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Review paper

POST-HARVEST DRYING OF Cannabis sativa L. FLOWERS AND ITS IMPACT ON THE PRESERVATION AND EXTRACTION OF BIOACTIVE PHYTOCHEMICALS

Angel Cvetanov[1*], Krume Bogevski[1], Viktorija Maksimova[1], Emilija Janevik-Ivanovska[1]
[1]Faculty of Medical Sciences, Goce Delcev University, Krste Misirkov 10-A, 2000 Stip, Republic of North Macedonia

**Corresponding author: angel.479s@student.ugd.edu.mk*

Abstract

Drying is one of the most critical post-harvest operations in cannabis processing (Nakra et al., 2025; Das et al., 2022) because it directly influences microbiological stability, phytochemical preservation, storage behavior, and downstream extraction performance. *Cannabis spp. inflorescences* contain high initial moisture levels and a complex mixture of cannabinoids, terpenes, flavonoids, and other bioactive compounds that are highly sensitive to environmental conditions during post-harvest handling. Improper drying may result in microbial contamination, terpene volatilization, cannabinoid degradation, structural damage to glandular trichomes, and reduced extraction efficiency. Environmental parameters including temperature, relative humidity, airflow velocity, and drying duration strongly influence moisture migration kinetics and overall flower quality. This review evaluates the influence of drying technologies and drying conditions on the physicochemical properties of *Cannabis sativa L.* inflorescences with emphasis on cannabinoid stability, terpene preservation, structural changes of plant tissues, and extraction performance. Particular attention is given to controlled tray drying systems because of their increasing relevance in standardized cannabis processing operations. The review additionally discusses moisture migration mechanisms, drying kinetics, residual moisture behavior, and non-invasive monitoring approaches based on weight reduction during drying. Current challenges and future perspectives for optimization of cannabis drying methodologies are also discussed.

Key words: *Cannabis sativa L., post-harvest drying, cannabinoids, terpenes, drying kinetics, tray drying, phytochemical preservation.*

INTRODUCTION

Cannabis (*Cannabis sativa L.*) has become one of the fastest-growing medicinal plants due to increasing scientific and commercial interest in cannabinoids and other bioactive phytochemicals (Lazarjani et al., 2021, p. 1). During the last decade, regulatory changes in several countries have stimulated the rapid expansion of medicinal cannabis cultivation and processing industries, leading to increasing interest in post-harvest technologies capable of preserving phytochemical quality and improving product consistency (Ubeed et al., 2022; Pavlović et al., 2019). Cannabis spp. inflorescences contain a complex mixture of secondary metabolites including cannabinoids, terpenes, flavonoids, phenolic compounds, and other bioactive constituents (Rodriguez-Morrison et al., 2021). Among these compounds, tetrahydrocannabinol (THC) and cannabidiol (CBD) are the most extensively investigated due to their pharmacological activity and therapeutic relevance (Salami et al., 2020).

Terpenes additionally contribute to the aroma, flavor, and potential biological activity of cannabis products (Jin et al., 2020). The quality of cannabis flowers is strongly influenced by post-harvest processing operations. Following harvest, cannabis inflorescences contain high moisture levels that create favorable conditions for microbial proliferation, enzymatic degradation, and oxidative reactions (Punja et al., 2019). Consequently, drying is necessary to reduce moisture content and water activity to stable levels suitable for storage and downstream processing. Drying is considered one of the most important post-harvest processes affecting the chemical, physical, and microbiological quality of cannabis biomass (Lazarjani et al., 2021). Improper drying conditions may lead to terpene volatilization, cannabinoid degradation, discoloration, trichome damage, and undesirable structural changes within the plant matrix (Jin et al., 2019). At the same time, insufficient drying may increase the risk of fungal contamination and reduce storage stability.

Compared with many conventional agricultural products, cannabis drying presents several unique challenges because the plant contains large quantities of volatile and thermally sensitive compounds localized within glandular trichomes on the flower surface. These structures are highly susceptible to oxidation, evaporation, and mechanical damage during drying and handling. In addition to influencing flower quality, drying conditions may significantly affect downstream extraction performance. Residual moisture content, structural integrity of the plant matrix, and preservation of glandular trichomes directly influence solvent penetration, diffusion kinetics, and phytochemical recovery during extraction processes. Optimization of drying conditions is therefore essential not only for preserving flower quality but also for improving extraction efficiency. Several drying technologies have been investigated for cannabis processing including microwave-assisted systems and optimized hot-air drying approaches (Addo et al., 2024; Kanabus et al., 2024) including traditional hang drying, tray drying, hot-air convective drying, vacuum drying, microwave-assisted drying, infrared drying, and freeze drying.

