Scientific Research Publishing

American Journal of Plant Sciences, 2024, 15, 222-234
https://www.scirp.org/journal/ajps
ISSN Online: 2158-2750
ISSN Print: 2158-2742

Modified Atmospheric Packaging and Its Effect on Postharvest Cannabis Quality

Luke L. MacLaughlin, Mason T. MacDonald

Department of Plant, Food, and Environmental Sciences, Faculty of Agriculture, Dalhousie University, Halifax, NS, Canada
Email: mason.macdonald@dal.ca

How to cite this paper: MacLaughlin, L.L. and MacDonald, M.T. (2024) Modified Atmospheric Packaging and Its Effect on Postharvest Cannabis Quality. *American Journal of Plant Sciences*, **15**, 222-234.
https://doi.org/10.4236/ajps.2024.153016

Received: January 18, 2024
Accepted: March 26, 2024
Published: March 29, 2024

Abstract

Cannabis sativa L. is used as fiber, food, and medicine in several countries. Though it is illegal for recreational use in most of the world, there are some countries that have legalized production and sale. There is a lot of research on production of cannabis, but less so on storage technologies. Cannabis contains several high value compounds, such as cannabinoids and terpenoids, that are susceptible to degradation via light, temperature, and oxygen. Several studies have explored temperature and light, and industry has adjusted accordingly. However, less is known about oxygen-induced degradation. Biochemical studies have demonstrated oxidative degradation of high value compounds, and many producers use some form of modified atmospheric packaging (MAP) for storage. However, the efficacy of MAP is unclear. The objective of this paper is to review our current understanding of MAP in postharvest cannabis storage and identify avenues where additional research is needed.

Keywords

Cannabinoids, *Cannabis sativa*, Marijuana, Nitrogen Packaging, Oxidation, Postharvest, Terpenoids, THC

1. Introduction

Cannabis sativa L. is an herbaceous annual plant that has been used as a source of fibers, food, and medicine in various countries for centuries [1]. Paleobotanical evidence suggests that *C. sativa* originated in central Asia over 10,000 years ago and spread to Europe and then the remainder of the world largely due to human cultivation [2]. *C. sativa* is a complex plant with over 400 biochemical entities, including cannabinoids, terpenoids, flavonoids, and alkaloids [3]. Cannabinoids, a class of terpene phenolic compounds, are the most active biochem-

ical compounds [4]. Delta-9-tetrahydrocannabinol (THC) is likely the most studied cannabinoid since it is the main compound associated with the psychoactive effects of *C. sativa* [5]. It is this psychoactive effect that had *C. sativa* as the most widely used illicit drug in the world [6], though use of *C. sativa* is now legal in several countries, Uruguay was the first country to regulate cannabis at the national level in 2013 [7]. Since regulation by Uruguay, several other countries have legalized cannabis for medicinal or recreational use. As of early 2023, Canada and 21 states in the United States of America have legalized cannabis for recreational use [8].

Cannabinoids and terpenoids are both high value compounds occurring in cannabis. Volatile organic compounds are an important component of cannabis' organoleptic properties [9] [10], while cannabinoids contribute to cannabis' psychoactive properties [11] [12]. Yet volatile terpenes decrease by 10 to 50% within 1 month of postharvest storage [13]. Cannabinoids are also susceptible to degradation during storage, generally through decarboxylation [14] [15] [16].

Retention of these high value compounds of dried cannabis inflorescence during storage has seen industry adoption of N_2 modified atmosphere packaging (MAP) technologies. Literature demonstrating the efficacy of MAP for the preservation of quality, aroma, and flavour, spans numerous agricultural products such as coffee (*Coffea arabica*), where aroma is important for customer satisfaction [17]. High N_2 conditions improve preservation of several volatile aromatic compounds over storage with atmospheric air [18]. Similar research has also demonstrated the efficacy of MAP for retention of aromatics, finding high N_2 storage of the aromatic plant lemon verbena (*Aloysia citrodora*) results in increased extractable essential oils content compared to atmospheric conditions [19]. Potato chip seasoning stored under high N_2 MAP has even been found to retain higher levels of volatile disulphides and terpenes compared toatmospheric control [20]. Use of MAP technologies for the storage of milk powder, a confectionary ingredient prone to oxidation and development of off-flavors, sees increased customer acceptance of downstream chocolate products [21].

Industry interest in the retention of these high-value compounds under storage has seen the adoption of MAP technologies within the Canadian market space. However, MAP infrastructure represents a significant cost to producers and limited research on its efficacy currently exists. This review discusses current research of cannabis stored under MAP, addressing limitations of previous work, and identifying gaps in our knowledge.

2. Modified Atmospheric Packaging (MAP)

2.1. History and Application

MAP alters the gaseous composition of atmospheric air surrounding perishable items to extend shelf life and preserve product quality [22]. Early research investigating modifying gaseous composition of apple storage environments for extended shelf life during the 1920s later saw the technology utilized for the trans-

port of hanging beef in the 1930s [23]. Industrialization and commercialization of MAP infrastructure eventually led to its adoption in the packaging of retail meats to prevent the development of aerobic bacteria and improve color retention in red meat via decreased oxidation [24]. Implementation by the seafood industry for inhibition of spoilage reportedly doubled or tripled shelf life in some circumstances [25]. However, widespread employment of MAP has been somewhat limited due to concerns around the potential development of anerobic microorganisms, such as *Listeria* monocytogenes in red meats and *Clostridium botulinum* in seafood products [24] [25]. The microbial pros and cons of using MAP for plant products are presented in other reviews [26].

