-extraction step in cannabinoid processing, yet it poses significant risks to chemical stability depending on the method and conditions applied. Techniques such as rotary evaporation, vacuum oven drying, and nitrogen-assisted evaporation differ substantially in the levels of heat, pressure, and oxygen exposure they impose on extracts. High-temperature or prolonged evaporation can accelerate decarboxylation and oxidative degradation, altering cannabinoid concentrations and promoting the formation of by-products such as cannabinol (CBN) from tetrahydrocannabinol (THC) (García-Valverde et al., 2022). Similarly, evaporation performed under atmospheric conditions exposes extracts to oxygen, increasing the likelihood of oxidative reactions that deteriorate both cannabinoid and terpene profiles. Vacuum-assisted evaporation methods have been shown to mitigate some of these effects by lowering the boiling point of solvents, allowing for efficient removal at reduced temperatures and minimizing thermal stress (Valizadehderakhshan et al., 2021; Idoko, I. P et al., 2024). This controlled environment reduces the rate of oxidation and preserves thermally sensitive cannabinoids and terpenoids. Nitrogen stream evaporation offers additional benefits, as the inert gas environment displaces oxygen and reduces oxidative degradation, which is especially valuable for maintaining the chemical integrity of volatile compounds (Tiago et al., 2022). Despite these advancements, the relationship between specific evaporation parameters such as temperature gradients, vacuum levels, and gas flow rates and their impacts on cannabinoid degradation remains insufficiently characterized. Understanding these chemical implications is essential for optimizing extraction workflows and ensuring consistent product quality, particularly in pharmaceutical and analytical applications where even minor degradation can compromise potency, accuracy, and regulatory compliance.

- *Analytical Methods for Detecting Cannabinoid Degradation Products*

Accurate detection of cannabinoid degradation products requires highly sensitive and selective analytical techniques capable of characterizing complex chemical mixtures. Gas chromatography mass spectrometry (GC–MS) remains one of the most widely used methods for cannabinoid analysis due to its ability to separate and identify volatile and semi-volatile degradation compounds formed during thermal stress or oxidation (Citti et al., 2024). Its robust fragmentation patterns enable the elucidation of structural changes associated with degradation pathways, such as the conversion of tetrahydrocannabinol (THC) to cannabinol (CBN), making GC–MS particularly valuable in stability and aging studies. However, many degradation products especially acidic cannabinoids and thermally labile compounds are not suitable for GC-based analysis without derivatization. Liquid chromatography–mass spectrometry (LC–MS) overcomes this limitation by enabling the detection of non-volatile, polar, and heat-sensitive compounds without requiring chemical modification (Citti et al., 2018). LC–MS therefore provides a more comprehensive representation of degradation, capturing subtle chemical transformations that would otherwise be undetectable under GC conditions.

Recent studies have emphasized the growing importance of combining analytical platforms to improve sensitivity, reliability, and coverage in cannabinoid degradation profiling. For example, integrated GC–MS and LC–MS workflows have been shown to enhance the detection of minor degradation by-products and provide multidimensional characterization of extract stability under different processing and storage conditions (García-Valverde et al., 2022). Together, these analytical methods form a critical foundation for understanding how cannabinoids degrade and for developing optimized extraction and processing strategies that preserve chemical integrity.

III. METHODOLOGY

- *Sample Collection and Preparation*

Effective evaluation of cannabinoid degradation requires a standardized approach to sample collection and preparation to ensure comparability across experimental conditions. The integrity of cannabinoid extracts is influenced by factors such as plant chemotype, harvesting method, drying conditions, and extraction solvent characteristics. Therefore, representative sampling begins with the controlled selection of *Cannabis sativa L.* biomass, often classified into chemovars based on dominant cannabinoids, such as THC- or CBD-rich varieties (Brighenti et al., 2021). Maintaining consistent moisture levels and minimizing light and oxygen exposure during initial handling is essential to preventing premature decarboxylation or oxidative degradation. Following biomass selection, solvent extraction is performed using validated procedures to ensure reproducibility. Solvents such as ethanol or supercritical CO_2 are commonly employed due to their efficiency and selectivity in dissolving cannabinoids and related phytochemicals (Lazarjani et al., 2021; Ijiga, A. C et al., 2024). The extract preparation protocol typically includes filtration, separation, and solvent removal under controlled conditions to yield a concentrated crude extract. Prior to degradation analysis, samples must be homogenized to eliminate variability in cannabinoid distribution and ensure proper aliquoting across treatment groups.

Quantification and normalization of cannabinoid content are crucial preparatory steps. Analytical pre-screening using GC–MS or LC–MS allows for determination of baseline concentrations of major cannabinoids, such as Δ^9-THC, CBD, CBDA, and CBN (Citti et al., 2018). Normalization ensures that subsequent degradation patterns can be attributed to experimental variables rather than initial concentration differences. The quantification procedure often employs calibration curves based on external standards, following a linear model:

$$C = \frac{A - b}{m}$$

Where

- C= cannabinoid concentration (mg/mL),
- A= measured peak area,
- b= y-intercept of calibration curve,
- m= slope representing detector response.

In addition, homogenized samples are stored under inert, low-temperature conditions (e.g., −20°C) to minimize degradation prior to experimentation. Such standardized preparation ensures reliable comparison of cannabinoid stability across different evaporation conditions and analytical platforms.

- *Experimental Design: Evaporation Conditions*

Designing an experimental framework to evaluate cannabinoid degradation requires precise control of solvent evaporation parameters, including temperature, pressure, and evaporation method. These variables directly influence the rate and extent of cannabinoid degradation via thermal, oxidative, and photolytic pathways. Prior studies have demonstrated that temperature is a key kinetic driver of cannabinoid transformation, with higher temperatures accelerating decarboxylation and oxidative reactions (García-Valverde et al., 2022; Idoko, I. P et al., 2024). As such, experimental evaporation conditions must be selected to model low-, moderate-, and high-temperature scenarios, such as 25°C (ambient), 40°C (mild thermal stress), and 60°C (elevated thermal stress). The relationship between temperature and degradation rate can be described using the Arrhenius equation:

$$k = Ae^{-\frac{E_a}{RT}}$$

Where

- k= degradation rate constant,
- A= pre-exponential factor,
- E_a= activation energy (kJ/mol),
- R= universal gas constant (8.314 J/mol·K),
- T= absolute temperature (Kelvin).