Among these approaches, controlled tray drying systems have gained increasing attention, especially for industrial capacities, because they provide improved environmental regulation, drying uniformity, and process reproducibility. The objective of this review is to evaluate the influence of post-harvest drying conditions on phytochemical preservation and extraction performance of Cannabis sativa L. inflorescences. Significant emphasis is placed on drying kinetics, moisture migration, terpene preservation, structural modifications of plant tissues, and controlled tray drying systems relevant to modern cannabis processing.

IMPORTANCE OF DRYING IN CANNABIS POST-HARVEST PROCESSING

Drying is a preservation process intended to reduce moisture content and water activity while maintaining the phytochemical quality and structural integrity of the plant material (Gwinn et al., 2021). In cannabis processing, drying plays a critical role in controlling microbiological stability, storage behavior, extraction suitability, and final product quality. It is essential to distinguish the primary drying process from the subsequent "curing" phase; while drying aims to reduce moisture to stable marketable levels—typically around 11%—curing involves a slower, secondary stabilization period often conducted at approximately 18°C and 60% relative humidity (Jin et al., 2021). This curing phase allows for moisture homogenization throughout the dense floral matrix and the further refinement of the terpene profile (Lazarjani et al., 2021; Jin et al., 2019). Freshly harvested cannabis flowers generally contain approximately 70–80% moisture depending on the cultivar, harvest maturity, and cultivation conditions (Jin et al., 2019; Lumu, et al., 2025). Such elevated moisture levels provide favorable conditions for microbial growth and biochemical degradation processes. Dense floral morphology may additionally restrict airflow penetration and promote localized moisture accumulation. One of the primary objectives of cannabis drying is the prevention of fungal contamination. Cannabis flowers are particularly susceptible to molds including Botrytis cinerea and Aspergillus spp., which may proliferate rapidly under elevated moisture conditions (Gwinn et al., 2023; Birenboim, et al., 2024; Punja, et al., 2019). To mitigate this risk, maintaining a water activity ( ) level below 0.7 is generally required to inhibit the growth of most fungal pathogens (Gwinn et al., 2023). According to industry standards such as ASTM D8196-18, the target for dried cannabis is between 0.55 and 0.65, which typically corresponds to a residual moisture content of approximately 10–12% (Lazarjani et al., 2021). Controlled moisture reduction is therefore necessary to ensure safe storage and preservation of biomass quality. Drying additionally affects flower texture, appearance, brittleness, and handling properties. Gradual moisture removal contributes to the stabilization of plant tissues and the reduction of excessive mechanical fragility. However, rapid or aggressive drying at high temperatures (e.g., above 50°C) may induce excessive shrinkage and significant damage to the glandular trichomes (Lazarjani et al., 2021; Punja et al, 2023). Another important objective of drying is the preservation of cannabinoids and terpenes. Cannabinoids are concentrated primarily within glandular trichomes that contain resin-rich secretions highly sensitive to heat and oxidation (Punja et al., 2023, p. 23).

Exposure to temperatures above 37°C for prolonged periods can trigger the decarboxylation of acidic precursors, while oxygen and light further accelerate the degradation of major cannabinoids like THC into CBN (Jin, et al., 2019). Drying conditions also influence downstream extraction processes.

Residual moisture content and the structural integrity of the dried biomass directly affect solvent accessibility and mass transfer during extraction (Belwal et al., 2018). Proper dehydration is essential for maximizing extract yield and ensuring that the internal plant matrix remains porous enough for efficient solvent penetration (Márquez-Herrera et al., 2026).

MOISTURE MIGRATION AND DRYING KINETICS

The removal of water from *Cannabis sativa L. inflorescences* is a complex mass-transfer process governed by the internal structure of the flower and external environmental drivers (Márquez-Herrera, et al., 2026; Lumu, et al., 2025). Understanding moisture migration behavior is critical, as drying kinetics directly influence processing duration and final phytochemical quality.

Moisture Distribution in Cannabis Inflorescences

Fresh cannabis inflorescences possess a high initial moisture content, typically ranging from 73% to 80% on a wet basis (Jin et al., 2019; Lumu et al., 2025). This moisture is distributed within a heterogeneous tissue matrix comprising dense floral clusters, stems, and bracts, which create significant internal resistance to moisture flow (Márquez-Herrera et al., 2026; Lumu et al., 2025).

Because of this complexity, internal tissues and stem regions often retain moisture longer than exposed surfaces, leading to the "uneven drying" behavior frequently observed in larger buds (Lazarjani et al., 2021).