The historical applications of MAP for products like baked goods, chips, coffee, and tea, offers examples seemingly aimed more towards the preservation of product quality and flavour, rather than prevention of microbial spoilage [23]. Improved organoleptic qualities like aroma and flavour under MAP in various food products has been reported in consumer panels [27] and studies exploring postharvest changes in the physical and chemical properties of plant products under MAP continue to emerge. The link between oxidation, degradation of lipids, and reduction in flavour is well documented, and presented in several reviews [28]. MAP technologies have demonstratable efficacy in delaying oxidation of lipids to improve the stability and shelf life of various food products including potato chips, red meats, and fish [24] [29] [30]. Molecules of oxygen present in atmospheric air react with unsaturated fatty acids, producing free radicals in the form of unstable hyperoxides which undergo a cascade of further reactions [31].

2.2. Challenges

MAP technologies are immensely popular and have a global value of more than $6 billion USD [32]. MAP slows deteriorative processes and limits microbial growth and therefore greatly extends product shelf life [32]. However, consumer preferences have shifted in recent years in favor of product quality as opposed to freshness [33]. The effect of MAP on many aspects of cannabis quality is not yet known.

The primary objective of MAP is to decrease the concentration of O_2 in storage packaging [32]. This can be done through a variety of methods, but one popular method is to add an inert gas, such as N_2, to the storage atmosphere to displace O_2 [32]. But the exact amount of O_2 displacement is critical and can pose a challenge. If O_2 is too low, anaerobic respiration can occur and postharvest quality rapidly decreases [32]. Taking MAP beyond tolerable limits has altered postharvest texture and aroma in other products, to the extent that consumers start to question freshness as well [34] [35].

MAP represents an additional cost for industry. Gases may be added directly from compressed gas cylinders or gas emitters may be added [36]. In the case of N_2 MAP, there is also the possibility of using a nitrogen generator or displace-

ment with liquid nitrogen [36]. Each application method has a fixed infrastructure cost that can range from tens to hundreds of thousands of dollars. There is also a residual cost, that would vary regionally with compressed gas or liquid N prices. As an example, in Nova Scotia it can cost up to $0.90 CAN per can to modifier the storage atmosphere using liquid N [37]. The challenge of the MAP additional cost is magnified considering there is a lack of knowledge in effectiveness of MAP in preserving postharvest quality of cannabis, including high value compound.

3. High Value Compounds and Preservation Targets

3.1. Identification

Cannabinoids and terpenoids account for most of cannabis' therapeutic effects, either individually and synergistically [38] [39] [40]. Cannabinoids and terpenoids are secreted from specialized disc cells and are then subsequently stored within trichomes on the surface of female inflorescence [41] [42] [43]. Many of these biosynthesized compounds, like cannabinoids and terpenoids, are lipidic in their nature and remain stored as oil-in-water emulsions contained within hydrophilic apoplast [44]. Cannabinoids are typically associated with cannabis, but are also found in some liverworts, rhododendron, and fungi [45]. Terpenoids are widespread throughout the plant kingdom [14].

3.2. Cannabinoids

The term cannabinoid refers to meroterpenoids, which comprise of a resorcinyl center with attached isoprenyl, alkyl, or aralkyl side chains [46]. Cannabis typically produces alkyl type cannabinoids with a 10-carbon monoterpene isoprenyl moiety and pentyl side chain [46]. The most abundant cannabinoids in *C.* sativa are THC, cannabidiols (CBDs), Cannabichromenes (CBCs), and cannabigerols (CBGs) and their respective acidic forms [47]. Natural biosynthesis usually forms acidic cannabinoids that contain a carboxyl group (COOH), but chemical processes such as oxidation, decarboxylation, or cyclization result in non-acidic forms [48] [49]. Such chemical processes are caused or accelerated by exposure to light, oxygen, or heat [14] [50].

Degradation of cannabinoids can result in loss of bioavailability, such as THC to cannabinol (CBN) [51]. However, cannabinoid oxidation to lesser understood compounds with unknown psychotropic and biological activity, or cannabinoids for which analytical testing does not exist presents some experimental design challenge. Oxidation to underappreciated and understudied cannabinoids that may even be beneficial under prolonged storage is also possible. Efforts to identify psychoactive forms of cannabinoids are still under way with recent research even seeing the application of machine learning [52]. "It is crucial to understand how cannabinoids are related with each other when studying cannabis, considering that degradation (including decarboxylation, isomerization, irradiation, and oxidation) can affect the chemical components through improper opera-

tions or during long-term storage with unsuitable conditions" [53]. Yet as reviewed by Rupasinghe *et al.* [54] the complex pharmacology and interactions of even the most well studied cannabinoids THC, and CBD, are still being unraveled.

3.3. Terpenoids

Terpenes and terpenoids are characterized by their strong aroma. These molecules are volatile hydrocarbons [14]. Terpenes are classified by the number of 5-carbon building blocks they contain. For example, sesqui-terpenes contain 15 carbons [55]. Terpenoids are modified terpenes that have incorporated various oxygen arrangements. Typically, terpenoids is an umbrella term including both terpenes and terpenoids [40].