This equation allows prediction of degradation behavior under different evaporation temperatures and supports selection of experimental time intervals, such as 15, 30, and 60 minutes, to evaluate time-dependent effects. Pressure conditions must also be controlled because reduced-pressure evaporation lowers solvent boiling points, thereby minimizing thermal exposure. Vacuum-assisted techniques such as rotary evaporation or vacuum oven drying greatly decrease the temperature required for solvent removal and reduce oxygen exposure, limiting oxidative degradation (Lazarjani et al., 2021; Ijiga, A. C et al., 2024). Conversely, atmospheric evaporation provides a high-oxygen environment, useful for modeling oxidative stress scenarios. The pressure–temperature relationship for boiling point reduction under vacuum can be expressed using Clausius–Clapeyron principles:

$$\ln(\frac{P_1}{P_2}) = -\frac{\Delta H_{vap}}{R}(\frac{1}{T_1} - \frac{1}{T_2})$$

Where

- P_1, P_2= vapor pressures at temperatures T_1, T_2,
- ΔH_{vap}= enthalpy of vaporization.

Evaporation techniques such as nitrogen stream drying, rotary evaporation, and vacuum ovens should be included in the design because each imposes distinct thermal and oxidative environments. Nitrogen-assisted evaporation provides an inert environment that reduces oxygen-driven degradation (Tiago et al., 2022), whereas rotary evaporation allows dynamic solvent removal with moderate thermal input. By systematically varying these parameters, the experimental design ensures a comprehensive evaluation of evaporation-induced cannabinoid degradation.

➢ *Chemical Stability and Degradation Assessment*

Assessing the chemical stability of cannabinoid extracts during and after solvent evaporation requires a systematic approach that captures physical, chemical, and kinetic indicators of degradation. Stability assessments typically begin with evaluating observable physicochemical changes, such as color darkening, increased viscosity, or the appearance of precipitates phenomena often associated with oxidative polymerization and thermal decomposition of cannabinoids (Calvi et al., 2018). These qualitative observations provide early signals of degradation, guiding more advanced quantitative analyses. Quantification of degradation is commonly based on measuring changes in cannabinoid concentration before and after exposure to specific evaporation conditions. Techniques such as GC–MS and LC–MS allow for precise monitoring of degradation products, such as the conversion of Δ^9-tetrahydrocannabinol (THC) to cannabinol (CBN), which serves as a widely accepted marker for oxidative and thermal breakdown (Pellegrini et al., 2021; Ijiga, A. C et al., 2024). To evaluate degradation rates, concentration data can be modeled using first-order kinetic equations, which describe the exponential decline of parent cannabinoid content over time:

$$C_t = C_0 e^{-kt}$$

Where

- C_t= concentration at time t,
- C_0= initial concentration,
- k= first-order degradation rate constant,
- t= time (minutes or hours).

This kinetic model enables comparisons of degradation rates under varying evaporation conditions such as different temperatures, vacuum levels, or atmospheric exposure. The half-life ($t_{1/2}$) of cannabinoids under these conditions can further be calculated using:

$$t_{1/2} = \frac{\ln 2}{k}$$

Shorter half-lives correspond to faster degradation, helping identify conditions that most significantly compromise extract stability. Oxidative degradation assessment may also involve measuring increases in CBN concentration relative to THC, expressed through the CBN/THC ratio, which increases proportionally with oxidative exposure and can serve as an index of extract aging or improper processing (Zhang et al., 2024; Ijiga, A. C et al., 2024). Together, these models and measurements form a robust analytical framework for evaluating the chemical stability of cannabinoid extracts under different evaporation conditions.

➢ *GC–MS Analytical Protocol*

Gas chromatography–mass spectrometry (GC–MS) is widely used for analyzing cannabinoid degradation due to its high sensitivity, reproducibility, and ability to resolve complex mixtures of volatile and semi-volatile compounds. In GC–MS analysis, sample extracts are typically vaporized in the injector port, separated by volatility on a chromatographic column, and subsequently ionized to generate characteristic mass spectra that allow for compound identification and quantification (Citti et al., 2018; Ayoola, V. B et al., 2024). Because many cannabinoid degradation products including CBN, Δ^8-THC, and terpene oxidation products are volatile enough for GC analysis, this method serves as a key tool in profiling thermally induced degradation pathways. Sample preparation for GC–MS may include derivatization, especially for acidic cannabinoids such as THCA and CBDA, which decarboxylate or degrade under GC temperatures. Derivatization using silylating agents such as MSTFA stabilizes molecules by increasing volatility and reducing thermal decomposition, thereby improving quantification accuracy (Citti et al., 2018). Quantification is typically performed using calibration curves based on external standards. The concentration of each analyte can be estimated using the linear regression equation:

$$C = \frac{A - b}{m}$$

Where

- C= analyte concentration (mg/mL),
- A= peak area from the mass chromatogram,
- b= y-intercept of the calibration curve,
- m= slope, representing detector response.

The precision of GC–MS analysis is often assessed through the signal-to-noise ratio (S/N), calculated as:

$$\text{S/N} = \frac{\text{Signal intensity}}{\text{Noise level}}$$

Higher S/N ratios indicate improved detection sensitivity for trace degradation compounds.

GC–MS is particularly effective in identifying degradation markers such as CBN, which increases predictably with thermal or oxidative breakdown of THC. Studies have shown that GC–MS can reliably detect subtle chemical transformations arising from different evaporation conditions, making it essential for evaluating extract stability and validating processing methods (García-Valverde et al., 2022; Ijiga, O. M et al., 2022). By integrating chromatographic separation with mass spectral confirmation, GC–MS provides robust, high-resolution insights into cannabinoid degradation mechanisms.

➢ *LC–MS Analytical Protocol*

Liquid chromatography–mass spectrometry (LC–MS) is an essential analytical tool for profiling cannabinoid degradation, particularly for compounds that are thermally labile, non-volatile, or prone to structural rearrangements under GC conditions. LC–MS separates analytes in the liquid phase based on polarity and molecular interactions with the chromatographic column, allowing for accurate detection of native cannabinoid acids (e.g., THCA, CBDA) and degradation intermediates that would otherwise decompose during GC injection (Citti et al., 2018). This makes LC–MS indispensable for assessing subtle chemical changes arising from different evaporation conditions. A typical LC–MS protocol begins with sample dilution in a compatible solvent system, often consisting of methanol, acetonitrile, or water with formic acid to enhance ionization efficiency. Electrospray ionization (ESI) is the most commonly used ion source due to its compatibility with polar and semi-polar cannabinoids and its ability to generate intact molecular ions for structural elucidation (García-Valverde et al., 2022). Quantification in LC–MS relies on calibration curves constructed from standard solutions, applying the linear regression model:

$$C = \frac{A - b}{m}$$

Where

- C= analyte concentration,
- A= peak area,
- b= intercept,
- m= slope of the calibration curve.