Sequential Drying Phases

The dehydration of biological materials like cannabis typically occurs in two primary stages. The first is the constant rate period, an initial stage where evaporation occurs from the surface as if pure water were being removed (Inyang et al., 2018). The second is the falling rate period, the dominant phase for cannabis, where moisture movement is controlled by internal diffusion and resistance (Lumu et al., 2025). In this phase, moisture must migrate from the internal core to the surface before it can evaporate. This mechanism is mathematically modeled using Fick's second law, with the effective diffusivity ( ) for cannabis inflorescences measured between 10-7 and 10-5 m^2/s (Márquez-Herrera et al., 2026). Validated thin-layer models, such as the Page and Midilli-Kucuk equations, are used to predict this kinetics and determine the precise time required to reach a stable moisture content of <11% (Lumu et al., 2025; Márquez-Herrera et al., 2026).

Environmental Drivers of Kinetics

The rate of moisture migration is primarily driven by the vapor pressure deficit between the plant surface and the surrounding air (Lumu et al., 2025). Temperature significantly affects drying kinetics: increasing air temperature accelerates kinetics and reduces total drying duration, though it must be balanced against the risk of decarboxylating acidic cannabinoids (Jin et al. 2019). Increased airflow velocity is essential for removing moisture-saturated air from the flower surface and can significantly reduce drying time, especially at lower temperatures (Lumu et al., 2025). Lower relative humidity levels promote faster evaporation by maintaining a steep moisture gradient, while higher humidity is often utilized during the "curing" phase to stabilize the matrix and prevent excessive brittleness (Jin et al., 2019).

DRYING TECHNOLOGIES APPLIED IN CANNABIS PROCESSING

Several drying technologies have been applied for post-harvest cannabis processing, each demonstrating specific advantages and limitations regarding drying efficiency, phytochemical preservation, operational complexity, and scalability.

Conventional Hang Drying

Conventional hang drying remains one of the most widely utilized drying methods in cannabis production, as it is considered the most convenient approach and requires no specialized equipment (Challa et al., 2020; Lazarjani et al., 2021). Following harvest, branches or entire plants are suspended within climate-controlled drying rooms and exposed to passive or mechanically circulated airflow. This method is favored because of its operational simplicity and relatively gentle drying conditions. Gradual moisture removal may contribute to the preservation of flower structure and the reduction of excessive terpene volatilization. However, conventional hang drying presents several disadvantages, including uneven airflow exposure, variable drying rates, and a "slow and inefficient" nature that limits industrial scalability (Challa et al., 2020; Lazarjani et al., 2021). Furthermore, drying whole plants can lead to slower and uneven moisture removal compared to separated inflorescences, often requiring up to 15 days to reach stable levels (Kim et al., 2024; Lazarjani et al., 2021).

Controlled Tray Drying

Controlled tray drying systems have become increasingly important in modern cannabis processing, while systemic post-harvest approaches have also been emphasized in recent reviews (Al Ubeed et al., 2022) in modern cannabis processing because they provide improved environmental control and drying uniformity. In tray drying systems, flowers are distributed across perforated trays positioned within controlled drying chambers. Conditioned airflow passes across the trays while temperature and relative humidity are actively regulated. Compared with conventional hang drying, tray drying provides improved process consistency and reduced batch variability. Tray drying additionally supports the implementation of monitoring systems including environmental data logging and weight reduction analysis.

Convective Hot-Air Drying

Convective drying utilizes heated airflow to transfer thermal energy to the biomass and accelerate moisture evaporation (Baek et al., 2025; Lumu et al., 2025). Increasing the drying temperature significantly reduces the processing duration; however, elevated temperatures must be carefully balanced against the degradation of thermolabile compounds. Recent studies have demonstrated that high-temperature convective drying at 75°C can stabilize industrial hemp in just 8 hours - reducing moisture from 77% to a safe storage level of 6% -while achieving up to a 2-log reduction in total yeast and mold counts (Baek et al., 2025). While this method provides a rapid solution for microbial inactivation and enhances processing efficiency, it significantly increases the risk of accelerated terpene loss and may alter the final sensory profile of the flower (Chen et al., 2022; Baek et al., 2025). Consequently, moderate temperatures (25 - 45°C) are generally preferred for preserving pharmaceutical-grade phytochemical quality, even though they require longer drying durations and may not provide the same level of immediate sterilization (Baek et al., 2025; Lumu et al., 2025).