Biosynthesis of terpenoids within the cannabis plant starts with isoprene diphosphate precursors that feed into the plastidial methylerythritol or cytosolic mevalonate pathway [9]. Cannabis essential oils are composed almost entirely of mono- and sesquiterpenes, accounting for 98% of constituents [56]. Characterization of both mono- and sesqui-terpenes classes across three different chemovars has identified a nearly even mixture of 46.5% monoterpenes and 53.5% sesquiterpenes [57]. The eventual fate of terpenes is dynamic, potentially ending up as cannabinoids via the addition of a phenol group or remaining stored as one of the many known endogenous terpenes present in the plant [58]. Natural degradation can also occur through chemical processes like isomerization, oxidation, dehydrogenation, polymerization, and thermal rearrangement [59]. The ultimate fate of any particular terpenes can be difficult to determine due to the number of products and functional groups that are formed. In cannabis alone, terpenes can be oxidized into alcohols, ketones, and aldehydes [60].

The roles and functions of plant terpenes are extremely diverse. As reviewed by Pichersky and Raguso [61], they act as antimicrobial, antifungal, signaling molecules, and contribute to interactions with their other organisms, such as pollinator attraction and deterring herbivory. Terpenes typically account for 3% - 5% of dried cannabis inflorescence biomass [62]. Potential medical benefits of terpenes, particularly those in cannabis, represent an area of great research interest. Consumption of plants rich in terpenes has a rich human history, and in-depth medical benefits of plant terpenes have been presented in other reviews [62] [63].

4. Location of High Value Compounds in Cannabis

4.1 Trichromes Structural and Functional Chemistry

Classified as multi-cellular appendages, the glandular trichomes of cannabis secrete and accumulate many economically important compounds, including cannabinoids, monoterpenes, and sesquiterpenes [41] [42] [43]. The metabolite storage cavities of *C. sativa* trichomes are subcuticular in nature and form via delamination of the primary wall [64] [65]. An anatomical arrangement that sees

two biological layers theoretically inhibit oxidation, and aid retention of high-value compounds under prolonged storage. The cell wall itself is rich in weakly bonded polysaccharides, and its composition has only recently been deduced via glycomic profiling and monosaccharide analysis by researchers investigating cell wall remodeling for prevention of metabolite leakage during trichome maturation [44]. However, the cuticle still represents the outermost layer of the modified epidermal cell, acting as a protective layer against water loss and oxidation, while serving as the interface for potential interactions with gaseous atmospheric environment.

From a structural perspective the glandular trichomes of cannabis are encapsulated by the cuticle, which is composed of varying lipidic layers [42] [66]. Structure of the cuticle varies amongst land plants, and working models of architecture vary, but the recent review from [67] defines the cuticle as three distinct layers: the cuticular layer, cuticle proper, and epicuticular waxes. With a composition of cellulose, polysaccharides, cutin, and waxes, the cuticular layer is constructed first and its assembly is adherent directly to the primary wall, or outermost layer of the polysaccharide rich epidermal cell wall [67]. The cuticle proper follows and is constituted mainly of cutin, intracuticular waxes, and, is typically considered void of polysaccharides, while a layer of epicuticular wax serves as the interface for potential interactions between the organ and the atmospheric environment [67]. The cuticle also contains additional embedded non-lipid polysaccharides and polyester linked phenolic compounds with their architectural and structural functionality under review [68].

4.2. Cuticle Degradation: A Potential Mechanism for Accelerated Degradation

The major macromolecular component of the cuticle is cutin, a polyester of covalently bound C16 and C18 hydroxylated fatty acids [69]. Reactions of the cuticle with oxygen species present in atmospheric air and generation of additional reactive oxygen species (ROS), offers a potential mechanism for the oxidation of the cuticular layer and subsequent oxidation of the primary cell wall (**Figure 1**). Accelerating degradation of the trichomes high value contents, however, mapping all potential interactions presents a challenge as the molecular assembly and mechanisms of linkage within the cuticle's constituents are complex [70] [71].

5. Cannabis Literature Conundrum

Most literature regarding postharvest degradation of high value compounds in cannabis have focused on other storage conditions, such as temperature and light. As one example, THC decreased by 63% when stored in light at 20°C for 98 weeks [72]. THC decreased by only 25% when stored in darkness instead, which was further reduced to 10% if storage temperature decreased to 5°C [72]. More recent studies have reported similar results [73] [74]. Most recently, it was shown that freezing samples in darkness could completely alleviate degradation of cannabinoids during storage even over several years [16].