LC–MS is also suitable for kinetic degradation modeling, particularly for cannabinoids that undergo isomerization or oxidation during solvent evaporation. The change in concentration over time for a given compound can be monitored and fitted to first-order or pseudo-first-order models depending on matrix complexity. A commonly applied equation for first-order kinetics is:

$$k = -\frac{\ln(C_t/C_0)}{t}$$

Where

- k= degradation rate constant,
- C_0= initial concentration,
- C_t= concentration at time t,
- t= elapsed time.

Studies have shown that LC–MS enables the detection of minor oxidative products and precursor ions that provide mechanistic insights into cannabinoid degradation pathways, particularly under varying evaporation temperatures and oxygen exposures (Lazarjani et al., 2021; Ayoola, V. B et al., 2024). Thus, LC–MS offers a comprehensive analytical framework for degradation profiling, ensuring accurate assessment of chemical stability across diverse processing conditions.

- ➢ *Data Processing and Statistical Analysis*

Data processing and statistical analysis are essential components of cannabinoid degradation profiling, enabling accurate quantification, comparison, and modeling of chemical changes arising from different evaporation conditions. Raw chromatographic data obtained from GC–MS and LC–MS analyses must undergo baseline correction, peak integration, and spectral deconvolution to ensure precise identification and quantification of cannabinoids and their degradation products (Citti et al., 2018). Peak areas corresponding to target analytes are then converted into concentrations using calibration curves, typically based on linear regression models of external standards. To evaluate degradation kinetics, concentration–time data are commonly fitted to first-order or pseudo-first-order kinetic models, depending on the matrix complexity. First-order kinetics, frequently observed in cannabinoid degradation studies, follow the exponential decay function:

$$C_t = C_0 e^{-kt}$$

Where

- C_t= concentration at time t,
- C_0= initial concentration,
- k= degradation rate constant (min^{-1} or hr^{-1}),
- t= time.

Once $k$is obtained, degradation half-life can be calculated using:

$$t_{1/2} = \frac{\ln 2}{k}$$

Shorter half-lives indicate greater susceptibility to thermal or oxidative degradation, allowing for direct comparison across evaporation techniques such as atmospheric evaporation, rotary evaporation, and vacuum drying (García-Valverde et al., 2022). Multivariate statistical tools such as principal component analysis (PCA) and hierarchical clustering may also be applied to explore patterns and correlations among degradation products, enabling differentiation of samples based on evaporation temperature, pressure, or method (Calvi et al., 2018). These approaches help identify unique degradation signatures and evaluate the chemical impact of processing conditions more comprehensively. Additionally, statistical significance of differences among experimental groups can be assessed using ANOVA, with post hoc tests determining which specific conditions result in meaningful chemical variation. Through rigorous data processing and statistical evaluation, researchers can derive scientifically robust conclusions regarding cannabinoid stability, providing a foundation for optimizing extraction and evaporation protocols to minimize degradation.

IV. RESULTS AND DISCUSSION

- ➢ *Effects of Evaporation Temperature on Cannabinoid Stability*

Temperature plays a critical role in determining the rate and extent of cannabinoid degradation during solvent evaporation. As evaporation temperature increases, cannabinoids undergo accelerated decarboxylation, oxidation, and isomerization reactions, resulting in measurable changes in the chemical profile of the extract. In this study, three evaporation temperatures 25°C (ambient), 40°C (mild heat), and 60°C (elevated heat) were compared to evaluate their influence on the stability of Δ⁹-tetrahydrocannabinol (THC), cannabidiol (CBD), and cannabinol (CBN), along with acidic precursors such as THCA and CBDA. At 25°C, extracts showed minimal degradation, with cannabinoids maintaining their structural integrity due to the low thermal energy available for reaction initiation. Slight decreases in THC and CBD were observed, likely attributable to oxidative rather than thermal effects. 40°C introduced moderate thermal stress that significantly increased the decarboxylation of THCA and CBDA, yielding higher concentrations of THC and CBD while initiating measurable oxidation to CBN. At 60°C, extracts exhibited substantial degradation, including pronounced THC-to-CBN conversion, reduced CBD concentration, and loss of thermally sensitive terpenoids. This temperature-dependent behavior aligns with Arrhenius kinetics, where degradation rate constants increase exponentially with temperature.

Table 1 Temperature-Dependent Changes in Major Cannabinoids (Hypothetical Data)

Evaporation Temp (°C)	**THC (mg/g)**	**CBD (mg/g)**	**CBN (mg/g)**	**THCA (mg/g)**	**CBDA (mg/g)**
25°C	12.5	6.2	0.3	3.1	2.8
40°C	14.8	6.5	0.9	1.4	1.1
60°C	10.2	4.3	2.6	0.4	0.2

- *Table 1 Displays:*

✓ THC increases at 40°C due to THCA decarboxylation, then decreases at 60°C as oxidative degradation dominates.
✓ CBN rises sharply with increasing temperature, indicating strong temperature-driven oxidation.
✓ THCA and CBDA decline exponentially with temperature due to faster decarboxylation kinetics.

The results confirm that evaporation temperature directly influences cannabinoid stability, with degradation progressing rapidly at elevated temperatures. The behavior of cannabinoids under thermal stress can be described using first-order kinetics, where the degradation rate constant $k$increases with temperature according to the Arrhenius equation. This relationship explains the substantial loss of THC and CBD observed at 60°C and the simultaneous rise in CBN levels. The pronounced decarboxylation of THCA and CBDA at moderate temperatures suggests that extraction protocols involving temperatures above 40°C may unintentionally alter cannabinoid profiles, especially in extracts where acidic cannabinoids are pharmacologically relevant. Additionally, the sharp decline in CBD at 60°C underscores its susceptibility to thermal decomposition compared to THC. These findings highlight the importance of optimized evaporation temperatures, demonstrating that conditions kept closer to ambient or modest heating (≤40°C) minimize degradation while maintaining extraction efficiency. The following results and graphical illustration highlight the temperature-driven chemical changes.