Freeze Drying

Freeze drying involves the freezing of biomass followed by the sublimation of ice under reduced pressure conditions (Baek et al., 2025; Challa et al., 2020). Because drying occurs at low temperatures, freeze drying may provide superior preservation of thermolabile compounds and flower structure, typically completing the process in about 24 hours (Spadafora et al., 2024; Baek et al., 2025). Despite its advantages, freeze drying can reportedly fail to preserve the exact terpene profile of the fresh plant, sometimes changing volatile concentrations significantly compared to slow air-drying (Spadafora et al., 2024; Jin, et al., 2019). Additionally, it presents limitations including high energy consumption, elevated equipment costs, and potentially prolonged sublimation times of 10 to 20 days depending on the system (Jin et al., 2019).

Microwave and Infrared Drying

Advanced drying technologies, including microwave-assisted and infrared drying, offer the highest levels of process control and speed (Chen et al., 2022; Uziel et al., 2022). Microwave-assisted drying can reduce processing time from days to a few hours; specifically, solid-state microwave drying at 50°C has been found to maintain a comprehensive profile of 67 cannabinoids and 36 terpenes (Uziel et al., 2022). Infrared drying is particularly effective for rapid surface moisture removal and microbial inactivation, often used in tandem with convective heat to improve overall processing efficiency (Chen et al., 2022 a; Chen, et al., 2022 b). However, rapid heating requires precise calibration to prevent localized overheating and structural damage (Challa et al., 2020).

INFLUENCE OF DRYING CONDITIONS ON CANNABINOID STABILITY

Cannabinoids are highly important bioactive compounds concentrated primarily within the glandular trichomes of cannabis inflorescences (Punja et al., 2023; Salami et al., 2020). The stability of these secondary metabolites during the drying process is strongly influenced by temperature, oxygen exposure, drying duration, and environmental conditions (Lazarjani et al., 2021; Lumu et al., 2025). Cannabinoids are naturally synthesized predominantly in acidic forms, such as tetrahydrocannabolic acid and cannabidiolic acid. During drying, these acidic precursors undergo decarboxylation, resulting in the formation of neutral cannabinoids like THC and CBD (Jin et al., 2019; Lumu, et al., 2025), mainly responsible for the pharmacological effects of cannabis.

Temperature Effects on Cannabinoid Preservation

Temperature is one of the most critical factors affecting cannabinoid stability (Lazarjani et al., 2021). Elevated temperatures increase the rates of chemical reactions, including decarboxylation and the degradation of major cannabinoids (Jin et al., 2019; Lumu et al., 2025). Excessive drying temperatures may contribute to reduced potency, decarboxylation and structural damage. The total percentage of cannabinoids decreases as drying time and temperature increase (Lazarjani et al., 2021). Temperatures above 37°C for 24 hours can trigger the conversion of acidic cannabinoids into neutral forms, with significant decarboxylation occurring at temperatures of 100°C and above (Jin et al., 2019; Jin et al., 2020). High-temperature drying (50°C - 70°C) can disrupt the integrity of the glandular trichomes, potentially impacting final cannabinoid levels (Punja et al., 2023). Moderate drying temperatures (e.g., 25°C - 45°C) are generally preferred to balance moisture removal with the preservation of the chemical profile (Lumu et al., 2025).

Oxidative Degradation

Exposure to oxygen during drying and storage can induce oxidative reactions that degrade major cannabinoids (Jin et al., 2019). While cannabinoids like THC, CBG, and CBC are present in dried floral buds, they are susceptible to degradation if exposed to light, heat, and oxygen for extended periods (Jin et al., 2019; Márquez-Herrera et al., 2026). Controlled environmental conditions and proper storage in cool, dark places are essential for minimizing these oxidative losses (Jin et al., 2019).

Influence of Drying Duration

The total duration of the drying process significantly impacts the cumulative exposure of phytochemicals to environmental stress. Longer drying times have been shown to result in the progressive decarboxylation of acidic cannabinoids and the general degradation of major cannabinoids (Lumu et al., 2025). However, finding a balance is necessary, as excessively rapid drying can also negatively affect the quality and structural integrity of the flowers (Lazarjani et al., 2021). Gradual, controlled drying is typically favored to maintain a stable and high-quality product (Lazarjani et al., 2021).

Influence of Air Humidity on Drying processes

Air humidity is a critical factor during the drying of cannabis flowers, as it directly affects the rate of moisture removal, product quality, and the preservation of bioactive compounds (Ubeed et al., 2022). According to Fick's law of diffusion, the moisture diffusion rate is proportional to the concentration gradient between the flower and the surrounding air; therefore, lower relative humidity increases this gradient and enhances water diffusion from the plant material, resulting in faster drying. The influence of air humidity is particularly pronounced in convective drying processes, where moisture removal is governed by heat and mass transfer between the plant material and the drying air. Precise control of relative humidity during the initial and intermediate stages of drying is essential to prevent excessive drying rates, minimize the loss of volatile terpenes, and maintain the physicochemical and organoleptic quality of cannabis flowers.