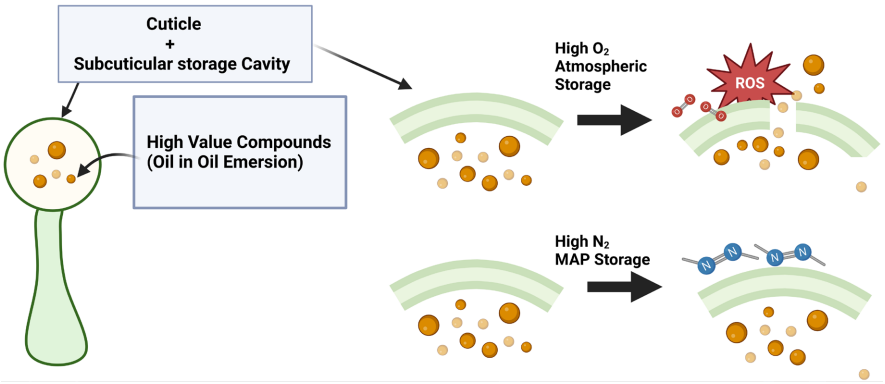

Figure 1. Graphical illustration for potential mechanism accelerated loss of high value compounds via oxidation of the cuticle and primary wall, resulting in escape of metabolites from the apoplastic storage cavity and their subsequent oxidation. Figure created with BioRender.com.

The presence of oxygen during storage is another factor that contributes to postharvest degradation of high value compounds. The addition of hydrogen peroxide, a strong oxidizing agent, greatly increased postharvest degradation of THC [75]. Conversely, storage with terpenes with established antioxidant properties effectively decreased degradation of THC [76]. Though terpene MAP was effective, it is more common for industry to use alternative MAP, such as N_2. The strategy with N_2 MAP is to greatly decrease the partial pressure of O_2 during storage, which should decrease the opportunity for oxidation. Industry currently does not typically include antioxidants with storage.

Despite commercial use, little is known on the effectiveness of N_2 MAP on preservation of high value targets in cannabis. One study investigated post-harvest changes in dried cannabis inflorescence terpene content under MAP using comparably unreactive argon but found no improvement versus storage in atmospheric conditions [13]. Storage at 2 weeks, and 4 weeks, saw terpene losses of 39.2% and 50.2% respectively under argon MAP, while losses of 40.5% and 51.6% were observed at the same time points for the control [13]. However, the flower sample used in this study had a very low terpene content of 0.170% w/w, due to its age at the time of sampling. With such a significant loss of volatile compounds having already occurred the potential for further loss would likely have been greatly reduced. A second study offered little experimental detail but reported storage in the absence of light to be more important for cannabinoid stability over storage with N_2, with major cannabinoids THC, CBD, and CBN measured [77].

N_2 MAP infrastructure represents a significant cost for industry. Further, liquid or gaseous N_2 dosage represents another incurred operational cost, yet little evidence for its efficacy over atmospheric storage exists. Other better-known factors can be addressed through cooling and storage in opaque containers. However, MAP requires more work to determine whether N_2 is effective. Even if N_2 MAP is effective, the exact effectiveness needs to be quantified and other potential strategies explored.

6. Conclusion

Though MAP has been used for almost 100 years commercially, it has only been used within the last few decades for legalized commercial production of cannabis. There is sufficient evidence that N_2 MAP or similar technologies are effective as increasing the shelf life of postharvest cannabis. However, there is less information available on effectiveness of N_2 MAP on the preservation of high value compounds, such as cannabinoids and terpenoids, in cannabis. The little information that's available academically supports the idea that N_2 MAP does not preserve those high value compounds. The lack of information available underscores a major gap in our knowledge that would be of value to the cannabis industry.

Acknowledgements

We thank Dr. Chijioke Emenike for reviewing an early draft of this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Piluzza, G., Delogu, G., Cabras, A., Marceddu, S. and Bullitta, S. (2013) Differentiation between Fiber and Drug Types of Hemp (*Cannabis sativa* L.) from a Collection of Wild and Domesticated Accessions. *Genetic Resources and Crop Evolution*, **60**, 2331-2342. https://doi.org/10.1007/s10722-013-0001-5

[2] Pisanti, S. and Bifulco, M. (2018) Medical Cannabis: A Plurimillenial History of an Evergreen. *Journal of Cellular Physiology*, **234**, 8342-8351. https://doi.org/10.1002/jcp.27725

[3] Andre, C.M., Hausman, J.F. and Guerriero, G. (2016) Cannabis Sativa: The Plant of the Thousand and One Molecules. *Frontiers in Plant Science*, **7**, Article 19. https://doi.org/10.3389/fpls.2016.00019

[4] Taura, F., Sirikantaramas, S., Shoyama, Y., Shoyama, Y. and Morimoto, S. (2007) Phytocannabinoids in Cannabis Sativa: Recent Studies on Biosynthetic Enzymes. *Chemistry and Biodiversity*, **4**, 1649-1663. https://doi.org/10.1002/cbdv.200790145

[5] Gaoni, Y. and Mechoulam, R. (1964) Isolation, Structure, and Partial Synthesis of an Active Constituent of Hashish. *Journal of American Chemical Society*, **86**, 1646-1647. https://doi.org/10.1021/ja01062a046

[6] Degenhardt, L., Coffey, C., Carlin, J.B., Swift, W., Moore, E. and Patton, G.C. (2010) Outcomes of Occasional Cannabis Use in Adolescence: 10-Year Follow-Up Study in Victoria, Australia. *British Journal of Psychiatry*, **196**, 290-295. https://doi.org/10.1192/bjp.bp.108.056952

[7] Queirolo, R., Repetto, L., Sotto, B. and Álvarez, E. (2023) Explaining the Impact of Legal Access to Cannabis on Attitudes toward Users. *International Journal of Public Opinion Research*, **35**, edad010. https://doi.org/10.1093/ijpor/edad010