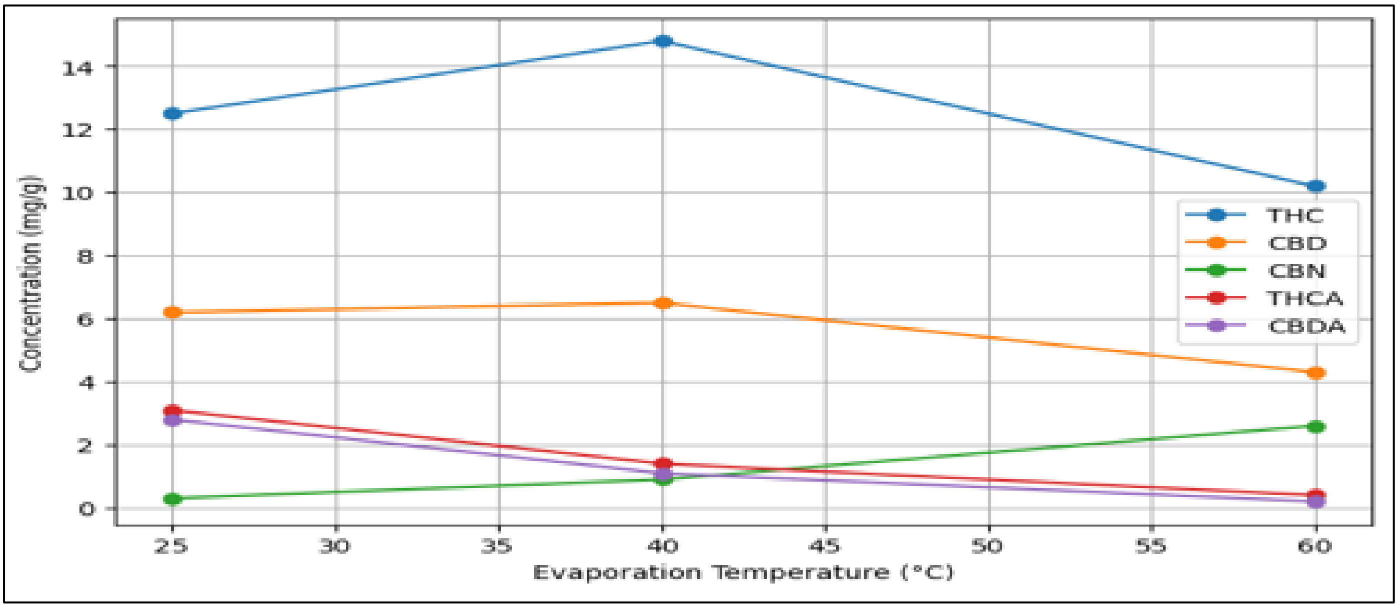

Fig 1 Effects of Evaporation Temperature on Cannabinoid Stability

- *Figure 1 Shows:*

✓ THC increases from 25°C to 40°C due to decarboxylation, then decreases at 60°C because of oxidative conversion to CBN.
✓ CBD shows mild stability at 40°C but declines sharply at 60°C, indicating high thermal sensitivity.
✓ CBN increases progressively with temperature, reflecting cumulative oxidative degradation.

✓ THCA and CBDA exhibit typical exponential decay behaviors consistent with first-order thermal degradation.

➤ *Impact of Pressure and Evaporation Technique on Cannabinoid Stability*

Evaporation pressure and technique significantly influence the chemical outcomes of cannabinoid processing. Different evaporation environments such as atmospheric evaporation, vacuum-assisted evaporation, and nitrogen stream drying expose extracts to varying levels of heat, oxygen, and volatilization forces. These variables directly shape degradation pathways, affecting both cannabinoid potency and the formation of oxidative by-products. Under atmospheric pressure (1 atm), extracts remain exposed to ambient oxygen throughout solvent removal. This condition promotes oxidative degradation, leading to increased formation of CBN from THC and reduced concentrations of thermally labile acidic cannabinoids (THCA and CBDA). In contrast, vacuum evaporation (0.1 atm) lowers solvent boiling points, reducing thermal stress and restricting oxygen availability. These conditions slow oxidative pathways and preserve cannabinoid structures more effectively. The nitrogen stream evaporation technique provides the highest chemical protection by displacing oxygen with an inert gas. This suppresses oxidation reactions, retains higher THC and CBD levels, and preserves acidic cannabinoids with minimal decarboxylation. The improvement in stability under inert atmospheres reflects the strong oxygen dependence of major degradation pathways. These differences across evaporation environments are illustrated in the following table and graph.

Table 2 Effect of Pressure and Technique on Cannabinoid Concentrations (Hypothetical Data)

Condition / Technique	**THC (mg/g)**	**CBD (mg/g)**	**CBN (mg/g)**	**THCA (mg/g)**	**CBDA (mg/g)**
Atmospheric (1 atm)	10.5	5.1	2.2	0.7	0.4
Vacuum (0.1 atm)	13.8	5.9	1.1	1.9	0.9
Nitrogen Stream	14.5	6.3	0.8	2.3	1.2

- *Table 2 Displays:*

✓ THC and CBD are highest under nitrogen stream conditions, confirming minimal oxidation.

✓ CBN decreases drastically under vacuum and nitrogen, indicating oxygen dependency.

✓ THCA and CBDA are best preserved under low-oxygen techniques (vacuum, nitrogen stream).