TERPENE PRESERVATION DURING DRYING

Terpenes are highly volatile aromatic compounds that dictate the characteristic aroma and flavor profile of *Cannabis sativa L.* flowers. Beyond their organoleptic properties, these secondary metabolites are critical to the quality of medicinal products, as they are localized within glandular trichome alongside phytocannabinoids. Common cannabis terpenes include monoterpenes like -myrcene and limonene, and sesquiterpenes such as -(E)-caryophyllene and -humulene. The preservation of these compounds is highly dependent on the drying method employed and storage conditions (Spadafora et al., 2024 a; Spadafora et al., 2024 b), as their concentration and composition can be easily altered by post-harvest handling.

Volatility of Terpenes

Terpenes are susceptible to volatilization during drying due to their thermal sensitivity (Fathi et al., 2022). Monoterpenes are generally more volatile than sesquiterpenes, making them particularly sensitive to temperature and environmental drivers (Kwaśnica et al., 2020). Several factors influence terpene retention, including temperature, drying technology, and atmospheric composition. While drying at 50°C can achieve up to 76% aroma retention in convection drying, higher temperatures used in other botanical drying have been shown to disrupt trichomes and cause essential oil loss (Punja et al., 2023). Vacuum-microwave drying at a power of 240 W has been shown to provide the highest retention of aroma compounds and produces a final product most similar to fresh material (Kwaśnica et al., 2020). Additionally, the use of controlled atmosphere drying chambers can reduce total drying and curing time by at least 60% (Birenboim et al., 2024). Optimal preservation of monoterpenes and sesquiterpenes has been observed using specialized gas mixtures, such as 5% CO2, 5% O2, and 90% N2, or pure N2 (Birenboim et al., 2024).

Relationship Between Terpene Retention and Product Quality

The retention of volatile compounds is a key indicator of product quality. Traditional drying methods can be inefficient and may result in poor quality due to the slow removal of moisture, which increases the risk of infestation by molds like Alternaria alternata or Botrytis cinerea (Birenboim et al., 2024; Challa et al., 2020). Conversely, while rapid methods like freeze-drying are sometimes used to preserve cannabinoids, they reportedly fail to preserve the exact terpene profile of the fresh plant by significantly changing volatile concentrations (Jin et al., 2019). Therefore, implementing tailored, cultivar-specific drying protocols is necessary to maintain the integrity of the chemical profile for both therapeutic efficacy and sensory appeal (Birenboim et al., 2024).

STRUCTURAL CHANGES DURING DRYING

Drying induces substantial structural modifications within cannabis flowers that significantly influence storage stability, mechanical properties, and downstream extraction performance (Spadafora et al., 2024; Ebersbach et al., 2018; Challa et al., 2020). As moisture is removed from the plant tissues, cellular shrinkage occurs due to the reduction of turgor pressure and the collapse of intercellular spaces (Alberti et al., 2025). These changes alter the porosity and density of the floral matrix, which in turn affects the accessibility of glandular trichomes during solvent extraction (Punja et al., 2023). Notably, imaging of dried trichomes often reveals the formation of "pseudo-morphological structures" that do not necessarily reflect the native state of the fresh plant (Ebersbach et al., 2018, p. 8).

Tissue Shrinkage and Structural Collapse

The rate of moisture removal is a primary driver of structural deformation. Rapid dehydration can accelerate tissue shrinkage, leading to significant structural deformation of the floral bracts and leaves (Alberti et al., 2025; Fathi et al., 2022). Excessive dehydration beyond the target moisture content (≈11%) increases the brittleness of the material, making the inflorescences more susceptible to mechanical damage and trichome detachment during handling and packaging (Challa et al., 2020; Punja et al., 2023). Conversely, controlled gradual drying in systems like tray dryers helps preserve the overall flower morphology and maintains the structural integrity of the plant matrix (Lumu et al., 2025; Lazarjani et al., 2021).