[8] Manthey, J., Jacobsen, B., Hayer, T., Kalke, J., López-Pelayo, H., Pons-Cabrera, M.T., Verthein, U. and Rosenkranz, M. (2023) The Impact of Legal Cannabis Availability on Cannabis Use and Health Outcomes: A Systematic Review. *International Journal*

of Drug Policy, **116**, Article ID: 104039.
https://doi.org/10.1016/j.drugpo.2023.104039

[9] Booth, J.K. and Bohlmann, J. (2019) Terpenes in Cannabis Sativa—From Plant Genome to Humans. *Plant Science*, **284**, 67-72.
https://doi.org/10.1016/j.plantsci.2019.03.022

[10] Lowe, H., Steele, B., Bryant, J., Toyang, N. and Ngwa, W. (2021) Non-Cannabinoid Metabolites of *Cannabis sativa* L. with Therapeutic Potential. *Plants*, **10**, Article 400.
https://doi.org/10.3390/plants10020400

[11] Mechoulam, R., Hanuš, L.O., Pertwee, R. and Howlett, A.C. (2014) Early Phytocannabinoid Chemistry to Endocannabinoids and Beyond. *Nature Reviews Neuroscience*, **15**, 757-764. https://doi.org/10.1038/nrn3811

[12] Pertwee, R. (1988) The Cental Neuropharmacology of Psycotropic Cannabinoids. *Pharmacology and Theurapeutics*, **36**, 189-261.
https://doi.org/10.1016/0163-7258(88)90106-4

[13] Bueno, J., Leuer, E., Kearney, M., Green, E.H. and Greenbaum, E.A. (2020) The Preservation and Augmentation of Volatile Terpenes in Cannabis Inflorescence. *Journal of Cannabis Research*, **2**, Article No. 27.
https://doi.org/10.1186/s42238-020-00035-z

[14] Milay, L., Berman, P., Shapira, A., Guberman, O. and Meiri, D. (2020) Metabolic Profiling of Cannabis Secondary Metabolites for Evaluation of Optimal Postharvest Storage Conditions. *Frontiers in Plant Science*, **11**, Article 583605.
https://doi.org/10.3389/fpls.2020.583605

[15] Mazzetti, C., Ferri, E., Pozzi, M. and Labra, M. (2020) Quantification of the Content of Cannabidiol in Commercially Available E-Liquids and Studies on Their Thermal and Photo-Stability. *Scientific Reports*, **10**, Article 3697.
https://doi.org/10.1038/s41598-020-60477-6

[16] Grafström, K., Andersson, K., Pettersson, N., Dalgaard, J. and Dunne, S.J. (2019) Effects of Long-Term Storage on Secondary Metabolite Profiles of Cannabis Resin. *Forensic Science International*, **301**, 331-340.
https://doi.org/10.1016/j.forsciint.2019.05.035

[17] Mahmud, M.M.C., Keast, R., Mohebbi, M. and Shellie, R.A. (2022) Identifying Aroma-Active Compounds in Coffee-Flavored Dairy Beverages. *Journal of Food Science*, **87**, 982-997. https://doi.org/10.1111/1750-3841.16071

[18] Marin, K., Pozrl, T., Zlatič, E. and Plestenjak, A. (2008) A New Aroma Index to Determine the Aroma Quality of Roasted and Ground Coffee during Storage. *Food Technology and Biotechnology*, **46**, 442-447.

[19] Ebadi, M., Sefidkon, F., Azizi, M. and Ahmadi, N. (2016) Packaging Methods and Storage Duration Affect Essential Oil Content and Composition of Lemon Verbena (*Lippia citriodora* Kunth). *Food Science and Nutrition*, **5**, 588-595.
https://doi.org/10.1002/fsn3.434

[20] Agarwal, D., Mui, L., Aldridge, E., Mottram, R., McKinney, J. and Fisk, I.D. (2018) The Impact of Nitrogen Gas Flushing on the Stability of Seasonings: Volatile Compounds and Sensory Perception of Cheese & Onion Seasoned Potato Crisps. *Food & Function*, **9**, 4730-4741. https://doi.org/10.1039/C8FO00817E

[21] Lloyd, M.A., Hess, S. and Drake, M. (2009) Effect of Nitrogen Flushing and Storage Temperature on Flavor and Shelf-Life of Whole Milk Powder. *Journal of Dairy Science*, **92**, 2409-2422. https://doi.org/10.3168/jds.2008-1714

[22] Utama, N.A. (2020) Usage of Heat Treatment and Modified Atmosphere Packaging to Maintain Fruit Firmness of Fresh Cut Cavendish Banana (*Musa cavendishii*).