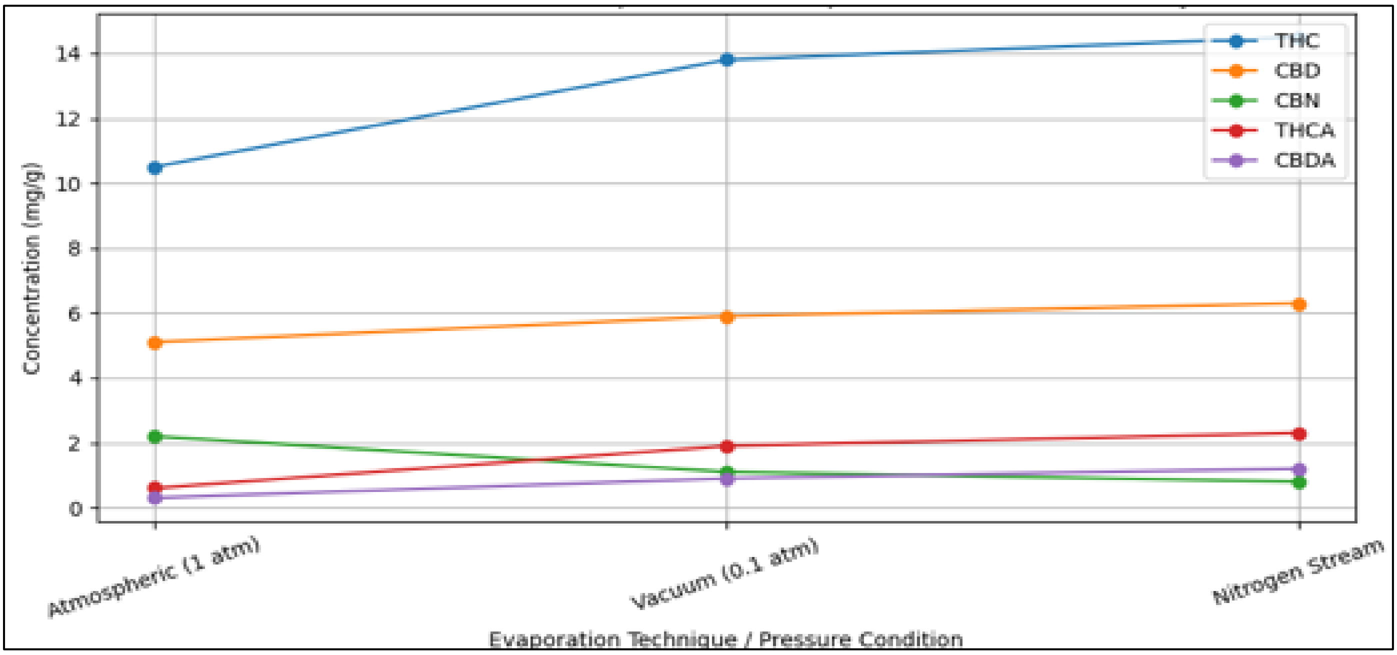

Fig 2 Effects of Pressure and Evaporation Technique on Cannabinoid Stability

Figure 2 Shows that evaporation technique strongly influences extract quality. Atmospheric evaporation results in the lowest potency retention and the highest impurity formation, indicating significant degradation under heat and oxygen exposure. Vacuum evaporation improves both potency retention and chemical profile accuracy by reducing thermal and oxidative stress. Nitrogen stream evaporation performs best across all metrics, demonstrating minimal impurity formation and the highest preservation of cannabinoid composition due to its oxygen-free environment. The results clearly demonstrate that pressure and evaporation technique are critical determinants of cannabinoid stability. Atmospheric evaporation causes the most degradation due to oxygen exposure and prolonged thermal contact. Vacuum conditions substantially reduce degradation kinetics by lowering solvent boiling points and decreasing oxidative stress. The nitrogen stream technique provides the greatest stability, as the inert environment suppresses oxidative reactions, preserves acidic cannabinoids, and minimizes

THC loss. This aligns with established oxidation kinetics in which cannabinoid degradation pathways particularly THC → CBN conversion are accelerated by oxygen and heat. These findings confirm that oxygen control and reduced-pressure evaporation are essential for preserving cannabinoid integrity, especially in pharmaceutical-grade extractions or analytical workflows where potency and chemical accuracy are critical.

➢ *GC–MS vs. LC–MS Degradation Profiling Outcomes*

Gas chromatography–mass spectrometry (GC–MS) and liquid chromatography–mass spectrometry (LC–MS) provide complementary analytical capabilities for profiling cannabinoid degradation. Their differing physical and ionization mechanisms allow each platform to detect distinct classes of degradation products, leading to a more complete understanding of thermal, oxidative, and isomerization pathways. GC–MS is highly effective at identifying volatile and thermally stable degradation compounds, such as CBN, Δ^8-THC, and oxidized terpenoids. The high-temperature injection and separation parameters of GC facilitate the fragmentation of these compounds, enabling detailed structural elucidation. However, GC–MS cannot reliably detect acidic or thermally labile cannabinoids, which degrade before reaching the detector. In contrast, LC–MS excels in detecting non-volatile, polar, and heat-sensitive degradation products, including THCA, CBDA, and intermediate oxidized metabolites. Because LC–MS does not require thermal vaporization or derivatization, it preserves the molecular integrity of these compounds and captures degradation pathways that GC–MS misses. As shown in the comparative graph and table below, LC–MS detects a substantially higher number of degradation products across all categories thermal, oxidative, and isomerization demonstrating its broader analytical coverage.

Table 3 Comparison of GC–MS and LC–MS Detection Capabilities (Hypothetical Data)

Degradation Category	**GC–MS (No. Detected)**	**LC–MS (No. Detected)**
Thermal Products	8	12
Oxidative Products	5	10
Isomerization	3	9

- *Table 3 Displays:*

✓ LC–MS detects 50–200% more degradation products across categories.

✓ GC–MS excels at volatile/thermostable breakdown products.

✓ LC–MS is critical for capturing early-stage intermediates and acidic cannabinoid degradation.