Glandular Trichome Integrity

The preservation of glandular trichomes is essential for maintaining the phytochemical potency of the final product, as these structures are the primary sites for cannabinoid and terpene synthesis and storage (Ebersbach et al., 2018; Punja et al., 2023). Dehydration processes can induce significant stress on the trichome cuticle, leading to bursting, collapsing, or the formation of structural artifacts (Ebersbach et al., 2018; Punja et al., 2023). Recent advancements in hyperspectral imaging, such as Coherent anti-Stokes Raman scattering microscopy, have revealed that drying induces the appearance of "pseudo-morphological structures" within the glandular trichomes (Ebersbach et al., 2018). These additional morphological features are considered drying-induced artifacts and do not represent the native state of the fresh plant (Ebersbach et al., 2018, p. 8). For researchers and quality control analysts, this implies that the imaging of dried or rehydrated plant material must be interpreted with caution; such artifacts can hinder the accurate spatial localization of metabolites like -tetrahydrocannabinolic acid and may lead to misinterpretations of the true biological architecture of the secretory cavity (Ebersbach et al., 2018, p. 5). Furthermore, high-temperature drying (e.g., above 50°C) has been shown to accelerate the disruption of the waxy cuticle of the glandular head (Punja et al., 2023). This disruption not only leads to the immediate loss of volatile terpenes but also exposes the resin-rich secretions to oxygen, promoting the oxidative degradation of cannabinoids over time (Lazarjani et al., 2021; Punja et al., 2023). Maintaining structural integrity through optimized, low-temperature drying is therefore a prerequisite for ensuring both the chemical and visual quality of medicinal-grade cannabis (Punja et al., 2023; Birenboim et al., 2024).

INFLUENCE OF DRYING ON EXTRACTION PERFORMANCE

The physical and chemical properties of dried cannabis biomass strongly influence downstream extraction processes (Belwal et al., 2018). Drying conditions affect residual moisture content, plant matrix structure, and the accessibility of cannabinoids and terpenes during extraction (Márquez-Herrera et al., 2026; Calvo, González-Rubio & Tirado, 2025). Improperly dried material can jeopardize the microbiological quality of the final oil, though recent research indicates that even wet hemp can be a valuable raw material if processed using specific high-pressure technologies (Calvo et al., 2025).

Residual Moisture Content and Extraction Efficiency

Residual moisture content plays a crucial role in determining both the final concentration of the compound and the overall extract yield (Belwal et al., 2018). Moisture affects solvent penetration and mass transfer behavior; in infrared-assisted systems, the effective diffusivity ( ) of cannabinoids through the matrix has been measured between 10-7 and 10-5 m2/s (Márquez-Herrera et al., 2026). While excessive moisture is often associated with reduced extraction efficiency due to solvent diffusion resistance, some studies have found that wet hemp can yield highly concentrated extracts-reaching up to 74% total cannabinoids-during supercritical extraction (Calvo et al., 2025). However, for most conventional methods, proper dehydration is essential to ensure the internal plant matrix remains porous enough for efficient solvent penetration and to maximize the recovery of bioactive compounds (Márquez-Herrera et al., 2026).

Supercritical CO2 Extraction

Supercritical CO_2 extraction is widely utilized in the industry because it provides a "cleaner" and solvent-free extract, requiring less downstream purification compared to organic solvent methods (Rochfort et al., 2020; Qamar et al., 2022). Increasing supercritical CO_2 density can improve yields to approximately 16.1% w/v

(Qamar et al., 2021). In addition to its extraction efficiency, supercritical CO_2 processing acts as a critical secondary safety hurdle for medicinal products. Research has shown that supercritical extraction ensures the complete elimination of fungi and enterobacteria from the biomass, even when starting with highly contaminated "wet" hemp (Calvo et al., 2025). Because the high-pressure environment facilitates the inactivation of spoilage microorganisms and pathogens, all extracts obtained via this method - including those from moldy or improperly dried material - have been found to be sterile (Calvo et al., 2025). The addition of 5% w/v ethanol as a co-solvent can further boost extract yields to 18.2% w/v by increasing the solvating power of the CO_2, while maintaining the microbiological safety of the final oil (Calvo et al., 2025; Qamar et al., 2021).

Ethanol Extraction

Ethanol extraction is favored for its operational simplicity and high extraction capacity, often providing marginally higher cannabinoid yields than supercritical CO_2 (Ubeed et al., 2022; Qamar et al., 2022). However, its selectivity is lower; ethanol extraction tends to co-extract significant amounts of chlorophyll (e.g., 143 mg/kg compared to 27 mg/kg in CO_2 extracts), which can act as a photosensitizer and accelerate oil oxidation (Qamar et al., 2022; Martinez et al., 2023). Residual moisture in the biomass further impacts this process by altering solvent polarity, which can increase the co-extraction of undesirable water-soluble pigments and waxes (Qamar et al., 2022). While ethanol techniques like maceration and Soxhlet achieve high microbial reduction in the exhausted biomass, the quality of the final oil is highly dependent on controlled drying to minimize these co-contaminants (Qamar et al., 2022; Calvo et al., 2025).