Planta Tropika: *Jurnal Agrosains*, **8**, 126-132. https://doi.org/10.18196/pt.2020.122.126-132

[23] Davies, A.R. (1995) Advances in Modified-Atmosphere Packaging. Springer eBooks, New York, 304-320. https://doi.org/10.1007/978-1-4615-2105-1_14

[24] Zhao, Y., Wells, J.H. and McMillin, K. (1994) Applications of Dynamic Modified Atmosphere Packaging Systems for Fresh Red Meats: Review. *Journal of Muscle Foods*, **5**, 299-328. https://doi.org/10.1111/j.1745-4573.1994.tb00538.x

[25] Stammen, K., Gerdes, D.L. and Caporaso, F. (1990) Modified Atmosphere Packaging of Seafood. *Critical Reviews in Food Science and Nutrition*, **29**, 301-331. https://doi.org/10.1080/10408399009527530

[26] Caleb, O.J., Mahajan, P.V., Al-Said, F.A. and Opara, U.L. (2012) Modified Atmosphere Packaging Technology of Fresh and Fresh-Cut Produce and the Microbial Consequences—A Review. *Food and Bioprocess Technology*, **6**, 303-329. https://doi.org/10.1007/s11947-012-0932-4

[27] Spencer, K.C. and Humphreys, D.J. (2002) Argon Packaging and Processing Preserves and Enhances Flavor, Freshness, and Shelf Life of Foods. *ACS Symposium Series*, **836**, 270-291. https://doi.org/10.1021/bk-2003-0836.ch020

[28] Labuza, T.P. and Dugan, L.R. (1971) Kinetics of Lipid Oxidation in Foods. *CRC Critical Reviews in Food Technology*, **2**, 355-405. https://doi.org/10.1080/10408397109527127

[29] Marasca, E., Greetham, D., Herring, S. and Fisk, I.D. (2016) Impact of Nitrogen Flushing and Oil Choice on the Progression of Lipid Oxidation in Unwashed Fried Sliced Potato Crisps. *Food Chemistry*, **199**, 81-86. https://doi.org/10.1016/j.foodchem.2015.11.136

[30] Kitabayashi, K., Tanimoto, S., Kikutani, H., Ohkita, T., Mabuchi, R. and Shimoda, M. (2018) Effect of Nitrogen Gas Packaging on Odor Development in Yellowtail Seriola Quinqueradiata Muscle during Ice Storage. *Fisheries Science*, **85**, 247-257. https://doi.org/10.1007/s12562-018-1253-y

[31] Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F.J., Zhang, W. and Lorenzo, J.M. (2019) A Comprehensive Review on Lipid Oxidation in Meat and Meat Products. *Antioxidants*, **8**, Article 429. https://doi.org/10.3390/antiox8100429

[32] Boz, Z., Welt, B.W., Brecht, J.K., Pelletier, W., McLamore, E., Kiker, G.A. and Butler, J.A. (2018) Review of Challenges and Advances in Modification of Food Package Headspace Gases. *Journal of Applied Packaging Research*, **10**, 62-97.

[33] Mangaraj, S., Goswami, T.K. and Mahajan, P.V. (2009) Applications of Plastic Films for Modified Atmosphere Packaging of Fruits and Vegetables: A Review. *Food Engineering Reviews*, **1**, 133-158. https://doi.org/10.1007/s12393-009-9007-3

[34] Shewfelt, R.L. (1999) What Is Quality? *Postharvest Biology and Technology*, **15**, 197-200. https://doi.org/10.1016/S0925-5214(98)00084-2

[35] Fillion, L. and Kilcast, D. (2002) Consumer Perception of Crispness and Crunchiness in Fruits and Vegetables. *Food Quality and Preference*, **13**, 23-29. https://doi.org/10.1016/S0950-3293(01)00053-2

[36] Parry, R.T. (1993) Principles and Applications of Modified Atmospheric Packaging. Springer Science + Business Media, Dordrecht.

[37] Air Liquid (2024) Nitrogen. https://www.airliquide.ca/nitrogen/category/IG-Nitrogen

[38] Guzmán, M. (2003) Cannabinoids: Potential Anticancer Agents. *Nature Reviews Cancer*, **3**, 745-755. https://doi.org/10.1038/nrc1188

[39] Russo, E.B. and Marcu, J. (2017) Cannabis Pharmacology: The Usual Suspects and a Few Promising Leads. *Advances in Pharmacology*, **80**, 67-134. https://doi.org/10.1016/bs.apha.2017.03.004

[40] Russo, E.B. (2011) Taming THC: A Potential Cannabis Synergy and Phytocannabinoid-Terpenoid Entourage Effects. *British Journal of Pharmacology*, **163**, 1344-1364. https://doi.org/10.1111/j.1476-5381.2011.01238.x

[41] Johnson, H.B. (1975) Plant Pubescence: An Ecological Perspective. *Botanical Review*, **41**, 233-258. https://doi.org/10.1007/BF02860838

[42] Mahlberg, P.G. and Kim, E. (1991) Cuticle Development on Glandular Trichomes of Cannabis Sativa (Cannabaceae). *American Journal of Botany*, **78**, 1113-1122. https://doi.org/10.1002/j.1537-2197.1991.tb14518.x

[43] Livingston, S.J., Quilichini, T.D., Booth, J.K., Wong, D., Rensing, K.H., Laflamme-Yonkman, J., Castellarin, S.D., Bohlmann, J., Page, J.E. and Samuels, A.L. (2019) Cannabis Glandular Trichomes Alter Morphology and Metabolite Content during Flower Maturation. *Plant Journal*, **101**, 37-56. https://doi.org/10.1111/tpj.14516

[44] Livingston, S.J., Bae, E.J.A., Unda, F., Hahn, M.G., Mansfield, S.D., Page, J.E. and Samuels, A.L. (2021) Cannabis Glandular Trichome Cell Walls Undergo Remodeling to Store Specialized Metabolites. *Plant and Cell Physiology*, **62**, 1944-1962. https://doi.org/10.1093/pcp/pcab127