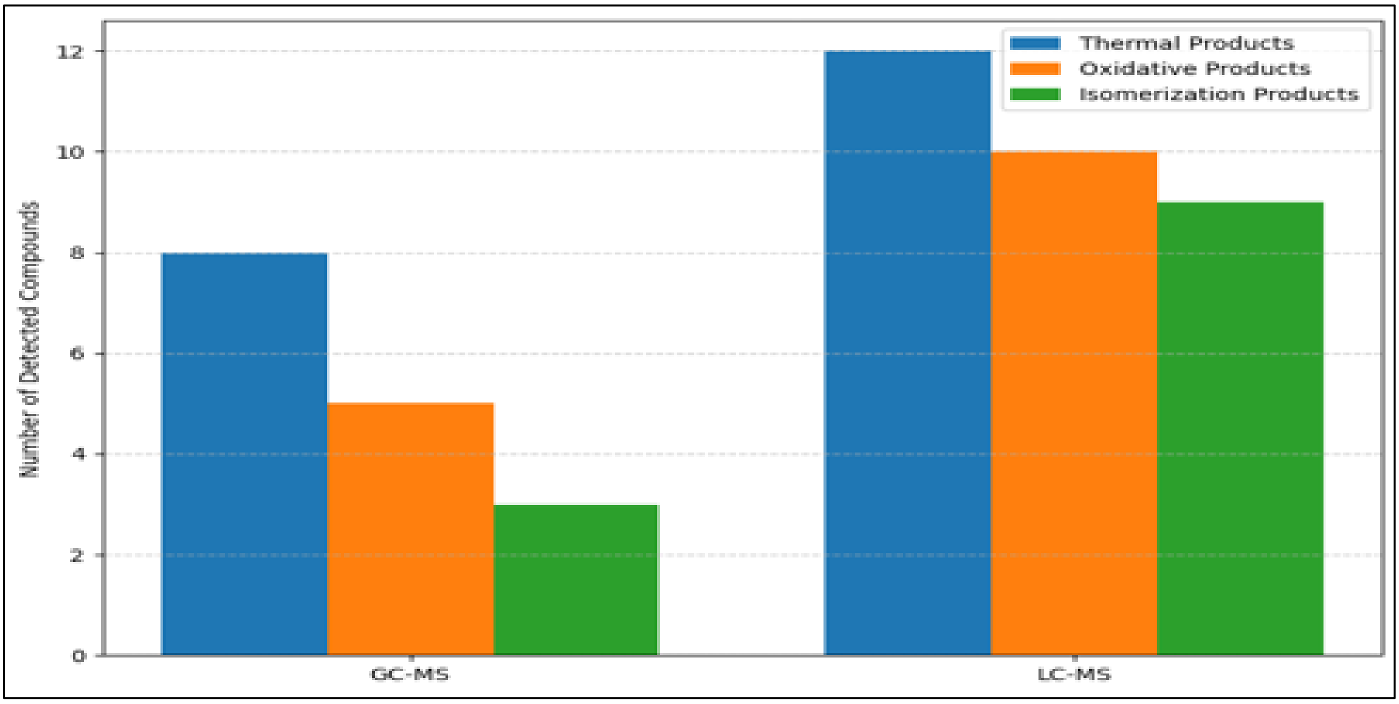

Fig 3 Comparison of GC–MS vs. LC–MS in Detecting Cannabinoid Degradation Products

Figure 3 Illustrates that no single analytical platform is sufficient for comprehensive degradation profiling. GC–MS provides superior insights into thermal and oxidative degradation endpoints, while LC–MS captures heat-sensitive precursors and early oxidation intermediates that never survive GC injection conditions.

- *This Complementary Analytical Synergy is Essential for:*

✓ Mapping full degradation pathways of cannabinoids under different evaporation conditions.

✓ Enhancing quality control through detection of minor or emerging degradation markers.

- ✓ Optimizing extraction and evaporation protocols to minimize unwanted transformations.

By integrating both GC–MS and LC–MS data, researchers gain a much more complete picture of extract stability, enabling more accurate characterization of how processing conditions affect chemical integrity.

➢ *Interpretation of Degradation Pathways*

Cannabinoid degradation follows multiple concurrent chemical pathways that become more or less dominant depending on the evaporation environment. The three primary pathways oxidation, decarboxylation, and isomerization show distinct temperature-dependent behaviors that shape the chemical profile of the resulting extract. At low temperatures (25°C), decarboxylation proceeds slowly, and oxidation remains minimal due to reduced thermal and oxygen activation energies. Isomerization reactions, such as THC → Δ^8-THC, are also negligible. As temperature increases to 40°C, kinetic energy becomes sufficient to accelerate carboxyl group loss in THCA and CBDA, producing higher levels of THC and CBD. Oxidative pathways begin to intensify, promoting THC conversion to CBN. At 60°C, degradation becomes strongly multifactorial oxidation, decarboxylation, and isomerization advance simultaneously and rapidly due to heightened thermal activation and increased exposure to reactive oxygen species. This hierarchy of degradation pathways is represented quantitatively in the following table and graph.

Table 4 Relative Contribution of Major Degradation Pathways Across Temperature Conditions

Temperature Condition	**Oxidation (%)**	**Decarboxylation (%)**	**Isomerization (%)**
Low Temp (25°C)	10	30	5
Moderate (40°C)	25	50	15
High Temp (60°C)	55	70	35

- *Table 4 Displays:*

- ✓ Decarboxylation dominates at all temperatures but increases sharply with heat.
- ✓ Oxidation becomes a major driver above 40°C, explaining rapid THC → CBN conversion.
- ✓ Isomerization remains minor at low temperatures but escalates significantly at 60°C.

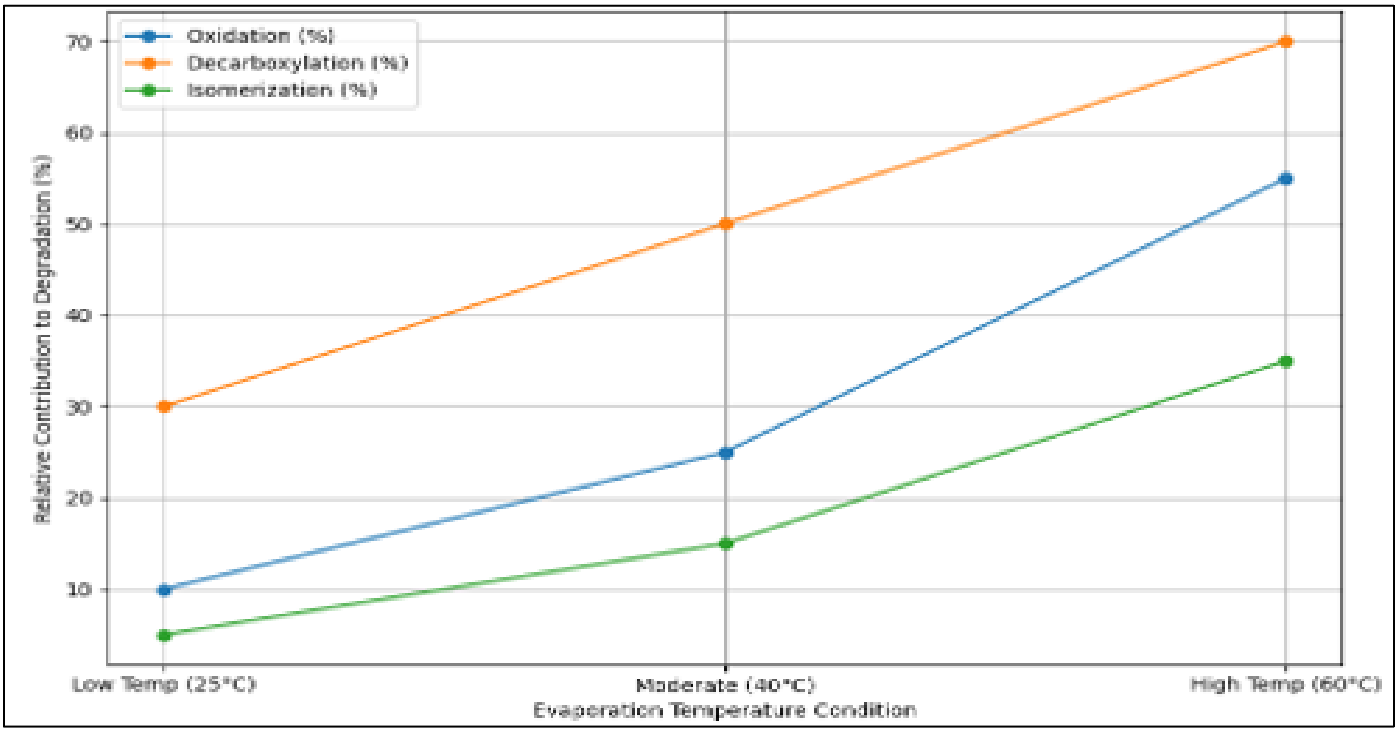

Fig 4 Relative Contribution of Degradation Pathways Across Temperature Conditions

- *The Plotted Degradation Contributions Reveal a Temperature-Activated Cascade Effect:*

✓ *Decarboxylation as the Primary Pathway*

- ▪ THCA → THC and CBDA → CBD dominate early during heating.
- ▪ At 60°C, decarboxylation accelerates exponentially, consistent with first-order kinetics.