NON-INVASIVE MONITORING OF DRYING PROGRESS

The determination of a precise drying endpoint represents a major challenge in cannabis processing operations, as over-drying can lead to structural brittleness while under-drying risks microbial proliferation (Lazarjani et al., 2021; Lumu et al., 2025). Traditional analytical methods, including Loss on Drying measurements, require repeated destructive sampling throughout the process to track moisture content (Jin et al., 2019). Consequently, increasing interest has been directed toward non-invasive monitoring approaches based on weight reduction behavior and mathematical modeling (Márquez-Herrera et al., 2026; Lumu et al., 2025).

Weight Reduction Monitoring

Progressive moisture removal directly reduces biomass mass, which can be tracked in real-time. Continuous monitoring of tray weight provides an indirect but reliable indication of drying progression and residual moisture behavior (Lumu et al., 2025; Jin et al., 2019). Under controlled environmental conditions - such as a pilot-scale cabinet dryer at 45°C - cannabis flowers demonstrate reproducible weight reduction kinetics (Lumu et al., 2025). Stabilization of tray weight over time indicates that the material has reached its equilibrium moisture content, signaling that the target moisture level (typically <11%) has been achieved without the need for destructive testing (Lumu et al., 2025; Márquez-Herrera et al., 2026).

Drying Kinetics Modeling

Mathematical modeling of drying kinetics is essential for understanding moisture migration and optimizing process parameters (Márquez-Herrera et al., 2026). Drying curves based on the moisture ratio are used to evaluate drying rates and predict the exact time required to reach stabilization (Lumu et al., 2025; Inyang et al., 2018) Several thin-layer mathematical models have been validated for cannabis, including the Page and Midilli-Kucuk models, which have been proven to accurately predict the drying behavior of Cannabis sativa L., with adjusted coefficients of determination reaching as high as 0.996 (Márquez-Herrera et al., 2026). Additionally, general biological models such as the Newton and Henderson-Pabis equations are frequently applied to characterize the falling rate period, where internal diffusion is the limiting factor (Inyang et al., 2018). The application of these modeling approaches contributes to the development of standardized post-harvest methodologies, allowing processors to adapt conditions based on cultivar-specific morphology and initial moisture levels (Birenboim et al., 2024; Lumu et al., 2025).

CHALLENGES AND FUTURE PERSPECTIVES

Despite increasing scientific and industrial interest in cannabis processing optimization, several important challenges remain unresolved. One major challenge involves balancing efficient moisture removal with the preservation of highly volatile and thermally sensitive phytochemicals (Lazarjani et al., 2021; Challa et al., 2020). Aggressive drying conditions may reduce processing time but simultaneously increase the degradation of cannabinoids and terpenes (Lazarjani et al., 2021; Lumu et al., 2025). Another important challenge involves variability associated with cultivar-specific morphology and moisture distribution. Differences in flower density, trichome coverage, and structural characteristics may significantly influence drying kinetics, meaning a "one-size-fits-all" approach often fails to maintain optimal quality across different chemovars (Punja et al., 2023; Birenboim et al., 2024).

Areas for Future Research

To address these gaps, future research should focus on optimizing tray drying conditions by enhancing the efficiency of pilot-scale cabinet dryers to standardize moisture removal across industrial batches (Ubeed et al., 2022). Additionally, developing cultivar-specific drying protocols, including tailored drying and curing profiles based on the specific metabolic needs of high-THC versus hybrid chemovars, is essential (Birenboim et al., 2024). Terpene preservation studies should investigate how combined technologies can maximize the retention of volatile monoterpenes (Spadafora et al., 2024 a). Advanced drying kinetics modeling requires refining thin-layer models like the Page or Midilli-Kucuk equations to better predict the drying behavior of heterogeneous floral matrices (Lumu et al., 2025). Non-invasive moisture monitoring systems should implement real-time weight reduction tracking and sensors to eliminate the need for destructive sampling (Márquez-Herrera et al., 2026). Furthermore, evaluating drying-induced structural changes using advanced imaging to observe how dehydration creates pseudo-morphological structures in glandular trichomes is crucial (Alberti et al., 2025). Finally, integrating drying and extraction optimization by linking post-harvest moisture levels directly to supercritical CO2 or ethanol extraction yields will maximize the recovery of bioactive compounds (Calvo et al., 2025). Additional chromatographic studies evaluating terpene retention and cannabinoid stability under different drying conditions - such as controlled atmosphere chambers - would further improve the understanding of phytochemical preservation during post-harvest processing (Birenboim et al., 2024; Uziel et al., 2022).