[45] Gülck, T. and Møller, B.L. (2020) Phytocannabinoids: Origins and Biosynthesis. *Trends in Plant Science*, **25**, 985-1004. https://doi.org/10.1016/j.tplants.2020.05.005

[46] Hanuš, L.O., Meyer, S.M., Muñoz, E., Taglialatela-Scafati, O. and Appendino, G. (2016) Phytocannabinoids: A Unified Critical Inventory. *Natural Product Reports*, **33**, 1357-1392. https://doi.org/10.1039/C6NP00074F

[47] Happyana, N. and Kayser, O. (2016) Monitoring Metabolite Profiles of *Cannabis sativa* L. Trichomes during Flowering Period Using 1H NMR-Based Metabolomics and Real-Time PCR. *Planta Medica*, **82**, 1217-1223. https://doi.org/10.1055/s-0042-108058

[48] Sirikantaramas, S., Taura, F., Tanaka, Y., Ishikawa, Y., Morimoto, S. and Shoyama, Y. (2005) Tetrahydrocannabinolic Acid Synthase, the Enzyme Controlling Marijuana Psychoactivity, Is Secreted into the Storage Cavity of the Glandular Trichomes. *Plant and Cell Physiology*, **46**, 1578-1582. https://doi.org/10.1093/pcp/pci166

[49] Flores-Sanchez, I.J. and Verpoorte, R. (2008) Secondary Metabolism in Cannabis. *Phytochemistry Reviews*, **7**, 615-639. https://doi.org/10.1007/s11101-008-9094-4

[50] Berman, P., Futoran, K., Lewitus, G.M., Mukha, D., Benami, M., Shlomi, T. and Meiri, D. (2018) A New ESI-LC/MS Approach for Comprehensive Metabolic Profiling of Phytocannabinoids in Cannabis. *Scientific Reports*, **8**, Article No. 14280. https://doi.org/10.1038/s41598-018-32651-4

[51] Huestis, M.A. (2007) Human Cannabinoid Pharmacokinetics. *Chemistry & Biodiversity*, **4**, 1770-1804. https://doi.org/10.1002/cbdv.200790152

[52] Ramesh, J. (2020) Identification of Psychoactive Metabolites from Cannabis Sativa, Its Smoke, and Other Phytocannabinoids Using Machine Learning and Multivariate Methods. *ACS Omega*, **5**, 281-295. https://doi.org/10.1021/acsomega.9b02663

[53] Jin, D., Jin, S. and Chen, J. (2019) Cannabis Indoor Growing Conditions, Management Practices, and Post-Harvest Treatment: A Review. *American Journal of Plant Sciences*, **10**, 925-946. https://doi.org/10.4236/ajps.2019.106067

[54] Rupasinghe, H.V., Davis, A., Kumar, S.K., Murray, B. and Zheljazkov, V.D. (2020) Industrial Hemp (*Cannabis sativa* Subsp. *sativa*) as an Emerging Source for Val-

ue-Added Functional Food Ingredients and Nutraceuticals. *Molecules*, **25**, Article 4078. https://doi.org/10.3390/molecules25184078

[55] Shapira, A., Berman, P., Futoran, K., Guberman, O. and Meiri, D. (2019) Tandem Mass Spectrometric Quantification of 93 Terpenoids in *Cannabis* Using Static Headspace Injections. *Analytical Chemistry*, **91**, 11425-11432. https://doi.org/10.1021/acs.analchem.9b02844

[56] Bedini, S., Flamini, G., Cosci, F., Ascrizzi, R., Benelli, G. and Conti, B. (2016) *Cannabis sativa* and *Humulus lupulus* Essential Oils as Novel Control Tools against the Invasive Mosquito *Aedes albopictus* and Fresh Water Snail *Physella acuta*. *Industrial Crops and Products*, **85**, 318-323. https://doi.org/10.1016/j.indcrop.2016.03.008

[57] Wanas, A.S., Radwan, M.M., Chandra, S., Lata, H., Mehmedic, Z., Alı, A., Başer, K.H.C., Demirci, B. and ElSohly, M.A. (2020) Chemical Composition of Volatile Oils of Fresh and Air-Dried Buds of Cannabis Chemovars, Their Insecticidal and Repellent Activities. *Natural Product Communications*, **15**, 1-7. https://doi.org/10.1177/1934578X20926729

[58] Aliferis, K.A. and Bernard-Perron, D. (2020) Cannabinomics: Application of Metabolomics in Cannabis (*Cannabis sativa* L.) Research and Development. *Frontiers in Plant Science*, **11**, Article 554. https://doi.org/10.3389/fpls.2020.00554

[59] Turek, C. and Stintzing, F.C. (2013) Stability of Essential Oils: A Review. *Comprehensive Reviews in Food Science and Food Safety*, **12**, 40-53. https://doi.org/10.1111/1541-4337.12006

[60] Calvi, L., Pentimalli, D., Panseri, S., Giupponi, L., Gelmini, F., Beretta, G., Vitali, D., Bruno, M., Zilio, E., Pavlovic, R. and Giorgi, A. (2018) Comprehensive Quality Evaluation of Medical *Cannabis sativa* L. Inflorescence and Macerated Oils Based on HS-SPME Coupled to GC-MS and LC-HRMS (q-Exactive Orbitrap®) Approach. *Journal of Pharmaceutical and Biomedical Analysis*, **150**, 208-219. https://doi.org/10.1016/j.jpba.2017.11.073