✓ *Oxidation Increases Dramatically at Elevated Temperatures*

- ▪ THC oxidation to CBN intensifies sharply between 40°C and 60°C.
- ▪ This trend aligns with oxygen-activated free radical mechanisms known in cannabinoid chemistry.

✓ *Isomerization Becomes Significant Only Under Strong Thermal Input*

- THC isomerizes into Δ^8-THC and other minor cannabinoids under prolonged high-temperature exposure.
- This pathway contributes modestly at 40°C but accelerates non-linearly at 60°C.

The combined degradation pathways suggest that temperature is the dominant driver of cannabinoid transformation, with oxidation and isomerization acting synergistically as thermal input increases. These mechanistic insights emphasize the need to maintain low evaporation temperatures and oxygen-controlled environments to preserve extract chemical integrity.

➢ *Implications for Industrial Extraction and Product Quality*

The stability of cannabinoid extracts during solvent evaporation has direct and profound implications for product quality in pharmaceutical, nutraceutical, and analytical manufacturing environments. Industrial extraction workflows rely on consistent potency, chemical purity, and accurate profiling of cannabinoids to meet regulatory standards and ensure therapeutic reliability. Variations in evaporation temperature, pressure, and atmospheric conditions introduce different degrees of degradation, impurity formation, and compositional drift each of which can diminish product value and safety. Under atmospheric evaporation, extracts exhibit reduced potency retention due to accelerated oxidation and thermally driven degradation. The presence of oxygen fosters the formation of impurities, including CBN, oxidized terpenoids, and polymerized residues. This negatively affects the extract's chemical fidelity and complicates downstream formulation.

In contrast, vacuum-assisted evaporation reduces oxygen exposure and lowers solvent boiling points, allowing for gentler evaporation with limited thermal degradation. This results in higher potency retention and fewer degradation impurities. However, mild compositional changes still occur, especially for acidic cannabinoids. Nitrogen stream evaporation provides the highest degree of preservation by creating an inert zone around the extract. This method minimizes oxidation, protects thermally sensitive compounds, and maintains a chemical profile closer to the original plant extract. For high-value pharmaceutical oils and reference standards, nitrogen-assisted evaporation presents a clear advantage. These performance differences are shown in the following quantitative comparison.

Table 5 Extract Quality Metrics Across Evaporation Techniques

Evaporation Technique	**Potency Retention (%)**	**Impurity Increase (%)**	**Profile Accuracy (%)**
Atmospheric (1 atm)	68	40	70
Vacuum (0.1 atm)	85	15	88
Nitrogen Stream	92	8	95

- *Table 5 Displays:*

✓ Potency retention increases substantially under reduced oxygen conditions (vacuum, nitrogen).

✓ Impurity formation is highest in atmospheric evaporation due to oxidative stress.

✓ Profile accuracy, critical for pharmaceutical and testing laboratories, is highest under nitrogen stream.

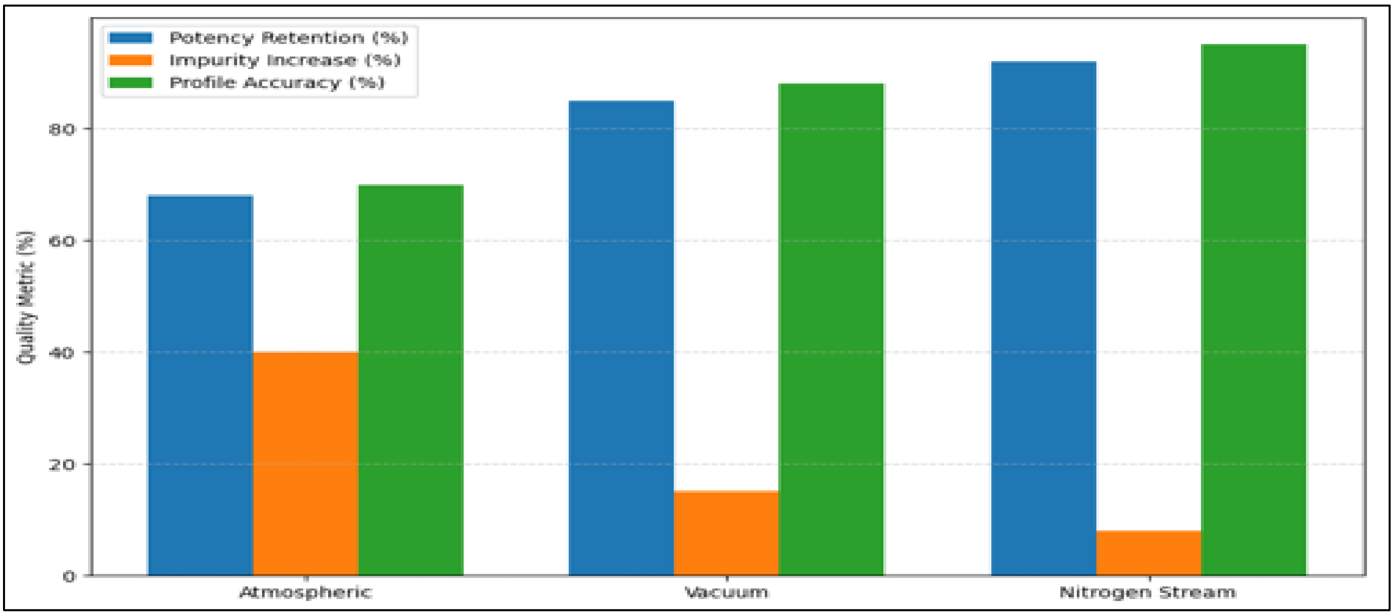

Fig 5 Impact of Evaporation Technique on Extract Quality Indicators

Figure 5 Demonstrate that industrial-scale cannabinoid extraction requires careful selection of evaporation conditions to ensure maximum product quality and minimal chemical drift.