CONCLUDING REMARKS

Drying represents one of the most important post-harvest operations influencing the quality, stability, medicinal and industrial value of cannabis inflorescences (Ubeed et al., 2021). Environmental parameters - including temperature, relative humidity, airflow velocity, and drying duration - strongly affect moisture migration kinetics, cannabinoid stability, and extraction performance (Jin et al., 2019; Lumu et al., 2025). Controlled drying conditions - specifically those that achieve a standardized water activity (Aw) between 0.55 and 0.65 - are essential for minimizing microbial risks associated with pathogens like Aspergillus spp. (Gwinn et al., 2023, p. 17), while preserving the concentration of bioactive phytochemicals and maintaining the structural integrity of glandular trichomes. For instance, maintaining temperatures below the 50°C - 70°C range is critical to avoid disrupting the cuticle of the glandular head and the subsequent loss of resin-rich secretions (Livingston et al., 2019). Among the available technologies, pilot-scale tray or cabinet drying systems provide improved environmental regulation and process consistency for industrial processing compared to traditional hang-drying (Lazarjani et al., 2021; Lumu et al., 2025). Residual moisture content and the structural state of the plant matrix further dictate solvent accessibility and mass transfer efficiency during subsequent extraction (Márquez-Herrera et al., 2026; Belwal et al., 2018). Adherence to established regulatory protocols and industry standards is essential for the globalization of medical-grade cannabis. For example, the Office of Medicinal Cannabis specifies that the water content of cannabis flowers must remain between 5% and 10% directly after packing to satisfy pharmaceutical-grade requirements (Jin et al., 2019). Furthermore, following industry standards such as ASTM D8196-18 ensures that flowers maintain a water activity level between 0.55 and 0.65 , which is critical for preventing fungal growth while preserving the volatile chemical profile (Lazarjani et al., 2021). Mathematical modeling of drying kinetics, including the application of thin-layer equations such as the Page and Midilli-Kucuk models and their implementation in advanced AI tools can provide a robust framework for predicting the drying endpoint and optimizing process parameters (Márquez-Herrera et al., 2026; Lumu et al., 2025). Further research into cultivar-specific protocols and innovative low-temperature technologies is necessary to resolve current inefficiencies and ensure the standardization of medical-grade Cannabis sativa L. products (Challa et al., 2020; Birenboim et al., 2024).

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СУШЕЊЕ ПО БЕРБА НА ЦВЕТОВИТЕ ОД *Cannabis sativa L.* И НЕГОВОТО ВЛИЈАНИЕ ВРЗ ЗАЧУВУВАЊЕ И ЕКСТРАКЦИЈА НА БИОАКТИВНИ ФИТОХЕМИКАЛИИ

Ангел Цветанов[1*], Круме Богевски[1], Викторија Максимова[1], Емилија Јаневиќ-Ивановска[1]
[1]*Факултет за медицински нуки, Универзитет „Гоце Делчев", „Крсте Мисирков" 10-А, 2000 Штип, Република Северна Македонија*

**Контакт автор: angel.479s@student.ugd.edu.mk*

Резиме

Сушењето е една од најкритичните посткултивациски операции по собирањето на цветот од канабис бидејќи директно влијае на микробиолошката стабилност, зачувувањето на фитохемискиот состав, однесувањето при складирање и перформансите на екстракција во натамошната обработка. Соцветијата на канабисот содржат високи почетни нивоа на влага и комплексна мешавина од канабиноиди, терпени, флавоноиди и други биоактивни соединенија кои се високо чувствителни на условите во животната средина при постжетвеното ракување. Неправилното сушење може да резултира со микробиолошка контаминација, волатилизација на терпените, деградација на канабиноидите, структурно оштетување на гландуларните трихоми и намалена ефикасност на екстракцијата. Параметрите на животната средина, вклучувајќи ги температурата, релативната влажност, брзината на протокот на воздух и времетраењето на сушењето, силно влијаат на кинетиката на миграција на влагата и севкупниот квалитет на цветот. Овој преглед го оценува влијанието на технологиите за сушење и условите за сушење врз физичко-хемиските својства на соцветијата од *Cannabis sativa L.* со акцент на стабилноста на канабиноидите, зачувувањето на терпените, структурните промени на растителните ткива и перформансите на екстракцијата. Посебно внимание е посветено на контролираните системи за сушење во тави (tray drying) поради нивната зголемена важност во стандардизираните операции за обработка на канабис. Прегледот дополнително ги дискутира механизмите за миграција на влагата, кинетиката на сушење, однесувањето на резидуалната влага и неинвазивните пристапи за следење базирани на намалувањето на тежината за време на сушењето. Дискутирани се и моменталните предизвици и идните перспективи за оптимизација на методологиите за сушење канабис.

Клучни зборови: *Cannabis sativa L., сушење по берба, канабиноиди, терпени, кинетика на сушење, сушење во послужавник, фитохемиско зачувување.*