[61] Pichersky, E. and Raguso, R.A. (2016) Why Do Plants Produce so Many Terpenoid Compounds? *New Phytologist*, **220**, 692-702. https://doi.org/10.1111/nph.14178

[62] Nuutinen, T. (2018) Medicinal Properties of Terpenes Found in *Cannabis sativa* and *Humulus lupulus*. *European Journal of Medicinal Chemistry*, **157**, 198-228. https://doi.org/10.1016/j.ejmech.2018.07.076

[63] Cox-Georgian, D., Ramadoss, N., Dona, C. and Basu, C. (2019) Therapeutic and Medicinal Uses of Terpenes. In: Joshee, N., Dhekney, S. and Parajuli, P., Eds., *Medicinal Plants*, Springer, Cham, 333-359. https://doi.org/10.1007/978-3-030-31269-5_15

[64] Hammond, C.T. and Mahlberg, P.G. (1978) Ultrastructural Development of Capitate Glandular Hairs of *Cannabis Sativa* L. *Cannabaceae). American Journal of Botany*, **65**, 140-151. https://doi.org/10.1002/j.1537-2197.1978.tb06051.x

[65] Tissier, A., Morgan, J.A. and Dudareva, N. (2017) Plant Volatiles: Going 'In' But Not 'Out' of Trichome Cavities. *Trends in Plant Science*, **22**, 930-938. https://doi.org/10.1016/j.tplants.2017.09.001

[66] Lara, I., Belge, B. and Goulão, L.F. (2015) A Focus on the Biosynthesis and Composition of Cuticle in Fruits. *Journal of Agricultural and Food Chemistry*, **63**, 4005-4019. https://doi.org/10.1021/acs.jafc.5b00013

[67] Skrzydeł, J., Borowska-Wykręt, D. and Kwiatkowska, D. (2021) Structure, Assembly and Function of Cuticle from Mechanical Perspective with Special Focus on Perianth. *International Journal of Molecular Sciences*, **22**, Article 4160. https://doi.org/10.3390/ijms22084160

[68] Reynoud, N., Petit, J., Brès, C., Lahaye, M., Rothan, C., Marion, D. and Bakan, B. (2021) The Complex Architecture of Plant Cuticles and Its Relation to Multiple Biological Functions. *Frontiers in Plant Science*, **12**, Article 782773. https://doi.org/10.3389/fpls.2021.782773

[69] Yeats, T.H. and Rose, J.K.C. (2013) The Formation and Function of Plant Cuticles. *Plant Physiology*, **163**, 5-20. https://doi.org/10.1104/pp.113.222737

[70] Pollard, M., Beisson, F., Li, Y. and Ohlrogge, J.B. (2008) Building Lipid Barriers: Biosynthesis of Cutin and Suberin. *Trends in Plant Science*, **13**, 236-246. https://doi.org/10.1016/j.tplants.2008.03.003

[71] Kunst, L. and Samuels, L. (2009) Plant Cuticles Shine: Advances in Wax Biosynthesis and Export. *Current Opinion in Plant Biology*, **12**, 721-727. https://doi.org/10.1016/j.pbi.2009.09.009

[72] Fairbairn, J., Liebmann, J.A. and Rowan, M.G. (1976) The Stability of Cannabis and Its Preparations on Storage. *Journal of Pharmacy and Pharmacology*, **28**, 1-7. https://doi.org/10.1111/j.2042-7158.1976.tb04014.x

[73] Lindholst, C. (2010) Long Term Stability of Cannabis Resin and Cannabis Extracts. *Australian Journal of Forensic Sciences*, **42**, 181-190. https://doi.org/10.1080/00450610903258144

[74] Trofin, I.G., Dabija, G., Văireanu, I. and Filipescu, L. (2012) The Influence of Long-Term Storage Conditions on the Stability of Cannabinoids Derived from Cannabis Resin. *Revista de Chimie*, **63**, 422-427.

[75] Carbone, M., Castelluccio, F., Daniele, A., Sutton, A., Ligresti, A., Di Marzo, V. and Gavagnin, M. (2010) Chemical Characterisation of Oxidative Degradation Products of Δ^9-THC. *Tetrahedron*, **66**, 9497-9501. https://doi.org/10.1016/j.tet.2010.10.025

[76] Bueno, J., Alborzi, S. and Greenbaum, E.A. (2023) Vapor Phase Terpenes Mitigate Oxidative Degradation of *Cannabis Sativa* Inflorescence Cannabinoid Content in an Accelerated Stability Study. *Cannabis and Cannabinoid Research*, **8**, 887-898. https://doi.org/10.1089/can.2021.0207

[77] Turner, C.E., Hadley, K.W., Fetterman, P.S., Doorenbos, N.J., Quimby, M.W. and Waller, C.W. (1973) Constituents of *Cannabis sativa* L. IV: Stability of Cannabinoids in Stored Plant Material. *Journal of Pharmaceutical Sciences*, **62**, 1601-1605. https://doi.org/10.1002/jps.2600621005