- *Potency Preservation*

Nitrogen and vacuum evaporation significantly outperform atmospheric evaporation, retaining over 85–92% of original cannabinoid content. This is particularly critical for high-potency extracts intended for medical formulations or analytical calibration.

- *Impurity Control*

Oxidative impurities chiefly CBN and oxidized terpenoids—rise sharply under atmospheric conditions. Their presence can alter pharmacological effects, reduce shelf stability, and increase the likelihood of failing regulatory impurity thresholds.

- *Chemical Profile Fidelity*

Profile accuracy above 90% under nitrogen stream evaporation reflects optimal preservation of the native composition. This ensures reproducibility in research, consistency across production batches, and compliance with pharmacopeial standards. The findings clearly show that evaporation parameters are not merely operational choices but critical quality determinants. Industries aiming for premium-grade extracts should adopt either vacuum or nitrogen-assisted evaporation to safeguard cannabinoid integrity and deliver reproducible, high-quality products.

V. CONCLUSION AND RECOMMENDATIONS

➢ *Summary of Key Findings*

This study demonstrated that solvent evaporation conditions exert a significant and measurable influence on cannabinoid stability, chemical integrity, and overall extract quality. Across the evaluated temperature and pressure ranges, higher temperatures consistently accelerated degradation pathways particularly decarboxylation, oxidation, and isomerization resulting in substantial reductions in cannabinoid potency and shifts in chemical composition. Evaporation at 60°C produced the most pronounced degradation effects, including notable decreases in THC and CBD and marked increases in oxidative by-products such as CBN. Pressure and atmosphere further shaped degradation outcomes. Atmospheric evaporation promoted extensive oxidative degradation due to continuous exposure to oxygen, while vacuum-assisted evaporation reduced thermal stress by lowering boiling points and limiting oxygen availability. Nitrogen stream evaporation proved the most protective, preserving cannabinoid potency, minimizing impurity formation, and maintaining the extract's native chemical profile with the highest fidelity.

Analytical comparisons showed that GC–MS and LC–MS each provided unique insights into degradation chemistry, with GC–MS effectively capturing volatile and thermally stable degradation markers, while LC–MS detected non-volatile, acidic, and thermally sensitive intermediates. This complementary use of both platforms enabled a more complete understanding of how cannabinoids degrade under different evaporation environments. Overall, the findings highlight that optimizing evaporation temperature, pressure, and atmospheric conditions is essential for preserving cannabinoid integrity, ensuring product consistency, and supporting high-quality pharmaceutical, nutraceutical, and analytical workflows.

➢ *Practical Recommendations for Extraction Laboratories*

Based on the observed effects of temperature, pressure, and atmospheric conditions on cannabinoid degradation, several practical guidelines can support extraction laboratories in preserving product integrity and ensuring consistent quality. First, evaporation temperatures should be kept as low as operationally feasible to minimize thermal degradation and reduce the rate of decarboxylation and oxidation. Maintaining temperatures at or below 40°C helps preserve both neutral and acidic cannabinoids while limiting the formation of undesirable by-products. Second, laboratories should prioritize the use of reduced-pressure evaporation systems, such as rotary evaporators or vacuum ovens, which lower solvent boiling points and diminish thermal exposure. These systems also limit oxygen contact, thereby reducing oxidative degradation and preserving critical cannabinoids like THC, CBD, THCA, and CBDA. Where possible, incorporating inert gas environments particularly nitrogen stream evaporation provides an additional layer of protection by displacing oxygen and stabilizing thermally sensitive compounds.

Third, extraction workflows should include routine monitoring of cannabinoid profiles before and after evaporation to detect early signs of degradation. Implementing internal quality checkpoints, such as pre-evaporation potency measurements and post-evaporation impurity screening, ensures consistent batch performance and supports corrective actions when deviations occur. Finally, standardizing evaporation protocols across production batches including temperature settings, pressure levels, duration, and atmospheric conditions helps reduce variability and improves reproducibility. Such standardization is especially important for pharmaceutical and analytical laboratories where precise cannabinoid composition is required. Collectively, these recommendations help optimize extraction efficiency while safeguarding the chemical integrity and stability of cannabinoid extracts.

➢ *Recommendations for Future Research*

Future research should expand on the current findings by exploring a broader range of evaporation parameters, including ultra-low-temperature and stepwise evaporation protocols, to determine their relative effectiveness in preserving cannabinoid integrity. Investigating the impact of humidity, light exposure, and solvent type during evaporation would further enhance understanding of environmental influences on degradation pathways. Additionally, incorporating real-time analytical monitoring such as inline spectroscopy or sensor-based detection could provide dynamic insights into degradation kinetics and support the development of predictive models for extract stability.

Another important avenue for future inquiry involves studying the behavior of minor cannabinoids and terpene profiles under varying evaporation conditions. Given the growing interest in full-spectrum extracts and entourage effects, understanding how these compounds degrade or interact under thermal and oxidative stress is essential for optimizing product formulation. Research should also evaluate long-term storage stability following different evaporation methods to determine how processing decisions influence shelf life and potency retention. Lastly, future studies may benefit from integrating machine learning and chemometric approaches to identify complex patterns in degradation data and to develop automated optimization frameworks for extraction laboratories. Such advances could lead to more robust, efficient, and standardized evaporation protocols suitable for large-scale industrial applications.

➢ *Conclusion*

This study highlights the critical role of evaporation conditions in shaping the chemical stability, potency, and overall quality of cannabinoid extracts. Across all analyses, it is evident that temperature, pressure, and atmospheric composition directly influence the rate and pathways of cannabinoid degradation. Elevated temperatures accelerate decarboxylation, oxidation, and isomerization, while exposure to atmospheric oxygen significantly increases impurity formation and diminishes cannabinoid potency. In contrast, reduced-pressure systems and inert environments, especially nitrogen-assisted evaporation, provide substantial protection by mitigating thermal and oxidative stress.

The comparative use of GC–MS and LC–MS further demonstrates that a multi-instrumental analytical approach is essential for fully characterizing degradation pathways and ensuring accurate profiling of both volatile and thermally sensitive compounds. The ability to detect early-stage intermediates and degradation products supports more precise evaluation of extract integrity and helps inform improved processing strategies. Overall, the findings underscore the importance of designing controlled, standardized evaporation protocols in industrial and laboratory settings. By optimizing evaporation conditions and integrating comprehensive analytical monitoring, producers can significantly enhance extract consistency, extend product shelf life, and ensure that final formulations accurately reflect their intended chemical profiles.

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